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BIRD FLIGHT AND AIRPLANE FLIGHT

A. Magnan

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16. Abstract

Prof. Magnan summarizes his life's work and surveys the related literature in the following series of lectures, which were given on the occasion of his appointment to the Collège de France. His research was based on a series of mechanical, electrical, and cinematographic instruments he developed with his coworkers to measure various features of air current behavior as well as bird and airplane flight. Magnan's investigation of rising obstruction and thermal currents led him to a theory of bird flight, especially of the gliding and soaring types. He then shows how a knowledge of bird flight can be applied to glider and ultimately motorized aircraft construction. In the last part of the book, Prof. Magnan describes the instruments and methods he used in studying stress in airplanes and in comparing the lift to drag ratios of airplanes and birds.

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Bird Flight and Airplane Flight

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Introductory Lesson /5*

It is not without some emotion that I take my place today in that great scientific institution, the Collège de France, which has acclaimed so many famous scientists in the four hundred years of its existence.

I therefore wish to convey before starting my lecture how much I am touched by the honor that Mr. Croiset, the administrator, and the professors at the Collège have paid me by accepting me as a colleague to teach the science of bird and mechanical flight.

It is not without apprehension that I prepare to teach this subject in an institution where that great scientific genius Marey has covered similar topics.

I hope that my temerity will be pardoned. Much of the research that I will analyze is in fact a continuation of his work, and most of the new data could be obtained only through the use of his marvelous invention, the motion-picture camera.

I also want to express my appreciation to all those who have aided my scientific work. First of all, there is Mr. Laurent-Eynac, Minister of the Air Force, who, with the approval of the Minister of Education, decided to establish the chair of animal mechanics as applied to airplanes at the same time as he was planning an Institute of Fluid Mechanics.

Science should be grateful to Laurent-Eynac for this innovation. He understood the important role that scientific research was beginning to play in the field of aviation, and did not want the Americans or the Germans to have a monopoly in aerodynamics. He not only encouraged researchers to work together in a close and fruitful collaboration, but also created new positions at the universities for doing the teaching and research that were vitally necessary.

It must also be added that if today I have the honor of being a professor at the Collège de France, it is because of the sympathetic support and encouragement that my own professors have given me. These include Professor Painlevé, that great expert in fluid mechanics and one of the fathers of aviation; Professor Cavalier, Director of Higher Edducation; Professors d'Arsonval, Bouvier, Koenigs, Rateau, and Vincent, all members of the Institute; and Professor Fortant, Inspector General of Aeronautics, who supported my work, as well as giving me indispensable encouragement. My heart-felt thanks to all of them.

*Numbers on the margin indicate pagination in the foreign text.

For at least the past hundred thousand years, living beings have been flying through the atmosphere. They have been supported by wings that are merely the transformed anterior limbs of earth-bound creatures. Among the precursors of animal flight, some, like the archeopteryx, were rather small, the size of a chicken. Others, such as the pteranodon, were practically airplanes with movable wings. They resembled giant bats with a wing spread of as much as ten meters and a weight of 300 kg. Thus, in a period when nature was enamored with bigness and had created the diplodocus, she had also designed a kind of living airplane with fabric-covered wings and the weight of modern passenger airplanes.

As Pitois has so well described it in his work on the origins of aeronautical navigation (published on the occasion of the official Aeronautical Exposition in 1926), the ancients also dreamed of rising into the air like birds. /6 Well before the twentieth century, bold attempts at flying occurred. It must be pointed out that is was these attempts that gave birth to aviation. Ovid has given us the story of Daedalus, the first airplane builder, and of Icarus, his son and the first pilot, who were victims of their audacity and temerity. This legend proves that already during the epoch of King Minos, people contemplated copying birds. The apparatus invented by Icarus was very primitive. It consisted of artificial wings made of feathers bound together with a linen core and wax coating the outside. This is what caused the loss of Icarus. Icarus had been advised by his father not to fly too high or too low. However, he went so high into the air that, as a result of excessive stress, the wax gave way and the first wing failure in recorded history resulted.

Although such ancient attempts at flight seem more legendary than real, others seem closer to reality or are even known to have taken place. The authors of these attempts had the same idea as Daedalus. They tried to unlock the secret of flight by imitating the birds.

Twenty centuries after Icarus's death, the monk Olivier de Malmesburg followed in his footsteps. De Malmesburg built a winged structure that resembled that of Daedalus as much as it did that of Lilienthal. He then launched himself from the top of a tower in an attempt to glide back to earth. Instead of crashing into the ocean like his predecessor, de Malmesburg hit the ground and broke both legs.

A hundred years later, an Arab tried to keep himself up with the aid of a sort of parachute with a wicker frame. He jumped from the top of the hippodrome at Constantinople and died.

At about the same time, a locksmith in Sablé constructed a rudimentary device and actually succeeded in making several short flights.

Then, in the fourteenth century, J.B. Dante of Perugia claimed to have been successful in trials with well-designed wings above Lake Trasimeno. He tried to repeat this success above Perugia, but fell on the roof of St. Mark's Church and broke a thigh bone. Nonetheless, Dante's experiments aroused so much interest that Dante eventually received a chair in mathematics at the University of Venice.

It was not until the eighteenth century that new attempts at flight were made. One such attempt was made by de Bacqueville, who jumped from the window of his townhouse, which was situated not far from the Institute. He succeeded in flying above the Seine for 100 meters. Unfortunately, a loss of speed caused him to crash into the roof of a wash-house and die.

A hundred years later, at the end of the nineteenth century, new experiments were made by the German Lilienthal. Using a glider of his own design, Lilienthal successfully made over a thousand flights in 1891 before he was finally killed.

His method was to take off from a cliff against the wind. He constantly tried to extend his flight, and his apparatus became more and more sophisticated.

Lilienthal's test flights lasted only two or three minutes at most. During these flights, he worked at perfecting his piloting ability and, thanks to some careful observations, the capabilities of his equipment. He thus paved the way for powered flight, which after all is only gliding with the addition of an engine for motive power.

It was precisely this powered gliding that Lilienthal's successors sought to achieve.

One of Lilienthal's imitators was the Englishman Pilcher. Pilcher lifted himself off the ground by driving a team of horses at full gallop while suspended in his glider. When he had reached a certain height, he released the reins. Pilcher also died in a crash.

We should also mention the Americans Herring and Chanute, who /7
were experts in flying, like the Wright brothers. Until 1903, the Wright brothers limited themselves to glided descents to learn how to maintain the airborne equilibrium of their airplane and to discover what kind of control mechanisms were needed in this vehicle. The final result of this series of tests was the magnificent performance at Auvour in 1908. On this occasion, W. Wright made a two-hour flight at 60 km per hour in a biplane equipped with only an 18 hp engine. Flying along with him to observe was Painlevé, who thus became the first passenger as well as the first mathematician to make a first-hand observation that the laws of attraction were relative. While powered flight was gradually evolving in America due to the tenacity of the Wright brothers, it was also coming into being in France. The French approach was somewhat different. Efforts just as tenacious as those of the Wright brothers went into creating engines that were powerful enough to lift into the air and to sustain in flight any airplane that could then be built.

The first successful test of a powered airplane was in fact that of Ader, who in 1897 flew a motorized airplane that was modeled on the way a bat flies.

The next successful tests were made in 1906 by Santos-Dumont, Blériot, Esnault-Pelterie, Farman, Delagrange, and Ferber. They began by making little more than leaps through the air, but then progressed to short flights. It must be stressed that it was advances in automobile engines that made these flights possible. The necessary light-weight internal combustion engines developed primarily for automobiles were then adapted for use in flying machines.

Soon the goal seemed to be to transform airplanes into projectiles. As Painlevé has correctly observed, "Research efforts concentrated on the motor and to some extent on the propeller, i.e., the propulsive force, to the exclusion of wing design and the relationship between wing type and driving mechanism. The dream was to rush through the air like a meteor while at the same time enjoying a state of equilibrium and security, to maintain oneself in the air by smashing into it with such force that the caprices of the fluid environment could be disregarded. Behind the dream lay a paroxysm of incredible violence. In the 'life or death struggle' with time, space, and the deadly force of gravity, this route imposed itself on human intelligence and the resources of modern industry. It also brought about the war, that imperious and ferocious mistress who could no longer be kept waiting."

In 1906 airplanes could attain only 45 km/h. By 1911 they had reached 120, 200 in 1913, 430 in 1924, and can fly at speeds of more than 500 km/h at the present time. It is obvious to say that this progress is not yet over and that one day much greater speeds will be seen, either by flying at higher altitudes or by using jet engines.

There is more than one type of possible motive force. The birds don't have propellers and they fly perfectly well all the same.

As L. Bréguet has stated in an informative lecture on aviation, its past and future, none of the progress in the fight against gravity would have been possible if the pioneers of this heroic epoch had not relied on laboratory scientists to provide them with information on how to design the best possible machinery. Many people worked in this field. However, not much has really been said on the subject. The basic laws of aviation, at least concerning resistance to bird and mechanical flight, were discovered by Newton in 1670. They state that fluid resistance is perpendicular to the surface, and that it is proportional to the square of the speed, to the density of the fluid, to the surface area, and to the square of the sine of the angle of incidence. The only part that has been significantly changed involves the last variable. Its relation to resistance was modified by Colonel Duchemin.

Reynolds, in 1874, proved that the coefficients of the formulas that contain the square of the speed are not constant for certain values of the product of the speed multiplied by the linear dimension of the object under consideration.

In any case, all these formulas are only applicable to flat surfaces. There have been no studies made on curved surfaces. We /8
are completely ignorant of the characteristics of surfaces shaped like those of birds.

While the engineers and pilots were carrying out their work in the limelight, others accomplished their tasks in the background. We must state our recognition of the achievements of these men. First of all was the great scientist Colonel Renard who not only built the first dirigible, but also made an important contribution to the science of aerodynamics. Then there was Eiffel who invented the wind tunnel, which was used to collect invaluable data on air resistance at the Auteuil laboratory. Around 1909, A. Rateau made another series of measurements of air resistance utilizing a similar wind tunnel. The fans and turbines in the tunnel enabled Rateau to study the phenomena of fluid flow with a great deal of precision.

Rateau also invented the supercharger for use on engines at high altitudes. Without this device, rapid air travel would not be possible. These and other studies which have been carried out in every country have made many important contributions to aviation. They have resulted among other things in the improvement of the lifting force of wings and more streamlined airframes.

In a related area, the marvelous flying ability of birds continues to be an object of fascination for researchers. Do the wings of birds have some special, still undiscovered characteristics? Many people have sought an explanation for birds' flight beyond just magic. Numerous others, meanwhile, have tried to prove that human beings can fly better than birds. They have braved storms to demonstrate that it is possible for us to travel long distances at 200 km/h and that we can cross the Atlantic in two days. At the same time, there are others who still claim that birds are the best flying machines. Birds never crash because of loss of speed. They make use of all the resources of nature and can fly immense distances and climb up to 9000 and even 10,000 meters into the air. Who is right? Those who think copying avian flight is a step backward, who are proud of their mechanical ability, and who believe that they have beaten the bird on its own territory, or those who seek their inspiration from nature? Which is the better machine? The airplane has a heart of steel and wastes an enormous amount of energy. It cuts through everything in its path with an incredible racket, as P. Painlevé has so well described. The bird, on the other hand, has only a little engine that runs on almost no fuel. For example, a pigeon can fly at 80 km/h for five hours without stopping to eat, and therefore without expending a great deal of energy. Birds lose almost no weight during flight. They take advantage of the force of the wind rather than fighting against it.

Many still think that the mystery of avian flight must be cleared up for the benefit of aviation.

Research has been done in every direction. Examples of the studies carried out include those concerning the wing spread, the weight, and the strength of birds.

What errors were made at first! Mention was made of condors with a 6-meter wing spread, and of albatrosses that weighed 25 kg and had a 5-meter wing spread. Observation has brought these figures closer to reality: 3 1/2 meters for the albatross, which is still pretty big, and a tail width of 23 cm, with an aspect ratio of 17. Navier once calculated that a swallow required 25 hp to fly. This calculation resulted in the term "Navier's error."

It is only in the last fifty years that a team of scientists has taken up where Archytas, the inventor of the screw, left off in trying to copy the movements of birds. They have pretty much succeeded in clearing up the mystery of live flight. In 1891, Penaud and Trouvé organized test flights of fifty meters with a moving wing machine. Another researcher, Marey, who was a remarkable inventor, attempted to determine precisely how birds flew.

I should say first of all that Marey's book on the flight of birds /9
is perhaps the most complete and perfect analysis that has been made up until now of a single wing movement. All the methods of experimental physiology were brought into play to examine its details. There can be nothing more ingenious than the dynamometric device that was placed across a pectoral muscle in a sort of corset to detect changes in the length of the muscle. The dynamometer was connected by means of a tube 10 cm long to another device which plotted the myographic curve on a cylinder while an electric chronograph recorded at what point the bird began to raise and lower its wing.

I obviously cannot describe in this first lecture the results of Marey's experiments on this subject. I also will not describe the tricks he used to discover the exact path that the wing makes in motion.

However, I do want to touch upon his invention of "chronophotographs", or motion pictures. This invention, as a result of the influence of the Lumière brothers, has become a device for entertainment and propaganda that has made its power felt throughout the entire world. From the scientific and aeronautic points of view, it has also been a very important instrument. It has been absolutely indispensable in studying bird and airplane flight, and was in fact invented by Marey for this very purpose.

Marey, as a great scientist and fore-runner, had an idea of the potential of motion pictures.

Not only did he invent cinematic photography on a moving film, but he also thought of possible uses of his invention. These include studies of walking (human and quadruped), of swimming, of flight, and of microscopic animals. He thought of using movies to record the trajectory of a glider in the air and thus to investigate the laws of resistance for moving objects of various forms. These are examples of applications in the physical sciences. I stress that Marey did not actually make any of these experiments, but he thought of them.

Marey completely understood the importance of his invention and its superiority over similar systems. He claimed that his method was simpler and more sensitive than the others for recording the evolution of a phenomenon. This was because no matter how complex the situation that was being investigated, motion pictures do not interfere at all with what is going on. This is certainly not the case for mechanical methods of recording motion.

I will not argue that the future of aviation lies in copying nature. However, I am going to show how it is linked in part to the study of what nature has done. The laws of physics were created by nature herself, and she knows them better than we do.

Birds and bats fly through the air to travel from one point to another. From this point of view, flight is not much different from walking or swimming either on the surface or under the water. All these methods of displacing a living organism are characterized by the prolonged continuity of the phenomenon as well as by the existence of a basic cycle that is repeated indefinitely, as long as the organism wants to continue moving.

Flapping flight in birds is a system of alternating propulsive shocks. The air constitutes only an indirect support. The immediate motive effect is due to the inertial reaction of the body with the moving wing during the downward thrust (the first phase of a flap).

The same distinguishing features are to be found universally, in every species of bird and flying mammal. The uniformity of flapping flight in living things is much greater than the similarities to be /10 found in comparing, say, the motion of a horse, a tiger, and a human being.

Flight rhythm can differ in frequency but not in pattern. When comparing a walk with a trot and a trot with a gallop, however, the pattern itself is found to change.

Should we continue to use airplanes in which the propulsive force and propeller are independent of the body of the airplane and act upon it like any other external force, as if it were pulling the airplane with a rope, for example?

Should we, on the contrary, try to constuct apparatus in which the motive force is not distinct from the body, but would fly by means of reactions with the environment, changing periodically in size, direction, and point of application?

Should we agree with the people who contend that movable wing aircraft are not practicable?

But who can foretell so definitely what the future has in store?

Remember the prediction of the famous astronomer Lalande. He stated that it was absolutely impossible that human beings could rise up and fly in the air. The use of movable wings for elevation was just as impossible as the use of hollow bodies voided of air, according to him. Lalande's calculations showed, fuethermore, that a human being would need wings with a surface area of 107 m^2 in order to fly.

Two years later, the Montgolfière was invented and Blériot crossed the English Channel in an airplane that had only 10 m^2 of lift surface.

As I have said, a bird does not lose any weight when flying from Paris to Brussels. The aerodynamic efficiency of its body is very great, so it glides most of the way and needs only a small amount of power.

Pre-war wind tunnel tests showed that a natural wing made of bones and feathers is inferior to the wings of an airplane. Lafay found that the drag to lift ratio was 11% for a Blériot blade, 20% for a pigeon wing, and 4% for a whole pigeon.

The conclusion to be gathered from this is that birds have a difficult time flying and encounter a great deal of air resistance. It follows that avian flight is very exhausting, if not impossible, and demands a great deal of energy. However, experience has shown us that the amount of energy consumed is very small and that the gracefulness and maneuverability of a bird is very great. A dead wing must not have the same characteristics as a living one. It is easy to prove this by studying the trajectory that birds follow.

Huguenard and Planiol developed for us cinematic equipment that can be used to photograph on the same film a bird and an airplane in flight, a chronometer, and a network of reference lines fixed to the ground a little way in front of the objective.

To accomplish this, a combination lens was designed that allows two objects at widely varying distances from the camera to be photographed in focus at the same time. In collaboration with Huguenard and Sainte Lague we showed that it was possible to derive the lift and air resistance from the paths followed by birds and airplanes in flight. We could thus compare the flight-worthiness of various kinds of apparatus.

In this manner, we found that a swallow, for the only polar curve point that was obtained after multiple attempts, had an aerodynamic efficiency of 19.5, whereas a good fighter plane had a maximum efficiency of less than 6. A bird is therefore at least three times more efficient than an airplane and much better suited for flying. This is why it requires only a very small motive force.

Birds do not just glide or fly by flapping their wings. They can also soar without using any energy at all.

Many tourists have observed birds rising up into the air with- /11
out moving their wings. Above cliffs at the edge of the ocean, soaring birds performing maneuvers that last a considerable length of time without moving their wings may be seen daily. Some, like the sea gulls, rise up almost vertically with their wings spread out and their beaks usually pointed into the wind. The initial rise from the crest of a wave is rather rapid, then they slow down as they reach their final altitude, which is highly variable. They look as if they are riding in an elevator. Having reached a certain height above the water, they stay there for a while. Then they slide through the air and lose altitude only to start all over again.

Sea gulls are also capable of flying horizontally without moving their wings. They turn to face the wind and fly sideways along the cliff in one direction or the other. The trajectory is almost parallel to the upper edge of the cliff. In order to do this, they turn the axis of their bodies so that their head is pointed in the direction in which they want to move.

Sea gulls make no sharp turn to change direction. They merely modify the direction in which the axis of their body is pointed when they want to change direction.

In the tropics, the soaring of vultures similarly presents a grandiose spectacle. Mouillard, who was a remarkable observer, described the flight of vultures in the following fashion:

> "These are the kings of the air, always soaring...They slowly describe immense circles, without any sudden jerks or stops...
>
> "As I have said before, a large vulture can fly without a single flap of its wings. Not once, but hundreds of times, I have seen large numbers of vultures in oriental cities hovering around slaughterhouses, waiting for their food while keeping themselves aflight without a single movement of their wings. They rise so high as to be invisible and then descend back to 220 meters above the ground, with the wind, against the wind, to the right, or to the left. They even fly off to explore the surrounding territory to see if there isn't some dead animal that is easier to get hold of. In the course of the day's tour they make twenty ascents of 1,000 meters each, and travel 100 leagues without beating their wings even once."

There is another type of soaring that is even more impressive than those I have already mentioned. This is the flight of the large ocean-going birds such as the albatross. Their rhythm is practically always identical, as they carry out, without ever flapping their wings, ascents, descents, and almost vertical turns. They skim the surface of the water, usually between two waves, then turn to face the wind and rapidly rise to twenty meters. After another turn they return close to the surface of the water. This cycle is repeated endlessly as the birds travel immense distances, even circling the globe.

Although naturalists had long ago discovered the existence of soaring, until the end of the nineteenth century no serious experimentation had been carried out on the question. This kind of flight was shrouded in mystery for a very long time.

Some curious souls soon noted that there was an obvious correlation between soaring and the presence of wind. The wind then became the basis of the various theories advanced to explain soaring. However, since not much was known of the structure of the wind, many errors were made.

When I began my study of soaring in 1914, using a flexible wing aircraft to carry out experiments in horizontal winds, it was clear /12 to me that the nature of the wind had to be studied. Unfortunately, this necessity was not recognized by airplane manufacturers of the period.

The means available to me to carry out my research were thus insufficient. I was not even able to make a rough evaluation of the usable energy contained in the wind.

In 1922, Huguenard, Planiol and I decided to build a very sensitive anemometer capable of measuring rapid variations of the wind. As our experiments progressed, we quickly realized the extent and complexity of soaring. We needed more than an anemometer to detect the structure of air currents. We also required an indicator of instantaneous direction for studying the atmosphere. A pilot would need a whole group of dashboard instruments to have a sense of atmospheric movements. In birds, the ability to sense changes in the air was attributed to a mysterious instinct.

We were led to design and build special devices which were as delicate as those found in physics laboratories.

We invented a hot wire anemometer with a compensating battery.

We also needed a device for measuring the instantaneous direction of the wind with the same period as the anemometer. It occurred to us to use hot wires also to record the directional fluctuations in air current. We thus constructed a simple apparatus by placing two identical hot wires inside a cylinder and equidistant from the axis of symmetry of this cylinder.

This equipment allowed us to take up the study of wind structure. The data already collected in this field was very small. It must be remembered that it was only fifty years ago that Langley proved that the wind had a variable speed, and that until Lilienthal discovered them thirty years ago, variations in wind inclination were unknown. The hot wires enabled us to discover that variations in inclination are greater near the ground than at 2000 meters and very much greater than over the ocean. This alone, however, was not enough to calculate the trajectory of a glider or a bird. Besides the wind speed, direction, and inclination for any given point at which the bird or airplane was located, it was necessary to known the time derivatives of these variables. We therefore built an apparatus for automatically plotting the curve of the change in wind speed and angular velocity over time.

Just as with balloons or smoke, hot wires can be used to determine the average speed of ascent of the air. During the course of these studies it was noted that temperature inequalities, like variations in terrain, cause ascending air currents.

When the sun beats down strongly upon the earth, the ground heats up and then gives up heat to the air with which it is in contact.

The air becomes lighter as it increases in temperature and rises up into the atmosphere, giving birth to ascending currents.

Ascending currents are also caused when horizontal winds hit an obstacle (cliff, mountain, tree, etc.) and are force upwards around it.

All these experiments, which were repeated in areas where soaring birds are active, have increased our understanding of the mechanics of the different modes of soaring and have shown that:

1) Sea gulls, which follow coastal cliffs, make use of the ascending current created by these obstacles.

2) Vultures take advantage of the rising currents caused by heat to perform their great circling flights in warm countries.

3) Albatrosses use variations in wind speed to support themselves in the switch-back paths they follow above the ocean. /13

Once the mystery of avian soaring was solved, human beings were able to successfully imitate two of its modes. Like the sea gulls, people have used rising air currents to take off from the tops of cliffs and glide for as long as 11 hours. People have also been able to travel as far as 150 km by using the rising thermal currents that exist under some kinds of clouds. This is a great victory for mankind. However, it could only have been obtained with the aid of experimental studies. The mathematical methods with which some people have tried to solve such problems have been shown to be completely inadequate for describing avian flight. Only research intothe external envirnoment and the characteristics of the soaring birds themselves could have furnished the key to the puzzle.

This essential point must be stressed. It was only in 1922 that people could for the first time imitate one of the flight patterns of birds. It is true that powered flight required that science had advanced to the point of inventing the internal combustion engine. However, Daedalus was capable of building a glider indentical to present models made of wood lathes and varnished canvas. Icarus, just like Maneyrol, could have remained suspended in the air for several hours if he had suspected the existence of rising currents of air along cliffs. It was precisely this ignorance of external conditions that caused Lilienthal to fly through ascending currents in front of his launching hill without being able to take advantage of them.

Wind studies have still another area of interest. The acceleration of the wind is not only responsible for keeping a glider in the air but also for the extra stress on the framework of an airplane that results from atmospheric turbulence. The usefulness of measuring and studying such turbulence is obvious.

The flight of birds and airplanes is usually examined in "standard atmospheric conditions" as defined in experimental physics. Standard conditions are an abstraction, an ideal limit that can only be approached in an artificial environment and have no direct relation to the actual atmosphere. The arbitrariness of this procedure is incompatible with what we already know. Although the air maintains an appearance of homogeneity and continuity, it is nevertheless the site of all sorts of more or less periodic phenomena. Aviation cannot afford to ignore these phenomena because they are closely associated with the forces brought into play by the material system formed by the bird or airplane and the air around it. We must become acquainted with the undulations of the atmosphere.

Fortant, the Inspector General of Aeronautics, has pointed out that when studying maritime history, one is struck by the fact that several thousand years passed before people began to get an idea of the dynamics of waves, even of those created by the passage of a boat through water that was originally calm. However, these two kinds of agitation, which superimpose their effects when the water is not calm, have always had a significant influence on the propulsive efficiency of boats, their use and their safety. Now, atmospheric navigation does not count its age in millennia, but only in decades. Almost nothing is yet precisely known about the undulatory movements in a turbulent atmosphere, nor, which is even worse, about the undulatory agitation created when an aircraft passes through the air. The ability of aircraft to withstand dangerous vibrations caused by turbulence or by the interaction between atmospheric agitation and the oscillations and vibrations that aircraft produce cannot be predicted.

It was thought until recently that the increased stress undergone by an airplane flying in turbulent air never exceeded 1/5 g. Huguenard, Planiol and I, with the aid of a mercury accelergoraph that we built, showed that unfortunately this is not true. /14

We attached this instrument to a Gourdou-Leseurre 180 hp airplane in such a way as to record the maximum component of acceleration normal to the wings. The maximum value attained was 6.5 g during flattening out. We also found that the magnitude of this value was greater than the acceleration due to gravity in a wind of 10 m/sec. In such a wind the airplane was supporting twice its weight.

This is also true for birds. Huguenard and I discovered this using a small accelerograph that weighed only 50 grams, and measured 7 cm long by 3 cm high. Despite its small size, it was able to record the vertical acceleration of the bird upon whose back it was attached.

However, for a bird, gusts of wind are not just something to be endured, as they are for an airplane. It is able to anticipate the coming changes in speed and direction of the wind and takes advantage of them. This ability is not linked to mysterious sense organs, but to gust strength indicators.

I now think that the mysterious sense that birds were thought to possess actually is based on the elementary laws of mechanics. Their sense organs simply allow them to estimate when a gust is coming.

First of all, any change in the wind causes a change in lift force which raises the bird up, as in an elevator. We all know that this kind of ascending motion is perceptible because of the effect it has on the weight of our bodily organs.

In the bird there is another indicator of gusts that is even more direct than the sensation of acceleration. Through the intermediary of the wing skeleton, their weight is supported by the wing muscles. The amount these muscles are stretched depends on the stress on the wing. Any variation of the aerodynamic stress caused by the wind is immediately translated into a variation of muscle tension. A very simple dynamometer indicating muscle activity could thus directly indicate the passage of gusts. This is exactly the method Huguenard, Planiol and I used. We constructed a wing stress indicator that enabled us, after static airfoil tests, to calculate the aerodynamic stress that the wing undergoes from the measurement of wing deformation. This instrument works by comparing fluid levels. It has the following advantages:

1) It allows the pilot to constantly survey the stress endured by the wing during flight maneuvers or when passing through air turbulence.

2) The normal stress caused by aircraft maneuvers and atmospheric conditions can be determined. This would contribute to the establishment of standard safety factors for airplane construction.

3) The aging of aircraft can be constantly checked because the indicator also detects permanent deformations, which no accelerometer is capable of.

The report that I have just made shows that the scientific study of avian flight is not the only field that calls for this type of instrumentation. Meteorology, aerology, powered aviation, and aeronautics in general face analogous problems. This apparatus has already made a contribution to their solution.

I would also like to show that the study of fish swimming is of great interest, too, even for aviation.

Few experiments have been carried out in this area, even fewer concerning the efficiency ratio of fish bodies. I believe that F. Houssay is the first person to study the resistance that a piscine body encounters when in motion. /15

Houssay, who was a professor of mine, was one of the most creative scientists that I have ever known. A partisan of the theory of evolution, he thought that the external environment played a considerable role in the life of an animal. This is why he tried to demonstrate experimentally the influence of diet on the physical constitution of birds.

He was particularly interested in the flight of birds and the swimming of fish, and he published an important monograph on this latter question in 1912. The first data on the strength of fish are contained in his book.

He also wrote several lengthy books on "form and life" in which he expressed some completely novel ideas, whose importance was later recognized. Among other things, he thought that the fish's body was plastic, and that it had been molded by the water. Its form was therefore perfectly streamlined. Any time perfect form is not attained, the water knocks against and rubs away the imperfection until it is reduced to the smallest size possible.

Houssay tried to study the form and efficiency of different types of hulls. To do this, he constructed a set of models all having a maximum width of 34 mm, the same surface finish, and only differing as to form. Six oblong shapes were chosen. Sixteen meters above the ground, he nailed a board holding a rudimentary pulley through which passed a rope. With this pulley he hoisted a more precise pulley carrying a fine wire. At one end the wire was attached to a weight and at the other end it first passed through a pulley 50 cm under the water and then was attached to one of Houssay's models.

The models were then immersed by a boat in the water of a large pond. They were allowed to move a horizontal distance of 16 meters, equal to the height of the weight. The time was measured with a Bréguet chronometer, which was started by a device fixed to the wire and halted when the boat touched the land.

For each model, a series of different weights was attached to the wire in order to obtain different rates of speed.

Houssay found that the hull modeled after a fish (which resembled fish like the red gurnet more than it did slender fish like the trout) was surpassed only by a hull with a large rear end. The addition of fins made the fish model the best of all.

Along with Sainte Lague, I followed up on these experiments by using real fish.

Even now it is thought that resistance is approximately proportional to the square of the speed. We wanted to see what was the law of resistance for fish. All the experiments carried out to study corporal resistance until then had involved solid bodies held by an arm or drawn by a rope. The interaction of the support and the floating body could render the results inaccurate.

This is why it appeared necessary to us first of all to find a way of eliminating any exterior support. A means of propulsion interior to the body was needed. The force of gravity furnished us with this means.

We chose fish with a range of forms. Immediately after their death, we measured their weight and buoyancy. We then weighted them down by putting particles of lead in their mouths. This gave them a certain speed of descent in water without changing their outward form. Each fish was then suspended above a tub full of water with all its fins folded up except the tail fin. It was then released and fell straight down, with the head first because of the lead ballast.

We filmed the descent of each fish through a set of reference lines simultaneously with an oscillating pendulum. Examination of the speed curves showed that for practically all the species studied, the time elapsed was directly proportional to the square root of the distance fallen. This is the same as saying that the resistance encountered is constant, at least for speeds of less than 2 m/sec, which was the maximum attained by the fish. /16

The proportionality of $\sqrt{x}$ and t, or of x and t^2, implies a law of descent identical to that of gravity, i.e. a law of constant acceleration. Since the excess of weight over buoyancy is constant, the force of resistance is also constant.

This was the case for most of the fish we studied, such as the mackerel or the meager. It was not true for the skate, whose spherical body encountered increased resistance with growing speed.

These results demonstrate the importance of such experimental research and the interest it has for aviation. They clearly indicate that there exist situations, which are not even suspected, in which the most established physical laws or the most generally accepted ideas do not hold.

The study of the phenomena of fluid flow around a moving body is therefore far from complete. The theory of fluid mechanics is not sufficiently advanced at the present time to produce reliable predictions.

The mathematicians and technicians must not be held in contempt for this. On the contrary, theory and mathematics are indispensable for the advancement of science. They just have to be based on experimentation or verified by experiments. Progress in a science like aeronautics can take place only if experimentation is given all the place it deserves.

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Lesson Two: Apparatus for Making Aerodynamic Measurements Pertaining to Flying /17

During this lesson, I am going to examine the methods used to study and measure the properties and movements of the air.

First of all, I wish to excuse myself if I mention my own work or that which I have done in collaboration too often. As you know, the chairs of the Collège de France have been established to allow researchers to publicize the results of their work. I am thus only following tradition.

The flight of birds and airplanes raises numerous problems, originating in both the characteristics of the birds and airplanes themselves and in the properties of the external environment, i.e. the atmosphere.

An analysis of flight is therefore possible only if air currents and structure are studied. Researchers in every country have had to design instruments capable of obtaining the necessary information, or at least the rough data needed for a first examination of the question. Generally speaking, the instruments made for use in meteorology are completely unsuitable for studying the interaction between wing surfaces and variable winds. In addition, the behavior of certain factors which play an important role in this interaction, such as the density of air, is poorly understood in the neighborhood of an airplane.

These considerations have led to experimental attempts to measure the rapid variations of certain parameters, although previously only the average value was needed.

The branch of physics that deals with the study of the atmosphere and its movements and which is closely connected to aerodynamics is called aerology. It is a very active area of research in Germany but does not receive enough attention in France. However, aerology is in fact the study of the environment that is encountered by aircraft in flight. It investigates the character of the different layers of the atmosphere as well as air currents and wind. Meanwhile, aerodynamics focuses on the forces exerted on moving surfaces in the air and the pressures felt by a body exposed to air currents. It is obvious that progress in aerodynamics and its application to aviation are linked to progress in aerology. Much attention must be paid to atmospheric studies before aerodynamics can move forward. It is by the scientific, empirical study of the atmosphere that the problems of flight will be understood, since the airplane, like the bird, is dependent on the properties of the air as it flies through it.

I. The Composition of the Air /17

As everyone knows, the atmosphere is a mixture of gases. In fact, this mixture is more complex than commonly thought. The proportions of the gases that make up the atmosphere are the following:

	%	Density (H = 1)
Nitrogen	78.03	13.92
Oxygen	20.99	15.94
Argon	0.94	15.96
Carbon Dioxide	0.03	22.09
Hydrogen	0.01	1
Neon	0.0015	9.96
Helium	0.00015	1.98
Krypton	0.00005	41.50
Xenon	0.0000006	65.35

This is the approximate composition of the lower layers of the atmosphere. The exact proportions vary according to atmospheric conditions.

II. General Properties of Gases and Air

Let us review the general properties of gases so as to be able to understand the rest of this article.

Matter is divided into three states: solid, liquid, and gas.

Solid bodies have a fixed shape that remains constant, as does the volume, if the temperature does not change.

Liquids, on the contrary, have a form that is easily changeable. They are unstable. Liquids mold themselves to the objects that contain them, but their upper surface remains free and horizontal. The volume of liquids changes only a little with increasing pressure.

Gases have a completely different nature. Their molecules are highly mobile and have a tendency to separate off from the others. This is why these bodies are always ready to expand. They always fill up the space that encloses them and only the force of a wall is capable of limiting their expansion. On the other hand, the volume of a gas can be reduced a great deal from its initial size. Gases are therefore very expandable and very compressible.

If a tube, one of whose ends is sealed while the other is fitted with a piston, is filled with air, it is possible, by pushing in the piston, to reduce enormously the volume occupied by the air. This is because of its compressibility. However, a growing resistance is felt as the volume is reduced. As soon as one stops pushing on the piston, the air acts like a spring and pushes the piston out as a result of its expandability.

When the temperature changes, all bodies, solid, liquid, or gas, change volume. They expand when heated and contract when cooled. However, gases expand a lot more than liquids, and liquids expand a lot more than solids. At constant pressure, if the temprature increases from 0° to 273°, the volume of a gas is doubled.

Nevertheless, gases are also viscous. They also weigh something and have a characteristic density. To prove this, take a 10 liter vessel fitted with a valve and evacuate it. Then weigh it and let the air return. The weight will gradually increase until the total gain is 12 grams. This experiment proves that the weight of a liter of air is 1.2 grams. If the experiment had been carried out at a pressure of 760 mm and a temperature of 0°, the weight of a liter of air would have been found to be 1.293 grams. The density of air is thus 770 times less than the density of water. /19

Like other gases, air exerts a force, either from the inside to the outside on the walls of receptacles in which it is contained, or from the outside inwards on the surface of objects surrounded by air. This force is always normal to the walls of containers or the surfaces of bodies.

Since gases are also compressible and fluid, they seem analogous to liquids. The fundamental principles of hydrostatics concerning the equilibrium of liquids, which were discovered by Archimedes and Pascal, are based on the compressibility and fluidity of liquids. They therefore also hold true for gases.

In order that a gas be in equilibrium, each of its points must be pressed equally from every direction, as is the case for liquids. Gases therefore exert an equal pressure at every point of a container. The pressure on any point in a gaseous mass is transmitted equally in every direction. The total force on a surface is proportional to the size of the surface.

It is because of the transmission of pressure equally in every direction that a soap bubble swells up and takes on a spherical form.

In a manner similar to liquids, when a body is plunged into the air it undergoes an upward force equal to the weight of the air that it displaces. The body loses a part of its weight equal to the weight of the air displaced. As some people have put it, this is Archimedes' Law applied to stationary fluids.

Thus, if a small balloon is filled with hydrogen, it rises into the air because it weighs less than the volume of air displaced. If small objects of greater and greater weight are attached to it by a string, there comes a moment when the balloon stops rising and remains in stationary equilibrium. The weight of the balloon and that of the object suspended from it are then equal to the upward force exerted by the air.

These are the properties that have been applied in the construction of small balloons for launching atmospheric soundings and of larger balloons for airborne transportation.

Finally, Stevin's Law is also applicable to gases. This law states that the pressure exerted by a liquid in equilibrium on the horizontal bottom of its container is equal to the weight of a column of the liquid whose base has the same area as the bottom of the container and whose height equals the height of the liquid in the container.

It follows from Stevin's Law that the difference between the pressure exerted at two different points of a liquid in equilibrium is equal to the weight of a column of the liquid having a base one unit in surface area and a height equal to the distance between the two points. This too is true for gases.

III. General Properties of the Earth's Atmosphere

All these considerations will help us to understand observations first made a long time ago concerning the earth's atmosphere, i. e. about the layer of air that surrounds our globe.

First of all, it is clear why the air that covers us did not disperse into space a long time ago. The reason is found in the earth's gravity which keeps the molecules of gas that make up the air close to the surface.

It is also understandable that lower layers of the atmosphere, which support the upper layers, are denser than them. This is because of the comresssability of the air. The lower layers also have a /20
great elastic force, as Pascal has shown. If one climbs a high mountain with a balloon half filled with air, the higher one goes the more it will expand.

All objects in contact with the air are pressed upon by a pressure known as atmospheric pressure. The existence of this pressure was proved by an experiment attributed to Toricelli, who used an instrument called a barometer. This instrument consists of a tube 90 cm long with a cross-sectional area of 1 cm^2 and closed at one end. It is filled with mercury, and then, after having been plugged with a finger, is turned over and its free end is submerged in a pool of mercury (figure 1). The height of mercury in the tube then falls, but stops approximately 76 cm above the surface of the pool. A balance is thus established between the pressure supported by the square centimeter of surface below the bottom of the tube and the pressure exerted on a square centimeter of the upper surface of the pool. The pressure of the air is thus equal to the weight of a column of mercury having a base of 1 cm^2 and a height of about 76 cm:

$$p = 1 \times 76 \times 13.6 = 1{,}033 \text{ gr/cm}^2$$

This pressure has been designated one atmosphere pressure. At sea level it is commonly approximated as 1 kg/cm^2.

One can make the same demonstration with other liquids, but tubes of a greater height will have to be used because other liquids are less dense than mercury. Thus, for water, a tube 10 meters long would be necessary because a column of water supported by atmospheric pressure can be as high as 10.33 meters.

For a column of air to be in equilibrium with the pressure of the atmosphere, 1 kg per square centimeter would be needed. This corresponds to a height of 8000 meters, if the air is uniform throughout.

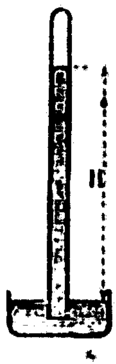

Fig. 1
Mercury
Barometer

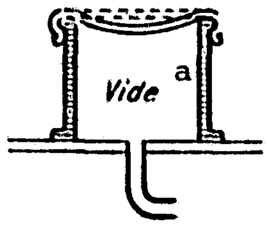

Fig. 2
Rupture
Chamber

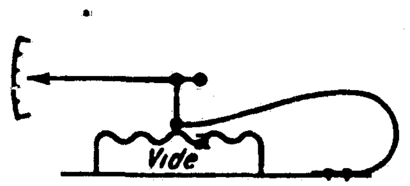

Fig. 3
Vidi
Barometer

Key: a) vacuum

It is interesting to show how great the force is that is exerted on an object by atmospheric pressure. One way this may be done is with a small glass container known as a rupture chamber. This vessel is open at one end and covered by a membrane on the other. The shape of the membrane is constant as long as there is air on both sides. If the uncovered end of the glass is attached to a vacuum pump and is partially evacuated, the membrane first bends inward (figure 2), then pops under the weight of the air. One can also get an idea of this pressure by noting that our body has a surface area of about 17,000 cm^2 and therefore supports a total of 17,000 kg. Such a weight does not crush us because the liquids that fill the cavities and tissues of our body counterbalance the pressure of the atmosphere.

Other experiments have proved that atmospheric pressure goes down as altitude increases, as would be expected from the hydrostatic law /21
explained above.

In the atmosphere, the reduction of pressure per meter of altitude equals the weight of a 100 cm^3 volume of air, or 0.13 grams per cm^2.

IV. The Measurement of Atmospheric Pressure

The most precise laboratory instrument for measuring the weight of the atmosphere is a mercury barometer. As everyone knows, this weight is variable at ground level and diminishes as one goes up in altitude.

Vidi Metal Barometers

However, because of their delicacy and the difficulty in transporting them, more convenient metal barometers have been invented.

Unfortunately, metal barometers must occasionally be compared with the readings obtained from mercury barometers if one wants to assure a consistent degree of accuracy.

Metal barometers have many uses. In meteorology, they serve to measure and record the value of atmospheric pressure on the ground. They are used in aeronautics to indicate and record the variation in pressure when a balloon or an airplane rises higher in the air. In this case they are called barographs. The markings on the dial do not necessarily represent centimeters of mercury. They can also be read in height above sea level in order to tell the pilot the altitude at which the airplane is flying. The instrument is then called an altimeter.

Metal barometers are in general made of a flat box. On the upper side, the box is sealed with a thin flexible metal plate and the air inside is evacuated. The curvature in the plate increases as the atmospheric pressure increases. The movement of the center of the plate, after being amplified, is transmitted to a needle (figure 3).

The construction of actual instruments designed in this manner is difficult. Especially for aeronautic use, they have to be very accurate and give consistent readings. Any hysteresis that exists must therefore be eliminated as completely as possible.

Because of the importance of possessing accurate instruments in this field, Huguenard, Planiol, and I have created a type of barometer and altimeter based on entirely different mechanical principles.

H.M.P. Bellows Barometers and Altimeters

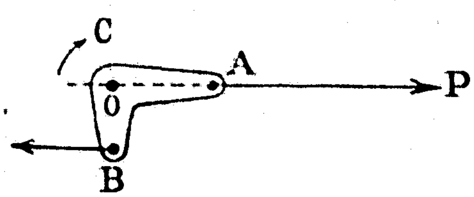

Figure 4
Moving Part
of H.M.P. Barometer

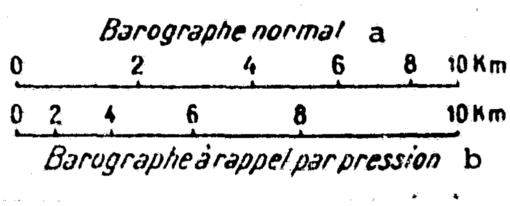

Figure 5
Comparison of the Scales
of an H.M.P. and a Conventional
Barograph

Key: a) Conventional Barograph
b) Compensating Bellows Barograph

a) Operating Principles

The force P produced by the action of atmospheric pressure on a deformable box void of air acts on the arm OA of the lever AOB, whose axis is at O (figure 4). OA tries to move in the direction of P when no other force is exerted on it (except for the force that holds O in /22 place). If a torque c is exerted on AOB, the piece is displaced by an angle θ (assumed to be small), which is proportional to c and inversely proportional to the ambient pressure. Contrary to what happens in ordinary instruments, the result is that the torque causes a rotation that increases as the air becomes more rarefied. This is because the restoring torque created by atmospheric pressure acting on the device diminishes along with this pressure.

In the H.M.P. barograph or altimeter, the force acting on point B of the arm OB perpendicular to the compensating arm OA is the result of a spring. The initial tension of the spring as well as its elastic constant are chosen so as to obtain the required sensitivity in the apparatus and the desired amount of displacement of the needle.

If the spring is very flexible, the difference between its tension of the ground and at the maximum altitude will be practically zero. The deviation of the needle will then be practically proportional to the reciprocal of the pressure, and its sensitivity will increase with altitude (figure 5).

If, on the other hand, a spring with only moderate flexibility is chosen, the sensitivity of the barograph will be constant. The increase in deviation will be proportional to the increase in altitude, at least under standard atmospheric conditions.

The first arrangement is adopted for a barograph destined for high altitude use. The second type is chosen for dashboard altimeters used in normal navigation.

b) Sylphon Capsules

The evacuated boxes employed are actually tubes, or capsules, made of special hard brass. Their form resembles that of a cylindrical bellows made of parallel plates connected by half toruses.

For the most common types that we used, the diameter of the plates is approximately 2/3 the exterior diameter of the toruses, and the thickness of the walls is about 0.15 mm. The number of sections of the bellows is usually between 1 and 12.

The elastic properties of the bellows are a result of their special form that confers upon them total superiority over the concave capsules found in ordinary barometers. The precision obtainable is much greater than before.

The range in which elastic deformations occur is much larger and the proportionality between stresses and deformation is much closer.

The following experiments prove this in an incovtrovertible fashion.

They have been executed on a four-chambered bellows with an interior diameter of 40 mm, an exterior diameter of 60 mm, and a total height of approximately 20 mm.

First Series: Depression Tests

The first series was carried out using a field microscope equipped with an eyepiece marked with crosshairs. Each division on the crosshairs was equivalent to 5 microns on the object being examined. The object was a special sighting mark in this case. It was attached to the moving end of the bellows. The other end of the bellows was restrained by a fixed support.

The displacements of the sighting mark were measured with the aid of the micrometric eyepiece. They corresponded to the reduced pressure created inside the bellows, which were measured by a water manometer with a precision of 1/4 mm of a column of water. /23

Pressure reduction (mm of H_2O)	0	200	400	600	400	200	0
Microscope reading	0	134	269	408	269	135	1
Displacement in mm	0	0,67	1.315	2,01	1,345	0,675	0,005
Difference between ascent and descent readings in mm	0,005	0,005	0				

As may be seen above, the maximum error in measurement is 5/2000 or 1/400 of the total value.

Second Series: Load Tests

The measurements were made by focusing a fixed crosshair microscope on a microscopic object located at the bottom end of the capsule with known weights suspended from it. The other end of the capsule was fixed.

Load in grams	0	500	1.000	1.500	1.000	500	0
Displacement in mm	0.00	0.86	1.70	2.49	1.71	0,87	0,00
Difference between ascent and descent readings in mm	0.00	0,01	0,01				

The measurements obtained are less precise than before. It is difficult to explain this large an error. It could equally well come from errors in reading the displacement as from an actual difference in the displacement of the bellows.

c) Design of the Altimeter

The altimeter was designed and built to enter general use as a special dashboard instrument.

We therefore wanted to provide all the characteristics required of this type of equipment, including graduations proportional to altitude.

Requiring proportionality is very logical since it facilitates the reading of the instrument and increases the precision of interpolations. For such interpolations to be possible, large divisions in the dial are often also necessary because of the poor visibility that exists in flight.

A linear scale also allows the meter to be easily set at zero to account for the pressure at the airfield.

Our goal was therefore to create a very sensitive apparatus with an absolutely linear scale. Contemporary altimeters only achieve this proportionality at the expense of a loss in precision. Cams or complicated compensatory mechanisms of variable amplification have to be employed for this purpose. The result is that the operation of the altimeter is obstructed.

All we had to do to achieve our goal was to select components of suitable size for our apparatus.

The altimeter was based on the right angle lever principle described above.

However, because of the fairly considerable margin of error found in the present case, the design was slightly modified, as indicated in figure 6.

The evacuated deformable bellows hinged to point F acts on A by means of the arm OA. Meanwhile, the other arm, OB, is pulled at by the spring, which is anchored at R.

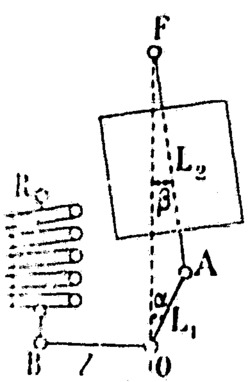

Fig. 6
Schematic
H.M.P. Altimeter

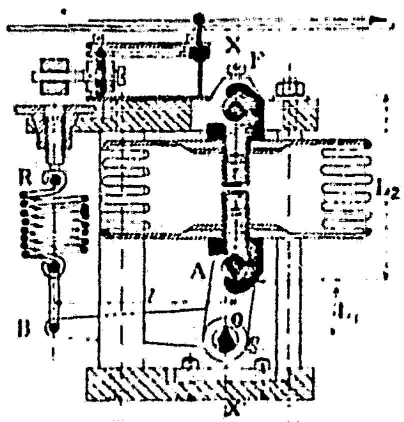

Figure 7
Actual Design
H.M.P. Altimeter

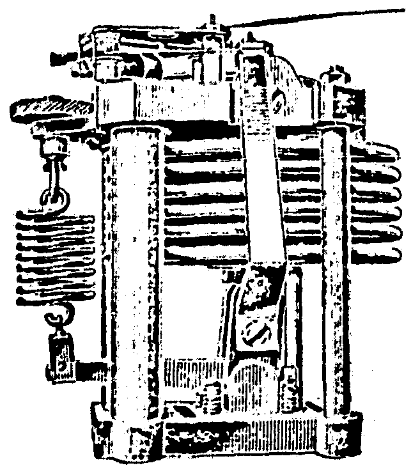

Figure 8
H.M.P. Altimeter

d) Construction and Testing of the Altimeter

As may be seen in figures 7 and 8, the parts of the altimeter upon which loads were exerted in the preceding studies are mounted entirely on knife edges.

It is this fact that makes for the extraordinary barometric precision of this instrument, which will be indicated later on.

Both the knife edges themselves and their yokes have been made with the same care as the knife edges in balance beam scales.

Another point that should not be overlooked is that the amplification mechanism is made up of only one moving part between the lever and the needle. This is true despite the fact that the angular displacement is magnified 120 times.

The total amplification that occurs between the elastic bellows and the point of the needle on the dial is approximately 2000. The bellows itself is only deformed by 0.12 mm.

During the first experiments carried out on the altimeter, it was equipped with only a paper dial whose 240 divisions were not exactly equidistant. The pressure in a bell jar was measured by a mercury manometer graduated in 1/2 millimeters. The manometer could be read without difficulty to the nearest tenth of a millimeter, while the dial of the altimeter could only be used to measure the pressure to the nearest fifth of a millimeter.

We obtained the following results, in the order given. H represents the pressure in millimeters of mercury and L the numbers read off of the altimeter.

H	285,1	337,1	398,5	431,7	469,8	517,9	645,7	751,8	645,7	547,8	469,8	431,8	398,3	336,9	285,1
L	240,6	201,0	161,2	141,0	120,8	81,0	41,0	1,9	41,0	81,0	120,8	141,0	161,0	201,0	240,6

Only one of the eight readings taken when reducing the pressure back to the starting point differed from the reading made when increasing the pressure. This difference amounted to only a one-fifth division on the dial, which was the smallest pressure change that could be detected. It represents less than a thousandth of the total magnitude.

The ascending and descending curves are thus practically equivalent. The degree of precision is probably greater than one in a thousand. The resulting hysteresis is therefore practically nul.

For purposes of comparison, below are the results of a test we ran in a bell jar of the latest model Richard Altimeter.

/25

Real Altitude	0	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000
Ascent readings	0	1,000	2,000	3,000	4,000	5,010	6,170	7,190	8,260	9,210	10,410
Descent readings	0	1,030	2,010	3,080	4,100	5,160	6,400	7,380	8,440	9,330	10,410
Average error	0	+ 15	+ 20	+ 40	+ 50	+ 100	+ 280	+ 280	+ 350	+ 270	+ 410
Width of hyster- mm	0	30	40	80	100	120	230	190	180	110	0
isis cycle %	0	0.3	0.4	0.8	1.0	1.2	2.3	1.9	1.8	1.1	0

Compare these values with the table below, which lists the corresponding measurements obtained with our apparatus.

Real altitude	0	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000
Readings (up and down)	0	1,005	1,995	2,990	4,000	5,020	6,070	7,000	7,960
Error	0	+ 5	— 5	10	0	+ 20	+ 30	0	— 40
Width of hysterisis cycle	Nul								

H.M.?. Hot Wire Altimeter

The hot wire altimeter is entirely different from the preceding model. We designed it based on the following principles.

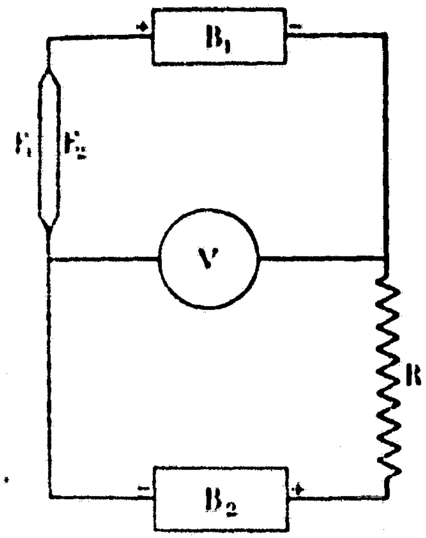

Figure 9
H.M.P. Hot Wire
Altimeter

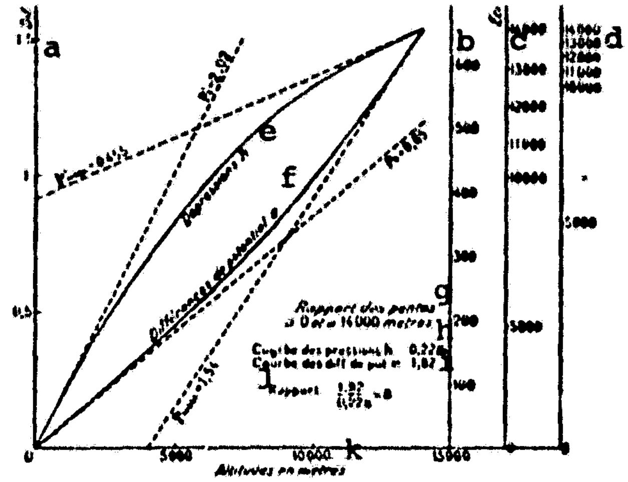

Figure 10
Sensitivity Curve of
Hot Wire Altimeter
0-14,000 m

Key:
- a) Potential difference in volts
- b) Reduction in pressure in mm of Hg
- c) Hot wire altimeter scale
- d) Barometric scale
- e) Pressure loss h
- f) Potential dfiference e
- g) Ratio of the slopes at 0 and 14,000 meters
- h) Pressure curve h
- i) Potential difference curve e
- j) Ratio
- k) Altitude in meters

Figure 9 is a schematic diagram of the altimeter circuit. The circuit is comprised of a 16 volt battery (B_1), two platinum wires (F_1 and F_2) connected in parallel and 25 microns in diameter by 7 cm long, a second, 18 V battery (B_2), and a variable resistor (R) that has a value of around 40 ohms. A voltmeter (V) is connected as indicated and the resistor is adjusted so that it reads zero. The surrounding air pressure is held at 760 mm and the temperature at approximately 20° C.

We then placed the two hot wires in a vacuum chamber in which the pressure is then lowered until it corresponds to an altitude of 14,000 meters.

We were thus able to obtain from numerous readings of the voltimeter the curve shown in figure 10. This curve shows that sensitivity of the device increases with increasing altitude and is approximately 1.8 times greater at 14,000 meters than on the ground. The second curve is that of pressure as a function of altitude. It can be seen that the change in pressure for a given increase in altitude is about /26
4.4 times smaller at 14,000 meters than at ground level. Therefore, if a hot wire altimeter and a barograph are of the same sensitivity on the ground, the altimeter will be 8 times more sensitive than the barograph at 14,000 meters.

V. The Measurement of Air Temperature

The magnitude of the air pressure is not enough to describe the characteristics of the air completely, whether at ground level or at high altitude. The temperature is also indispensable because an airplane flying at high altitude and trying to set an altitude record has to take account not of changes in the pressure but in the density of the air. Both the atmospheric pressure and the temperature affect the density.

The Teisserenc de Bort Thermometer

Among the thermometers that have been built to study variations in the temprature of the atmosphere, let me first of all describe Teisserenc de Bort's instrument. This thermometer is made of bimetallic plates of brass and invar. The plates are curved in circular arcs, with the invar on the inside (figure 11). Because of the difference in expansion between the two metals, the curvature of the strip changes as the temperature varies. A needle is attached to the end of the strip and records the changes in curvature.

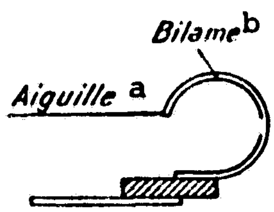

Figure 11
Teisserenc de Bort
Thermometer

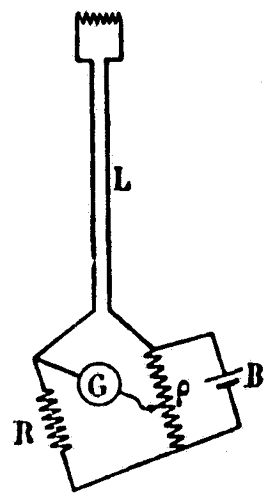

Figure 12
Idrac
Thermometer

key: a) needle
b) bimetallic strip

The thermometer used to be hooked up to inscribe the temperature on a cylinder simultaneously with a barometer made up of a Bourdon tube and a hygrometer made from a bundle of hair.

Such an apparatus corresponds to what is now internationally known as a meteorograph. Built very compactly, these instruments are used in atmospheric probes launched by balloon. Larger versions are installed in airplanes, for example in Germany, to study rising air currents.

Hergensell, who worked in Strasbourg before the war, created a thermometer based on slightly different principles. His thermometer includes a metal column 20 cm long supported by three invar feet. The tip of the column works a system of amplifying levers.

The Idrac Thermometer

/27

Idrac used a completely different kind of instrument for measuring temperature. It was built especially to register small temperature changes occurring in a single region.

The thermometer is based on the manner in which the resistivity of platinum changes with temperature.

It is composed of a spiral made of platinum wire a few hundredths of a millimeter thick whose total resistance is approximately 300 ohms. The spiral is shielded from the rays of the sun by placing it in a black tube open at both ends.

It is then attached to a kite, for example, and connected to the ground by electric wires running along the kite string. The wires end at one of the arms of a Wheatstone bridge. The resistors on the Wheatstone bridge are adjusted so that at the beginning of the experiment the galvanometer reads zero. A schematic drawing of the thermometer can be found in figure 12.

The resistors in the bridge are made out of constantan and are independent of temperature. As the temperature of the air around the platinum wires changes, the reading of the galvanometer varies also. After preliminary calibration, this will allow the temperature to be evaluated.

A galvanometer with a moving dial was constructed by Idrac especially for transport in the African bush. It had a fixed graduated scale read through a telescope aimed at a mirror reflecting the scale's image. One had only to note the number lined up with the cross-hairs of the telescope to get a reading.

The thermometer was adjusted so that a small division on the scale (1/2 mm) was equivalent to a temperature change of 1/40 °C.

This type of apparatus was useful in studying temperature variations around the kite and also in an area where birds were soaring.

VI. The Measurement of Air Density

From the data furnished by a recording barometer and thermometer, the density of the air can be deduced. However, if this method is to be accurate, the two instruments must respond rapidly and equally to atmospheric changes. If not, the two values obtained at a given point will not correspond and an erroneous value for the density of the air will be derived.

The rating of the climbing performance of airplanes according to the altitude attained is such an obvious absurdity that there is no need to dwell on it very long.

To speak of altitude when pressure has been measured is first of all nonsense. Altitude is not really determinable by any of the procedures currently employed for this purpose. In addition, the assumption of the equivalence at any point of standard and real atmospheres is in fact only a very rough approximation. This is demonstrated by all the attempts to set altitude records, which irrefutable arguments have shown to be filled with miscalculations resulting in figures more than a kilometer off. (It is well known, of course, that competitors are quite talented in taking advantage of a large margin of error.)

Moreover, it is well known that the atmospheric factor limiting the ascent of an airplane is not at all the ambient pressure, which is the only variable observable from the ground.

Only the record of the ambient density constitutes an approximate basis for studying and rating high altitude performance.

The H.M.P. Bellows Densigraph /28

These considerations are self-evident even if they might be considered revolutionary. They have motivated us to develop a recording densigraph based on the same principles as the altimeter that has just been described.

Here too, the apparatus works by using a compensatory torque caused by atmospheric pressure. In this instrument the spring acting on the lever OB is maintained at a constant tension, i.e. it has a very great elasticity. On the other hand, the distance OB is made proportional to the absolute temperature of the surrounding air by means of a rapid response thermometric device using linear metallic expansion. (See figure 13.)

The drive torque is therefore proportional to the absolute temperature, while the compensatory torque is proportional to the atmospheric pressure p, and the angle of rotation $\theta = hT/p = k/\delta$, where δ is the density of the surrounding air. The sensitivity of the densigraph increases with altitude, like the compensating bellows barograph. /29

The former only differs from the latter by the addition of a thermometric system. This system is composed of a series of thin walled tubes of graduated diameter. Each tube is enclosed in the next larger one. The even numbered tubes are made of a metal such as aluminum which has a large coefficient of expansion. The odd numbered tubes are made of a relatively low expansion metal, like invar. (See figures 14 and 15.)

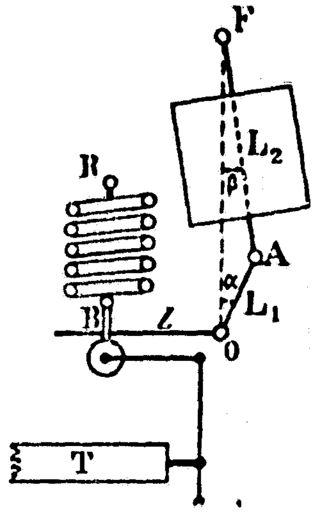

Figure 13
Schematic Drawing
Right Angle Lever
Densigraph

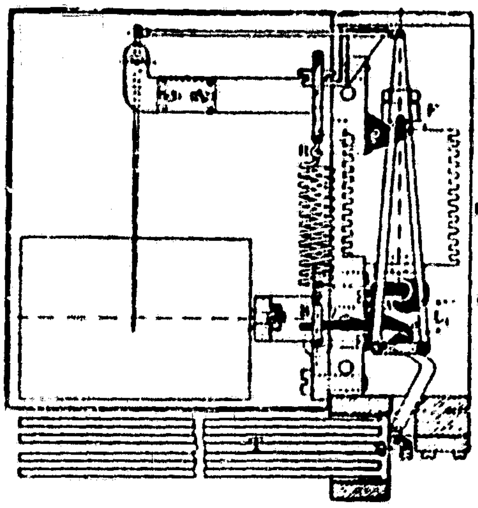

Figure 14
Actual Design
of Densigraph

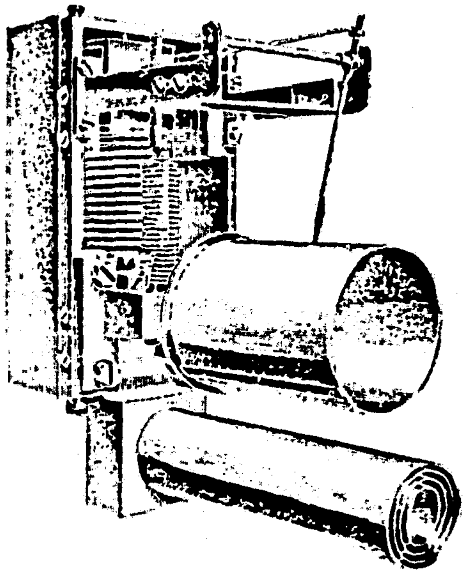

Figure 15
Right Angle Lever
Densigraph

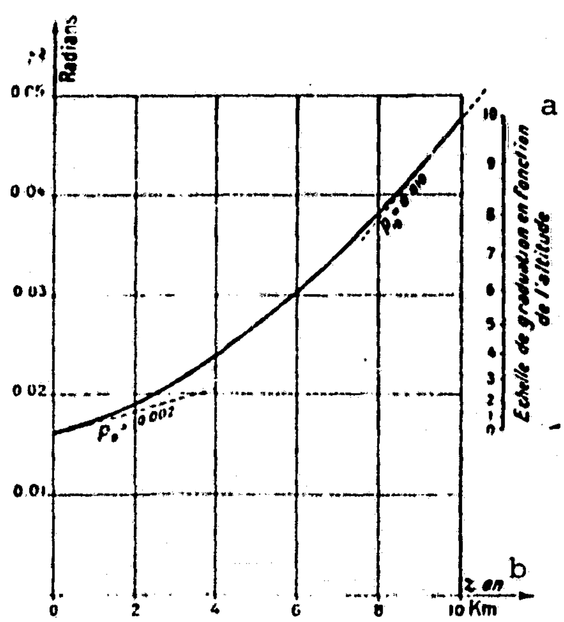

Figure 16
Response Curve
of Right Angle Lever
Densigraph

key: a) Scale of graduations as a function of altitude
b) z in kilometers

Between each pair of tubes is a gap on the order of a half millimeter. through this gap runs a rapid current of air at ambient temperature.

The establishment of a thermal steady state in such a system, which works by restricting the flow of air, is very rapid because of the thinness and the high degree of thermal conductivity of the tube walls. The device can respond without any appreciable delay to a change in air temperature.

The theoretical response curve of the densigraph is reproduced in figure 16 along with a scale of graduations showing that the sensitivity at 10,000 meters is approximately five times greater than on the ground. The precision of measurements made at high altitude is increased by the same proportion, which is a very advantageous feature when trying to measure an airplane's maximum altitude. This is exactly the function, so difficult for usual methods, that this device was designed to fulfill.

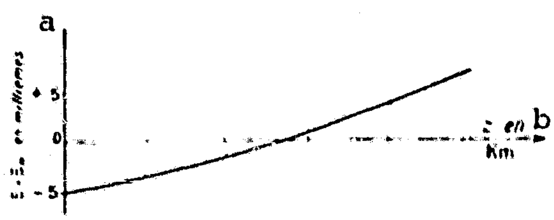

Figure 17

key: a) $e-e_m$ in thousandths
b) z in km

Figure 17 shows the curve of error as a function of altitude. This curve was drawn according to previously calculated values.

H.M.P. Hot Wire Densigraph

Our research into the influence of air density on the cooling of hot wires led us to the conclusion that it is possible to directly measure the density of a calm atmosphere.

Figure 18 represents the schematic diagram of such a device, which we have built in the laboratory.

The 10 volt battery B powers two densimetric wires 25 microns in diameter and 35 mm long as well as an iron lamp L. A special galvanometer is connected to the ends of the two wires. It is the use of this special galvanometer that has allowed us to avoid the compensatory battery that was necessary for the hot wire altimeter circuit. At the same time, the increased sensitivity at high altitudes, which was the principal advantage of the altimeter, has been preserved.

The galvanometer (figure 19) is made up of a double platinum wire held under tension by a bronze spiral supported by a spindle mounted on two pivots.

Attached to the spindle is the mirror needed to photographically record the meter readings. The lengthening of the wire caused by the heat produced by the current going through the galvanometer determines the amount the mirror rotates. /30

A galvanometer of this kind is almost completely insensitive to any possible jolt that it could endure on board an airplane. Disturbing the galvanometer only causes harmless vibration of the wires.

Tests were carried out in the laboratory by placing the hot wire system in a more and more rarefied atmosphere. These tests have shown that the densigraph accurately reflected changes in the density of the air in the bell jar. Its sensitivity was observed to increase as the air became more rarefied.

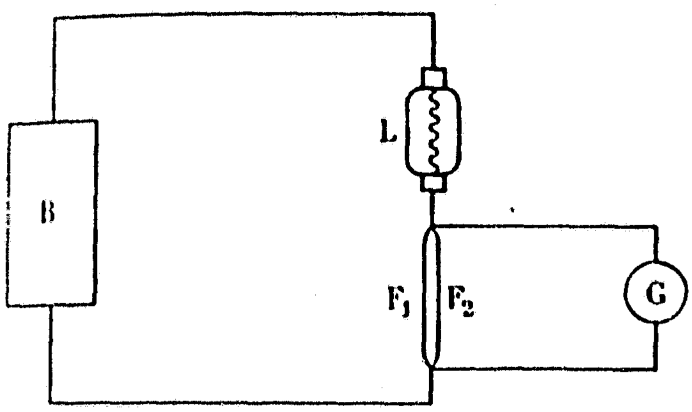

Figure 18
H.M.P. Hot Wire Densigraph

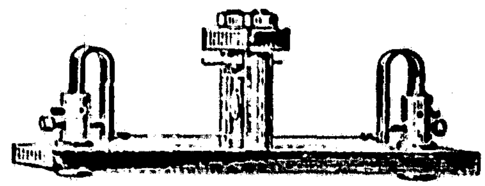

Figure 19
H.M.P. Thermal Galvanometer

VII. The Measurement of Wind Speed

The atmosphere is not just a mass of immobile gas. As a result of the formation of centers of high and low pressure, caused by unequal rates of heating of the ground, displacements of masses of air occur. They take place either along the ground or from lower to higher altitudes. The former are called surface winds and the latter are ascending thermal currents.

These winds have both an average speed and direction and instantaneous ones. It is very important for aviation to be able to determine their values. Both the experimental study of aerodynamic phenomena and research into the principles of soaring cannot be carried out without the knowledge of wind speed and direction.

Langley in 1860 was the first person to prove that the wind was not regular. For this purpose, he used an extremely light anemometer made with paper cones. The weight of these cones was only 5 grams, and their inertial moment was 300 gr/cm^2.

The time needed for each half revolution was electrically recorded and measured with the aid of an ordinary astronomical chronograph. The wind speed was derived from the interval between two electrical contacts.

Pitot Tube Anemometers

Since then, many different instruments have been invented for measuring wind speed. We shall first of all describe the Pitot tube, which is based on Bernoulli's equation and is used for compressible gasses when variations in density and volume cannot be /31 measured.

Given the wind speed v and the air density ρ, Bernoulli's equation gives the value of the static pressure p:

$$p + \frac{\rho v^2}{2} = C,$$

where C is constant.

Furthermore, if P is the total pressure at a stagnant point in a body of air in movement, one has:

$$P - p = \frac{\rho v^2}{2}$$

If P and p are known, v can be calculated from the formula:

$$v = \sqrt{2(P - p)/\rho}$$

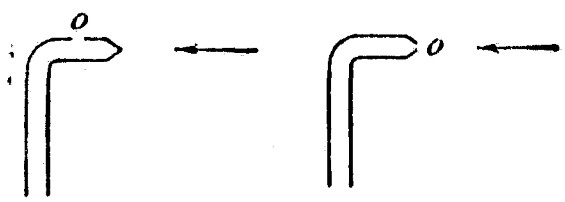

Figure 20
Pitot Tubes

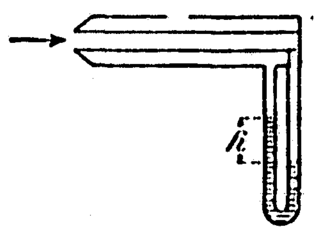

Figure 21
Double Pitot Tube with
Differential Manometer

In order to find the static pressure p, the pressure on one point of a surface placed in a fluid is measured. To do this, a tube curved at one end is used. At the end of the curve is a conical section that is pointed against the direction of the fluid flow and which contains an orifice O on its side (figure 20). The speed near the hole should be that of the general fluid flow.

If an identical tube is used, but with the orifice at the tip of the conical section (figure 20), the hole O faces a wind perpendicular to its surface. Since the speed at the orifice is zero, the total pressure P can be measured.

By using the two so-called Pitot tubes one after the other, P and p can be obtained and v calculated from their values. It has been found more convenient to join these two tubes together to make a differential manometer out of them. The difference P - p = h is thus directly obtained. (See figure 21.)

In reality, since Bernoulli's equation assumes that the fluid is perfect and incompressible, v can never be obtained directly. It is necessary that each Pitot tube be calibrated beforehand with an apparatus that measures wind speed.

Venturi Tube Anemometers

Much more accurate measurements of wind speed are obtained by using Venturi tubes.

When a liquid is moving through a pipe or nozzle, the pressure on the walls in general decreases as the speed increases. According to the study that Bernoulli made on this question, the pressure at a given point will diminish as the effective speed becomes greater. This pressure is equal to the hydrostatic pressure H less the height /32
H' of a column of the liquid which would flow out at the speed occurring at the chosen point.

If the actual speed is greater than than the theoretical speed, as occurs in nozzles, H - H' is negative and the fluid separates from the walls.

Venturi verified this theory by connecting one end of a U tube with a nozzle while submerging the other end in water. He observed that the liquid rose in the tube (figure 22). This proves that the pressure was smaller in the nozzle than in the exterior air.

Several physicists have attempted to use this principle to construct anemometers. Such devices are based on the mechanics of "Venturi" tubes.

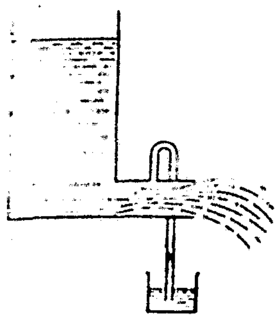

Figure 22
Device for Studying the Pressure In a Nozzle

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a) The Dines Anemometer

A Venturi tube is composed of two truncated cones joined together at their smaller ends and whose larger ends have approximately the same area. The tube through which the air enters is one third as long as the tube by which it leaves. (See figure 23.) As soon as a fluid in movement traverses the Venturi tube, it produces a partial vacuum in the narrow part (throat) of the tube. This vacuum can be measured with a manometer. The difference in average pressure between the entrance to the tube and the throat gives the value of V. It is upon this principle that Dines based the design of his anemometer.

He used the vertical displacement of a double bell jar to determine the difference in pressure.

Figure 23
A Simple Venturi Tube

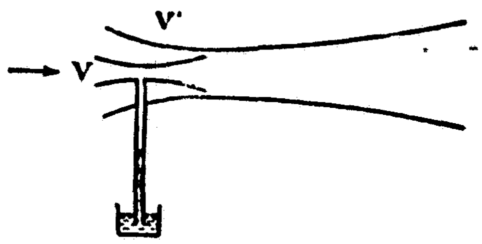


Figure 24
A Double Venturi Tube
with Manometer

b) The Bourdon Anemometer

In order to obtain increased sensitivity, Bourdon placed a small Venturi tube inside a large one (figure 24). This was done in such a manner that the exhaust of the smaller tube was located in the throat of the larger one. As a result of the reduction in pressure in the throat of the larger tube, the speed of the air current in the smaller Venturi tube is increased. This causes a greater vacuum in its neck.

Very large pressure reductions are produced by this system. The amplification in the smaller tube can thus be increased to 20.

c) The H.M.P. Anemometer

Huguenard, Planiol, and I have built a recording apparatus that measures the vacuum created inside a Venturi tube and, therefore, the speed of an air current. This device consists of a metal manometer of the sort that we have used in our accelerographs, only much more sensitive. (See figure 25.) The manometer, equipped with a very light pen, has an intrinsic period of 1/40 second.

The response curve of the manometer was plotted at the large wind tunnel in Issy-les-Moulineaux. A small tube connected the Venturi tube to the manometer. A mercury manometer measured the pressure within the Venturi tube at the same time our device did.

Cup Anemometers /33

A windmill or a propellor placed in a wind of speed V so that its axis of rotation is parallel with the wind takes on a certain speed of rotation if friction is negligible. The number of turns n varies with V and, from the value of n, V can thus be deduced.

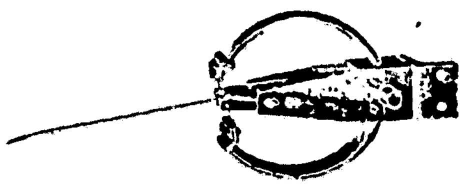


Figure 25
Flexible Plate
H.M.P. Manometer

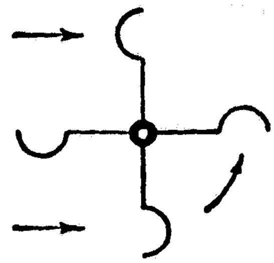


Figure 26
Cup Type
Anemometer

Certain anemometers, such as the Richard and Robinson models, are based on this principle. They consist of a small rotor (figure 26) turning in a vertical plane and oriented by a weather vane to face the wind.

a) The Magnan Anemometer

I myself used to use a cup anemometer that was directly linked to a magneto. The magneto's armature was mounted on bearings and the rotor was mounted on top of it.

The current produced by the magneto was read by a protable voltmeter of large size and resistance which had three different ranges. The voltmeter caused a light aluminum pen to deflect. In this manner the curves were recorded in ink on a cylindrical recorder or in a modified fluxmeter. (See figure 27.)

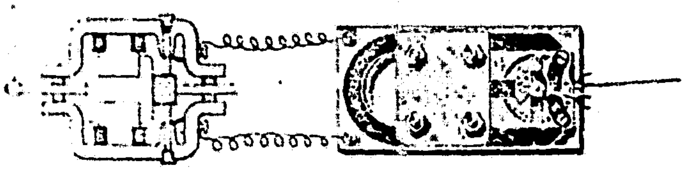


Figure 27
Magnan Anemometer
On the left: Magneto with Rotor
On the right: Recording Galvanometer

Key: a) Deviation in m/m
b) Wind speed in m/s

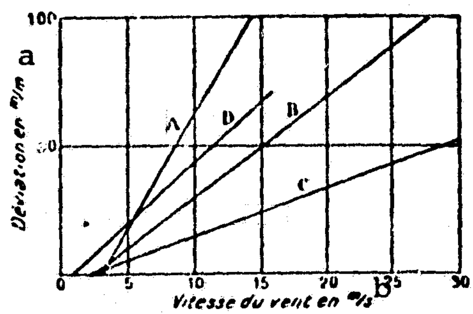


Figure 28
Magnan Anemometer
Calibration Curves
A, B, C: 1st Device
Ranges 15, 30, 60
D: Most Recent Device

Unfortunately, the measurements made with electromagnetic anemometers did not achieve the desired precision. The curves plotted were greatly distorted. The rotors did not begin to turn until the wind was about 2 meters because of excessive friction. In addition, in calm air they needed 2 seconds to stop if their initial speed corresponded to 5 m/sec. They slowed down under the combined effect of friction and the resistance torque. However, this effect was partly offset by their considerable moments of inertia.

The result was that although the times recorded between gusts were fairly close to reality, the amplitudes of the variations were much smaller than they should have been. /34

The calibration curves of these instruments (figure 28) show the inadequacy of such instruments for weak winds. On the other hand, the curves also show that the scale is a linear function of wind speed as soon as the rotors have begun moving.

b) H.M.P. Oscillating Blade Anemometer

Huguenard, Planiol, and I have developed an anemometer that works by measuring the speed of rotation of a shaft. The shaft opens and closes an electric contact which allows a constant amount of electricity to pass into the recording circuit at each closing. The net result is that the average current in the circuit is proportional to the number of times the contact is closed by the shaft in a unit time period.

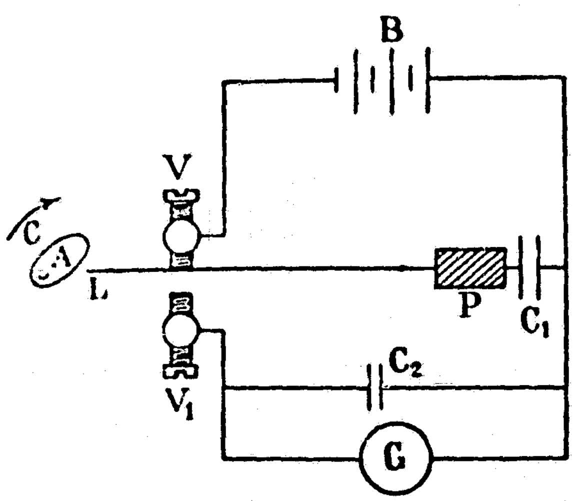


Figure 29
H.M.P. Oscillating
Blade Anemometer

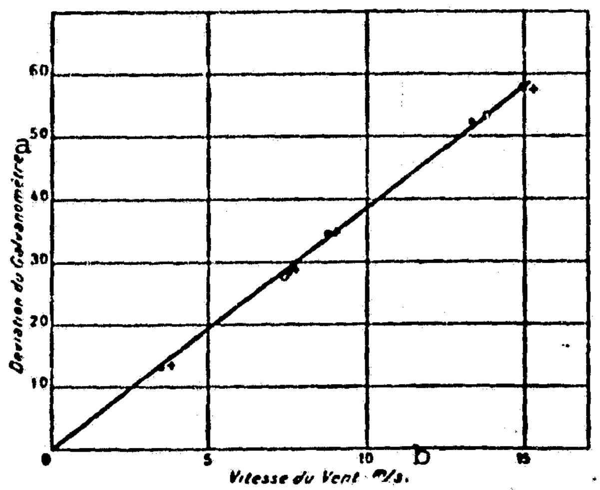


Figure 30
Response Curve
Oscillating Blade
Anemometer

Key: a) Deviation of Galvanometer
b) Wind Speed m/s

Our anemometer contains an oscillating blade inserted into the recording circuit and deflected by the shaft whose speed is supposed to be measured. After each movement of the shaft, the blade oscillates a predetermined number of times (once, for example) to close the circuit by hitting the contact.

As shown in figure 29, the blade L is in contact with the contact screw V when at rest and connects the capacitor C_1 with the battery B. The blade, when deflected by the cam C (moved by shaft A), comes into contact with the contact screw V_1, to which is connected a galvanometer and one of the wires leading to the capacitor C_2.

In its resting position, the blade charges up the capacitor C_1 by connecting it with the source of electricity. The cam, which turns in the direction of the arrow, hits the blade and forces it into contact with V_1, thus causing the capacitor to discharge into the galvanometer.

After the cam moves away, the blade returns to its resting position against V.

The series of impulses, averaged out by C_2, received by the galvanometer causes it to be permanently deflected. Figure 30 shows the response curve obtained in a small wind tunnel and allows the precision of the measurements to be judged.

The H.M.P. Hot Wire Anemometers

Despite these results, we thought there was still a need for more sensitive anemometers. We therefore tried to build an improved /35
instrument better suited to our purposes.

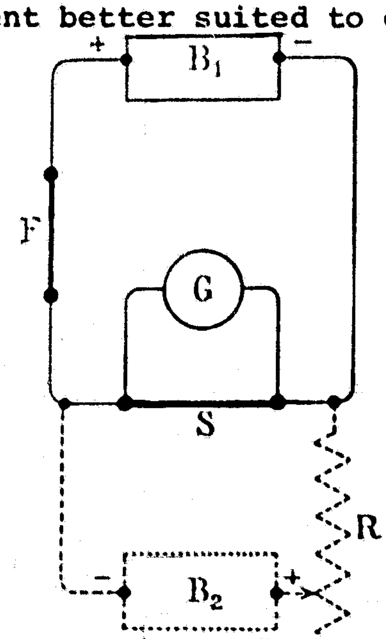
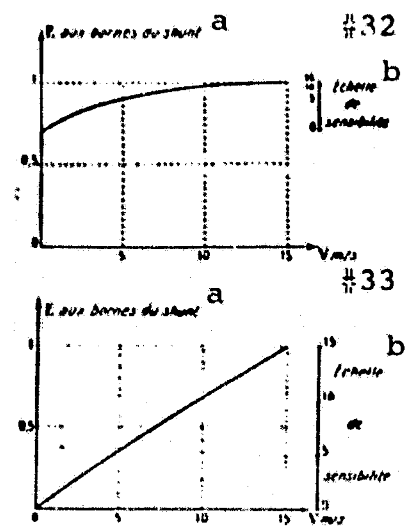


Figure 31
H.M.P. Hot Wire
Anemometer



Figures 32 & 33
Current vs. Speed in
Noncompensated (#32) and
Compensated (#33) Anemometer

Key: a) E at ends of shunt b) Scale of sensitivity

It is for this reason that we developed a hot wire anemometer and then a directional indicator using two hot wires. They offer the advantage of only inserting into the wind a very small structure which does not obstruct it.

A hot wire anemometer (figure 31) is composed of a platinum wire F, a battery B_1 providing the current to heat the wire, and an ammeter G with a shunt S to measure the current. When the wind blows over the wire, which has been heated so that it is red hot, it cools it down. This causes the current to increase.

Figure 32 represents the current variation in the wire. It /36
proves that such an anemometer's sensitivity becomes so low that it is unusuable at speeds of more than 5 m/sec.

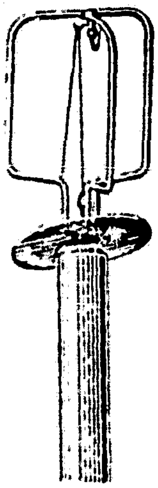


Figure 34
Anemometer Wire
with Support

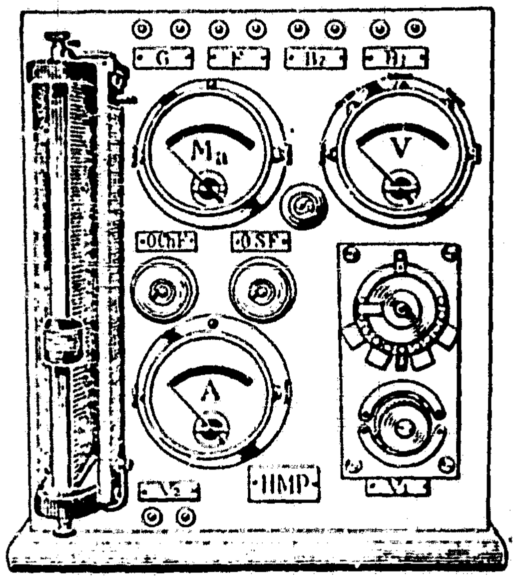


Figure 35
Control Panel
for Hot Wire
Anemometer

In order to alleviate this problem, we added, as is shown in the dotted part of figure 31, a compensatory battery B_2 and a resistor R which is adjusted so as to reduce the current in the shunt to zero when there is no wind. In addition, the shunt does not have a constant resistance but is constructed of a fine wire sheltered from the wind whose resistance increases considerably as the current going through it grows. With these modifications, the readings obtained from the anemometer are practically proportional to the wind speed. (See figure 33).

In the anemometer that we built for the Service Technique de l'Aéronautique, the hot wire is mounted in a support at the end of a tube (figure 34) and linked by wires to a control panel (figure 35) containing the instruments used for adjusting the equipment. The wind speed can be read on the voltmeter V or recorded by an oscillograph (figures 36 and 37). The moving part of this highly responsive oscillograph is a small iron plate held in place by a constant magnetic field and displaced from its steady state position by a varying perpendicular field created by the current being measured.

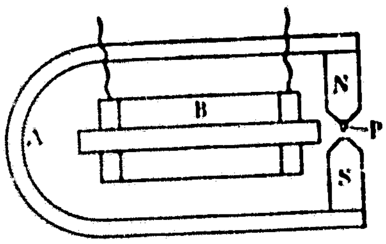


Figure 36
Schematic Diagram
H.P.M. Oscillograph

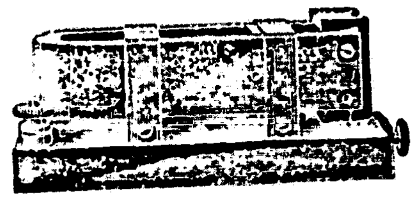


Figure 37
H.M.P. Oscillograph
for Recording Wind Speed

In practice, for measuring real wind, the wire is protected by a metal screen (figure 38) which reduces the speed of the wind by half. By changing the dimensions of the holes of the screen, the sensitivity of the anemometer can be changed as desired.

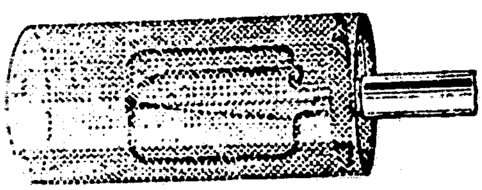


Figure 38
Anemometer Wire
in its Lantern

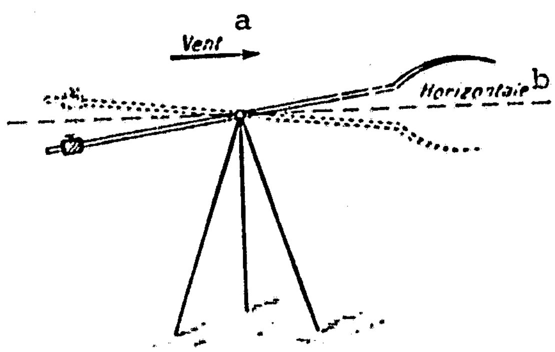


Figure 39
Lilienthal Weather Vane

Key: a) Wind
b) Horizontal

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In the experimental trial that we carried out, we wanted to find out if the anemometer was sufficiently sensitive to very rapid pulsations of air.

We therefore placed a hot wire inside a resonant pipe which was set vibrating by compressed air. We then recorded the image of the wire on sensitive film with the aid of a lens. Despite the small variation in speed caused by the sound waves and the fairly high frequency, the wire underwent great variations in temperature that were easily noticeable on the film and allowed the period of vibration to be directly /37
measured.

We then connected the hot wire to an anemometer circuit in the same pipe and used the oscillograph to trace the results. Even the irregularities in the vibrational cycle of the air in the pipe were clearly plotted.

The hot wire anemometer that we developed yields relative measures and has to be calibrated with the aid of absolute anemometers. Until now we have had to be content with calibrations made in the small wind tunnel that we put together and in the Eiffel and Issy-les-Moulineaux tunnels. The different speeds were determined first by Pitot or Venturi tubes.

VIII. The Measurement of Wind Direction

Lilienthal was the first person to wonder whether the wind was really horizontal across the surface of a flat area.

Lilienthal Weather Vane

To answer this question, Lilienthal used vertical recording vanes (figure 39) made of a horizontal arm turning on a tripod. At one end of the arm was a curved surface and at the other was a counterweight. An alternative arrangement had five parallel horizontal arms linked together with a flat surface at one end and a counterweight at the other. Lilienthal was thus able to obtain the first diagrams of vertical wind direction and to record its variations. He noticed a continual variation in the vertical component of the wind and an average ascendance of 3 degrees at the location of his equipment.

The Constantin-Idrac Weather Vane

Idrac used a similar piece of equipment, a weather vane designed by Constantin. This ingenious device was made of two wing sections from an airplane placed backwards and connected together. The pressure exerted by a horizontal air current created an equilibrium position. The least variation in the horizontality of the wind produced a considerable difference in wind pressure, which caused the wing sections to find a new equilibrium by rotating around their axis. Since the forces brought into play were considerable, the movement could be amplified by a system of quadrilaterals and transmitted electrically as far as desired. A series of small numbered lamps corresponding to electrical contacts in the circuits enabled an observer to read the inclination of the wind from a distance.

However, this apparatus could not detect rapid variations in inclination because of its inertia.

H.M.P. Hot Wire Directional Indicators

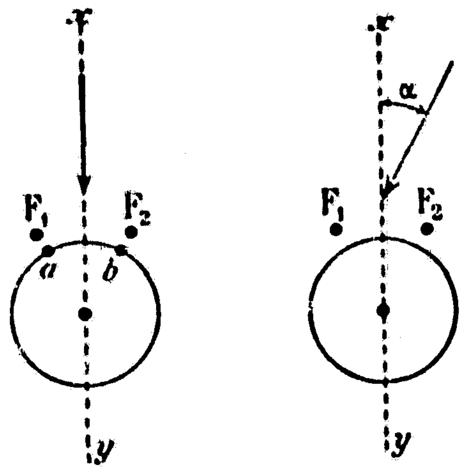

Figure 40
Cross Section of
H.M.P. Directional Indicator

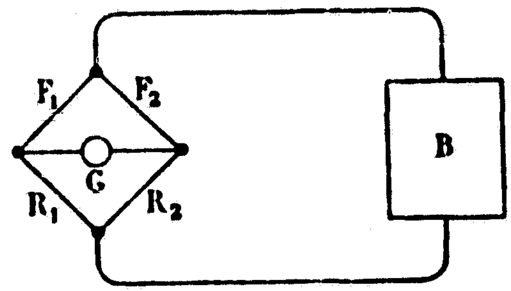

Figure 41
Circuit Diagram
H.M.P. Directional Indicator

I have already said that for the study of the wind, it is necessary to know the instantaneous direction of the wind in addition to its speed. Consequently, an apparatus that indicates wind direction with the same lag time as the speed indicator in use is required. We decided to use hot wires also to record the fluctuations in air current and we then constructed a simple directional indicator by placing two identical hot wires equidistant and parallel to the axis of a cylinder. (See F_1 and F_2 in figure 40.) The two wires constitute two branches of a Wheatstone bridge (figure 41) which is completed by two resistors of approximately the same resistance as the hot wires and an ammeter or galvanometer G. /38
A battery B maintains a constant voltage across the bridge. The bridge is balanced in calm air, and the wires heated to 1,200°. If the wind blows in a direction parallel to the plane of symmetry of the instrument, the two wires are equally cooled and the current through each one is still equal. The galvanometer continues to read zero. If the wind blows from the right, one of the wires is cooled more than the other. The current is then greater on one side and the needle of the galvanometer moves. This is how the inequality of current due to variations in resistance in the two hot wires can be used to measure the inclination of the wind relative to the axis of the apparatus.

Figure 42 depicts the cylinder on which the two hot wires are mounted. The wires are connected to the control panel in figure 43, which contains the variable resistors, the ammeters, and a zero-center scale milliampmeter.

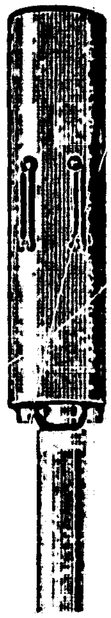

Figure 42
Double Hot Wire
Directional Indicator

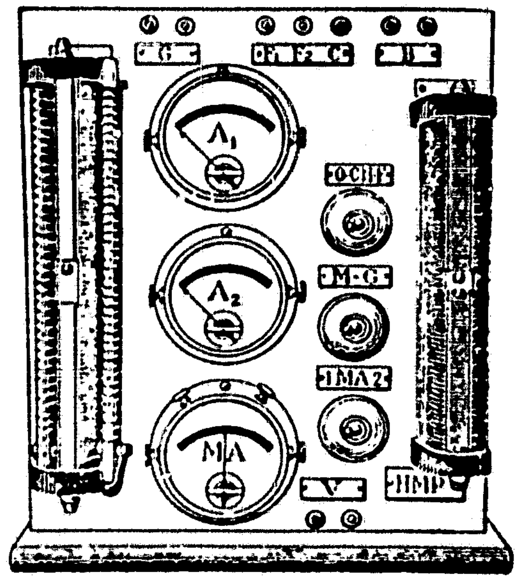

Figure 43
Control Panel of
Directional Indicator

What would happen if the speed of the wind changed while the direction remained constant? Experience has shown that, contrary to what one might think, the deviation is more or less independent of wind speed within the range studied. The first tests were made in our own small wind tunnel at speeds up to 20 m/sec. The operation of the directional indicator was found to be reliable up to this limit. Later, in the large wind tunnel at Issy, the current was observed to be practically constant from 0 to 45 m/sec. /39

IX. The Measurement of the Acceleration and Angular Velocity of the Wind

To use the results obtained from the study of natural winds in the calculation of the trajectory of a glider or a bird, more complete data for the speed, direction, and inclination of the wind are needed. The time derivatives of these variables must also be known.

In order to analyze mathematically the problem of variable surface winds heading in a constant direction, we had to construct an apparatus that could automatically trace the acceleration curve from a given anemometric plot. Figure 44 shows one of these derived curves from an electromagnetic anemometer and another obtained simultaneously with a hot wire device placed in the same location. The accelerations obtained from the hot wire anemometer are much greater and go as high as 10 m/sec^2. Since it is these accelerations that provide the support for a glider and also cause added stress to the frame of an airplane, there is a great deal of interest in finding means of measuring them.

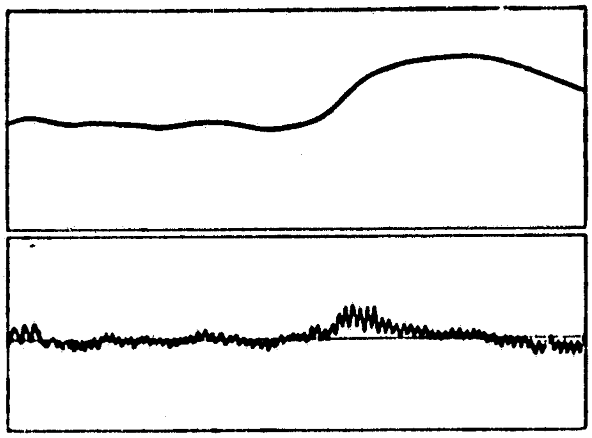

Figure 44a
Above: Instantaneous velocity of a wind N recorded with an electromagnetic anemometer
Below: Acceleration curve

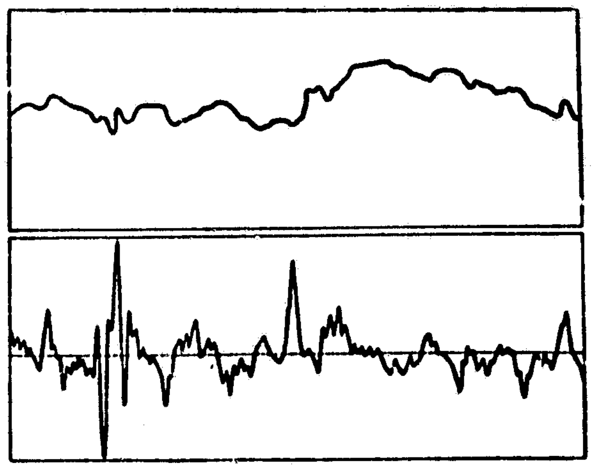

Figure 44b
Above: Instantaneous velocity of the same wind N recorded with a hot wire anemometer
Below: Acceleration curve

H.M.P. Converters

We have constructed devices that we call converters and that simultaneously record the amperage of a variable current and its time derivative. They are based on the following principles:

A hot wire apparatus produces a current i whose voltage e is proportional to the parameter being measured: speed V, inclination α, or direction β of the wind. The movement of a galvanometer (1) is therefore placed in a magnetic field (figure 45). This galvanometer gives the value of i or e as a function of time. One way this can be done is to record the angular displacement of the movement on a moving photographic film with the aid of a light. A second galvanometric movement (2) is rigidly attached to the first and placed in the same magnetic field. An electromagnetic force is induced in it proportional to di/dt or de/dt because of its angular motion proportional to changes in i or e.

Finally, a third movement is placed in another magnetic field and measures the current produced by the induced voltage in number 2. It does this in an isolated circuit where the resistance is the only factor that needs to be considered. The effect of the small movement on the large one is negligible in the present experimental set-up. /40

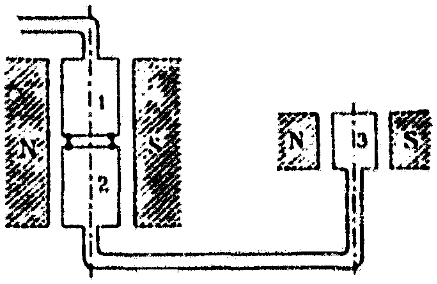

Figure 45
Schematic Diagram
H.M.P. Converter

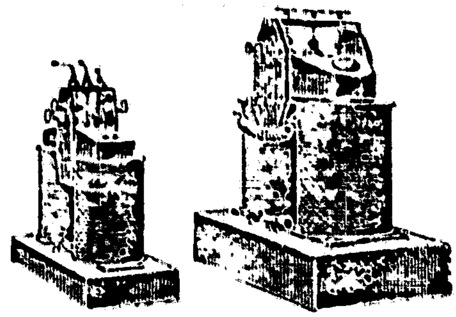

Figure 46
H.M.P. Converter

The instrument is thus composed of two electromagnets, a large one and a small one. Within the gap between the poles of each of the two magnets are three galvanometric movements, large ones in the larger magnet, and small ones in the smaller magnet. (See figure 46.)

The large electromagnet consumes about 25 watts of power and creates a 4,500 gauss field. The smaller one consumes 12 watts and produces a 5,000 gauss field.

The bigger magnet holds three double movements. One is used to measure wind speed, the second is for inclination, and the third measures direction. The resistance of the windings is 1 ohm for all the number 2 movements, 30 ohms for the number 1 movements that indicate direction, and 250 ohms for movement 1 of the wind speed indicator. The small movements are all of 1 ohm resistance.

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Lesson Three: The Structure of the Atmosphere. The Characteristics of Horizontal Winds. /41

In the last lesson we made a rapid survey of the instruments used to study the atmosphere and its movements. Today I am going to describe for you the results that we have obtained and give a picture of the general structure of the atmosphere and of surface air currents.

Our planet is surrounded by an enormous ocean of air which goes up to a considerable height. As the real ocean is the atmosphere for fish, the actual atmosphere is our ocean, as it is for birds. It is the medium in which we move, sometimes like crabs walking along the bottom, sometimes, when we imitate the birds and fly, like fish in the sea.

Just as sailors need to know the behavior of the ocean both on the surface and in its depths, so it is in the interest of aviators to understand the activity that goes on in the ocean of air. Professor Fabry, in a very interesting lecture, has described the state of our knowledge on this subject. I could not do better than to summarize what he said, particularly as concerns the upper atmosphere. As I have already mentioned, the quantity of air which surrounds the earth, if it was all at standard atmospheric pressure, would only have a thickness of 8,000 meters and would not reach the highest peaks of the Himalayas. If the temperature of the air were suddenly reduced to -200° C, the air would condense into a liquid ocean only ten meters deep.

For the time being, this has not occurred, and experimental studies have shown that in fact the atmosphere extends well beyond the highest mountains.

I. The Structure of the Lower Atmosphere

We have several means available to study the lower atmosphere. We can, it is true, carry our instruments up to the tops of the highest mountains. The method is practical up to a certain altitude, but becomes very strenuous higher up. Fortunately, other, more convenient ways exist. These are:

- the balloon
- and the airplane,

which currently allow researchers to make use of heavy instruments up to a maximum of 12,000 meters. There are two reasons for this limit. In the first place, 12,000 meters is the highest altitude balloons and airplanes can attain at present. Secondly, the human body cannot function at altitudes higher than this.

There is also the sounding balloon which is capable of carrying apparatus to 30,000 meters above sea level, although the scientist has to remain on the ground. Its lifting force is small and only very light pieces of equipment can be attached to it. Not only is lighter equipment more delicate than normal apparatus, but precision sometimes suffers when it is used. /42

A sounding balloon is a spherical balloon made of a thin sheet of very elastic rubber inflated with hydrogen. Its diameter before takeoff is from 0.75 to 2 meters. In a small basket it contains a light instrument for recording pressure, temperature, and humidity. The weight of this weather station is only a few hundred grams.

The balloon expands while rising. Its walls grow thinner and eventually burst. The maximum attainable altitude before bursting is usually around 20 km. However, sometimes 30 km. is reached. The small basket releases a parachute as it falls and lands on the ground gently enough not to break the weather station within.

Sounding balloons were introduced by Teisserenc de Bort. They were perfected by Hergesell in Germany, Rotch in the United States, and Gamba in Italy. Such probes are now made quite regularly. The Trappes observatory in France directed by Idrac is particularly active in this field.

Reduction of Pressure with Increasing Altitude

The observations that have already been carried out, although sometimes of questionable accuracy, have built up a body of data concerning the composition of the atmosphere at high altitude.

First of all, it is known that atmospheric pressure decreases with increasing height. At 5.5 km the pressure is half that at sea level. If one goes up to 18.4 km, the pressure is only a tenth of that on the ground. Figure 47a represents the change in air pressure under standard conditions as a function of altitude, according to the Service Technique de l'Aéronautique.

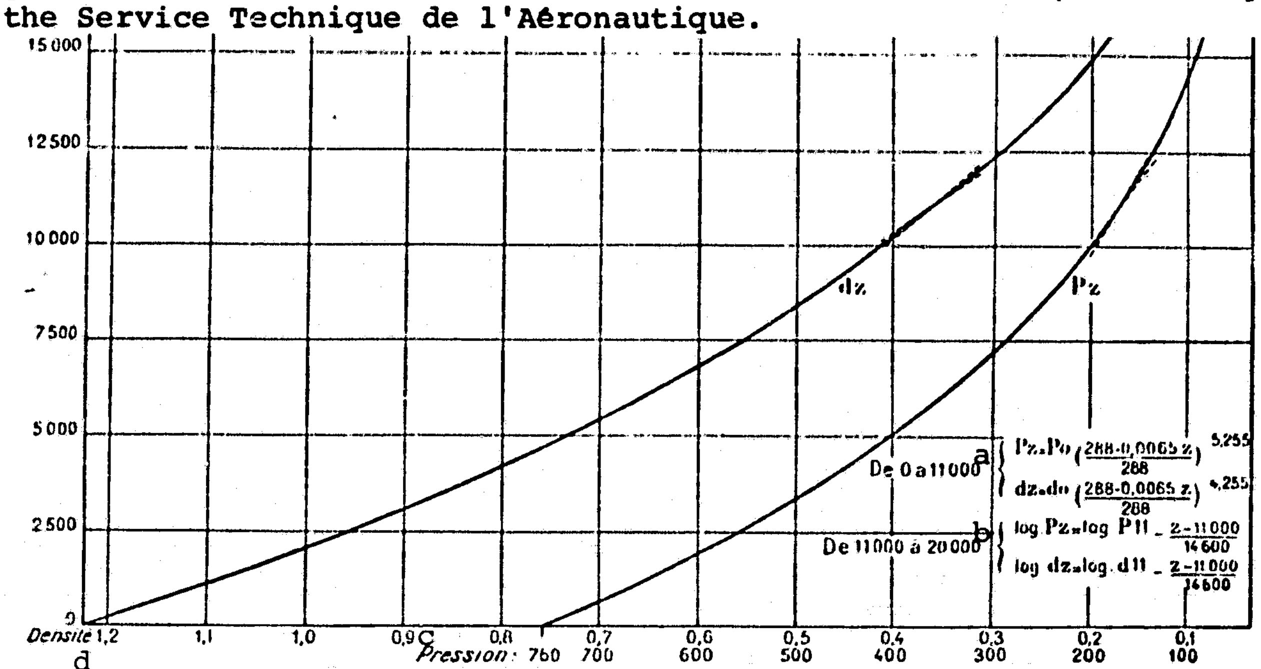


Figure 47a

Decrease in Pressure Pz and Density dz with Increasing Altitude

Key: a) From 0 to 11,000 b) From 11,000 to 20,000 c) pressure d) density

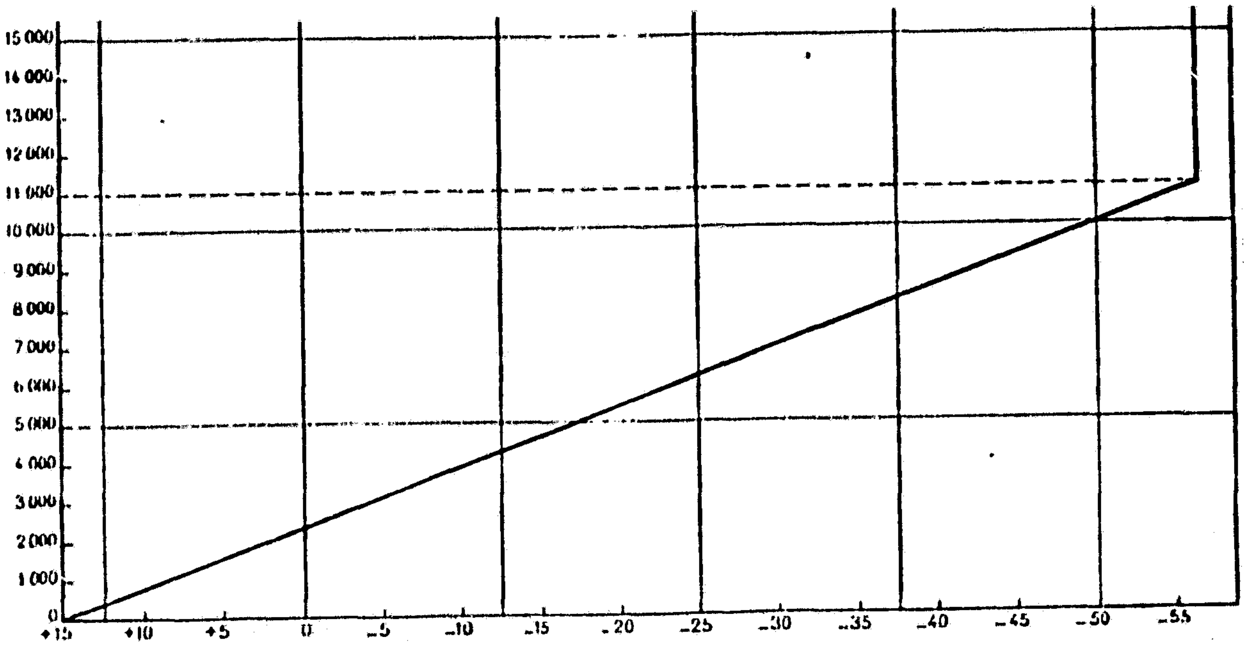


Figure 47b
Decrease in Temperature with Increasing Altitude

Reduction in Temperature with Increasing Altitude

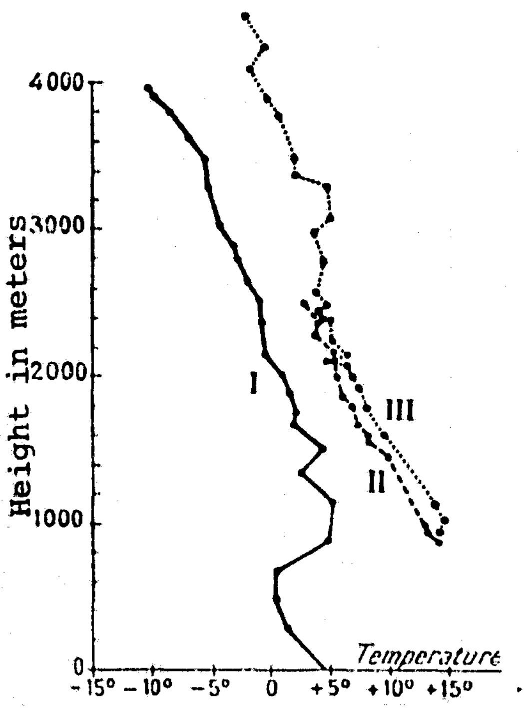


Figure 48
Several Instantaneous Temperature Curves

Up to 10,000 meters, temperature also decreases with altitude. After this point it remains between -50° and -60° no matter what the location or season. The reason why the temperature remains constant may be that at 10 km there is a transition from the turbulent lower regions to a more stable layer known as the stratosphere.

The change in temperature according to increasing altitude, under standard conditions, is graphically illustrated in figure 47b, again according to the Service Technique de l'Aéronautique. With this information, the decrease in density can then be calculated. It is shown in figure 47a. The density curve was made from measurements taken in flight. It is not entirely clear that the measurements of pressure correspond exactly to measurements of temperature taken at the same altitude. This is because it is not known whether the response times of the two measuring instruments was the same. What is more, temperature does not decrease /44
regularly up to 10,000 meters. It has been observed that there are very frequent temperature inversions up to 4,000 meters and even higher, as is shown in figure 48. As a result, the density will not diminish regularly either.

The importance of exact figures for density lies in the fact that an airplane trying to establish a high altitude record is struggling against a reduction in air density. This is in contrast to the birds, who are concerned with diminished pressure.

Samples taken up to 15 km have shown that at least the composition of the air is constant. To take air samples, an evacuated glass bottle whose end has been drawn out is placed in the basket of a balloon. When the balloon bursts, a device breaks the drawn out end and rarefied air enters. Another device then seals the end up again.

II. The Structure of the Upper Atmosphere

Even though we cannot reach altitudes above 15 or 20 km with soundings, we can still find out something about the character of the upper atmosphere. The methods used to do this are very ingenious. Fabry has described them exceedingly well.

The Ozone Layer

First of all, there is the study of the absorption of light waves as they traverse the atmosphere. We have already received some valuable information from this line of research.

Take the light that comes from a star. By the time it arrives on the ground, it has been filtered by the atmosphere. The nature of this filtration reveals some of the properties of our gaseous ocean. From the moment when the light coming from stars was first analyzed, it was noticed that the atmosphere absorbed some of the light waves, particularly in the ultraviolet. The explanation of ultraviolet absorption by the presence of ozone in the atmosphere came very quickly thereafter. The actual amount of ozone, if it were purified and at atmospheric pressure, would only make up a layer three millimeters thick. However, its importance to us is considerable since it protects us from the harmful effects of ultraviolet radiation. The ozone layer is not immediately around us, but is found at an altitude of 40 to 50 km, which is much higher than a sounding balloon can go. There are also seasonal variations in the ozone layer. In the northern hemisphere, much ozone is observed in the spring and only a little in the autumn. Just the opposite is found in the southern hemisphere. Thus, a cyclonic atmospheric flow increases the quantity of ozone, and an anticyclonic flow diminishes it. This proves that, contrary to what has been claimed, the troposphere and the stratosphere do not form two independent zones.

The Temperature 60 Km Up

Another method of studying the upper atmosphere consists of analyzing reflected sound waves. It was noticed during the war that at certain spots one could hear a cannon fire whereas at other locations closer to the cannon it could not be heard. In studying those "zones of silence", it was noticed that the upper atmosphere played an important role because of the way in which the speed of sound varied with altitude. The variation occurs because the atmosphere becomes hot again at very high altitude. At high altitude the temperature reaches 30° C and the speed of propagation of sound in warm air is not the same as in cold air. Thus, it is basically warm at ground level, very cold at 10 km, and hot at 80 or 100 km. It is thought that this is the result of the presence of ozone at these altitudes. The ozone is supposed to warm up the air by absorbing ultraviolet waves. /45

Is There a Layer of Hydrogen above 60 Km?

Another phenomenon that helps us to deduce the properties of the upper atmosphere is the behavior of the shooting stars that come to us from the depths of space with the speed of comets. The spectrum emitted by a shooting star at the moment when it first lights up is not that of an incandescent solid body, but that of a gas, namely hydrogen.

The shooting star is therefore not itself luminous. It is the surrounding environment that lights up.

Shooting stars first become visible at around 100 km in altitude. They disappear around 60 km. There is thus some basis for wondering if a region of high concentration of hydrogen exists in the upper atmosphere, although some people reject this possibility.

There is Still Some Air at an Altitude of 700 Km.

Finally the aurora borealis of the polar regions furnishes us with some interesting data. It is a luminosity of the upper gaseous layers resulting from bombardment by electrical charges thrown off by the sun. Its spectrum is that of oxygen. Usually the aurora borealis has an altitude of 100 km, but sometimes it exists at 700 km. Even at this high an altitude there must still be some air.

Figure 49 summarizes our current knowledge of the constitution of the earth's atmosphere.

The relation between pressure and altitude will be much better understood by examining figure 50, on which has been marked the altitudes attained by various human and natural creations. /46

The importance of pushing forward in the study of the atmosphere should be obvious at the present time. Already there is talk of flying at high altitudes in order to reach speeds of 1,000 km per hour to facilitate intercontinental communications. The possibility of interplanetary travel has even been seriously raised. Aeronautics, which did not exist a few decades ago, is thus now witnessing the birth of a competitor, astronautics.

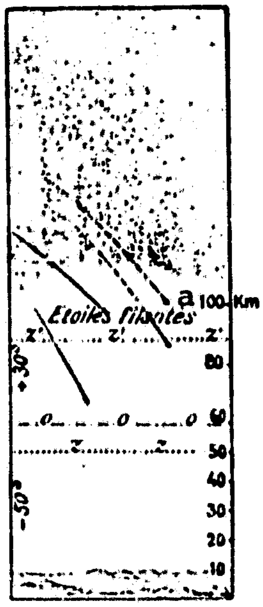


Figure 49
Summary of our
Knowledge of
the Constitution
of the Atmosphere
(o = ozone)

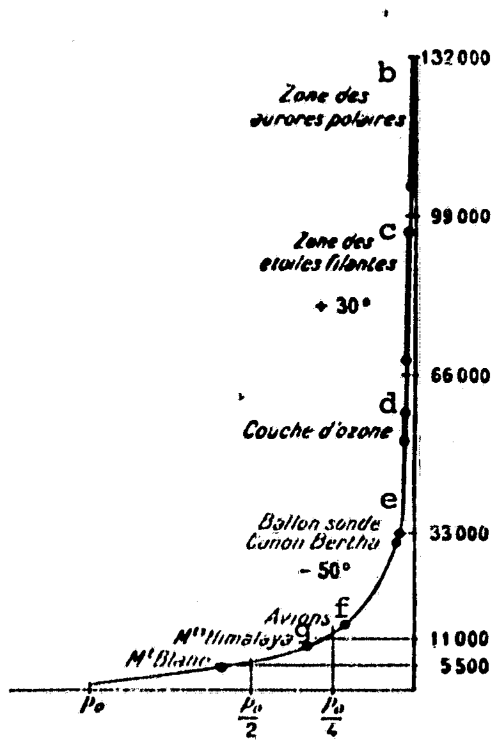


Figure 50
Pressure-Altitude Curve
with Indication of
the Altitude of
Various Vehicles and
Natural Phenomena

Key: a) Shooting stars
b) Aurora borealis zone
c) Shooting star zone
d) Ozone Layer
e) Cannon Bertha sounding balloon
f) Airplanes
g) Himalaya Mountains

III. Horizontal Winds

Until we are able to propel ourselves to the surface of our atmospheric ocean, let us study the lower levels, which could be called the ocean floor. This is the only part that affects us directly, since it is only the lower regions through which we can transport ourselves at the present time. The higher reaches are still forbidden to us.

It is customary in aerodynamic studies to represent the movement of the air in such a way that each particle follows a regular, straight path parallel to that of its neighbors. However, in the atmosphere, particles of air move in a completely different manner. Their trajectories describe vortices and curves. They ascend and descend, usually in a forward direction, although sometimes backwards, sometimes quickly, sometimes slowly.

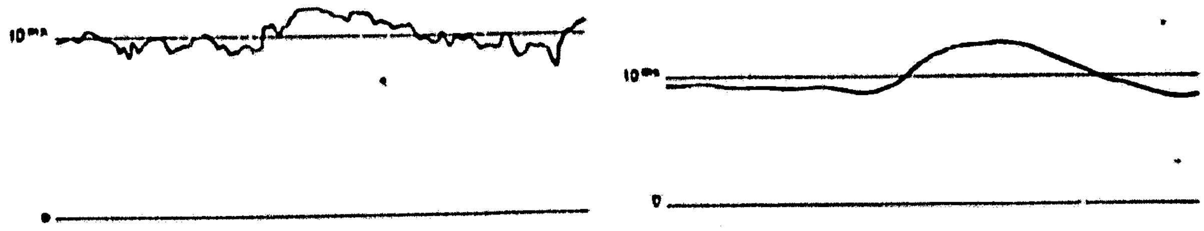


Figure 51
Two Recordings of the Instantaneous Speed of the Same Wind N
Left: with a Hot Wire Anemometer
Right: with an Electromagnetic Anemometer
(1 second = 5.4 mm)

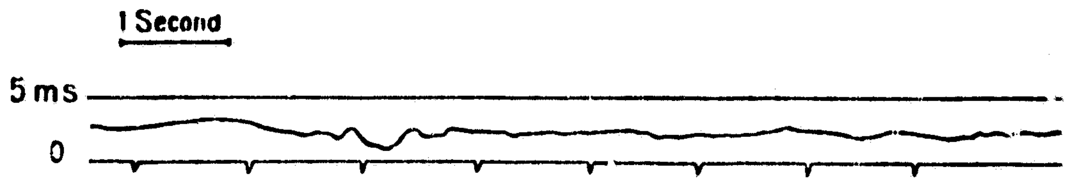


Figure 52
Instantaneous Speed of an ESE Wind Recorded by a Hot Wire Anemometer

The Germans have pointed out that winds of less than 4 m/sec are laminar.

This means that such winds have a configuration that is constant over a certain period of time. The needle of a galvanometer used to record wind speed and direction will therefore trace a straight line on the recording cylinder. Such tracings are indeed obtained if an electromagnetic anemometer is employed. However, it can be observed with the aid of more sensitive hot wire anemometers that very rapid oscillations of speed and direction occur in weak winds. The curves traced by the same galvanometers are then more or less undulated, with the needle going sometimes above and sometimes below the average line.

On the left side of figure 51 is found the tracing produced by a hot wire anemometer on a cylinder that makes a complete revolution every 26 seconds. The average speed of the wind, recorded on the Crau plain, is approximately 10 m/sec. On the right side is a tracing /47 that was made on the same cylinder by an electromagnetic anemometer situated right next to the other one. The first curve, obtained with the hot wire, shows rapid fluctuations of speed 3 to 5 times per second. The second curve, although it furnishes useful informaton for some purposes, only indicates oscillations whose period lasts more than a second.

Figure 52 is a recording on the instantaneous speed of a wind averaging 2 m/sec observed on the beach at Le Havre with a hot wire anemometer. It reveals, thanks to the sensitivity of the

instrument, that rapid oscillations exist, even though the wind has a speed of less than 4 m/sec.

Variations in the Speed of the Wind

The study of the wind rapidly reveals that variations in wind speed are different in different situations.

From the recordings that I have made above the sea, on the ground, on mountains, and in the desert, the first thing I noticed was that in the vicinity of the earth's surface, the wind has one constant property: irregularity.

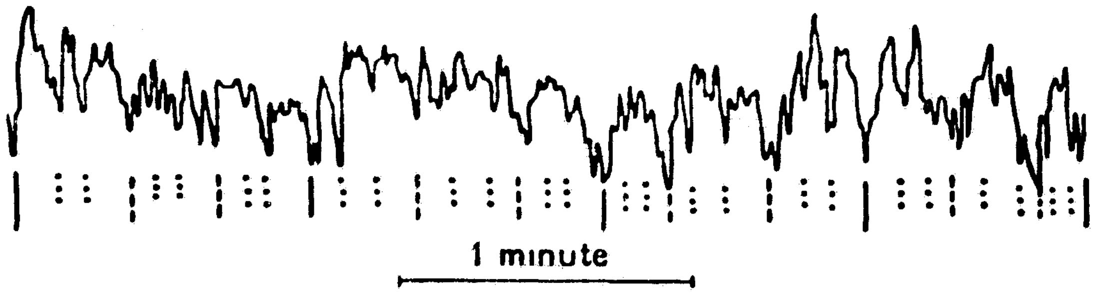


Figure 53
Recording of the Instantaneous Speed of a Sea Breeze Showing Atmospheric Waves (Solid Vertical Lines), Gusts (Dashed Lines), and Pulsations (Dotted Lines)

In the lower layers of the atmosphere, the wind never has a constant speed. It always shows momentary variations of speed and is like a series of rapid oscillations or gusts. It also seems that the amplitude of the oscillations is highly variable. It probably has something to do with the topography of the region over which the wind is blowing.

I have been able to demonstrate that, at least up to 100 meters above the ground, the wind undergoes a type of oscillation whose average duration is approximately one minute (figure 53).

I have given the name atmospheric waves to these slow oscillations. Each wave in its turn is made up of shorter oscillations whose duration varies between 8 and 20 seconds, very often being around 15 seconds long.

I call the shorter oscillations gusts. I have observed that the variations in wind speed occurring in gusts that pass over very uneven ground easily attain several meters per second. Sometimes at the end of a gust, wind speed drops down almost to zero and then quickly increases to 10, 12, or even 15 meters per second.

The difference between the maximum and minimum speed of strong winds varies a great deal. It is always at least 3 or 4 meters per

second, and sometimes goes as high as 15 meters per second. For weaker winds, the amplitude of the oscillation is smaller. It thus appears that the size of the momentary variations in wind speed increases as the average wind speed increases. Horizontal winds also contain even smaller oscillations than gusts. I called these minute /48
fluctuations pulsations. They are variable in number, sometimes 5 to 7 per second. The stronger the wind is, the more rapid the fluctuations are.

The winds of the open sea are more regular than those that cross the land. I have observed through the use of recordings that the gusts of a sea breeze have a smaller amplitude than land breezes. A wind in the ocean whose average speed is 11.5 m/sec will in general have a maximum speed not much greater than 13.5 m/sec and a minimum speed fluctuating between 9 and 10 m/sec. However, this does not always hold true and I have encountered sea breezes with much greater oscillations. It is very rare, though, that winds in the open sea show sudden decreases in speed, as occurs on land.

Figure 54
Speed of a Wind in the Crau Plain
Recorded with a Hot Wire Anemometer
(1 min. = 4.7 cm)

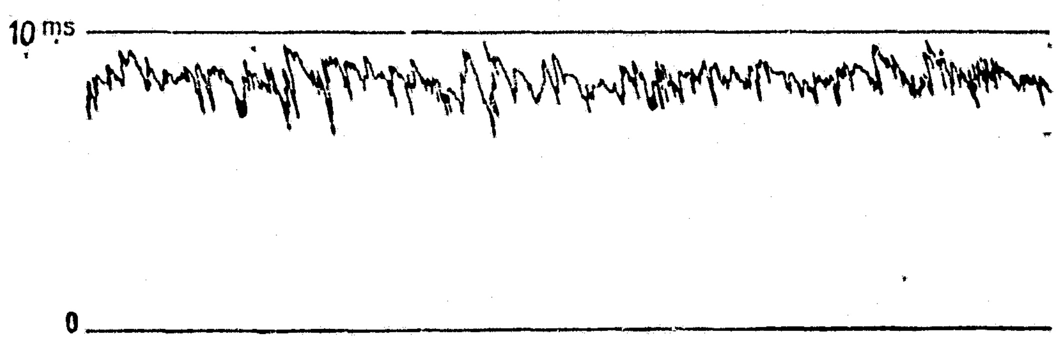


Figure 55
Speed of a Wind on the Summit of Mont Ventoux
Recorded with a Hot Wire Anemometer
(1 min. = 4.7 cm)

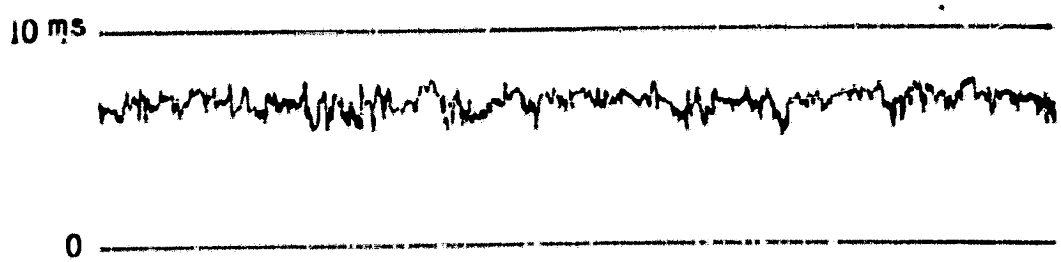


Figure 56
Speed of a SSW Sea Breeze in Brittany
Recorded with a Hot Wire Anemometer
(1 min. = 4.7 cm)

An examination of the tracings reveals in addition that generally the period of increasing speed in a sea gust is practically equal to the period of reducing speed. This is contrary to what occurs on land. Often gusts of sea breezes have sudden reversals and decrease speed for 1, 2, or 3 seconds only to increase speed anew. One or two such reversals are frequently found in a gust. Sometimes there are as many as four or five.

It also seems that the character of the wind changes, as much on the sea as on land, according to the direction in which it is blowing. Only repeated experiments can reveal the reasons for this change. /49

Figures 54, 55, and 56 provide some examples. They reproduce tracings of wind speed obtained with a hot wire anemometer. The first tracing is from the Crau plain, the second from the summit of Mont Ventoux (1,912 meters), and the third is that of a sea breeze.

It can be seen that the wind is less turbulent over the ocean than on land, even when blowing over a plane.

The above observations were made with fairly simple equipment. Research done between 1925 and 1929 on the Ile de Ré by Huguenard, Planiol and me has confirmed all these facts.

Figure 57
Speed of a WSW Sea Breeze
Recorded at the Ile de Ré
with a Hot Wire Anemometer
2 M above the Ground
1 sec = 3.5 mm
Scale of Speed: 1.3 mm per m/sec

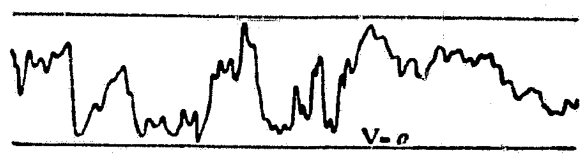


Figure 58
Speed of a NE Land Breeze
Recorded at the Ile de Ré
with a Hot Wire Anemometer
10 M above the Ground
1 sec = 3 mm
Scale of Speed: 1.3 mm per m/sec

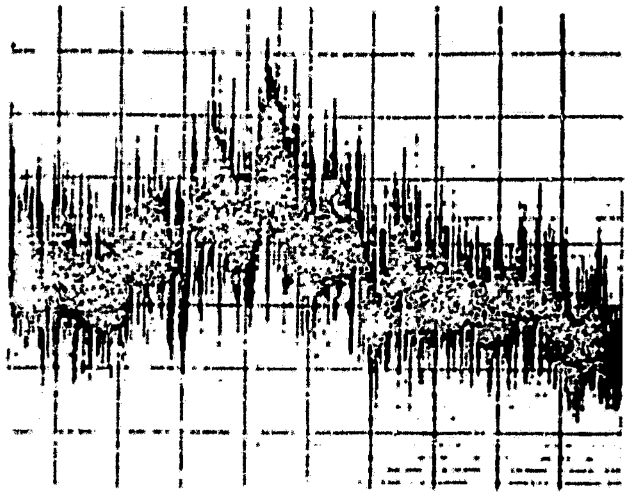


Figure 59
Recording of a Blizzard
Made in 1914
by the Scott Mission

Figure 57 shows the tracing of a sea breeze whose largest variations are smaller than 1/3 the average speed. The second tracing (figure 58) was made 10 meters above the ground of a NE land breeze, which arrived at our instruments after having crossed the Ile de Ré. Here, the size of the variations is much greater than in the preceding figure. Occasionally wind speed changed from 0 to 14 m/sec in less than 2 seconds.

Finally, figure 59 reproduces a recording made by Captain Scott in a blizzard he encountered during his mission. The fluctuations in this tracing are very large indeed. In a wind whose average speed is 50 m/hr, there are variations of more than 20 m/sec over very short periods of time.

Variations of Wind Speed with Increasing Altitude /50

The study of the wind naturally includes research into the way in which wind speed changes with increasing altitude. Experiments on this subject are very difficult to carry out, but they are indispensable for learning about the local structure of air (in the vicinity of flying birds, for example.) To measure speed as a function of height, it is useful to compare the readings of two anemometers, one fixed near the ground and the other positioned at various points above the first.

Accurate results have been obtained using ten meter tall masts braced by a system of three guy wires attached to the top of the mast and to three points on the ground. An anemometer is attached to a rope passing through a pulley located on a cross piece at the top of the mast. The purpose of the pulley is to raise the anemometer to various altitudes while a support leaning against the mast keeps the anemometer pointed in a constant direction.

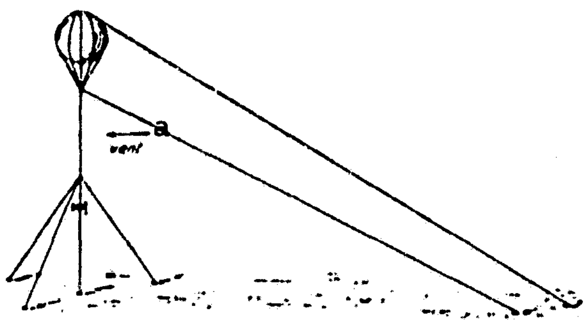


Figure 60
Balloon for Lifting an Anemometer to High Altitudes

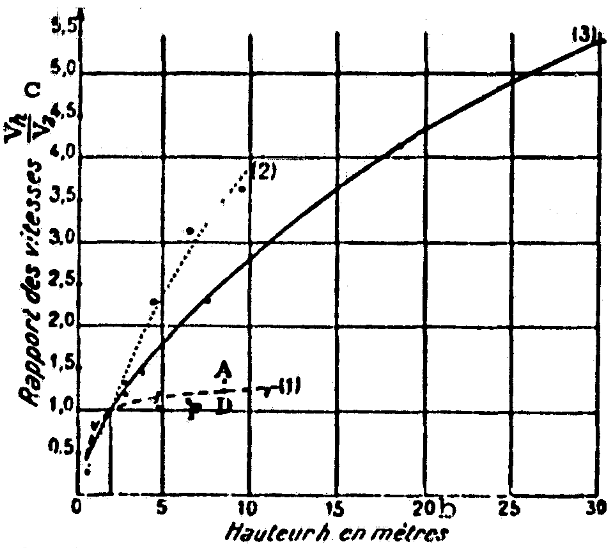


Figure 61
Wind Speed vs. Altitude According to Topography (1, flat - 2,3 with obstacles)

Key:
- a) wind
- b) height in meters
- c) ratio of speed above the ground to speed at ground level

To go higher up, a 4 meter balloon is attached to the three guide wires. (See figure 60.) The height is changed by changing the lengths of the three wires. The balloon is held directly above the two anemometers by two wires, one attached above and one below the balloon. The wires are anchored to the ground a good distance upwind from the balloon. The advantage of this arrangement is that it can be used either on land or in shallow water and that it allows higher altitudes to be observed.

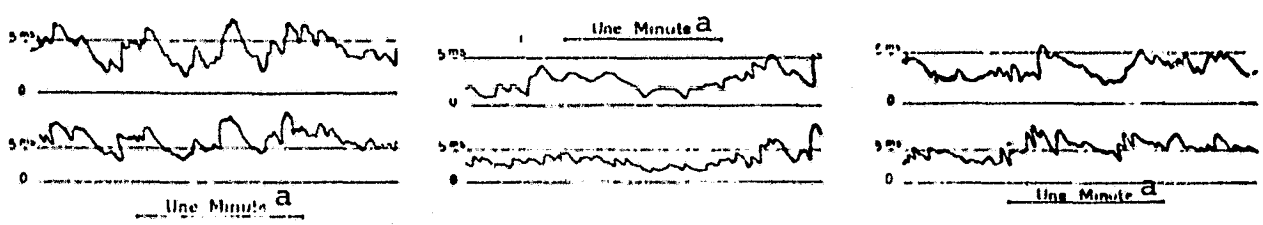
Experiments have been done on bare, level surfaces and also in front of and in back of obstacles. A comparison of 200 simultaneous readings, taking into account the fluctuation of the wind, has enabled us to learn the relationship between the average wind speed on the ground and the average speed higher up. A graph of this relationship can be found in figure 61. The abscissa of the points is the altitude attained by the movable anemometer. The ordinate is the ratio of average speeds above the ground to that 2 meters above the ground.

The end result of this research is that the change in the speed of wind as altitude increases depends on the size of obstacles encountered by the wind. Curve 1 in figure 61 was made from measurements taken at Saint-Inglevert on a large level area and at a beach covered by an incoming tide on the Ile de Ré. It shows that there is a rapid increase in the wind from 0 to 2 meters, after which /51 the increase is much slower.

Curves 2 and 3 were made from readings taken at Saint-Inglevert 100 meters behind some large hangars 30 meters high and at the Ile de Ré in front of a 5 meter tall sand dune. They indicate that the increase in wind is less rapid than curve 1 at first, but that wind speed continues to increase at almost the same rate up to the highest altitude measured.

The Propagation of the Wind

If the speed of the wind changes with altitude, what takes place at ground level? Do gusts remain stable as they advance?



Figures 62, 63, & 64
Simultaneous Recordings of the Speed of a Land Breeze Made in Brittany with 2 Electromagnetic Anemometers Placed: Side by Side 1 m apart (#62); one 55 m upwind from the other (#63); one 115 m upwind from the other (#64)

Key: a) one minute

To learn about wind propagation, we placed two anemometers on a heath in Brittany 3 meters high and 1 meter apart in a plane perpendicular to the wind. The resulting tracings were almost identical (figure 62)

One of the anemometers was then placed upwind from the other. The generally flat area in which the anemometer was located was scattered with small obstacles less than a meter high. The distances separating the two instruments was successively 5 meters, 10 meters, 20 meters, 55 meters, and 115 meters.

The tracings obtained at 55 meters (figure 63) still show a very close resemblance. At greater distances, the congruence remained for slow oscillations. The tracings made at 115 meters apart (figure 64) prove that low frequency oscillations are propagated without major modification, while the others are ephemeral and do not appear in both curves.

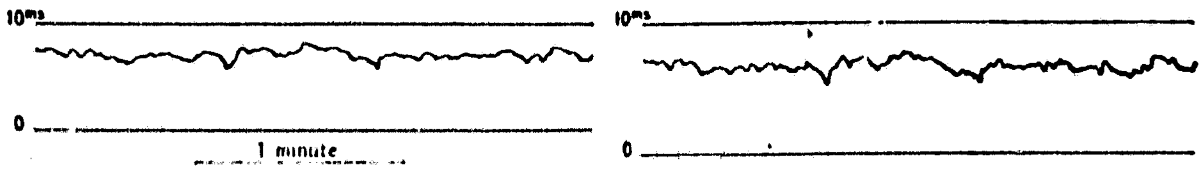


Figure 65
Simultaneous Recordings of the Speed of a Sea Breeze Made in Brittany with 2 Electromagnetic Anemometers Placed 46 m Above Sea Level, 5 m Apart in a Plane Perpendicular to the Wind

Figures 62, 63, and 64 justify the hypothesis that, within the zone that has been studied, the wind is propagated without deformation, like sound waves. In other words, the measurements made by two anemometers, one upwind from the other, will be practically the same as far as low frequency oscillations are concerned. The only observable difference will be that the readings of the second anemometer will be somewhat later than the first.

In fact, the fluctuations, i.e. the gusts, are preserved pretty exactly. /52
The alterations observed are not much greater than those of sound waves traveling at ground level.

In another experiment, two anemometers were placed side by side 5 meters apart at the summit of the signal tower at Pointe Saint-Mathieu [Saint Mathew's Point] 46 meters above sea level. They were exposed to a sea breeze blowing from the SSW. The resemblance of the two curves thus obtained is striking. (See figure 65.) The two tracings are almost identical.

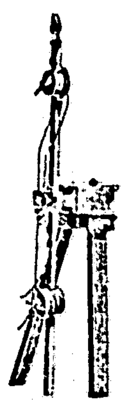


Figure 66
Pendulum
with Hot Wire

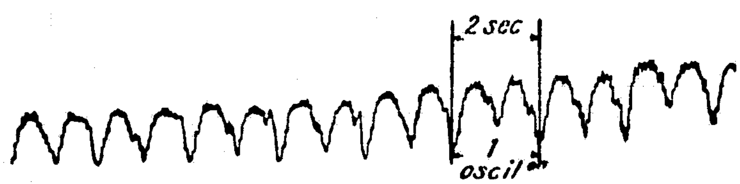
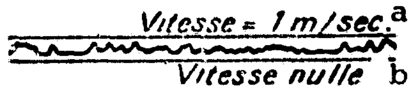


Figure 67
Wireless Transmission
from the Pendulum in Figure 66



Key:
a) Speed = 1 m/sec
b) Zero Speed

Figure 68
Wireless Recording
of the Speed of a Gentle Wind

In studies of this type, the weight of the equipment to transport or remove can be troublesome.

As a matter of fact, when the signals from a hot wire anemometer have to be transmitted over a great distance the weight of the wire alone is an impediment to the experiment.

We have searched for a means of resolving this intricate problem. An apparatus that doesn't need insulated transmitting wires, which are always fairly cumbersome, is required.

We have been successful in finding such apparatus for the study of wind speed. The measurements made by the hot wire can be transmitted by radio.

The accuracy of wireless transmissions was demonstrated by the following experiment. We attached a hot wire to the end of a pendulum 60 cm long (figure 66). The period of the oscillations was 15 cm, which gives a maximum air current speed of 21 cm/sec. The curve in figure 67, traced by the receiving galvanometer, reveals the extreme sensitivity of the apparatus and the excellence of the method employed. In this experiment, the hot wire was not compensated. If it had been, the curve traced would have been sinusoidal.

Figure 68 also demonstrates the sensitivity of wireless apparatus. The tracing here is of a wind whose maximum speed was less than 0.40
m/sec. Even so, all the small fluctuations of the speed of the wind /53
are shown with a remarkable clarity.

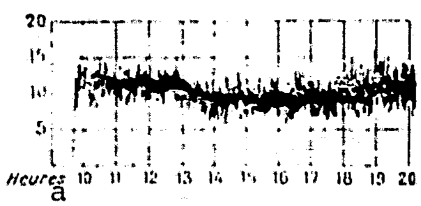


Figure 69
Wind Tracing
Made at Aberdeen
with an Anemometer 12 m
above the Ground,
900 m from the Sea
(after Taylor)

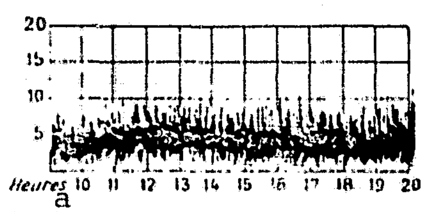


Figure 70
Wind Tracing
Made at the Same Time
23 m above the Ground,
9 km Inland, above
a Grove of Trees

Key: a) hours

Figure 69 is an anemometric tracing taken at Aberdeen on September 26, 1922 between 10 A.M. and 8 P.M. The anemometer was placed 12.2 meters above a cultivated field located 900 m from the ocean. The average wind speed was 10 m/sec.

A record of the wind on the same day and time, but 9 km inland, is found in figure 70. The anemometer was placed in the midst of a grove of fairly tall trees. It was located 23 meters above the ground, or about 5 meters above the tops of the trees. The average speed observed between 9 A.M. and 8 P.M. was 4 m/sec.

It can be seen that the fluctuations in the second tracing are much larger than in the first and that the average speed is much smaller.

Fluctuations in the Inclination of the Wind

The wind not only changes speed, its inclination and direction also fluctuate. (See figure 71.)

The determination of inclination is particularly important for flight, as will be seen later on.

We, as well as others, have recorded the inclination of the wind with our hot wire apparatus close to the level of the ocean. At the time of our observations, the ocean was covered with waves .50 to 1 meter high. We made a similar recording from the top of the signal tower at Pointe Saint-Mathieu. (See figure 72a and b.)

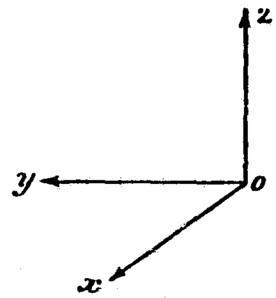


Figure 71
Principal Axes
of Wind Oscillation

Our recordings showed that the wind doubled in speed between 2 and 46 m, whereas the pulsations diminished by a factor of six.

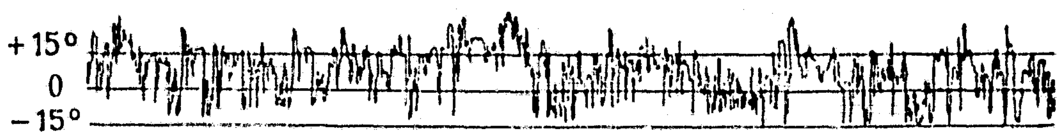


Figure 72a
Instantaneous Inclination of a Sea Breeze
Near the Surface of Slightly Choppy Water

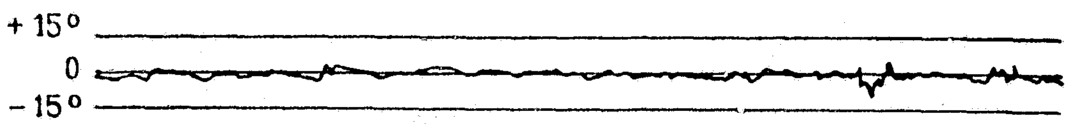


Figure 72b
Instantaneous Inclination of a Sea Breeze
46 m above the Water

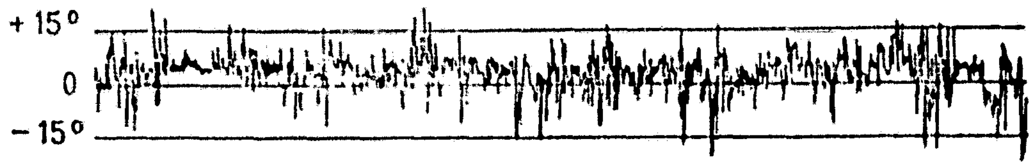


Figure 73
Instantaneous Inclination of a Land Breeze on the Crau Plain

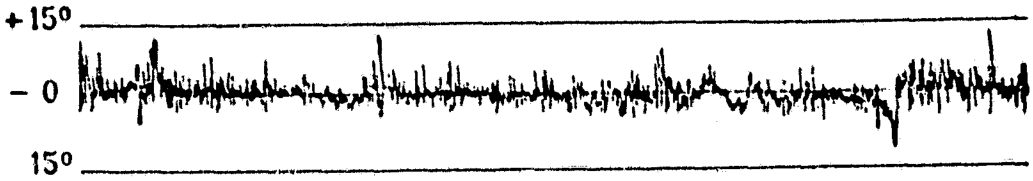


Figure 74
Instantaneous Inclination of a Wind at the Summit of Mt. Ventoux
(for Figures 73 and 74: 1 minute = 4.7 cm)

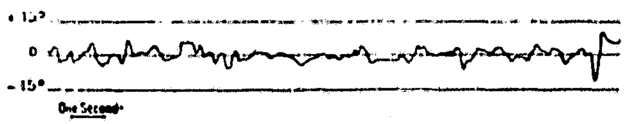


Figure 75
Inclination of a Wind
at the Summit of Mt. Ventoux

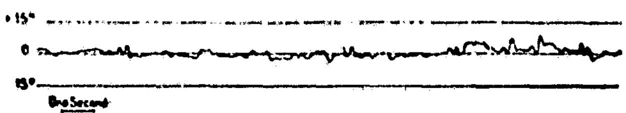
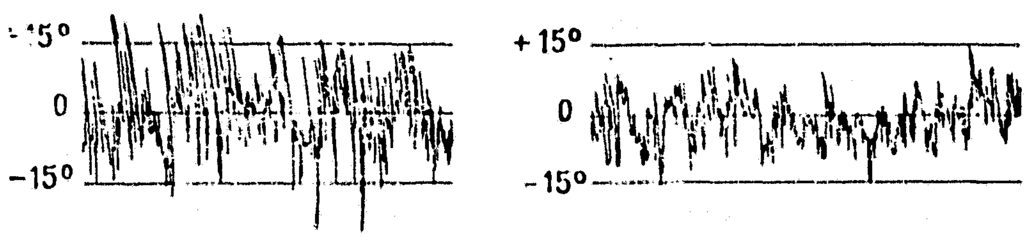
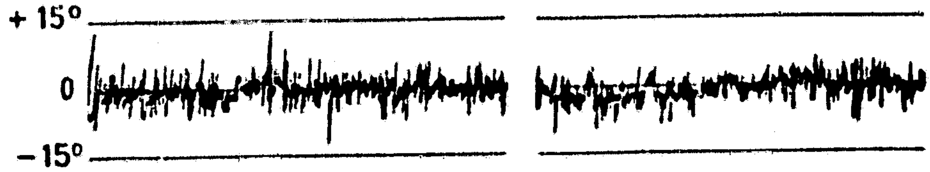


Figure 76
Direction of the Same Wind



Figures 77 & 78
Inclination of a Land Breeze at Saint-Inglevert
2 m (Left) and 10 m (Right) from the Ground
1 min. = 4.7 cm

Figure 73 shows how the instantaneous inclination of the mistral blowing over the Crau varied. The total amplitude of the oscillations is rarely less than 5 or 6°. Changes occurred several times per second and were sometimes as great as 30°. The average was about 15°.



Figures 79 & 80
Inclination of a Sea Breeze on a Flat Beach
200 m from the Edge of the Water
2 m (Left) and 5 m (Right) from the Ground
1 min. = 4.7 cm.

Wind direction curves recorded by the same methods at the summit of Mont Ventoux are represented in figure 74. Here, the fluctuations are much weaker, and the amplitude is usually much less than 5 or 6°, rarely going as high as 10°. /55

In figures 75 and 76, the inclination and direction of a wind also at the summit of Mont Ventoux can be compared. These high speed tracings show that directional oscillations have a larger amplitude than those of inclination.

Lastly, figures 77 and 78 show that on uneven terrain at a height of 10 meters, the oscillations of the vertical component of the wind have an amplitude half the size at 2 meters. This is not true on a large beach, as shown in figures 79 and 80, where only small differences were found between 1 and 5 meters.

Our experience thus shows that the amplitude of oscillations of wind inclination is related to topographic conditions.

Simultaneous Study of Speed and Inclination

It is often necessary to compare simultaneously fluctuations of speed, inclination, and direction in a given wind.

For this, all one needs is a single hot wire instrument and two double hot wire meters, one placed in the horizontal plane and the other in the vertical. The first double hot wire device measures inclination, the second direction. The signals from the three instruments are then all recorded on the same paper. We were able to record all these instruments at once by creating a device that automatically unrolls and develops photographic paper (figure 81). The unroller contains a 6 cm wide reel of film. The film goes through a series of rollers and past a lens where it is exposed. It then passes over a roller impregnated with developer and another roller impregnated with fixer. A final roller conveys the film out of the machine. The motion of all these rollers is synchronized by means of a circular chain driven by a variable speed motor. By means of this arrangement, the film is developed and fixed in 1 to 3 minutes after exposure.

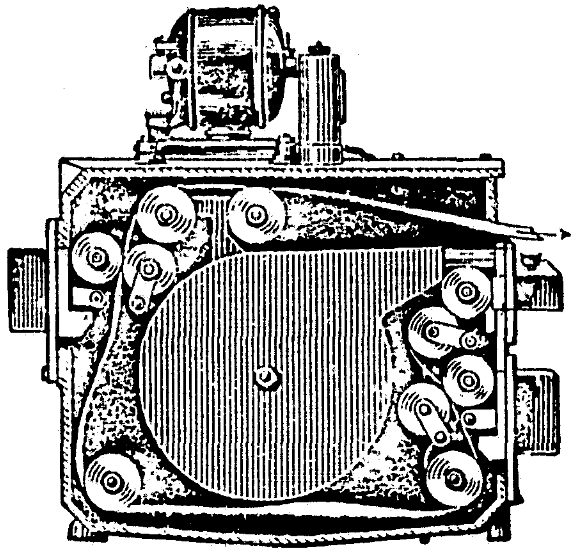
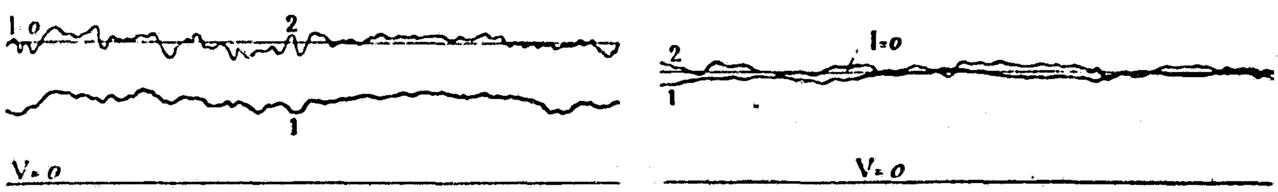


Figure 81
H.M.P. Unroller

A series of recordings made with the unroller may be found below (figures 82 and 83). /56



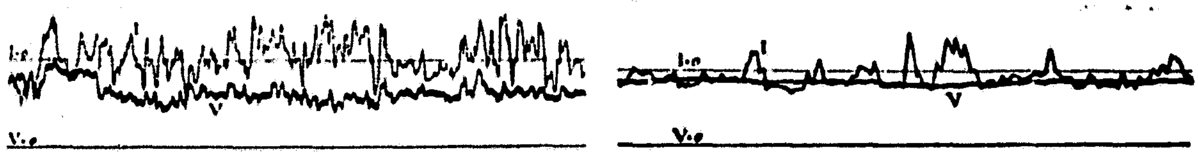
Figures 82 & 83
Speed (1) and Inclination (2) of a Sea Breeze Recorded Simultaneously at the Ile de Ré
Left: 5 m from the Ground, Right: 10 m from the Ground
Scales: Speed, 14 mm = 1 m/sec Inclination, 7 mm = 16°
Time, 1 sec = 11.8 mm

These curves confirm the results already mentioned and show that speed actually does increase with altitude, while the amplitude of its fluctuations diminishes. At the same time, the magnitude of the variations in inclination also decreases with height. In addition, it can be noticed that in sea breezes the speed holds constant over periods of several seconds at 10 m.

There are, however, cases in which a sea breeze has a different configuration. We once were able to observe the behavior of a coastal tempest from beginning to end.

During the tempest, sudden changes in speed of 7 m/sec in 1/5 second were common. The inclination of the wind also showed oscillations of large amplitude (figure 84).

At the end of the storm, the speed of the wind, which still averaged 10 m/sec, returned to a regular form as usual, and large changes in inclination occurred rarely (figure 85).



Figures 84 & 85
Speed (V) and Inclination (I) of the Wind
During a Storm at the Ile de Ré
Left: Middle of the Storm, Right: End of the Storm
Scales: Speed, 5.6 mm = 10 m/s; Inclination, 3.7 mm = 10°;
Time, 3.7 mm = 1 sec

RECOMMENDED READING

Dives, Quarterly Journal of the Royal Meteorological Society, 5, 20 (1894).

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Maurain, "Sur les variations du vent" [The Fluctuations of the Wind], Bulletin de l'Institut aérotechnique de l'Université de Paris, 3 (1913)

Scott, Last Expedition, Volumes 1, 2, London, (1914).

Taylor (see Toussaint), "Etude sur la structure interne et la turbulence du vent naturel dans les couches inférieures de l'atmosphère" [A Study of the Internal Structure and Turbulence of Natural Wind in the Lower Layers of the Atmosphere], Technique aéronautique (February 15, 1925).

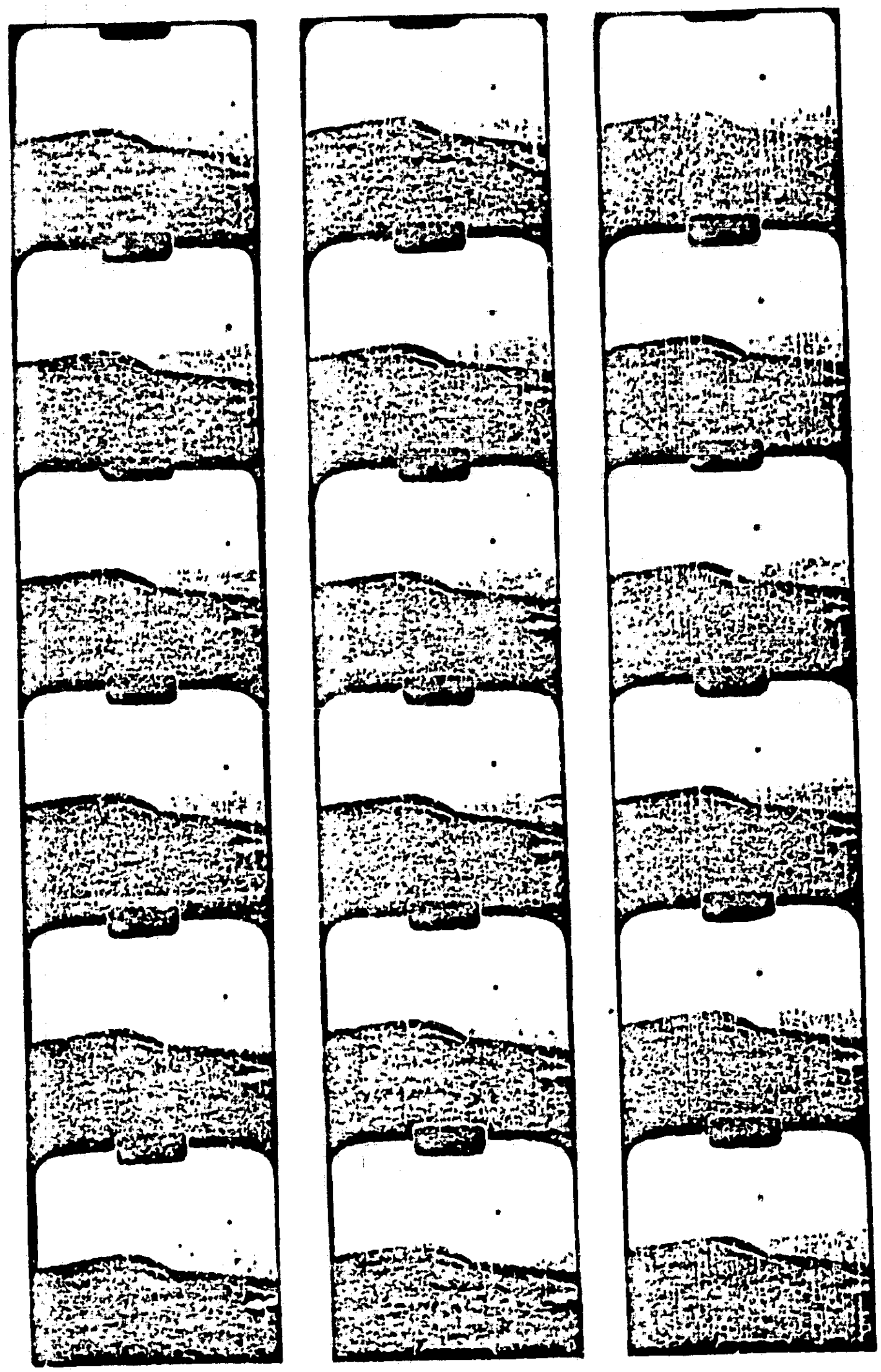


Figure 86
Film of the Path of a Balloon 75 cm in Diameter Launched at a Height of 5 m in the Blanc-Nez Region in a Wind (E) Blowing from the Right
(Read from Top to Bottom and from Left to Right)

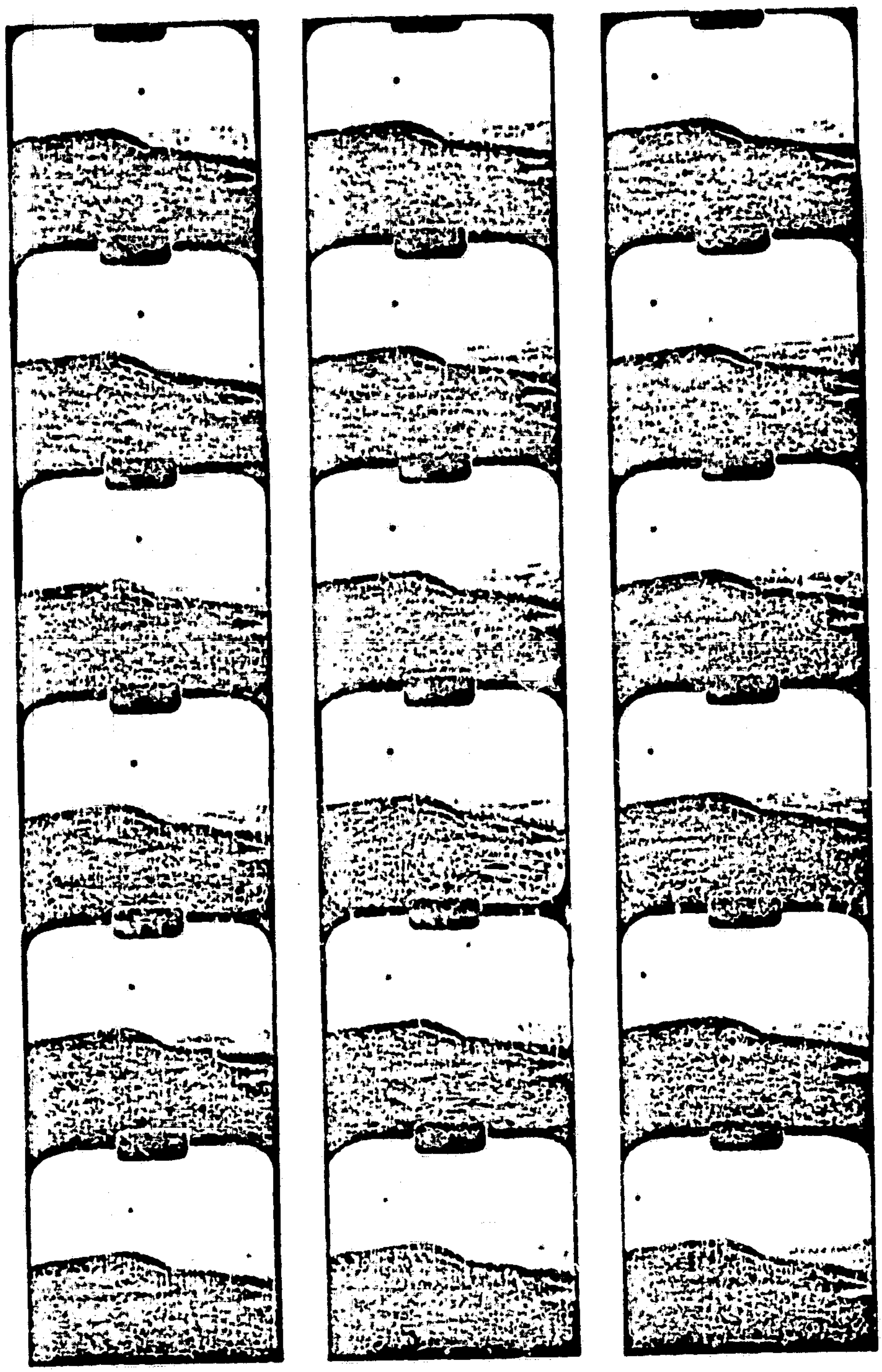


Figure 86 (Continued)

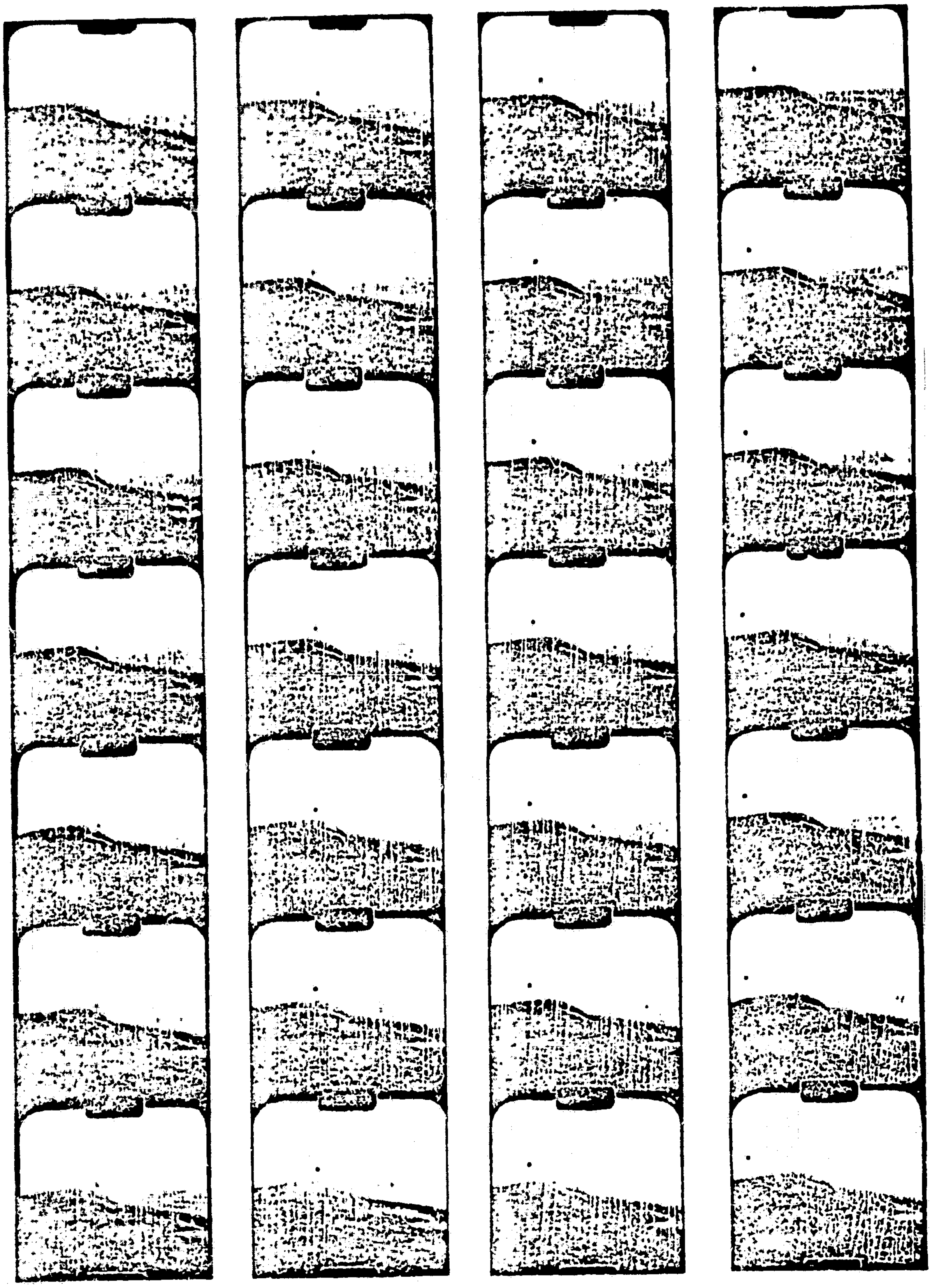


Figure 87
Path of the Same Balloon in an Easterly Wind
Launched at a Height of 1 m in the Blanc-Nez Region
(Read from Top to Bottom and from Left to Right)

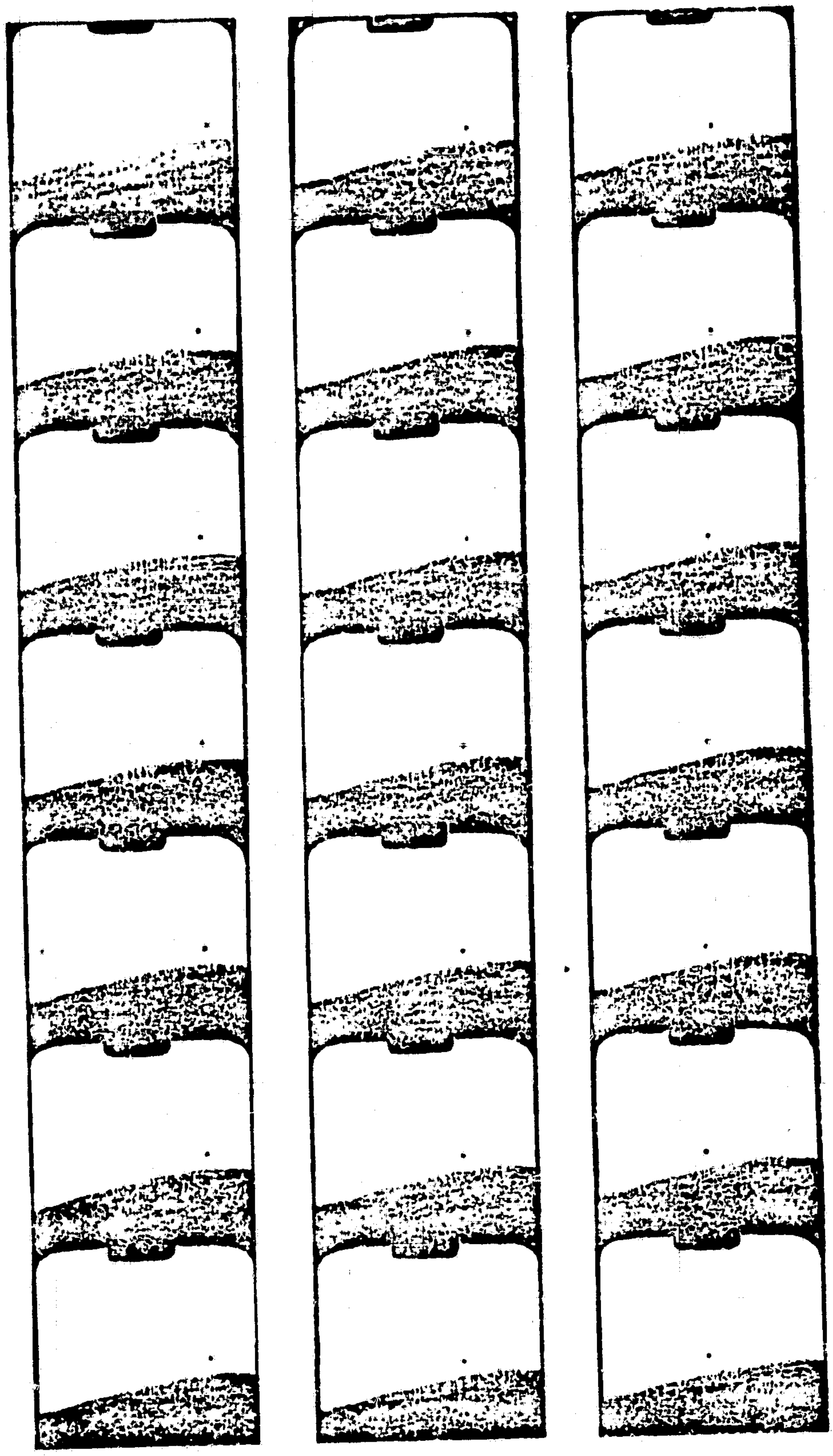


Figure 87 (Continued)

Lesson Four: Rising Air Currents. Air Turbulence. The Periodicity of the Wind. /57

In the last lesson we studied horizontal air motion, which is caused by differences in pressure between two regions. The air moves from a region of high pressure to one of low pressure.

I. Rising Obstruction Currents

Although the winds that traverse relatively calm seas or flat plains appear to be generally horizontal, this is no longer the case when they encounter uneven terrain. They then conform to the deformations they find. I have proved this in experiments which I shall describe here.

Methods for Detecting the Existence of Ascending Winds

I employed balloons 40, 75, and 100 cm in diameter, according to the speed of the wind under study and the height of the obstacle in the path of the wind. Once the balloons were inflated with hydrogen to the desired diameter, they were counterweighted so as to float at rest in calm air. The ballooons were then launched at different points exposed to the wind. Since the buoyancy of the balloons was cancelled out, they were pushed along by the air current and followed its path very closely. If the wind were horizontal, the trajectory of balloons would also usually be horizontal. They would ascend or descend only if the air current was rising or falling. If they were observed to be moving back and forth, it was because they had entered a region of turbulence.

Once the balloon was launched, its movements could be followed with a theodolite. However, it was preferable to film them. It was thus possible, with the aid of a reference mark or coordinate lines in the field of the camera, to deduce the height of the balloon above the horizon (if the diameter of the balloon is known) and then the exact trajectory that it had followed. Similar results may be obtained by using smoke, which has been used in some very fruitful wind studies, especially concerning eddies. However, only a restricted area can be studied at one time.

The film reproduced in figures 86 and 87 was made at Blanc-Nez in a strong wind. The counterweighted balloon in the film was 75 cm in diameter. As the frames progress, they show the displacement of the balloon, released 5 and 10 meters from the ground, and 100 meters away from a 20 meter high hill.

The trajectory of the balloon was drawn by plotting point by point the positions found in the film. Instead of having to measure the /58
position of the balloon on all the frames, a photographic method which directly traced the balloon's path on one print is imaginable. This would consist of successively projecting all the negatives onto the same sheet. (See figure 88.)

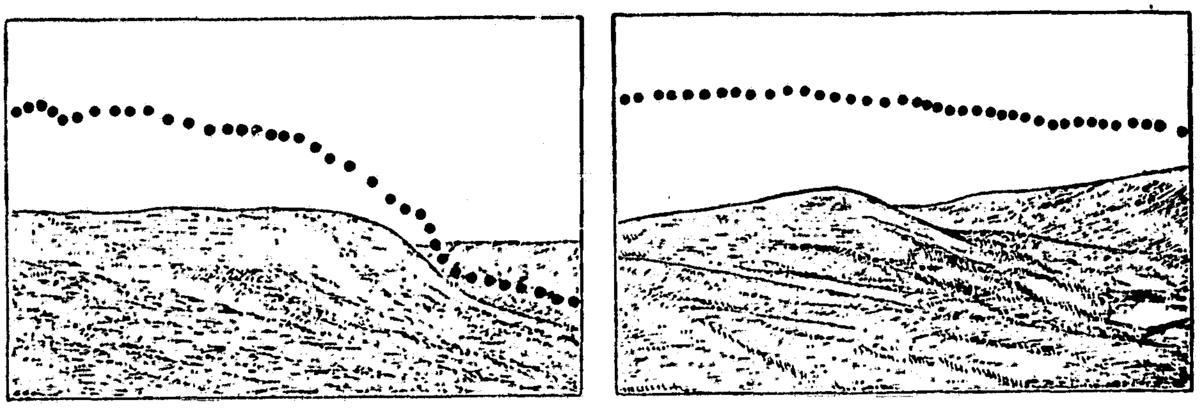


Figure 88
Path of Counterweighted Balloons in a Wind Flowing from Right to left. Left: Released 2 m from the Ground; Right: Released 10 m Up (Transferred from Successive Film Frames)

Another method of obtaining the exact direction of the wind above uneven terrain is to use a double hot wire indicator, as has already been described.

The following approach, based on changing the refraction index of part of the air current, serves to map out the path of a stream of air encountering an obstacle in a wind chamber. A very fine electric wire is placed at the entrance of the experimental chamber in a wind tunnel. The stream of warm air that leaves the wire refracts light differently than the neighboring streams of cool air. An arc lamp is placed 10 meters from one of the ends of the chamber, whose two sides are covered by mirrors. A uniform lighted area then exists on a screen placed perpendicular to the light beam. The warm air streams are then easily distinguishable against the screen. In figure 89a, a photograph of a stream propelled by the air in a wind tunnel is reproduced. It is horizontal. What happens when the same air stream comes up against an obstacle is shown in figure 89b. It is first deflected upwards and then is pushed back down again.

The Influence of Terrestrial Obstacles on Horizontal Winds

I have conducted a great deal of research on the effect of obstacles on winds passing over them. Except on the part of myself and Idrac, there has not been much work done on this subject. Here are the conclusions I have reached.

My research has shown that the smallest obstacle causes changes in the path of a normal, horizontal surface wind. A wall, for example, causes a very clear deflection of an air current. The wind goes up and over the wall, producing small eddy currents in front of it. The eddy currents are more noticeable if the weather

is dry and there is dust or sand near the wall. A small pile of sand or dust is then formed in front of the wall. The higher the wall, the further away the pile is. In back of the wall, another zone of eddy currents may be found. Turbulence is caused here by /59
a reduction in air pressure and the consequent rush of air toward that spot. A tree or small cabin is enough to cause similar perturbations. (See figure 90.)

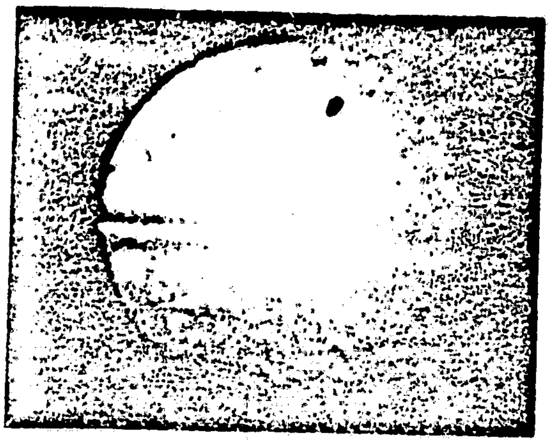


Figure 89a
Warm Air Stream Propelled from the Left by Cool Air Current in Wind Tunnel

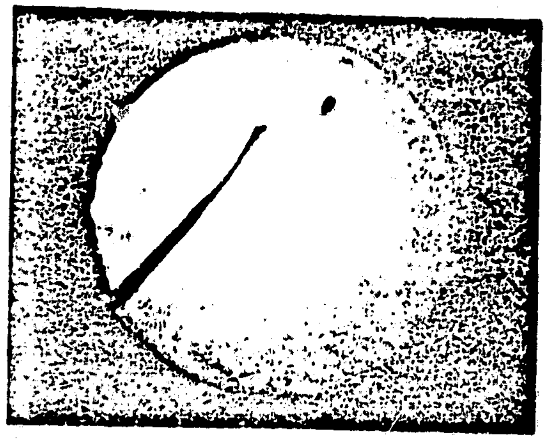


Figure 89b
Warm Air Stream Propelled from the Left by Cool Air Current in Wind Tunnel and Encountering an Obstacle

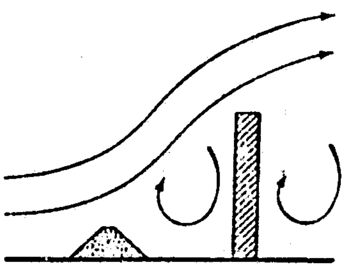


Figure 90
Path of Air Current Hitting a Wall, Showing Eddies and Sand Pile

When a horizontal surface wind encoutners a vertical cliff or a slope, the lowest layers of the wind give rise to local eddy currents at the foot of the obstacle (figures 91 and 92), just as in the case of the wall. Meanwhile, the other layers are forced upwards, towards the top of the slope or cliff.

As the air moves upwards, it comes against other layers of air which have preserved their original horizontal trajectory. These upper layers are then also deflected upward, the extent of this deflection depending on how high they are above the top of the obstacle. At the same time, the series of collisions between layers of air has the effect of gradually pushing the upward moving layers back down towards the general direction of the current. The deflection is usually not detectable beyond a distance of three times the height of the cliff at the point where the wind passes over the ridge. Sometimes a deflection is noticeable at four times the cliff's height because the magnitude of the deflection depends on the average speed of the wind.

The area where ascension is the greatest is located above and /60
ahead of the edge of a cliff and a little ahead of the summit of

a hill. I call this part of the airflow an obstruction current.

In contrast, an unfavorable zone exists on the plateau in back of the edge of a cliff.

Let me add that the obliquity of the wind in relation to the obstacle diminishes considerably the force causing the air current to rise.

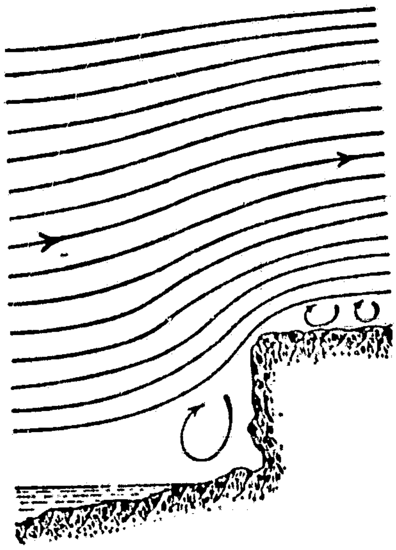


Figure 91
Path of Air Current
Encountering a Cliff

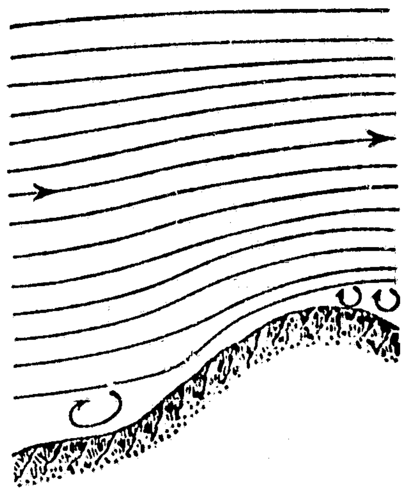


Figure 92
Path of Air Current
Encountering a Slope

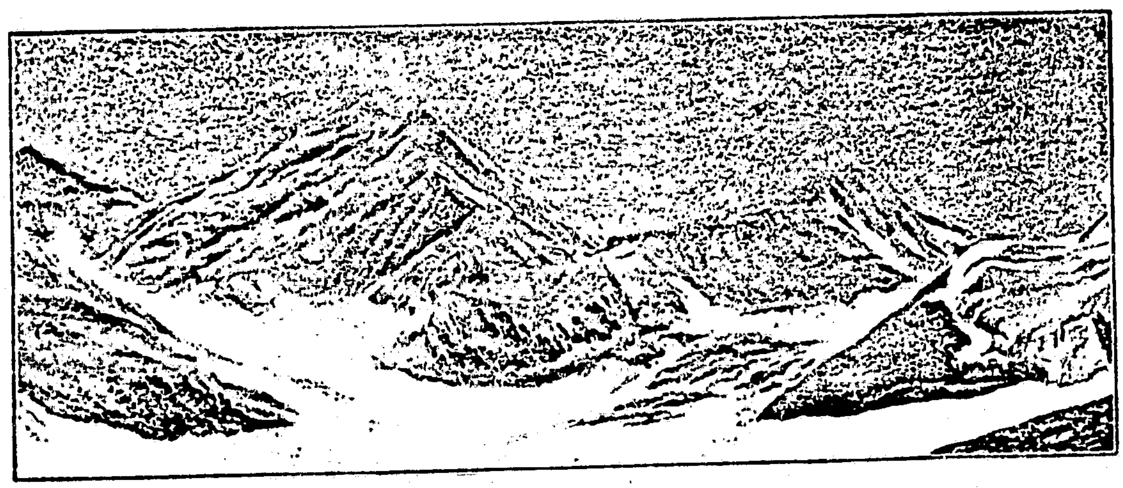


Figure 93
Snow Lifted Up by Wind Blowing from Right on Mt. Everest, Showing the Size of the Turbulent Zone (from Howard-Bury)

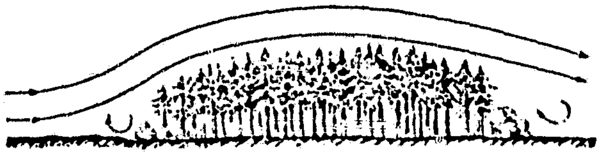


Figure 94
Path of Lower Layers
of an Air Current
Encountering a Forest

Figure 96
Path of Lower Layers
of an Air Current
Encountering a Wave

Key: a) Direction of the wind and the swell

The photograph in figure 93 shows in an incontrovertable fashion the size of the turbulent zone existing on the leeward side of obstacles. The snow suspended in the air clearly outlines the large area occupied by the zone.

Forests cause a similar disturbance in the flow of air (figure 94). The same may also be said for waves.

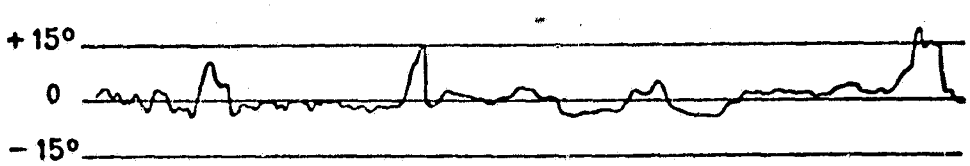


Figure 95
Recording of the Ascensions Causes by an Ocean Swell
as Measured by an Anemometer 0.50 above the Crest of the Waves
The Oscillations Greater than 5° Are Due to the Wave
The Rest Are from the Wind Itself

As everyone knows, when a steady wind blows across the sea, it produces waves separated by regular intervals. A "swell" is the name given to this phenomenon.

In strong winds, swells, or waves, if you prefer, ripple up in their turn and form supplementary wavelets. If the wind becomes violent, the crests of the waves are foamy. I got an exact idea of the phenomenon by placing a hot wire inclination indicator 50 cm above the crests of the highest waves.

The oscillations of large amplitude, representing the passage of the waves, can be seen in figure 95. As a whole, the phenomenon is the same, whether it consists of a hill or a wave (figure 96). In both situations the deviation depends on the height and inclination of the obstacle. However, in the case of a wave, the upper deflections of the lower layers of air are not linked to the absolute speed of the wind, as is the case for an obstacle on the land, but to the speed of the wind relative to the wave. This is why the deflections observed in the ocean are usually smaller than those observed on land. If the speed of the wind is less than the speed of the waves, everything takes place as if the wind was going in the opposite direction. The rising current is located at the spot where the wind is encountered by the leeward side of the wave.

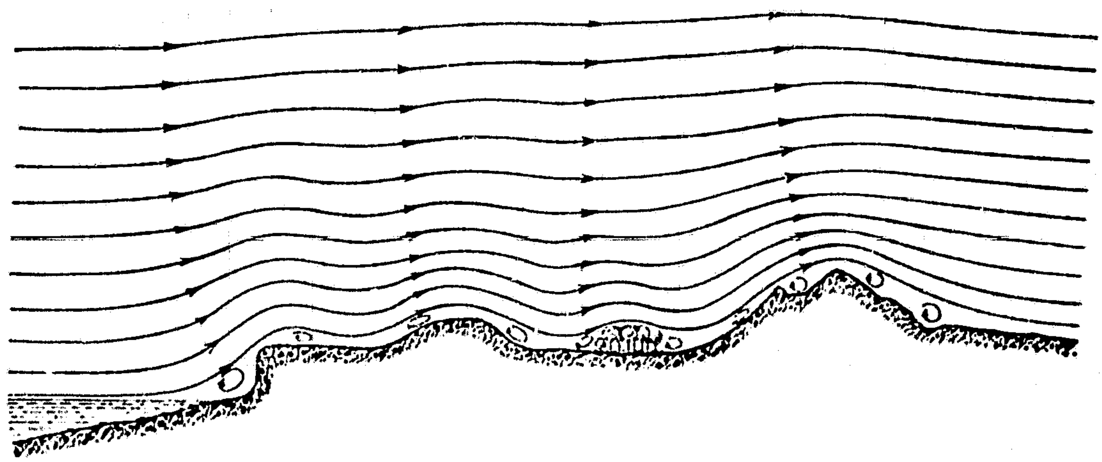


Figure 97
Flow of Air Streams above a Calm Sea and Uneven Ground

Figure 97 illustrates the manner in which air streams flow over a calm sea and a region of uneven ground.

It also seemed to me to be important to find out at what distance before a hill or a cliff the deflection of the air current caused by the obstacle could first be detected. I have learned that this distance is a function of the height of the obstacle and of the speed of the wind. For a wind of 8 to 10 m/sec, the influence of a high cliff or hill with straight slopes can normally be felt about 15 times its height ahead and 20 times its height behind the obstacle. For winds of 15 m/sec, greater distances were found. /61

I have observed that the cliffs of the English Channel and the heights of Villacoublay, which are 100 meters high, induce deflections 2 km after the winds have passed them by.

The Speed of Rising Obstruction Currents

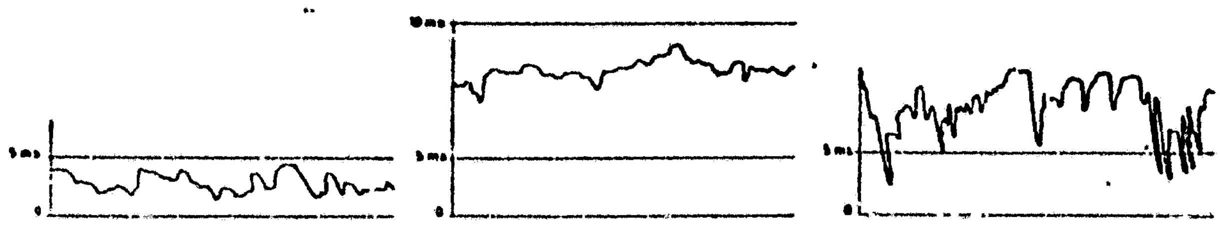
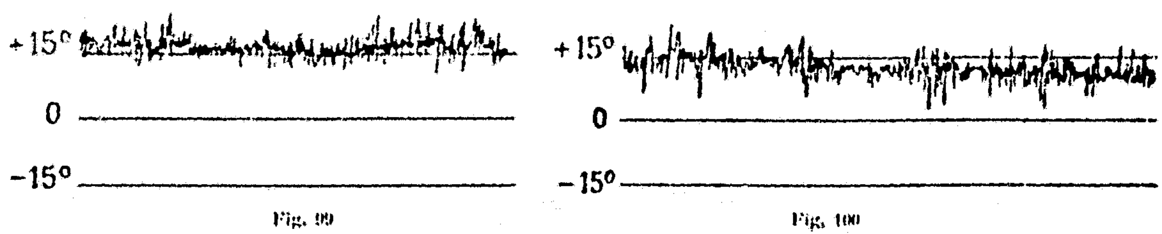


Figure 98
Simultaneous Recordings of a Sea Breeze Made at Cap Gris-Nez
Left: at the Foot of an 80 m High Cliff; Middle: 2 m above the Edge of the Cliff; Right: 50 m behind the Cliff

The speed of the wind is also greatly altered by the obstacles that the wind encounters. Thus, the strength of the wind is 20% greater in the vicinity of a cliff. In certain cases, the increase attains 30% or even more. Moreover, the degree of reinforcement does not always appear to be independent of the original speed of the wind. At Cap Gris-Nez [Cape Grey Nose], I have observed winds of 4 m/sec at the bottom of a 80 meter cliff peak at 8 m/sec 5 meters above the top, and retain a speed of 7 m/sec 50 meters later. (See figure 98.)

I have, however, also noticed that forests have the opposite effect. They usually reduce the speed of the wind. In the lee zone itself, the reduction is often 25% and the effects of the trees persist for several hundred meters, depending on the forest's extent.



Figures 99 & 100
Simultaneous Recordings of the Inclination of a Sea Breeze
Left: 0.50 m above the Top of a Sand Dune
Right: 2 m from the Top of the Same Dune

Finally, rising vertical currents have variations in inclination just as surface winds do, as may be seen in figures 99 and 100.

The study of rising air currents by means of counterweighted balloons also allows the vertical component of wind speed to be measured near a slope.

This was the method I used to discover the distribution of speeds as a function of altitude for a westerly /62 wind in the Villacoublay region whose average speed was 15 to 20 m/sec. (See figure 101.)

Because of the nature of the terrain, there is a constant upward air current around Villacoublay. The winds, after blowing through the Vallée de la Bièvre [Bievre Valley], come across the heavily wooded slopes of the Homme Mort [Dead Man] and are forced upwards. They thus acquire a vertical speed which still has a magnitude of 1 to 2 m/sec 200 meters behind the slope, at 300 meters altitude. This speed is also caused by the fact that the terrain slopes upward from the wooded area to the edge of the airfield.

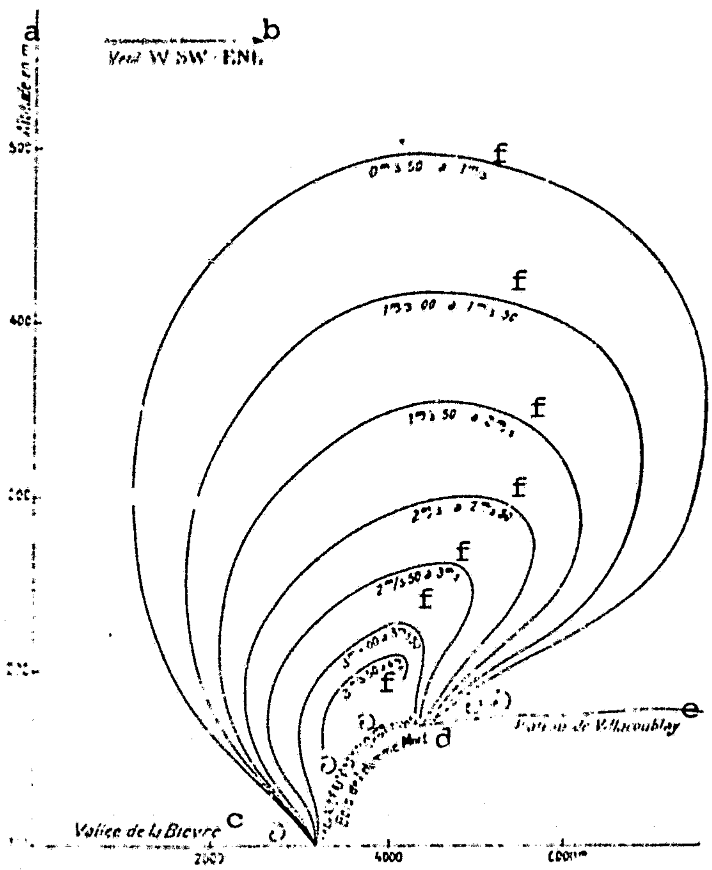


Figure 101
Curves of Equal Vertical Speed for a 15 to 20 m/sec Wind in the Villacoublay Region

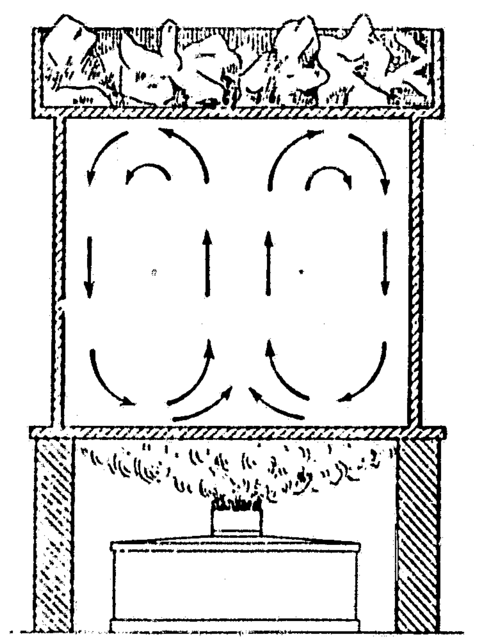


Figure 102
Hiram Maxim's Apparatus for Studying the Formation of Convection Currents

Key: a) Altitude in meters
b) Wind: WSW to ENE
c) Bievre Valley
d) Dean Man Woods
e) Villacoublay Plateau
f) (Read: 0.50 to 1 m/sec, 1.00 m/sec to 1.50 m/sec, etc.)

II. Rising Thermal Currents

Inequalities of heat also lead to disturbances in the flow of air.

In fact, vertical currents can occur in the absence of any obstacle. /63

Experience has demonstrated this. When the intensity of the sun's rays is great for a long time, the surface of the earth heats up and warms the air in contact with it. The air becomes lighter as it warms up, and this gives birth to rising currents. Idrac has observed that the temperature of such currents is higher than the surrounding air by as much as 1.5°.

As the air rises, it gradually cools down and becomes heavier. It then descends again toward the earth's surface. The entire performance seems identical to the convection currents observed in the laboratory by Sir Hiram Maxim, who produced them by heating a metal plate with a lamp. The air expands, ascends, and hits another plate cooled by a container of ice. It then cools down and descends (figure 102). Idrac has been able to photograph such convection currents.

The important point is to be able to recognize the presence of rising currents of this sort.

Methods for Detecting Thermal Currents

One would think that it would be sufficient to launch balloons of perhaps 1 meter in diameter inflated with hydrogen. The balloons would then be tracked with a theodolite or filmed by a camera with a telephoto lens. By knowing the exact diameter of the balloon, the distance of the balloon from the observation site at predetermined intervals could be calculated. From the angle of ascent, the height of the balloon could then be figured out. All the elements needed to calculate the vertical speed of the balloon, and therefore of the air current, are thus present.

It is also possible to use counterweighted balloons which are launched at various points in the area under study. If the balloons rise, its is because the air currents are lifting them. If they descend, it is beause the air current is descending.

It must be noted here that the results thus obtained are never more than relatively accurate, especially after the balloon reaches an altitude of 1,000 meters.

To get a real idea of a rising current, other ballasted balloons must also be released from a certain height. The differences in speed observed between the balloons in their ascents and descents will then reveal if there really are rising currents in the locality. /64

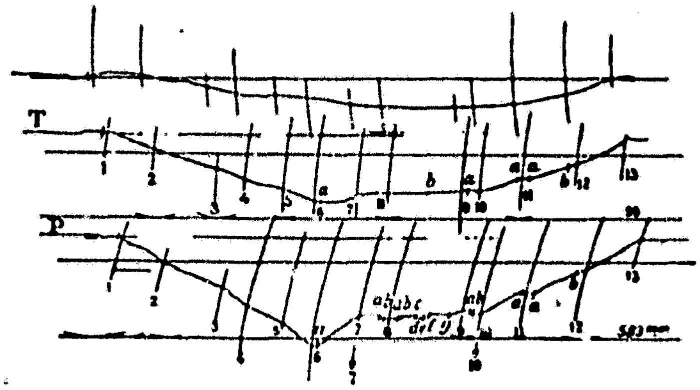


Figure 103
Meteorogram Obtained from a Powered Aircraft
Points 6-10 on the Lower Curve Correspond to
a Level Flight with Engine Stalled
T = Temperature; P = Pressure

There is another, more convenient method for exploring the atmosphere at high altitudes. This is to mount a meteorograph on an airplane to record the pressure and temperature during the ascent and descent of the airplane. If there is no rising current in the region traversed during the part of the flight made with the engine shut off, there will be a regularly decreasing pressure curve.

If the air is indeed rising, the path the airplane takes will no longer be inclined toward the ground, but will be horizontal, or even pointed upwards. As long as it is flying through a rising current, the pressure curve will be more or less horizontal. This very characteristic curve may be seen in figure 103.

It is thus possible to draw from such data the fluctuations in the inclination of the airplane and to deduce the vertical speed of the wind.

Distribution of Thermal Currents

From my experience both on land and sea, I have come to realize that there exists a constant exchange in the atmosphere. The cold air descends towards the earth in certain places, spreads out on the surface, warms up, and then rises up again in other places. This phenomenon takes place everywhere, on the land as well as on the sea.

Such rising thermal currents are very obvious in Africa, where I observed them during several field trips. As soon as the sun's rays become strong, the earth heats up rapidly, especially in the desert. The air is then heated up in its turn and immediately begins to rise. An ascending current is thus produced. In calm air it is practically vertical. Balloons rise with a speed greater than that produced by their buoyancy, and their trajectory is almost vertical. The actual vertical speed is generally rather weak; it depends on external conditions.

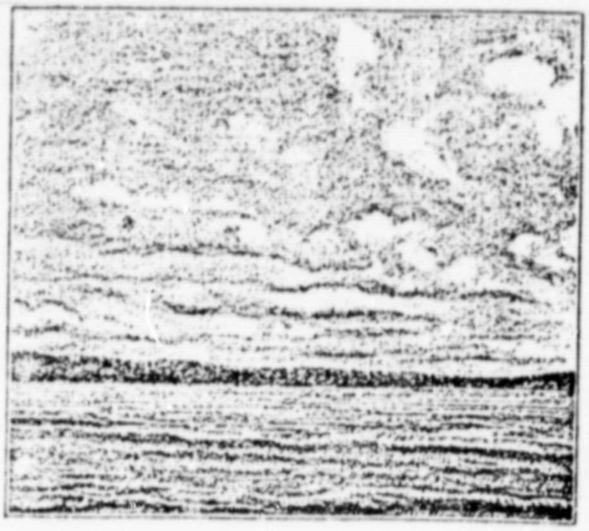
Thermal currents increase in intensity with the heat of the day. They are strongest at midday. They are also related to atmospheric conditions, and, for example, diminish or cease entirely when thick clouds cover the sun for a period of time, thus reducing the heat of the soil. In addition, thermal currents are linked to the seasons. They are stronger in summer than in winter.

The most important influence, the sun's rays, is evident when comparing diurnal and nocturnal currents. The large difference between nighttime and daytime is on the one hand based on the fact that the lower layers of air are heated up during the day, while they cool back down again during the night. On the other hand, the earth's surface heats up unequally, in terms of both speed and temperature. This has to do with the nature of the surface in a particular locality. The water, wet regions, even the forests heat up more slowly and less strongly than fields, arid steppes, or rocks. For this reason, during the day, and if the wind is weak, a descending current of air is formed everywhere that water and land come together, e.g. marshy prairies or swamps and fields, and ascending ones wherever steppes and forests meet.

Above hills, towns, and in the middle of the country, rising air masses are also found, whereas in nearby forests and waterways equal masses of air are descending and compensate for the rising masses. It has been noticed that air masses rising above a very hot region converge higher up, i.e. they have the form of a chimney, and sometimes attain the remarkable speed of several meters per second. All around them descending currents form. The position of the chimneys changes rapidly. Sometimes they may be found at one place, sometimes at another. Cumulus clouds arise above the chimneys. Such clouds are characteristic of /65 ascending wet, warm air masses. In and below the cumulus clouds (figures 104 and 105), rising air currents predominate, while in the intervals between the clouds, the air descends.

The largest vertical movement inside a cloud has been estimated at 0.5 m/sec. The greatest speeds have been found on the southern faces of clouds. On the opposite side, the air has often been observed to be falling. Even the form of the cloud may be used to draw conclusions about the vertical movements in its area of influence. Within and underneath clouds resting on a definite unified base, rising motion is greatest if the cloud has a rounded bottom. The rounded bottom is really detached parts of the clouds which are in the process of dissolution and consequently have only fleeting vertical motion.

To sum up, as an absolute rule, it may be expected that under a cumulus cloud a rising current will exist, and that in the gaps between the clouds the air will flow downwards.



Figures 104 & 105
Types of Clouds under which Exist Rising Currents (from Georgii)

Experimental Data

Here are the results of one set of measurements:

Height	Vertical Movement (-descending, +ascending)
0 -- 50 m	--
50 -- 242 m	+0.18 m/sec
242 -- 316 m	+0.63 m/sec
316 -- 698 m	+1.35 m/sec

These measurements were taken while approaching a squall cloud. They show that vertical upward motion increases as one gets near the cloud.

In Germany, Georgii has done some very interesting work in this area. He too found that below cumulus clouds (figure 104) there always exist strong updrafts. Figure 106 shows very clearly the magnitude of the vertical wind under a cloud. This was obtained by observing the alterations occurring in the path of an airplane.

Georgii also observed that in front of storm clouds there are always strong rising currents with a vertical speed as high as 7 m/sec. /66

Rising currents of this sort are very frequently encountered in all equatorial regions, which are very hot. They can be formed as easily on dry land as over the ocean. In temperate regions, they occur especially during the summer. Figure 107 illustrates

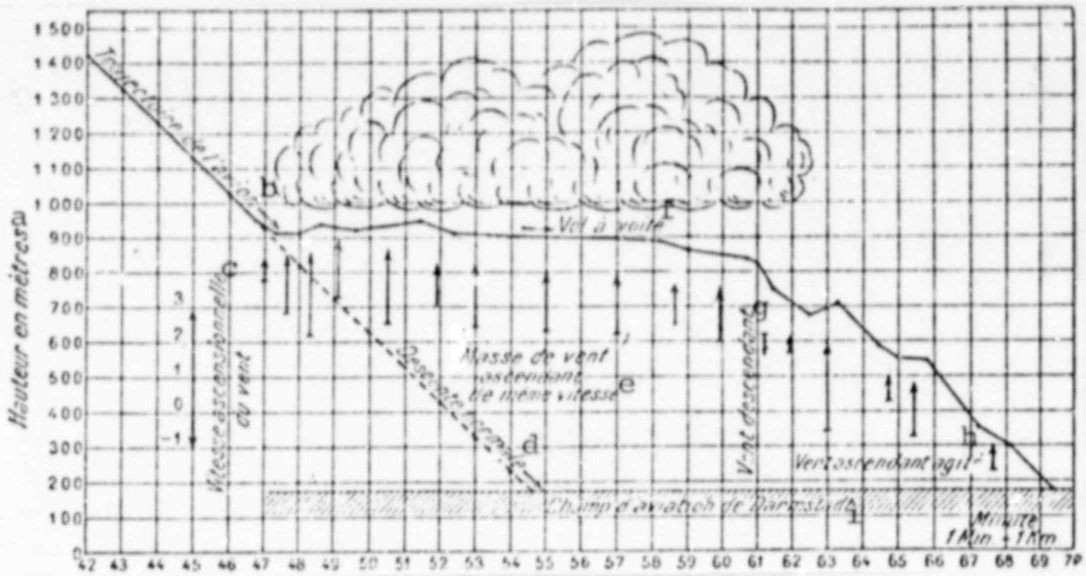


Figure 106
Path of an Airplane with Stalled Engine, Calculated from Meteorograms and Showing the Horizontal Portion under a Cumulus Cloud, in Contact with an Updraft (from Georgii)

Key:
- a) Height in meters
- b) Path of airplane
- c) Vertical speed of wind
- d) Normal descent
- e) Air mass ascending everywhere at equal speed
- f) Powerless flight
- g) Descending wind
- h) Turbulent ascending wind
- i) Darmstadt Airfield

the areas where thermal currents are almost certain to be encountered. However, their speed is lower than in hot countries and is rarely greater than 0.50 to 1 m/sec on the average, whereas they almost always attain several meters per second in Africa. In our part of the globe, they can at times be detected above 3,000 meters.

It should also be noted that when a horizontal wind exists at the same time, the rising currents are carried along and take on an inclination relative to the horizon. The faster the wind is, the greater will be the inclination.

Huguenard, Planiol, and I have made studies of the structure /67
of winds caused to rise by the heating of the ground in the desert, specifically in the region of Medenine in southern Tunisia. To collect the desired data, we used a tubular mast 10 meters high.

The hot wire instruments were installed in a van which was converted into a laboratory. We obtained the tracings reproduced in figures 108 and 109 on a clear, almost windless day when the temperature outdoors was 27°. Notice that the air current at 1 meter is horizontal taken as a whole, while at 10 meters it is

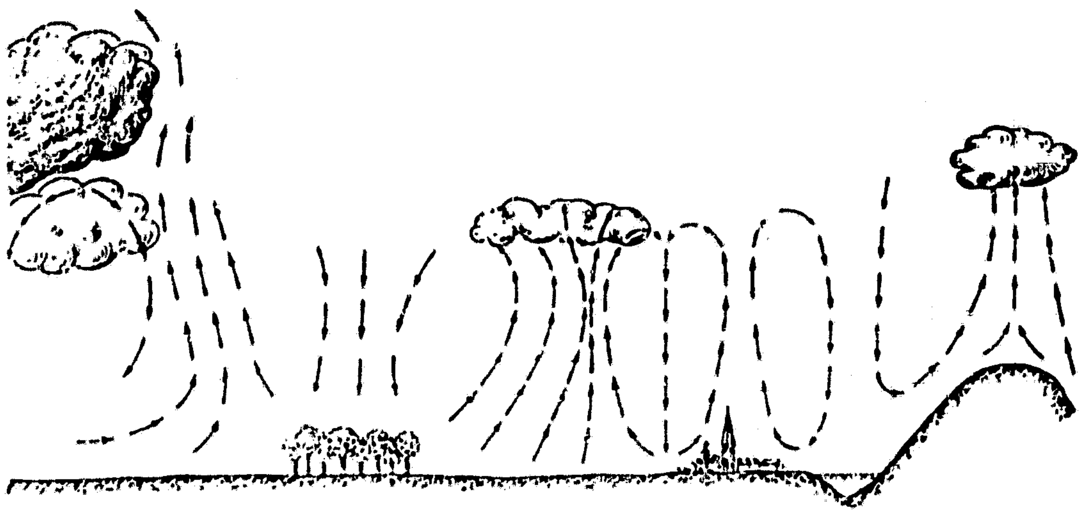


Figure 107
Distribution of Thermal Currents above a Region Including Mountains, Rivers, Villages, Planes, Forests

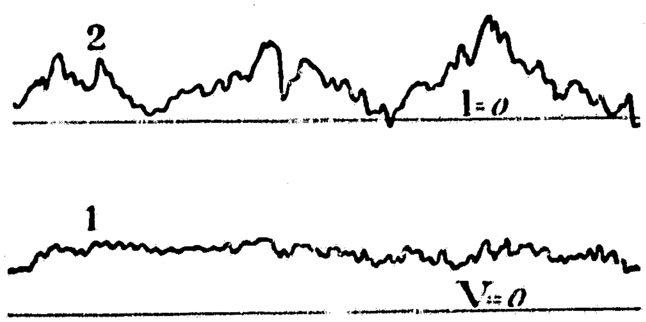


Figure 108

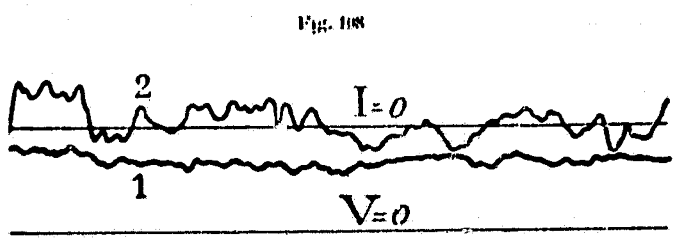


Figure 109
Simultaneous Recording of the Speed (1) and Inclination (2) of an Air Current in Southern Tunisia
Figure 108: 10 m from the Ground; Figure 109: 1 m from the Ground
Scales: Speed, 15 mm = 2.5 m/sec; Inclination, 1 mm = 1°

clearly rising at an overall angle of 6 to 7°. It also appears that the air current is more turbulent at 10 meters from the ground than at 1 meter. This demonstrates the existence of what have been called solar gusts, which are probably due to the presence of eddies swirling about a vertical axis.

"Solar gusts" resulting from differences in the composition of the layer covering the earth's surface, can coincide with "terrestrial gusts" caused by the irregular configuration of the ground (as in the case of cold deep valleys.) When this happens, the vertical movement of the air can take on a perturbed and dangerous form.

Solar gusts are always found at the same specific spots. They can always be observed where there are humid excavations, bare rocks, wooded areas, a pond, or a section of moor. As he flies over the ground, an experienced flyer can recognize the location of these spots in advance by the change in surface appearance. He will therefore not be surprised by sudden oscillations. It is considered that in general solar gusts are more "difficult" than terrestrial ones. During the night, the effects of vertical gusts are much weaker because the difference in temperature between wet and dry regions is less.

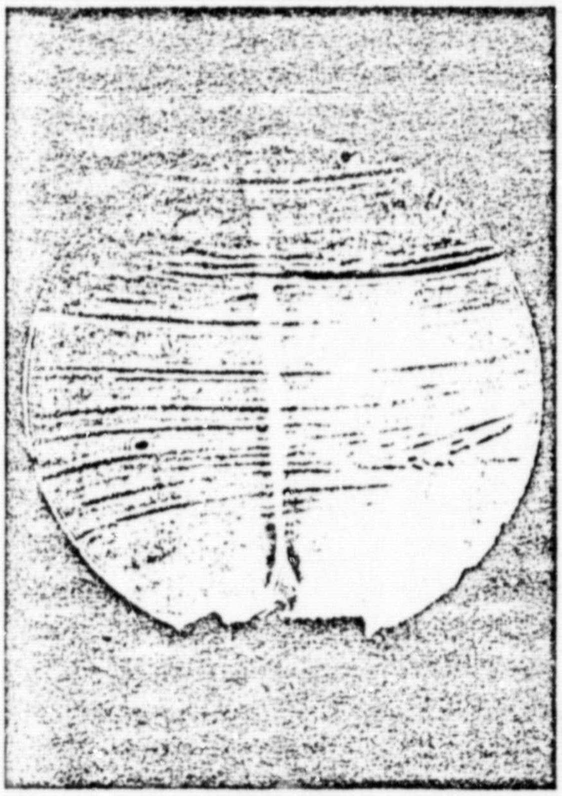


Figure 110a
Stream of Warm Air
Rising Vertically
in Calm Air

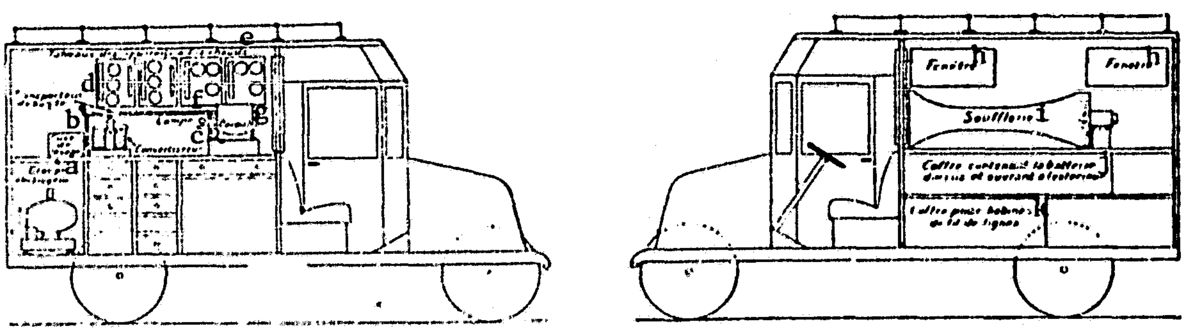
Figure 110b
Rising Stream of Warm Air
Encountering Small, Ephemeral
Horizontal Cold Air Current

C-2

A photograph of a rising current of air made by heating a wire is reproduced in figure 110a. Its upward motion is absolutely vertical. The following photograph (figure 110b) shows the perturbed, turbulent appearance taken on by the current when it is struck by a slight horizontal draft.

III. Air Turbulence /68

All currents, whether horizontal or ascending, seem to contain internal movements that it would be useful to investigate more thoroughly.



Figures 111 & 112
Interior Views of Laboratory Truck

Key:
a) Electric generator
b) Washbowl
c) Convertor
d) Film transporter
e) Hot wire instrument panel
f) Light
g) Unroller
h) Window
i) Wind tunnel
j) Compartment containing battery, openable from the outside
k) Compartment for reels of wire

Recording the Acceleration and the Angular Velocity of the Wind

Huguenard, Planiol, and I equipped a laboratory truck with the necessary adjusting, measuring, and recording apparatus, including the convertors mentioned previously. On one table was an unroller and on another was a wind tunnel for calibrating the instruments in the field. On the side, there was a compartment containing the storage batteries needed to power the hot wire instruments. These batteries could be recharged by a Homelite generator on board. With the aid of the instrumentation in the truck, we were able to begin the measurement of the accelerations and angular velocities existing in winds. (See figures 111 and 112.)

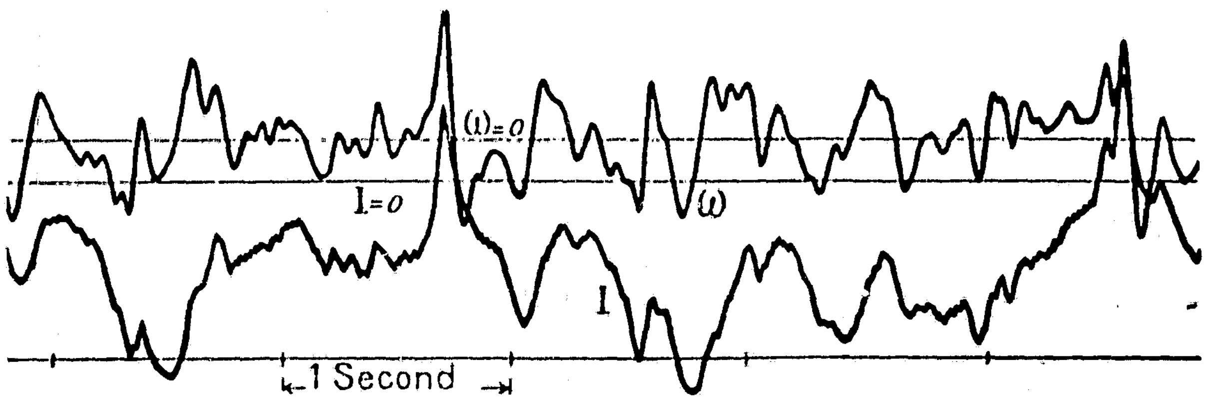


Figure 113
Simultaneous Recording of the Inclination I
and the Angular Velocity ω of a 10-12 m/sec NNW Wind
Observed at Marignane at a Height of 5 m
Scales: Inclination, 1 mm = 1°; Angular Velocity, 1 mm = 12°/sec

Figure 113 is a simultaneous recording of changes in inclination of a 10 to 12 m/sec NNW wind observed at Marignane 5 meters from the ground. The maximum values are +27.5° and -30°. Located above the inclination curve is a tracing of the angular velocity, which was provided by the convertor. The maximum observed angular velocity was 200°/sec, while the average angular velocity came out to be 53°/sec. Note that in 1/3 second, the angular velocity changed from -108°/sec to +96°/sec, and from -120°/sec to +100°/sec. /69

Figure 114 is of interest because it contains a simultaneous recording of the speed and inclination of a gentle NNW wind made at 30 meters above the ground.

The speed turned out to be fairly constant. As to the inclination, its fluctuations had a maximum amplitude of only 7 to 8°.

The acceleration and angular velocity curves are also quite regular. The maximum acceleration was less than 8 m/sec^2, and the average was 3 m/sec^2. For the angular velocity, the maximum was 90°/sec, and the average was 26°/sec.

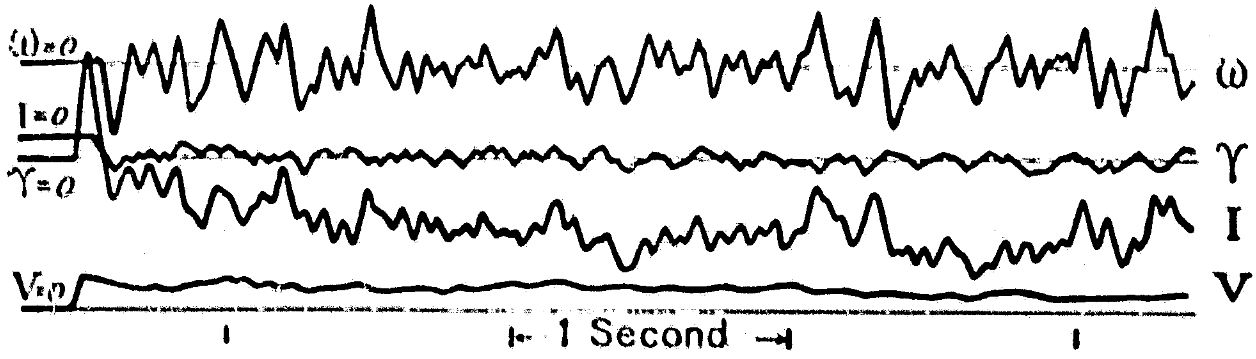


Figure 114
Simultaneous Recording of the Speed V, the Inclination I, and their Derivatives, Acceleration γ, and Angular Velocity ω of a NNW Wind 30 m above the Ground
Scales: Speed, 0.75 mm = 1 m/sec; Acceleration, 1 mm = 5 m/sec^2; Inclination, 1 mm = 1°; Angular Velocity, 1 mm = 12°/sec

Our tests revealed that the wind accelerations during a storm at sea are no greater than those in a wind rubbing against the earth and only having a speed of 3 to 5 m/sec.

The observations that could be made about the inclination of the wind are similar to those made before. A sea breeze recorded at a height of 10 meters reveals the smallest angular velocity, while a land breeze exhibits a greater variety of inclinations and large angular velocities.

A Formal Definition of Turbulence

With the aid of our study of the accelerations and angular velocities found in the wind, we have been able to start measuring air turbulence.

Given a mass of air at rest or moving at a uniform constant translational speed V, any supplementary, superimposed movement of speed v, variable in magnitude or direction, is considered turbulent. For an observer propelled by the wind at its average speed, for example in a free floating ballasted balloon, air movements capable of being detected by the anemometers placed on board are what constitutes air turbulence.

This definition is obviously arbitrary since it depends on the choice of instruments for measuring the characteristics of the wind. With sensitive instruments of a low response time, such as we have built for our studies, the detectable turbulence is usually much smaller than that which has an appreciable effect on an airplane or even a bird.

In our previous studies, we exposed instruments that recorded speed and direction to the wind. Our apparatus was set up at a point O, and we recorded on a cylinder the wind velocity W, its inclination α and its orientation β in relation to the general direction of the wind. /70

During the period of observation, the wind possessed an average velocity V which was defined in terms of both magnitude and direction. If, at every instant, we find the difference between W and V, we obtain a set of vectors u (figure 115), which represents the turbulence of the mass of air passing over the apparatus at point O at each instant.

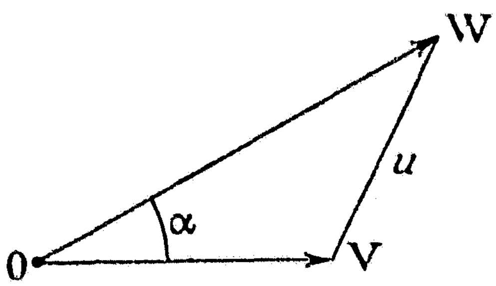


Figure 115
Calculation of the Turbulence Vector u
(α = inclination)

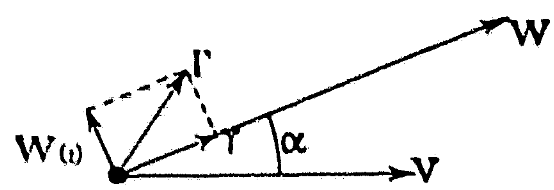


Figure 116
Calculation of the Acceleration γ of the Wind and the Instantaneous Change in Velocity W_ω Due to its Rotation Permitting the Acceleration Γ of Turbulence to be Obtained

The plots of the anemometric readings containing the value at every instant of V and α, provide the basis for deducing the geographic distribution of turbulence along the line of the current between the times T and T + t. The characteristics of the turbulence for the entire air mass can be gathered from the grouping of the vectors u along all the parallel lines of current.

In addition, the acceleration of air turbulence is the basic cause of the extra loads the wind imposes on, e.g., a glider. The value of this load can be derived by constructing at every point in the atmosphere the vector Γ, which represents the acceleration of the turbulence. This vector is the geometric sum of the acceleration $dW/dt = \gamma$ of the wind and of the instantaneous variation of the velocity of the wind W_ω due to its rotation (figure 116.)

The Measurement of Turbulence

On the portion of the curves of velocity V, acceleration γ, inclination I, and angular velocity ω reproduced in figure 114, we have measured the turbulence and the acceleration of turbulence every 1/32 second. In the table that follows are listed the results obtained by applying the method described above.

	W	γ	I	ωθ's	ωθωl s	W'ω	Γ
1	4,90	+ 3,81	— 9°07	— 56	— 0,98	— 4,85	6,2
2	4,75	— 4,23	— 11°6	+ 27	+ 0,47	+ 2,2	4,8
3	4,10	— 2,8	— 8°75	+ 30	+ 0,52	+ 2,15	3,5
4	4,3	— 3,1	— 7°7	+ 54	+ 0,94	+ 4,05	5,1
5	4,2	— 2,7	— 4°57	+ 37	+ 0,212	+ 0,89	2,8
6	4,5	— 0,96	— 5°01	— 23	— 0,134	+ 0,565	1
7	4,25	— 2,3	— 9°07	— 69	— 1,2	— 5,1	5,6
8	4,25	— 9,2	— 9°92	— 41,5	— 0,72	— 3,05	9,7
9	3,75	— 6,7	— 10°53	0	0	0	0
10	4	+ 1,92	— 10°2	— 9	— 0,156	— 0,63	2,0
11	3,9	+ 3,81	— 10°8	— 25,5	— 0,115	— 1,12	4
12	3,9	0	— 12°6	0	0	0	0
13	4	+ 1,51	— 11°5	— 69	— 1,2	— 4,8	5
14	4,1	+ 2,3	— 13°25	+ 76	+ 1,32	+ 5,4	5,9
15	4	— 2,9	— 7°7	+ 23	+ 0,4	+ 1,6	3,4
16	3,9	— 3,85	— 8°7	— 4,6	— 0,08	— 0,31	3,9
17	3,9	— 4	— 11°3	— 32,3	— 0,56	— 2,24	4,6
18	4	— 1,92	— 11°2	+ 9,2	+ 0,16	+ 0,64	2,0
19	4	0	— 10°45	0	0	0	0
20	4	0	— 10°6	— 83	— 1,44	— 5,76	0
21	4,05	+ 0,96	— 12°25	+ 1,8	+ 0,037	+ 0,092	0,9
22	4	— 2,1	— 10°3	— 7	— 0,124	— 0,50	2,2
23	3,9	— 4	— 11°6	— 18,4	— 0,31	— 1,22	4,2
24	4,1	+ 1,15	— 11°15	— 18,4	— 0,32	— 1,42	1,8
25	4,25	— 1,15	— 12°9	+ 4,6	+ 0,08	— 0,34	1,2
26	3,9	— 4,8	— 12°0	0	0	0	0
27	4	— 0,96	— 12°4	+ 25,4	— 0,435	+ 1,75	2
28	4,25	+ 3,1	— 11°0	0	0	0	0
29	4,3	+ 5,2	— 11°1	— 25,4	— 0,435	— 1,86	5,5
30	4,25	+ 1,92	— 11°25	— 11,5	— 0,2	— 0,85	2,1

[Commas in tabulated material are equivalent to decimal points]

In figure 117 we have represented the real magnitude and direction of the resultant vector Γ representing the acceleration of turbulence over the period of one second. /71

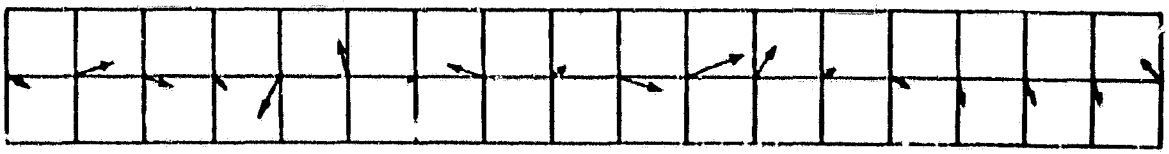


Figure 117
Fluctuations in Magnitude and Direction of the Acceleration Γ of Turbulence of a Portion of a Breeze Recorded at Marignane at a Height of 30 m
The Intervals Separating Two Vectors Correspond to 1/32 sec.
On each Vector: 1 mm = 1 m/sec^2

Notice that during this period of time the value and direction of turbulence . . varied considerably. This variation indicates the existence of periodic undulations similar to a sort of atmospheric swell. A whirlwind-like appearance may also be inferred at certain moments from the variation in turbulence. The whirwind seems at first to turn clockwise, and then suddenly to reverse direction.

In any case, examination of the vectors in these first results shows that the rotation is sometimes so rapid that measurements should be made not every 1/32 second, but every 1/100 second.

The measurement of air turbulence made in this manner by hot wire instruments allows the state of the atmosphere to be described independently of the speed with which the wires encounter the wind. It would therefore be possible to place the instruments in an airplane and make a series of flights through the atmospheric region /72 under study. The airplane could fly through a given volume of air in the direction of the wind at various altitudes and thus obtain measurements of turbulence along regularly spaced lines of flow.

The actual speed of the airplane would not interfere with the measurement of wind acceleration or angular velocity. A single disturbance du encountered by an airplane is of relative magnitude. It is greater the faster an airplane is flying. However, as the airplane increases in speed, the disturbance acts on it for a shorter period of time. In other words, the amount of motion communicated by a disturbance to an airplane depends only on the disturbance itself, and not on the speed of the airplane.

Variations in Turbulence

Here are several observations on what we know about atmospheric turbulence.

If the turbulence or agitation from the ground up to 150 meters is represented by the number 100, studies have shown that the turbulence at 300 meters is only 50, at 600 meters it is 43, and at 1,200 meters the value would be 26.

Whereas the wind increases by 10% between 10 and 20 meters up, the turbulence decreases by 27%. It is consequently the region near the ground that is the most turbulent, and the turbulence diminishes rapidly thereafter. It has also been observed that the greatest agitation of the wind occurs around noon. In good weather, a more regular motion takes over towards evening.

From all that precedes, it must be concluded that atmospheric agitation is due to heating of the soil by the sun's rays and to the rubbing of the air against the earth's surface. Agitation is facilitated by a rapid decrease in temperature with increasing altitude. This is generally at a maximum in our part of the globe when the wind is blowing from the northwest or north.

The leeward sides of forests or mountains are distinguished by a much greater turbulence than the windward sides. The faster the wind is blowing, the further from the mountain can turbulence of this sort be detected. It has not yet been definitely established that there exist sources of turbulence in unobstructed parts of the atmosphere.

In the meantime, increased turbulence has been observed within and at the edges of cloud layers.

At night, the internal agitation of the air diminishes, not only on the ground, but at high altitude, though probably to a lesser degree.

The calming of the air begins in the evening at ground level and climbs slowly upwards toward higher layers of the atmosphere.

However, at dusk there is frequently an ephemeral agitation that is greater near the ground than higher up. This phenomenon has been attributed to an unequal cooling of the soil.

Increasing the wind speed increases the turbulence by an equal amount. The oscillations of the wind around its average value are on the order of 25 to 30%.

How does such agitation affect an airplane? The motion of an airplane through turbulent air may be very aptly compared to a path through a terrain broken by trenches. When gliding at a large angle of inclination, the effect of the air is less because it is forcefully compressed under the wings and weak oscillations are not as significant.

Because of the small extent of undulatory turbulent movements, an airplane is hit by several waves at once, which partially cancel each other out. At most a light vibration of the aircraft can be felt. At first, however, before the airplane has attained sufficient speed, oscillations near the ground could be much more unsettling, since the puffs of air often touch only a single wing.

To sum up, it has been noticed that the agitation and the turbulence of the air are strongest in the spring and at the beginning of summer, when the wind is blowing from the north and the northwest, and when the temperature goes down rapidly with increasing altitude. Atmospheric turbulence is least before dawn, in autumn, during southerly or southwest winds, and when the fluctuations of the wind are small. /73

All the past investigations that we have undertaken have confirmed that turbulence varies in inverse proportion to the distance from the ground. It would thus be interesting to extend our research by using an airplane specially equipped to study the movements of the atmosphere and to see if it would be possible to detect the approach of the ground by the increase in turbulence.

IV. The Periodicity of the Wind

A natural extension of the preceding discussion is to try to find out the shape of air currents and to learn what their general motion looks like.

An examination of wind speed curves of diverse origins all show a clear periodic character. Even if periodicity does not exist in the rigorous sense of the word, it nevertheless seems that normal winds contain disturbances of constant length. An examination of figure 118 reveals large disturbances visible at first sight. In the interior of these, other, smaller perturbations exist which have a certain periodicity.

Figure 118
A Tracing of a Land Breeze's Speed, Showing an Obvious Periodicity

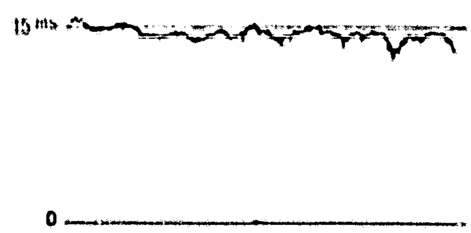


Figure 119
Wind Speed Curve Made 300 m from the Ground Showing Periodic Characteristics

Constant Length of Sections of Air

If the average speed of the wind is multiplied by the duration of the most regular appearing disturbances, the product, which would represent the wave length if the phenomenon were really periodic, is usually around 375 meters, as the table below shows.

	Direction	Vm m.s.	P sec.	λ metres
Crau Plain	N	9	41	369
--	N	6,20	60	372
Le Havre Beach	SE	3,80	103	391
--	SE	4,20	93	390
Paris	W	7	55	385
Beach at Sables	SE	5	77	385
Mont Ventoux	N	8	48	384
Sea (Conquet)	W.SW	8	47	376

It can thus be seen that the higher the speed is, the shorter the period is. Everything seems to occur as if there were sections of air of a definite length which passed by at various speeds. If this were indeed the case, the sections of air in motion would have a constant length independent of the strenght of the wind.

A recording of wind speed made at 300 meters altitude (figure 119) had a tracing revealing slower oscillations with a duration of 150 seconds.

If the average speed, 15 m/sec, is multiplied by 150 seconds, the resulting product is 2,250 meters, or six times 375 meters, the wave- /74 length found near the ground. The large disturbances seem to be made up of many smaller ones, some of which have a duration of about 25 seconds and thus a wavelength of about 375 meters.

Ways of Studying the Undulatory Movement of the Air

What conclusions may now be drawn? Does this not prove that the atmosphere exhibits a wave motion analogous to that observed in the ocean? Does this not prove that there are atmospheric waves and swells just as there are waves and swells in the ocean, with wavelets in both media?

Fortant, the Inspector General of Aeronautics, has investigated these questions. He has shown the importance of resolving them for aviation in a study specifically concerning the undulatory movements of the atmosphere and their effect on aircraft.

It is Fortant's opinion that the study of undulatory agitations in the air should be undertaken for the purpose of discovering their influence on the propulsion of aircraft and on their safety. Not only should the general study of the atmosphere be promoted, but undulatory motion must be particularly emphasized.

He says that the idea of a probable relationship between atmospheric waves and those of the ocean naturally comes to mind when it is noticed that it is precisely the atmospheric agitations that create and maintain the waves of the ocean. Conversely, the great oceanic swells, which last a long time after the wind has fallen off, must engender or maintain a harmonic counterbalance in the surrounding air.

Since the undulations of the atmosphere are not visible as are those of the water, Fortant thinks that it is expedient to search first of all for atmospheric phenomena that seem directly linked to its regular agitations and that may be easily detected by an observer. He thinks that it is in the clouds and what occurs in the vicinity of the clouds that the most useful data on this subject may be collected. At this point, he made a theoretical model of atmospheric swells, and showed that they could have a distinct series of waves going in different directions at different altitudes. These waves could sometimes cross each other, superimpose, and combine into complex forms without losing their individual characteristics. /75

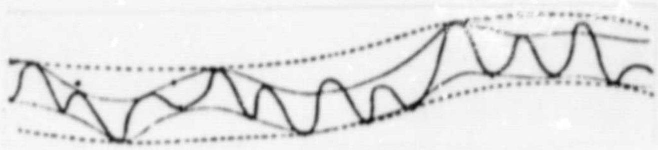


Figure 120
Schematic Reproduction of a Recording of the Inclination of a Wind Showing its Quasi-periodic Character

In figure 120, which reproduces a recording of the larger variations in inclination, the existence of three oscillatory systems is striking.

One of them is a slow undulation having a duration of 6 seconds, the second lasts 2 seconds, and the third and smallest is 1/2 second long.

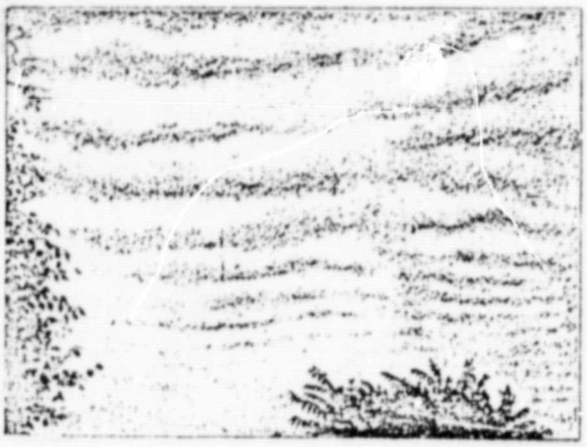


Figure 121
Billowing Clouds above the Ile de Ré

Figure 122
Clouds Flowing into a Valley
(from V. Zotier)

Consider also the two photographs reproduced in figures 121 and 122. The first, which was taken above the sea, shows clouds that are separated into distinct billows with an axis perpendicular to the wind. Given their equal widths, does it not seem that they clearly prove the existence of a sort of atmospheric swell phenomenon? The second photograph shows clouds forced to flow through a mountain pass by a strong wind. They recall the foamy waters of a stream gushing between steep banks.

It is now possible to conduct research into atmospheric swells with the equipment I have designed in collaboration with Huguenard and Planiol.

One useful device is our hot wire directional indicator equilibrated with two resistors and powered by a battery. The galvanometer of the bridge thus constructed could be the thermal galvanometer indicated in figure 19, but placed in a carefully evacuated tube. In this case, the sensitivity will be very great, while the lag time will increase considerably. Only the average inclination of the wind will then be recorded. Since such a galvanometer is practically insensitive to vibrations and since its response time is about 6 seconds, slow oscillations are the only ones detectable.

It is possible to study the undulatory motion of the atmosphere at different altitudes with a directional indicator mounted on an airplane. The pilot would have to fly as horizontally as possible with the altitude of the aircraft checked by an accelerograph.

An accelerograph, after several modifications, could also be used in the study of atmospheric swells. All that must be done is to attach an accelerograph to an airplane in such a way that it records the component of acceleration normal to the wings. By having the pilot execute a series of rapid elevations and dives and then let the airplane maneuver without intervention, the period of the oscillations intrinsic to the airplane may first of all be measured. The oscillations of the airplane, which are vertical and centered at the airplane's center of gravity, are recorded by the accelerograph and their period may be calculated from the recording. Once the period of the intrinsic oscillations is known, the accelerograph is used to record the oscillations of the airplane caused by whatever atmospheric undulations exist. /76

Another procedure consists of filming the movements of an airplane or a dirigible in relation to some sort of reference mark or coordinate lines. The camera could be placed either on the ground or on the aircraft itself.

This study of air currents shows how important it is to be able to describe the configuration of the air and the wind accurately.

To facilitate our lives and our movements on the surface of the earth, to which we have been riveted up to now, we have measured and recorded as exactly as possible the least change in the level of the land. We have also measured the size of waves that occur on the surface of the ocean and plotted the position of ocean currents for purposes of maritime navigation. The atmosphere also has its waves and its currents. If we want to understand the role played by these currents and waves in the flight of machines or living things, it is absolutely necessary to gain a detailed knowledge of their structure.

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Huguenard, Magnan, Planiol, Etude sur les accelérations et les vitesses angulaires du vent naturel [Acceleration and Angular Velocity in Natural Wind], Bulletin technique du Service Technique de l'Aéronautique, 49 (1928).

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Georgii, Der Segelflug und seine Kraftquellen im Luftmeer, Berlin (1923).

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Magnan, "Recherches expérimentales sur le vol à voile" [Experimental Research on Soaring], Technique aéronautique (1922).

Magnan, Le vol à voile, avec contribution à l'étude expérimentale de la physique et de la mécanique des fluides [Soaring, with a Contribution to the Experimental Study of the Physics and Mechanics of Fluids], Part I, Roche d'Estrez, Paris (1925).

Maxim, Le vol naturel et le vol artificiel [Natural and Artificial Flight], Paris (1909).

In the opinion of most observers, the characteristic feature of avian flight is the flapping of wings.

It is true for almost all birds that flapping flight is the usual method of flying. (For a long time, flapping flight was called "rowing flight" becuase it was thought that the animal was rowing.) It is practically continuous for many birds. However, even if a great number of birds belonging to all orders, from the raptors to the palmipeds, rely on flapping flight almost exclusively, there are some birds that are capable of utilizing other methods coming under the general name of soaring. We will study these other methods later.

Before embarking on the description of flight, it is first necessary to make a quick study of how the bird-machine is constructed and to have a general idea of the anatomy of birds. This will enable us to understand the mechanics of flight better. Even if the examination of a locomotive apparatus does not explain its functioning, it is still indispensable to this explanation.

The Body of a Bird

Birds form a very homogeneous class with an organization completely adapted to flight.

A bird consists of an ovoid or fusiform trunk preceded by a usually small head separated from the trunk by a neck of highly variable length.

The trunk, neck, and head are covered by feathers. Some are relatively large and somewhat rigid. They are called tectrices. Others, known as down, are smaller, very flexible, and more numerous on certain parts of the body.

Inside the body is a large cavity in which are located the middle part of the spinal column and the viscera: the heart, lungs, liver, and digestive tract.

Between the viscera and the walls of the body are the air sacs (figure 123), which can be observed by blowing air into the trachea, thus causing them to expand. The air sacs are connected to the lungs at one end and to the sternum, humerus, and femur at the other. These bones are riddled with cavities in which air circulates. The air sacs serve especially as reserves of air and also act as cushions. In addition, they reduce the density of the body somewhat.

The vertebral column includes the thoracic, lumbar, and sacral regions, which are more or less rigid, and the more mobile cervical and coccygeal regions. The ribs form rigid arcs linking the vertebral column to the sternum. This creates a resistant structure that provides a solid support for the muscles used in flight.

However, what characterizes birds is the existence of a pair of wings and a tail, each covered with feathers that play an important role.

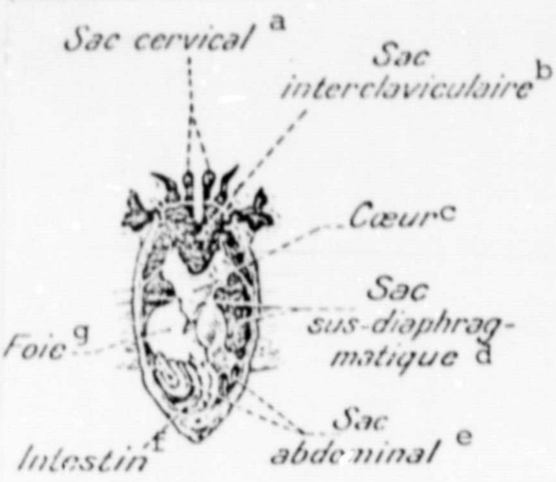


Figure 123
Air Sacs in a Pigeon
Ventral View
(from L. Jammes)

Key:
a) Cervical sac
b) Interclavical sac
c) Heart
d) Subdiaphragmatic sac
e) Abdominal sac
f) Intestines
g) Liver

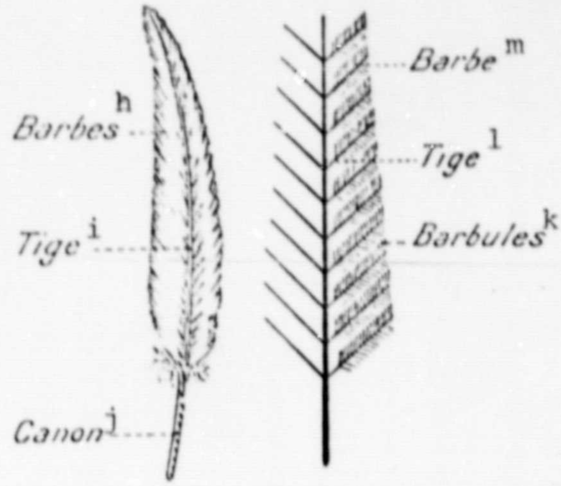


Figure 124
Left: Remex of a Pigeon
Right: Schema of a Feather
(from L. Jammes)

h) Barbs
i) Rachis
j) Calamus (barrel or quill)
k) Barbules
l) Shaft
m) Barb

The Feathers /78

Feathers are a special feature of birds. In the entire animal kingdom, they alone possess them.

Every feather is essentially composed of a shaft, on the sides of which is a flat, symmetrical arrangement of barbs which in turn bear barbules. (See figure 124.)

The feathers found on the wings of a bird are called remiges. Those on the tail are known as rectrices. Their structure and dimensions have an obvious relation to the needs of airborne locomotion.

The most important characteristic of wings is that they possess a general rigidity which gives them the appearance of stiff plates. This is the result of a special structure. Implanted on one side of the barbs are barbules equipped with hooks. The hooks extend over the barbules on the neighboring barb. These last (posterior) barbules are shaped so as to latch onto the hooks. The barbules are thus tightly linked together (figure 125).

In addition, the remiges located near the ends of the wings are much stronger and larger than the others. This is because they move more quickly and are therefore subjected to greater air resistance, as will be explained later on.

Characteristics of the Remiges

In all remiges, the shaft becomes thinner as it approaches the tip of the feather. It is most often curved in such a way that, when the wing is extended, the feather's concave side points forward and downward.

The shaft is made up of two parts. One, the quill, is hollow and bare. The other section is solid and filled with barbs.

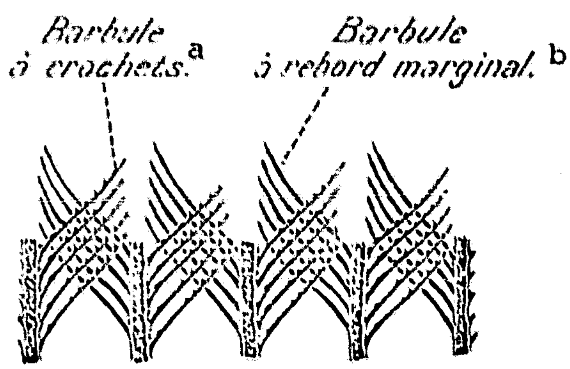


Figure 125
Arrangement of Hooks
Binding Neighboring Barbs
(from L. Jammes)

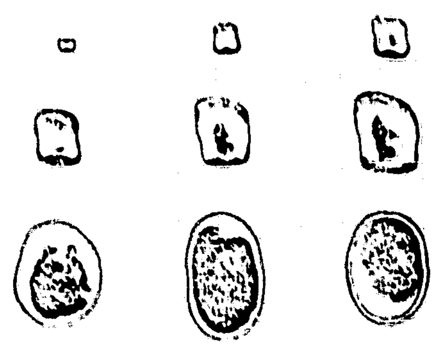


Figure 126
Cross Sections of the
Shaft of a Primary
Remex of a Gannet
Made 3.3 cm apart

Key: a) Anterior barbule (with hooks)
b) Posterior barbule (scroll shaped)

If cross sections of the shaft are made at various heights (figure 126), it may be seen that the hollow barrel has an elliptical shape, with the major axis perpendicular to the plane of the wing. As a result of this configuration, the feather is more difficult to bend in this direction. In contrast to the quill, the sections made in the part of the shaft that holds the barbs are quadrilateral. While the entire shaft is made of horny material, the sides of the shaft corresponding to the top and the bottom of the feather are much thicker than elsewhere. In addition, the cross sections show that the central part of the shaft is filled with a softish substance resembling the pith of an elder, only harder. /79

To obtain an idea of the characteristics of remiges, Planiol and I investigated their flexibility and ability to dampen oscillations. We conducted tests on feathers from the wings of a gannet and a golden eagle to see how they behaved under the effects of static and dynamic bending.

We first studied the oscillation of the remiges. Part of the shaft was placed in a wooden holder and mounted on a recording cylinder with a speed of up to 500 mm/sec. The feather, deflected from its steady state position, was suddenly released and a hair attached to its end traced the curve of the dampened oscillations.

We then removed the barbs from the feather and repeated the test.

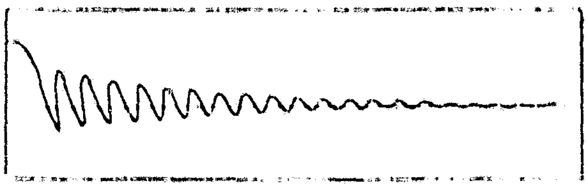


Figure 127
Dampened Movement of the Shaft of a Primary Remige on a Gannet

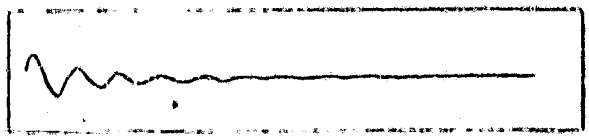


Figure 128
Dampened Movement of an Entire Primary Remige of a Gannet

The test results showed that the entire feather is dampened more rapidly than the shaft alone without its barbs. The comparison of the tracings makes it clear that almost the entire dampening effect is due to the effect of air resistance on the barbs.

The tracings used for studying dampening (figures 127 and 128) reveal the frequency at which the remiges vibrate. These frequencies are recorded in the following table:

	Length	Frequency	
	(cm)	w/barbs	w/o barbs
Gannet, lg. remex	31	36.3	51.5
" sm. remex	15.2	38.3	83
Eagle, lg. remex	51.5	13.3	21
" sm. remex	38	41.7	45

The high value of the frequencies observed shows that the remiges are able to follow the rapid pulsations of the wind faithfully. The flexibility of the wing feathers is therefore very great. /80

Figure 129
Deformation of the Shaft of a Primary Remex on a Gannet Caused by a Load

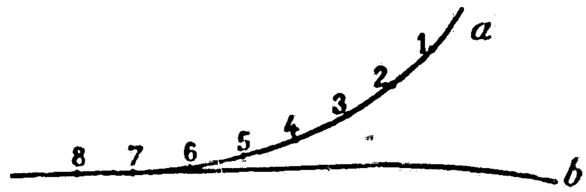


Figure 130
Deformation of the Shaft of a Secondary Remex on a Gannet Caused by a Load

To test the exact flexibility of a remex, a feather whose barbs had been removed was held down so that its concave side pointed upward and the constrained part of the feather was horizontal. The feather was then weighted down with metal brackets. A cathetometer was aimed at a number of points along one of the contours of the shaft both before and after the load was applied. Seven 10-gram brackets were spaced 3.3 cm apart on a large gannet remex. There were eight brackets weighing 7 grams each placed 1.5 cm apart on a small one. In this situation, the feather took on a double curvature, with the curvature near the end of the feather being appreciably greater than the other. The curvature of the feather at rest and under a load is illustrated in figures 129 and 130.

The extreme flexibility of the tip of a feather is remarkable. It is hard to believe that any fabric covered framework could ever combine this degree of flexibility with sufficient strength. The felxibility is accompanied by an equally amazing elasticity, comparable to that of a spring.

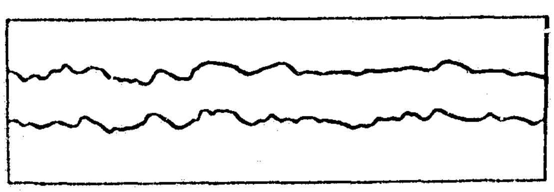


Figure 131
Recordings of Speed of Wind from a Rotor Made Simultaneously with a Primary Tropic Bird Remex (above) and a Primary Gannet Remex (below)

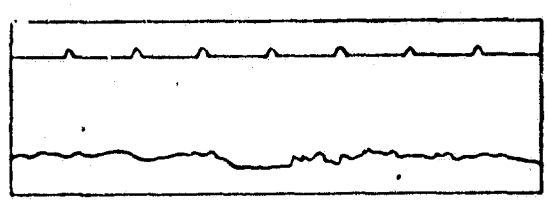


Figure 132
Recording of the Speed of a Natural Wind of 2.5 m/s by Means of a Secondary Gannet Remex

I have been able to demonstrate the extreme flexibity of the tips of remiges by placing them in both an air current created by a fan and a natural wind after having fastened the shaft in a wooden clamp, as described above. The ends of the feathers start to vibrate in the air current and the hair stylus attached to them traces the variations of air current speed acting on the barbs. The degree of vibration of the barbs is dependent on the wind speed and they are thus the basis for a high precision anemometer. This is demonstrated by figures 131 and 132.

How the Remiges are Implanted

The remiges are implanted either directly in the bone of the wing or in an auxiliary membrane.

The wing is itself nothing other than the upper limb of the bird, adapted to flight. It therefore includes a humerus leading to a radius and a cubitus (ulna), which end in a greatly modified hand (figures 133 and 134). The thumb of the hand is free and has been reduced to a single phalanx. The thumb forms a "bastard wing" with its small tuft of feathers. The other bony parts are fused into a double finger.

The large, or primary remiges adhere to the hand. They form /81
what is called the active surface or hand wing.

Other, smaller remiges are located along the rear of the entire forearm when the wing is extended and the bird is flying. These "secondary" remiges are implanted in the cubitus and form the passive surface or arm wing. It supplies the bird's lift.

Finally, there are tertiary remiges which begin at the elbows and continue up to the flanks of the birds. They are attached to an auxiliary membrane and form a sort of extension of the passive surface of the wing.

The distal barbs of all these feathers are shorter than the proximal ones. They are arranged in such a fashion that proximal barbs are always covered by distal barbs.

Besides the remiges, there is another type of less rigid feather, the coverts, which exist above and below the wing between the forward edge of the wing and the barbs of the remiges. They serve to cover this region and give it a continuous form.

When the wing is extended, it thus forms a flat surface analogous to a fabric covered airplane wing. In theory it is impermeable to the air when a bird glides or lowers its wings.

The Bony Parts of the Wing

The head of the humerus is lodged ina cavity called the glenoid fossa which is situated at the junction of three bones: the coracoid, the scapula, and the acromion fork. Together they form a groove pointed downward and obliquely toward the rear. This groove is convex in the legnthwise direction and laterally concave. The head of the humerus, on the other hand, is convex in every direction, but is flattened parallel to the major axis of the body. As a result, it has a major and minor axis like the glenoid fossa. Thus, the two most normal movements are those in which the humeral head rolls either along the large diameter or the small diameter.

In the first case, the humerus separates from the body and the wing is extended. In the second case, the extended wing is either raised or lowered. It would seem from what has been said that these are the only two ways a bird can maneuver its wing. However, the head of the humerus can in fact move in every direction because the glenoid fossa is not deep enough to restrict its movements. The humerus can consequently rotate about its own axis.

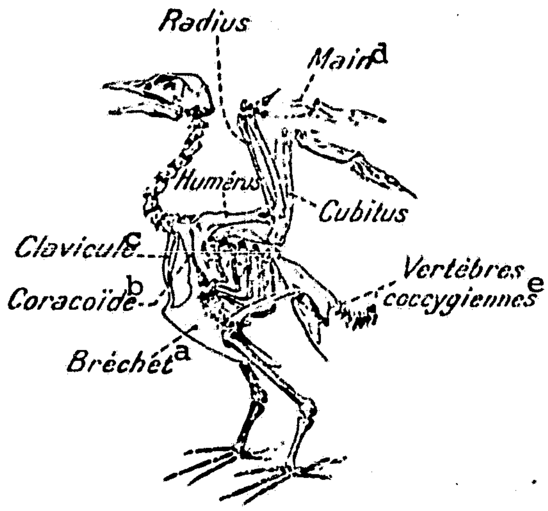


Figure 133
Skeleton of a Pigeon
(from L. Jammes)

Key: a) Breast bone
b) Coracoid
c) Clavicle
d) Hand
e) Coccygeal vertebrae

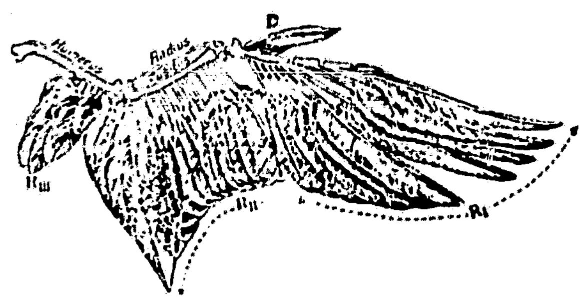


Figure 134
Dissected Eagle Wing

RI) Primary Remiges
RII) Secondary Remiges
RIII) Tertiary Remiges
D) Bastard wing

The animal is therefore able to turn its wing around its lengthwise dimension in either direction at any given moment or position. It can shift the wing into the appropriate angle. Similarly, the jointed structure of its wings enables it to move the tips of its wings forward by a simple contraction of its muscles.

The cubitus is capable of making flexing and extending motions in relation to the humerus. It can also rotate about its axis from the outside inwards or in the opposite direction, according to whether it is being flexed or extended. However, flexing of the /82 forearm on the arm cannot take place without the band bending reciprocally in its turn. All these movements are connected and are executed at the same time without the animal having to intervene consciously.

Finally, the phalanges and, consequently, certain primary remiges, can rotate about themselves to a small extent and also move downward between the others. This makes possible hand wing movements used to ensure lateral stability in flight.

Because of its jointed structure, the primary remiges attached to the posterior edge of the hand are spread out and separate from each other when the wing is extended. The hand, drawn by the small palmaris muscle, becomes curved in such a way that its posterior edge is convex. Also, the primary remiges located there are forced to separate from each other. When the wing folds up, on the other hand, the posterior edge becomes concave and the feathers are pushed together until they touch. In a similar manner, when the wings are bent, the secondary remiges pivot and slide over each other. This changes the orientation of the barbules and layers along the cubitus. When the wing straightens out, the secondary remiges once again pivot and spread out as they stand up above the cubitus, becoming practically perpendicular to it.

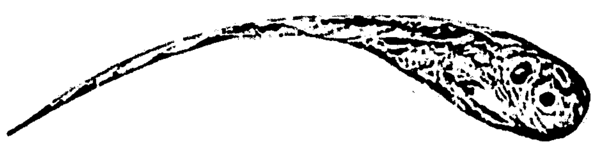


Figure 135
Anterio-posterior Section of the Wing of a Gannet

Figure 136
Deformation of the Ends of the Wings of a Golden Eagle (Frontal View)

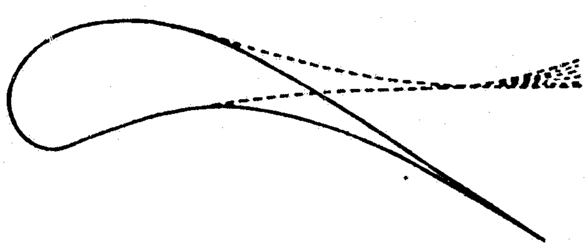


Figure 137
Anterio-Posterior Wing Section of a Marine Soaring Bird Showing the Deformation Occurring in Flight and the Vibrations at the Trailing Edge Caused by the Wind

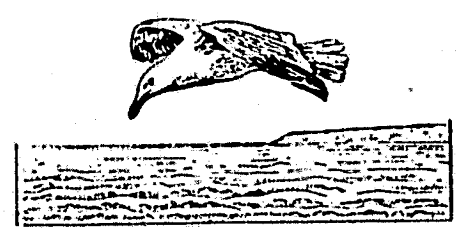


Figure 138
Sea Gull in Gliding Flight with Wings Extended Showing the Double Curvature of Secondary Remiges

The Properties of Wings

All bird wings are concave on the ventral side, regardless of their form. This concavity extends in all directions. It is not very great longitudinally, but the transversal concavity is more accentuated. An examination of a wing's anterio-posterior section (fig. 135) reveals first of all a resistant plane on the bottom side. This plane is fairly shallow, inclined upwards by a few degrees, thick, and located directly underneath the bony masses and musculature of the upper membrane. The remiges, partly covered by the coverts, come next. At rest, they are always arched downward and make an angle with the plane. The angle becomes less obtuse as it gets closer to the body.

When a bird flies, the wing undergoes characteristic deformations that modify its shape independent of any outside influence. During flight, when the wings have to support the body weight and are affected by the action of flapping, the accentuated curvature observable at rest is considerably attenuated. /83 First of all, the longitudinal curvature appears null or reversed at the end of the wing's active surface (figure 136). In addition, the wing shows a new double curvature going from front to back. The shape of the anterior two-thirds remains partly fixed because of the rigidity of the bony masses and of the shafts. This section of the wing still conserves a little of its grooved shape, with the concave side pointing downwards. In contrast to this, the posterior third of the passive surface is raised upward (figures 137 and 138).

I have put wings through some true static tests. Figure 139c shows the form that a gannet wing assumes under the effect of a 11.800 kg load. The considerable resistance of such materials, which support thirteen times their weight without breaking or permanent deformation, can thus be appreciated. The flexible part of the wings only supports 1.480 kg. The rest of the weight is spread out over the bony masses. In this situation, the wing had a normal double curvature.

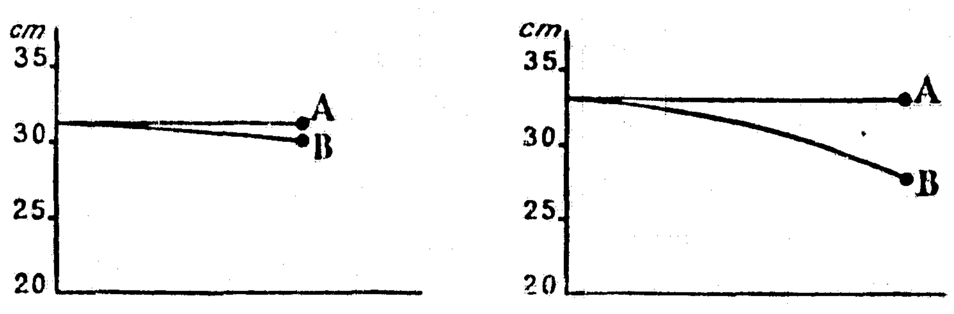


Figure 139a and b
Deformation (B) of the Hand Bones (Left) and Forearm Bones (Right) of a White Stork Caused by an Applied Load

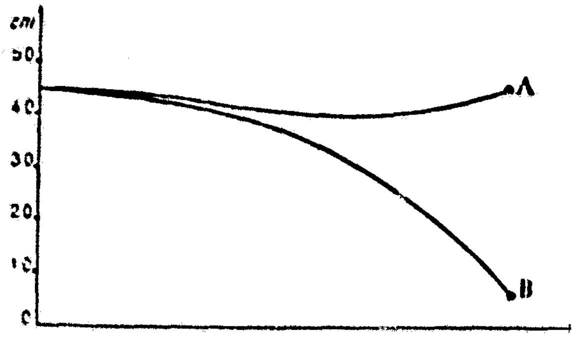


Figure 139c
Deformation (B) of a Gannet Wing Caused by a Load of 11.8 kg

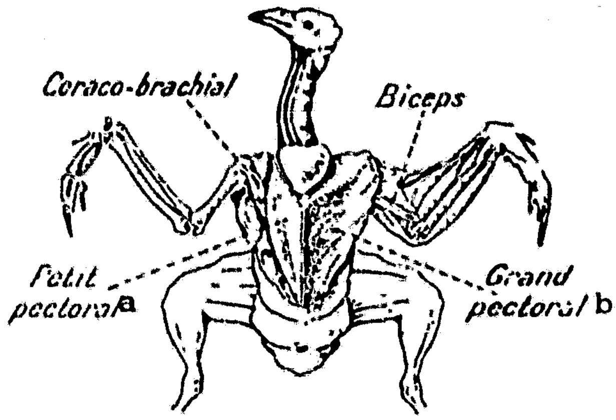


Figure 140
Arrangement of Muscles of the Anterior Member of a Pigeon (from L. Jammes)

Key: a) Small pectoral
b) Large pectoral

Nature has thus made wings very solid, very resistant to stress, and very flexible.

Wing Muscles

Wings are activated by muscles which are arranged in the same way as the muscles of the anterior members of other vertebrates. The only difference is that some muscles have atrophied and others are more developed than in other animals. The wing muscles enable birds to: 1) Extend their wings, 2) make the wings move in a more or less vertical up and down motion during flight, 3) fold their wings up against their bodies when they want to rest. These movements are made by extensor, flexor, elevator, and depressor muscles. /84

The most characteristic muscles are the depressors and elevators, which have undergone considerable development. The depressor is the large pectoral. It makes the wing descend when flapping and is usually of very large volume. It is anchored to the large tubercle of the humerus and to the ribs, the clavicle, the outer surface of the sternum, and the carina, a sort of keel with which the sternum is provided and which is perpendicular to it (figure 140). The elevator, or small pectoral, which lifts the wing during flapping, takes up less space and is found below the large pectoral. It is inserted at one end in the angle that the carina forms with the body of the sternum (figure 140). After having passed between the clavicle and the coracoid, it terminates on the upper part of the humeral head. This represents a very ingenious mechanical arrangement.

The Tail

The small coccygeal vertebrae can move over each other. The last of these vertebrae, which holds the retrices, which are feathers with a constitution similar to that of the remiges, is very large and flat and possesses an extreme mobility.

Because of this property, the tail has a considerable importance for birds. It is most frequently used as a rudder during flight, although it is true that it is not always an organ of flight. (For certain species, it often serves as an ornament or even, in the case of the wagtails, as a balancing mechanism when walking on the ground.)

Birds can, as a matter of fact, separate their retrices from each other or squeeze them into a smaller space. When the tail is well spread out, they can also raise it, lower it, twist it about its axis, and point the left or right part upwards or downwards.

Thanks to its very great mobility, the tail of a bird is a veritable rudder which can form either a rigid surface or a surface that is deformable in any direction. The retrices are imbricated in the same manner as remiges are.

Finally, birds have posterior limbs. These include first a femur connected by a joint with a bony belt that constitutes a sort of pelvis. The femur is oriented so that its end is close to the center of gravity of the organism when it stands on its feet. After the femur come a tibia and a very thin fibula, then a tarsus and metatarsus joined together in one piece, and finally the digits.

Such an arrangement led Belon in the sixteenth century to compare the skeletons of a man and a bird, indicating the analogous bony parts along with the modifications that they had undergone.

RECOMMENDED READING

Alix, Essai sur l'appareil locomoteur des oiseaux [An Essay on the Locomotive Apparatus of Birds], Paris (1874).

Jammes, L., Zoologie pratique basée sur la dissection [Practical Zoology Based on Dissections], Masson, Paris (1904).

Magnan, A. Le vol à voile [Soaring], Roche d'Estrez, Paris (1925).

Magnan, A. and Planiol, Essais sur l'amortissement, la fréquence, et la flexibilité des remiges des oiseaux voiliers [Essays on the Oscillation Dampening, Frequency, and Flexibility of the Remiges of Soaring Birds], Roche d'Estrez, Paris (1922).

Marey, Le vol des oiseaux [Avian Flight], Masson, Paris (1890).

Marey, La machine animale [The Animal Machine], Paris (1873).

Owen, Comparative Anatomy and Physiology of Vertebrates, London (1866-68).

With the aid of the system which has just been described, birds are able to remain in the air and to move forward by flapping their wings.

Let us now try to understand the manner in which birds beat their wings and to analyze the various movements involved in this activity.

The observation of a bird like the pigeon, for example at the moment when it is just taking wing and is repeatedly flapping its wings, is not helpful in getting an idea of the behavior of a flapping wing. The eye of the observer perceives the entire movement as a blur and the final impression is merely one of alternating up and down motion. It is thus impossible to specify the details of flapping precisely by simply observing birds in flight.

The number of times a bird beats its wings varies and could be 3 to 6 or 8 times per second according to whether it is in mid-flight or about to take wing. The movement of a wing is so rapid that our eyes only detect the general outline of the movement. We notice only that there is up and down beating, that an alternating movement of the upper limbs exists.

The best proof of this is the fact that the majority of painters depict birds in flight in the form of a V or, most often, in the form of a circumflex accent.

With the aid of the motion picture photography invented by Marey, he and his successors have precisely identified the steps involved in a single wingbeat.

Methods for Studying Wing Motion

When one wishes to study the actual movements of a wing in relation to a bird's body, an ordinary fixed motion picture camera will do well enough. The erection of a set of reference marks in the field of the camera to determine the exact position of the bird is not necessary. However, if one wishes to go deeper into the analysis of flight, for example to determine the effects of a wing-beat, the displacement of the bird, its trajectory, or its speed, the unsuitability of this method is obvious. If it is desired that the film contain a fairly large portion of the bird's trajectory, the image of the bird itself will be too small. To increase the dimensions of the photographs in order to make precise measurements, it is indispensable to increase the focal distance of the objective. Since the width of the film is constant, the photographic field is reduced, and it is no longer possible to keep the camera in a fixed position.

It is therefore necessary to use an apparatus that moves about a point and has a telephoto lens. Consequently, the field of vision will be small. The moving object to be photographed can then be followed by eye with this type of instrument, while the position of the camera is recorded on each photograph made. One is thus led to using two systems of coordinates: one for locating the object in the field of the camera, and the other for locating the axis of the camera in relation to a fixed set of coordinates /86 on the ground.

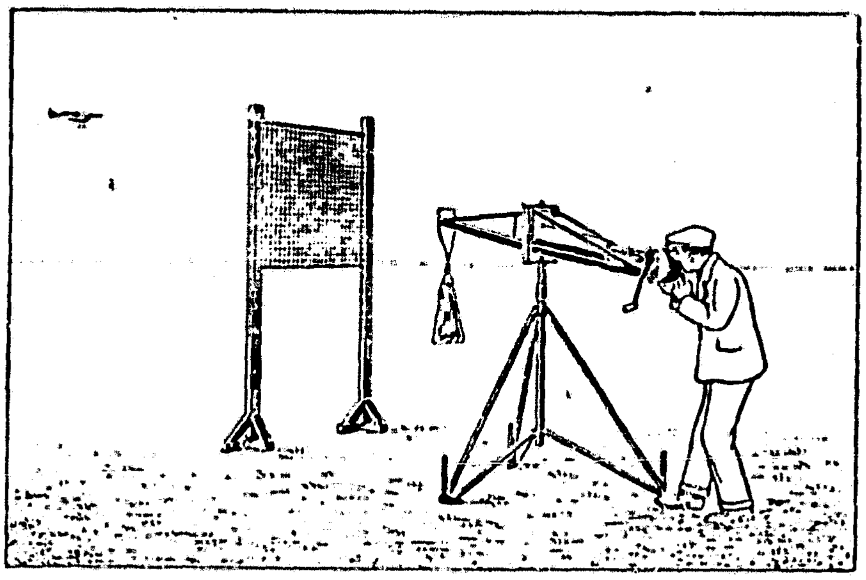


Figure 141
Double Objective Camera Gun for Recording the Path of an Airplane in a Coordinate System

<u>H.M.P. Double Objective Camera</u>

Huguenard, Planiol, and I have studied a whole series of equipment that can simultaneously photograph a moving object and two fixed graduated circles before which the axis of the objective can be moved.

However, such an instrument must practically attain the perfection of astronomical instruments to achieve a satisfying level of precision. This is a prohibitive demand for an apparatus that we wanted to be transportable.

We have been able to resolve this problem thanks to the generosity of Fortant, the Director General of Aeronautics, who made the necessary funds available to us.

The studies were conducted in the testing department directed by Dumanois who, along with the engineer Earlaut, helped us as much as possible to find a solution to the problem of determining flight paths. This is a problem that has preoccupied the entire field of aviation.

We used a Debrie camera gun to carry out our experiments. This apparatus is used to train fighter pilots. It has the same dimensions as a machine gun and is installed in an airplane in place of the actual weapon. The pilots who are engaged in combat exercises strive to get their adversary within the field of their camera gun, which is "fired" like a real machine gun and simultaneously photographs the enemy airplane and a chronometer. Since the two chronometers were synchronized before the exercises began, the winner, the one who first got his adversary within his line of sight, may be easily determined.

We originally used the Debrie camera gun to record at the same time an airplane, a chronometer, and a square mesh netting erected on the ground a little bit in front of the objective. To accomplish this, we mounted the camera gun on a stand containing a universal joint which can be used to adjust the position of the axis passing through the fixed optical center of the camera lens. The stand is comprised of a special light, rigid, collapsible tripod made of steel /87
tubes. In the center, it holds a large steel tube in an upright position.

The large tube contains a shaft which turns on ball bearings. On top of the shaft is a frame containing two ball bearings with a common horizontal axis which intersects the vertical axis of rotation of the shaft and frame. Between the bearings is placed a second frame, which can rotate around the horizontal axis. On this frame is fixed a support that holds a counterweight in the front and the camera gun in the rear. The camera gun is adjustable in all directions so that the optical center of the objective can be made to coincide with the point common to the two axes of rotation. The camera gun is thus moveable in every direction around the optical center of its objective. This point then becomes a fixed center of perspective around which photographs are taken independent of the position of the camera gun.

The fixed reference lines that are used to measure the angular displacement of the airplane are made of square steel wires held in a frame. The wires are spaced both horizontally and vertically at regular intervals. The regularity of their spacing is maintained by kinking the wires so that they have a twisted form and a sawtooth profile of fairly large slope.

To use the apparatus, the frame is placed in a vertical plane perpendicular to the direction in which one wants to film the airplane. The airplane is thus viewed through and approximately perpendicular to the frame.

However, to carry out this simple procedure, the coordinate network must be placed far enough away to obtain a clear image. To preserve a sufficiently large field of action, it would then be necessary to have an excessively large framework, which would make the method impractical. This is because the Debrie camera gun has a 210 mm objective with an f/6 focus, which means that the hyperfocal distance corresponding to an acceptable clearness of image is very great.

We avoided this difficulty by means of a combination optic which can simultaneously obtain in the same plane clear images of two objects, one situated at infinity and the other, the coordinate network, as close as possible (figure 141). For this, a secondary objective, with a focal distance equal to the distance at which one intends to place the wires, is mounted in front of the actual cinematographic objective. The former objective masks a part of the surface of the latter. This section may be chosen at will and, in our apparatus, is the annular zone external to the principal objective.

The light rays coming from the airplane or bird that hit the free central zone of the cinematographic objective provide a clear image of the flying object in the conjugate plane. The rays coming from the coordinate network, which hit the annular objective, give an image of this framework placed at the same distance as the airplane and, consequently, after their passage across the cinematographic objective, converge equally on the same conjugated plane. Clear images of the network and of the airplane are thus simultaneously obtained in the same picture.

Experience has shown that the two blurred images, one provided by the airplane through the double objective system, and the other by the reference framework through the principal objective alone, do not appear on the film if the annular lens and the uncovered part of the principal objective have the same area.

What is more, the angle covered by the coordinate network is fiarly small, since the network, which contains close to 500 squares 46.2 mm on a side, is only 1 meter by 1 meter and is placed 2.25 meters from the camera gun. When the optical axis slants toward the normal to the plane of the reference lines, the focal point of the annular objective is never far enough away to bring about an annoying decrease in clarity.

Making Films /88

I have used this apparatus to determine the path and the form of avian wing movements every time my studies involved a large species in its natural surroundings flying at a fiarly great distance from the apparatus. In contrast, when I was able to work in the laboratory with birds that I was able to make fly around in front of the objective, I used only a single lens movie camera focused on a set of coordinate lines placed several meters away. I then filmed the experimental animals as they passed in front of the network.

However, only birds that beat their wings two or three times a second can really be studied with an ordinary motion picture camera, which takes only 16 frames a second. Unless considerable lengths of film are used, only fuzzy images, always corresponding to approximately the same position of the wing in space, are obtained with birds that flap 10 to 15 times a second. In this case, ultra-high speed equipment, such as the camera designed by Noguès or the one built by Debrie, which take more than 200 frames per second, have to be used. The film is then projected at 16 frames a second and the movement of the wing is thus slowed down for the viewer. I have employed such cameras to record the flight of various birds simultaneously with a square mesh marking out reference coordinates and the oscillations of a pendulum, which indicated the film speed.

Description of a Wingbeat in Horizontal Flight

Films of this nature still do not provide precise information on the position of the wings during a single beat, despite the slow motion. To discover the exact positions of the wings, it is necessary to enlarge each frame corresponding to part of the flapping cycle. They must then be examined and the images measured. This is what I have done for the parts of the films that are the most interesting.

Figure 142 shows a pigeon flying in front of and parallel to a set of coordinate lines. The successive frames contain the various positions of the animal in almost horizontal flight during a complete flap of the wings. The point where the wings begin to be lowered has been arbitrarily chosen as the beginning of the cycle.

The first thing that strikes the observer is that the wing moves forward at the end of the downward movement of the wings. Few observers have noticed this. On the contrary, before the invention of the motion picture camera, many believed that the tip of the wing was thrust rearward by the bird and had innacurately concluded that birds make a rowing motion. This error was the result of confusion caused by the relative movement of the body and the upper limbs.

Before moving downward, the wings of a pigeon are raised above the body, forming two almost parallel vertical planes. They are then brought downward until their lower surface is more or less horizontal.

It can then be seen that the ends of the primary remiges soon bend upward under the effect of air resistance. At this point, the twisting of the wing is very clear and whereas the plane between the body and the hand is basically horizontal, the active surface moves upward. One can thus see both the upper and lower surface of the wing at the same time.

Little by little, the tips of each wing move forward in such a manner that they approach each other in front of the breast with their lower surfaces facing.

While maintaining this position, the leading edges of the wings rise up and completely encircle the anterior part of the body.

During this time, the articulations of the wing are bent little by little, with that of the hand rising above the body. As soon as the rising motion is finished, which causes the forearms to be parallel and directed upwards, the hand wings separate until they /89
form a continuous line. They then rise until their upper surfaces touch each other. This is the end of the elevation of the wings.

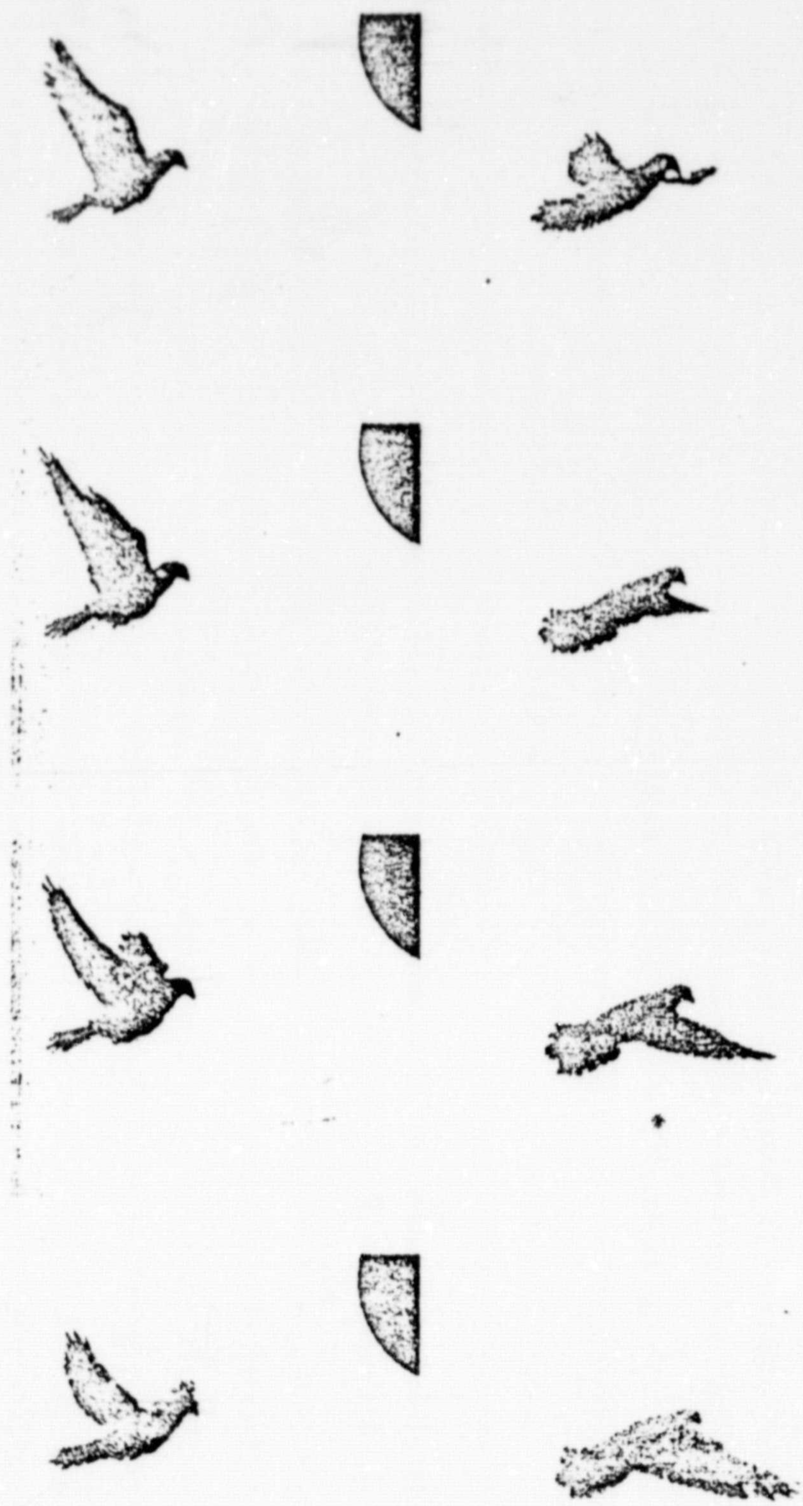


Figure 142
Film Made through a Set of Coordinate Lines of Pigeon Wing Motion in the Course of a Wingbeat during Horizontal Flight, 110 Frames per Second
(Read from Top to Bottom and from Left to Right)

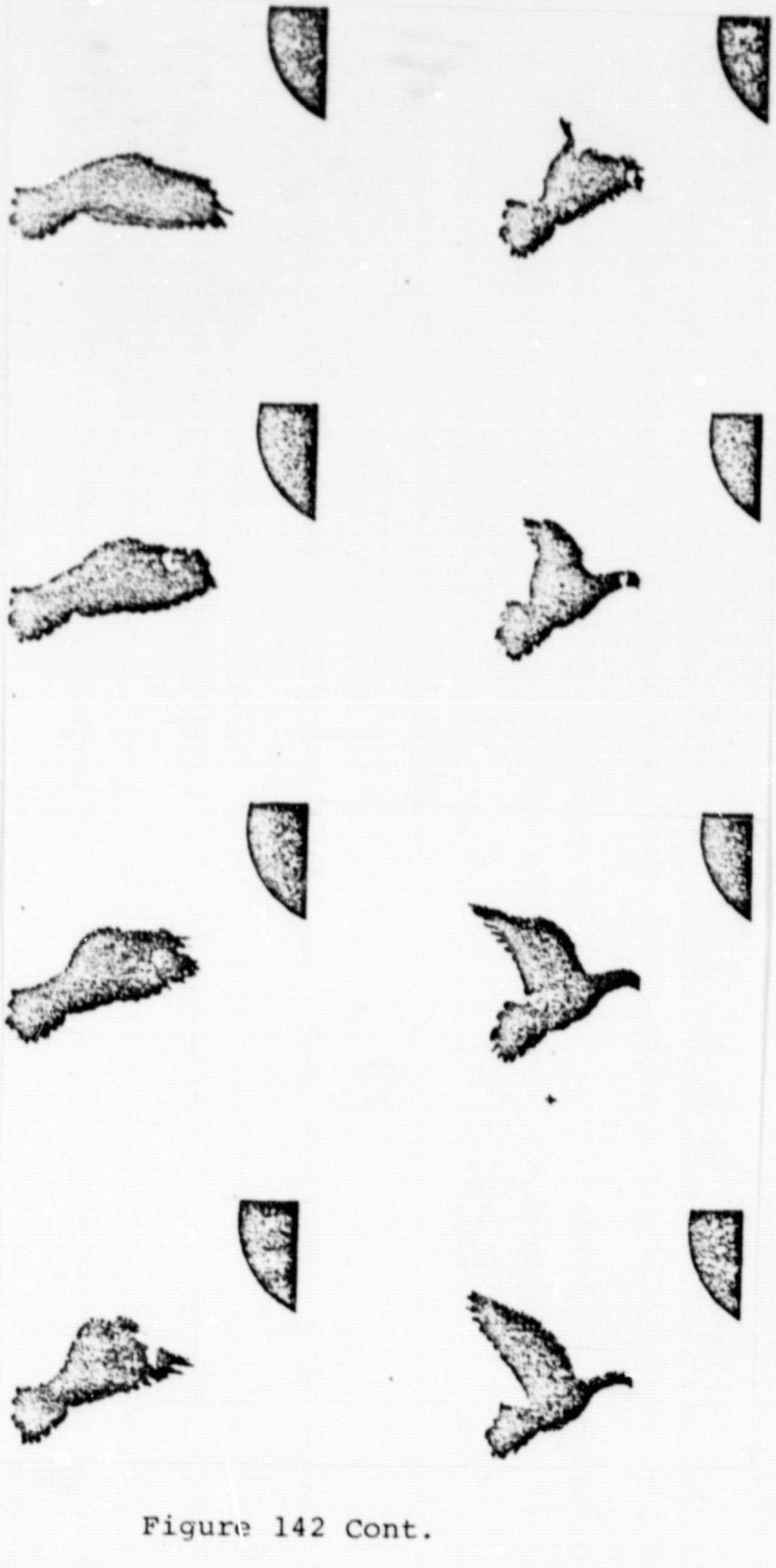


Figure 142 Cont.

Tracings of an Anterio-Posterior Section of a Wing in Flight

Let us take the articulation of the hand and the part of the trailing edge, i.e. of the remex, located on an anterio-posterior cross section parallel to the body and passing through the articulation of the hand, as reference points in the study of wing movement. A faithful representation of the various inclinations of this section may then be obtained by projecting it on the plane of symmetry. In fact, to get a correct representation, the projections should be made on three perpendicular planes, one horizontal and two vertical. To do this requires recordings made by three movie cameras. Unfortunately, this is a very difficult operation to carry out successfully, first of all because the bird's trajectory cannot be controlled and secondly because it is very difficult to obtain the synchronization of the three cameras. Marey attempted it, however, 40 years ago with chronophotographic apparatus.

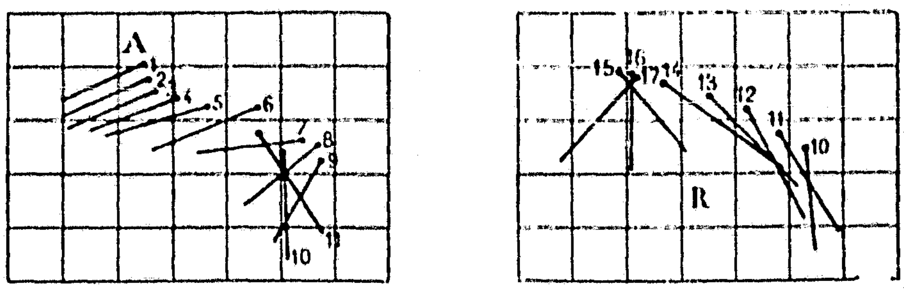
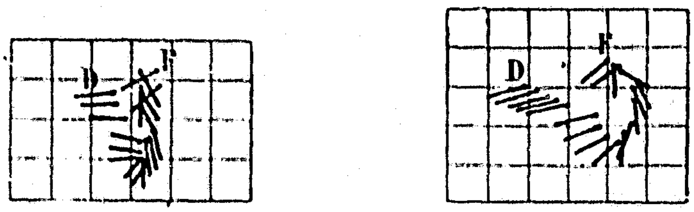


Figure 143
Tracings in the Vertical Plane of an Anterio-Posterior Section of a Pigeon Wing during a Stationary Wingbeat
Left: Downward Motion, Right: Upward Motion



Figures 144 and 145
Tracings in the Vertical Plane of the Anterio-Posterior Section of the Wings of Two Pigeons in Flight

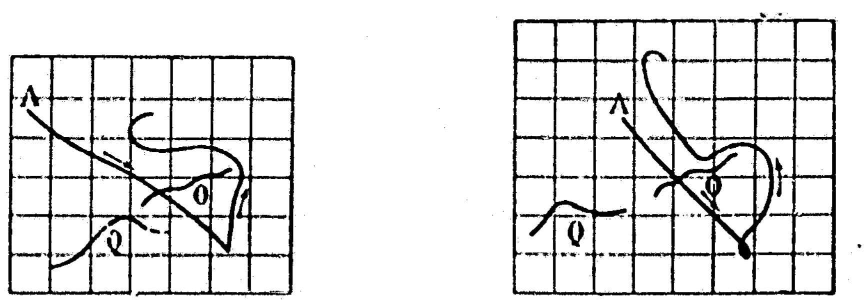
Figure 143 gives the tracings of the anterio-posterior section of a wing through the articulation of the hand, that result from such projections on a vertical plane. In this case, they are for a wingbeat made by a pigeon sitting on a perch and flapping its wings while stationary. It should be noted that at the end of the downward stroke, the wing plane at the level of the hand, which was directed backward and slightly downward, suddenly changes direction. The downward stroke ends with the lower surface forward. Then, at the moment when the wing returns rearward, the lower surface is pointed slightly upward and remains so during the entire retraction. At the end of the rearward movement, a new change of direction occurs and the lower surface is returned to an approximately horizontal position.

Figures 144 and 145 reproduce tracings made on the animal's plane of symmetry by the anterio-posterior section of the wings of two pigeons in mid-flight. Taken at wrist level, they reveal analogous changes of direction while flapping their wings. The tracing is /90
less spread out in one of the figures than in the other because the speed of the bird was less.

One thing to remember is the change in inclination of the wing' plane at the moment when upward motion starts and when the wrist bends. (This results in the remiges hanging almost vertically.) Nature has created a fortunate arrangement here. If the upper surface of the wing struck the air in an upward direction during the raising of the wings, a notable loss of altitude would occur and would cancel out the effect of the downward push. Instead of striking the air as they do when bird and wing advance, each remex pivots as the elbow and wrist bend and cuts through the air. Standing up almost vertically, it only exposes its leading edges to the air when the wing is moving upwards, as Marey has already pointed out.

<u>Path of the Wing Tip During Horizontal Flight</u>

The study of the same successive frames of a pigeon in flight also enables the vertical projection of the path of the wing tip and its translational speed to be traced. One could even record the motion of any given point of the body, from the eye to the tip of the tail. Figures 146 and 147 illustrate such paths for two different pigeons. One curve, A, traces the movement of the wing tip, another, Q, is the displacement of the tip of the tail, and the last, O, records the motion of the eye.



Figures 146 and 147
Paths of a Wing Tip (A), the End of the Tail (Q), and the Eye (O) of Two Pigeons in Horizontal Flight

Curve A shows that the tip of the wing moves downward and forward during horizontal flight. It then moves back upward and rearward. The speed of the tip can be found at every point of the flight from the separation that exists between two consecutive points of the trajectory. It has been found to be greater than 5 m/sec.

As has frequently been observed, the wing tip moves rearward before going upward at the end of the downward stroke. It thus describes a sort of loop.

At this moment the speed is the greatest. The tip then rises more or less vertically and returns rearward. At the moment when the wing is extended, the tip is suddenly thrust forward. Furthermore, analogous movements are found in both projections.

Finally, notice that the vertical projection of wing tip displacement oscillates around the axis of flight, which it crosses twice during a revolution.

If one first defines, as we have, the end point of the downward wing stroke as when the tip of the extended wing is at its lowest point, an examination of the path of the tip will then prove that the downward thrust is quicker than the upward thrust. This is calculated from the time intervals between frames and is the opposite of what Marey thought.

Rocking Motion of the Body during Flight /91

The curve produced by the movement of the tip of the tail illustrates another phenomenon: the elevation of the posterior part of the body during the downward thrust of the wing. The rocking motion reaches a maximum when the wing tip is located down below the body. The tail occupies a lower position when the wing tip has been thrust completely upward. This conclusion can be drawn just as easily from either figure 146 or figure 147.

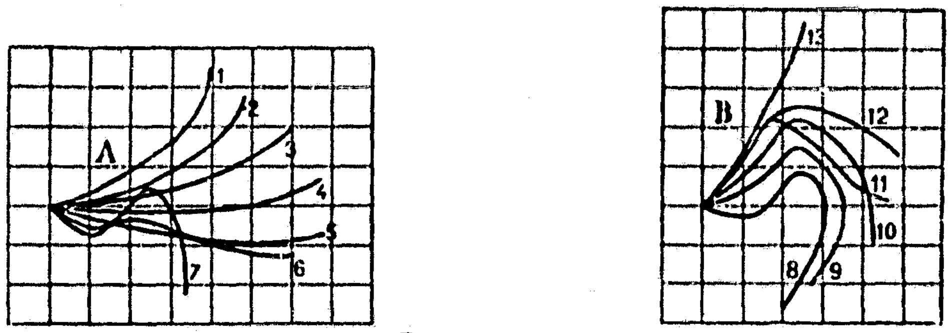
The curve produced by the motion of the eye also reveals undeniable oscillations.

Finally, a fact learned from a film is that wing speed is lowest immediately after downward and upward thrusts. Its speed is the greatest in the middle of each thrust.

The Frontal View of Wing Movements

We have had the opportunity to examine successive prints made by two other birds, a vulture and a seamew, viewed from the front.

The lowered wing is extended in vultures and becomes almost flat. The exception is at the end of the wing, where the primary remiges are pushed upward by air resistance. Note that the wing is rigid until the end of the downward stroke (figure 148).



Figures 148 and 149
Form and Successive Positions of Vulture Wing (Frontal View) during Downward Motion (Left) and Upward Motion (Right)

The wing starts to fold up with the beginning of the upward thrust. The joints at the elbow and the hand bend little by little at the same time that the arm wing inclines in relation to the axis of flight in such a manner that its lower surfaces faces slightly frontward. The forearm becomes more and more vertical and the hand wing, which was hanging down almost vertically, is raised upward again. It is extended until the bones of the hand form a single line with the bones of the arm and forearm.

Figure 150
Form and Successive Positions of a Seamew Wing (Frontal View) during Downward Motion (Left) and Upward Motion (Right)

Figure 149 clearly illustrates the movements of the wing. The curves are a reproduction of the forms that the leading edge of the wing assumes during wingbeats. /92

Figure 150 is derived from a film of a seamew flying toward the camera.

As a whole, the movements of the wing are the same as for the vulture. However, an examination of the figure reveals that the ends of the primary remiges are not pushed upward. Further on we will see that this is the result of the greater resistance of the wing tips of these birds.

I was also able to study wing motion in birds who beat their wings very rapidly in flight.

Figure 151, which is the film of a weaver in flight, proves that movements of the wing in this case are again similar to those of pigeons or falcons, for example.

It now remains for us to examine the takeoff and landing of birds.

As for takeoff, it can be accomplished at an angle or even vertically in certain species, such as pigeons.

Wing Motion while Hovering

Let us take the case of vertical flight. A film of a pigeon so engaged is reproduced in figure 152. Everyone knows that this animal is perfectly capable of hovering at a fixed point in the air by flapping its wings in an almost horizontal plane. It meanwhile holds its body absolutely straight.

The wings first strike the air with their inner surface, i.e. the bottom of the wing, a little like a pigeon on a perch. The wings also change inclination after each half flap. However, in this mode of flight the tip of the wings at the end of a stroke directed frontwards meet almost directly above the head, like a muff around the front part of the body.

Wing Motion during Oblique Ascending Flight

During oblique ascending flight, wings move in approximately the same manner as before, but the body is inclined at 45° instead of being horizontal.

In a pigeon rising obliquely, the two wings are extended almost completely above the inclined body at the moment when they begin to move downward. As the wing is lowered more, it forms an approximately horizontal plane except at its tip, where it is twisted by air resistance. This causes the ends of the primary remiges to stand up. The wing remains flat during descent until the moment when its tip is clearly below the body. At this point the plane is inclined towards the rear until it becomes almost vertical. The wing tip is simultaneously projected strongly forward until it reaches the level of the head and joins the tip of the other wing.

The articulation of the folded hand, like the elbow rises above the body. The hand wing, which was spread out parallel to the body is then raised upward more and more and forms a plane perpendicular to the major axis of the bird. The remiges then become distinctly separated. Following this, the articulations straighten out and the remiges come together again. Finally, the wings are completely elevated and extended, with their dorsal surfaces almost touching.

During this period, the tail is greatly spread out.

Figure 151
Film with Reference Coordinates of the Wing Movement of a Weaver (Ploceus sanguinrostris) in Oblique Ascending Flight During One Wingbeat (110 frames/sec)
(Read from Top to Bottom and from Left to Right)

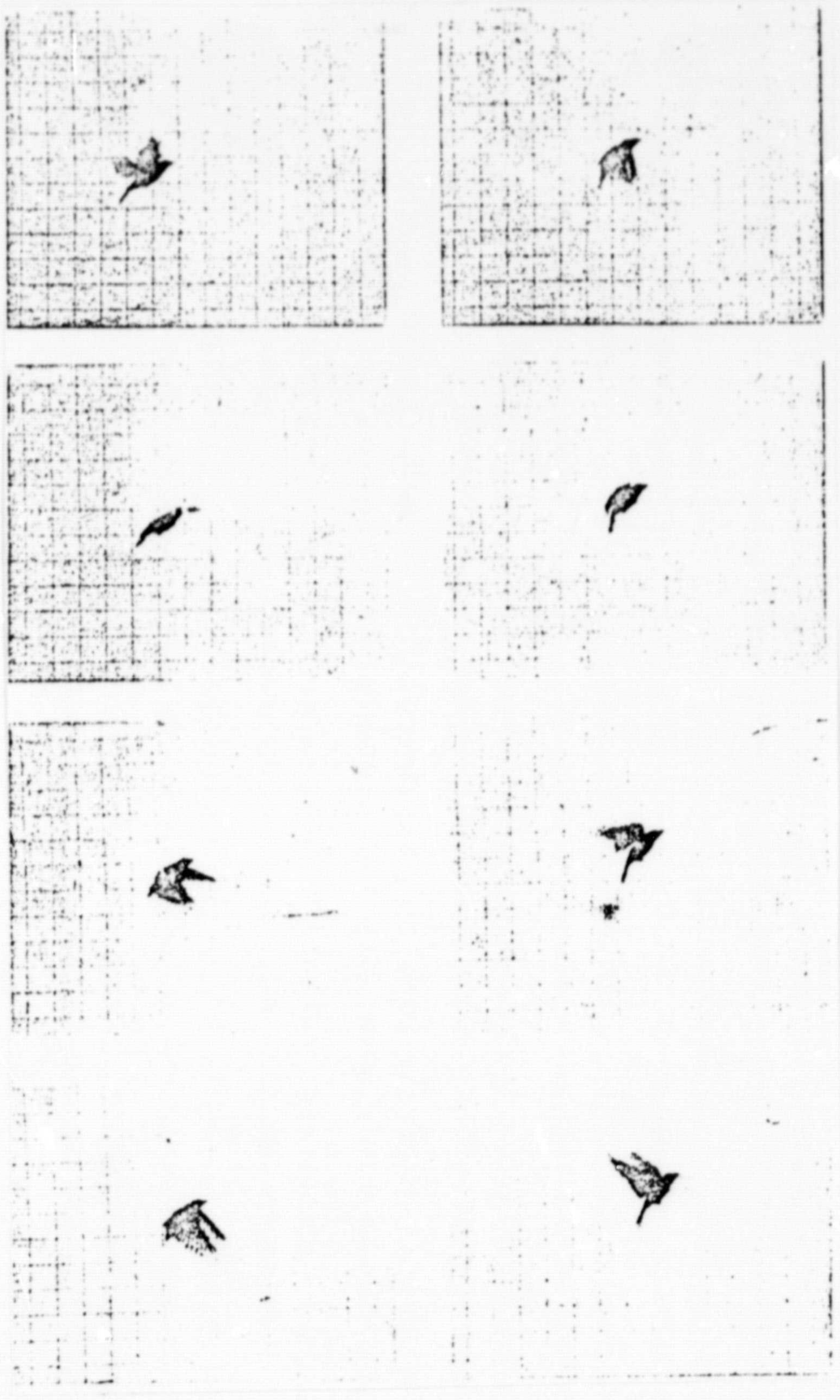


Figure 151 (Cont.)

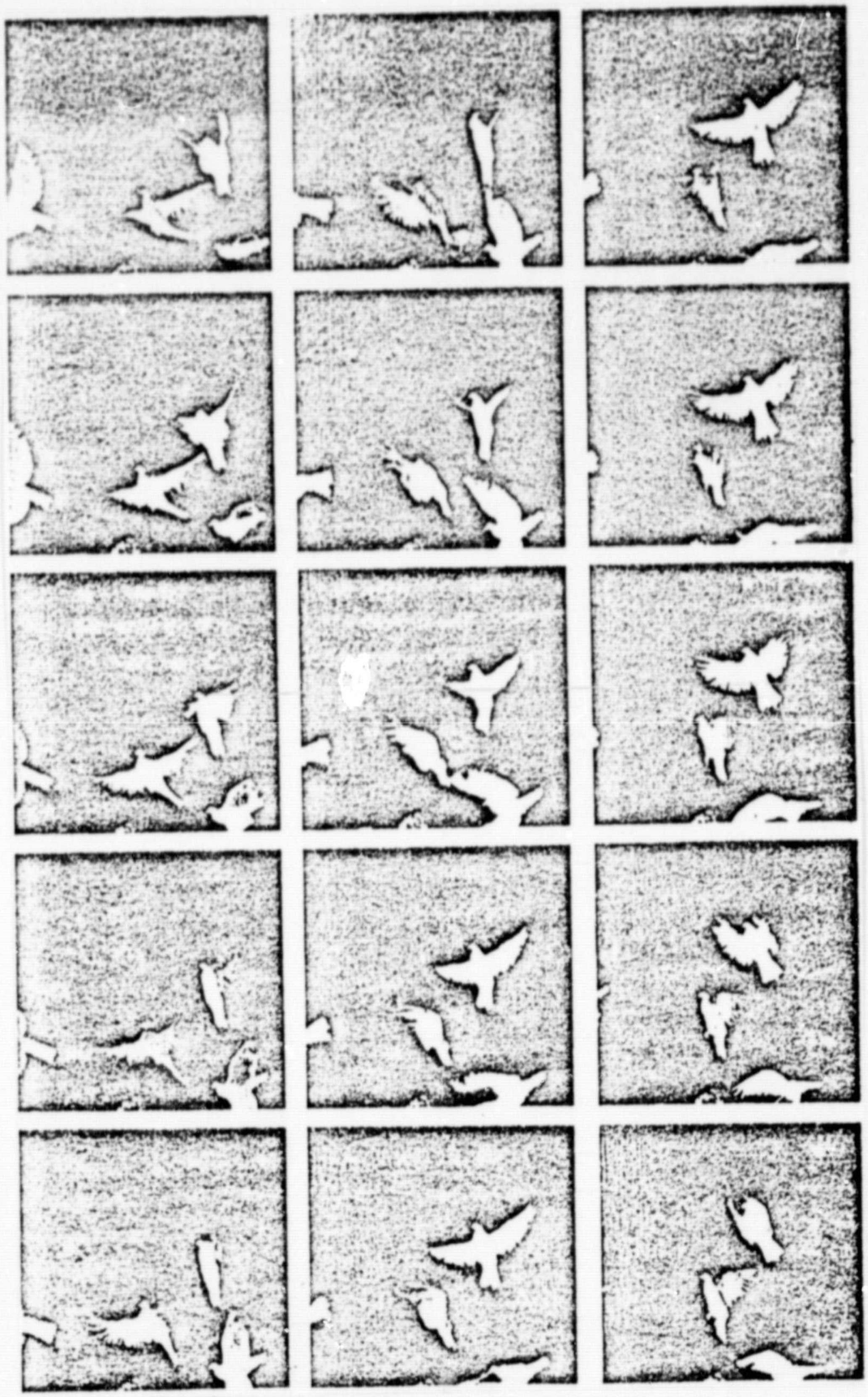


Figure 152
Film of the Wing Movement of a Pigeon in Ascending Flight or while Hovering (film by Noguès)
(Read from Top to Bottom and from Left to Right)

A balancing of the body around its center of gravity can also be observed. This causes its posterior end to be raised upwards when the wing completes its downward stroke and to be moved downwards at the end of the upward stroke.

Wing Motion during Oblique Descending Flight /93

During an oblique descent, wing motion has been found to be analogous to that detected during oblique ascent, with the body once again inclined at a 45° angle and the head pointing upward. However, at the beginning of the wingbeat, the wing tips are first thrust forward, above the head. They are reunited in the rear at the end of the wingbeat. This occurs in such a way that the wings are no longer moving in a vertical plane, but in a practically horizontal one, similar to when a bird tries to ascend almost vertically. Here again, the tail is greatly spread out, the feet hang freely, and the oscillations of the body are very clear.

During the landing, a bird advances its feet and rotates its major axis into a vertical postion. Its wings are then extended and the leading edge is turned upward so as to break the speed of the bird.

To conclude with a general picture of the movements of bird wings, one might present the following summation:

The surface of the remiges forms an approximately horizontal plane striking the air during descent. This inclination is most often accompanied by a deflection of the secondary remiges which give a double curvature to the wing. The primary remiges are also deflected and the tips of their shafts more or less stand up.

At the end of the downward stroke, the remiges return to their original curvature in the manner of a spring going back to its original shape.

During the upward stroke, the wing rotates and cuts through the air with its thin edge.

RECOMMENDED READING

Magnan, A., "Détermination des trajectoires d'oiseaux ou d'avions" [The determination of the Paths Followed by Birds or Airplanes], Rev. Gen. des Sciences (August 15, 1927).

Marey, Le vol des oiseaux [Avian Flight], Masson, Paris (1890).

Lesson Seven: The Effects of a Wingbeat /94

Researchers have been working on unraveling the system of avian flight for a very long time. From the beginning, publications have emerged based on their work. Such publications are very numerous at the present time. The researchers' goal is to discover the unknown aspects of flight that allow the animal first of all to keep itself aloft and then to move forward.

The study of ordinary flapping flight shows that in this mode there is a method of providing lift and propulsion very different from the methods used up to now in aviation. Trying to understand flapping flight with analogies from aviation would lead today, as it has before, to attributing to avian muscles a strength greater than what physiology tells us is possible. This is precisely what Navier did in his calculations.

It is a fact that many birds are capable of traveling over very great distances without stopping to eat and without appreciable loss of weight. When they beat their wings in calm air, birds produce a force without tiring themselves out very much. In any case, this force comes into being without a consumption of energy the least bit comparable to that needed to make an airplane fly.

Captain Lucas-Girardville argued a few years ago that the flight of a bird could only be explained when it is shown how it can occur with an expenditure of work compatible with the known strength of the flying organism. This is exactly the way the question must be posed.

We will see in this lesson and in the ones that follow that our research has allowed us to describe, at least in large part, the sources of the lifting and propulsive power in flapping flight. It has furthermore shown that to obtain the required lift and propulsion the animal does not in fact engage in efforts so great as to be incompatible with its constitution.

I. The Theories of Flapping Flight

It was believed for a long time that when the wing is lowered it strikes the air in a downward and rearward direction. Basing himself on what he took to be the truth, Fabrice d'Acquapendent compared the movement of a wing to that of an oar. A little more than half a centruy ago, R. Owen again argued that the downward thrust only caused the bird to ascend and that to push itself forward the wings have to take on an angle so as to strike both downward and rearward.

Pettigrew's Theory /95

Other scientists, such as Pettigrew, thought that gravity was not, as might be expected, a factor simply and directly opposed to flight. Rather, it played a useful role in flapping flight.

All those who carried out experiments on human or mechanical flight at the end of the nineteenth century were soon forced to reject this theory. They demonstrated that while gravity certainly had a useful role to play in descent during gliding flight, it was insufficient to explain the mechanism of flapping flight.

Oehmichen's Theory

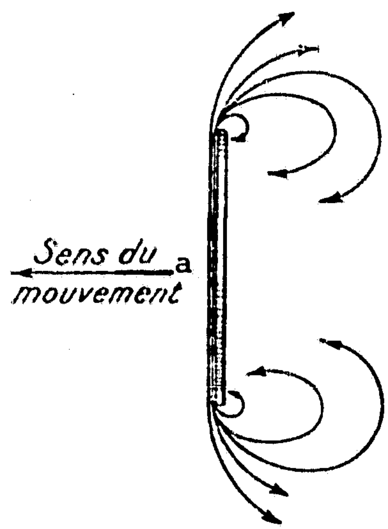


Figure 153
Relative Paths of
Circular Flow Produced
by the Normal Displacement
of a Disc in a Flu:d
(from Oehmichen)

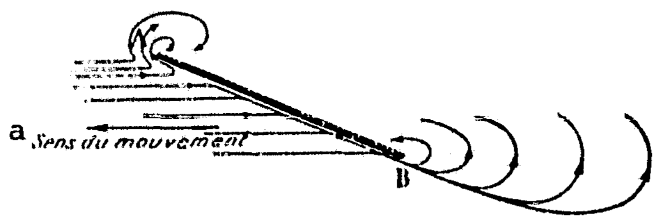


Figure 154
Circular Flow during
Inclined Displacement
in Air (from Oehmichen)

Key: a) Direction of motion

Oehmichen had a theory of wing motion. He carried out a very precise study of rowing flight, and of the circular current and waves in the wake of a bird. These come into being, according to him, during wing movement. (See figures 153 and 154.) He thought that while downward strokes lift a bird, it is the beginning of the elevation that projects it forward. The forward motion is thus a result of the recovery of the energy contained in the waves in the wake of the bird. His assertion that it was his observations of avian musculature that led him to conceive of this type of rowing flight is regrettable. He argued, while claiming to agree with Marey, that the muscles of birds are just ordinary muscles, not much superior to those of mammals of the same weight. They are not at all extraordinary given the size of the animal. Although they are certainly developed, they are not any more so than the thighs which do not, however, have any especially strenuous tasks to perform.

Such a statement does not square at all with reality, as I shall prove farther on.

L. Kahn's Theory

L. Kahn thought up the following explanation for the swimming of fish and the flight of birds.

It is not in the jerky movements that the explanation may be found but in the constantly maintained correspondence between the movement of the wing and its angle of incidence with the air. While the orientation of the wing can vary by tens of degrees, the angle of incidence retains a value of a few degrees, especially in horizontal flight. This is equal to that which aerodynamics indicates would make for an efficient use of the mechanical work done in agitating the wing.

It must thus be shown how the correspondence between the changes in wing position and its orientation can come about in a general fashion. Such an explanation would hold for any type of animal propulsion produced by aerodynamic surfaces in a fluid environment, the swimming of fish as well as the flight of birds. /96

If one considers motion in relation to the fluid, it is bound to consist of movement propelling the body as a whole and a periodic transverse movement of the motive elements. The combination of the two movements makes the motive elements describe a periodic, undulated movement in the fluid.

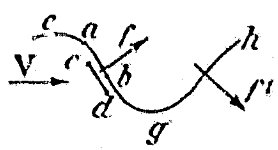


Figure 155
Study of the Movement of an Element ab Describing an Undulated Surface eh with a speed V or W<V (from Kahn)

Let us suppose, like Kahn, a cylindrical surface with regular undulations immersed in a field of which figure 155 represents the cross section eh in the plane of the figure. Picture a surface element ab which follows the undulated surface in the general direction V along the surface eh. When ab follows eh in this manner, the fluid does not produce any retarding effects due to friction.

The movement ab can be regarded as the result of the following components:

(1) A unifrom translational motion of velocity V, equal to the average velocity measured parallel to the general direction of propulsion.

(2) An orbital motion, closed on itself.

(3) A motion that orients ab so that it is constantly parallel to the tangent of the resulting curve eh.

(4) A motion deforming ab so that it conforms to all the bends on eh, but which can be ignored in a first approximation.

Still following Kahn's analysis, now suppose that components 2, 3, and 4 remain constant, but that component 1 no longer has a magnitude of V, but of W, which is less than V.

Instead of remaining on the surface eh, ab will then move to cd and a reaction of the fluid directed approximately in the direction f, perpendicular to ab, will appear.

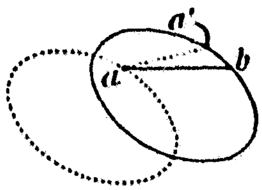


Figure 156

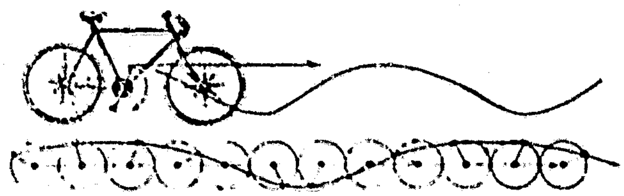


Figure 157
Path of a Pedal on a
Bicycle in Motion

It is in fact known that a profile attacked at a small angle undergoes a force approximately normal to its general direction. This force increases about in proportion to the square of its velocity, and as a function of the angle of incidence, at least up to a certain value of that angle.

The effects produced would thus depend on the value of W relative to V. They would increase as the difference increased and diminish as it diminished. For example, the cruising speed in rapid horizontal flight would be that for which the resistance and weight are balanced by the average resultant of aerodynamic effects.

Calculations have established that the form of the movements and the power consumed would be well in accord with reality.

In low speed flight, liftoff, or hovering, birds, instead of using the action of the velocity, substitute that of the augmentation of the angles of incidence coupled with a stationary agitation of the wing. This causes a decrease in yield, an increase in the instantaneous efforts, and a rapid increase in muscle fatigue.

In place of a single element ab, suppose a flexible body able /97
to conform to the shape of an undulated curve All its elements will then undergo reactions of the same order. The transversal components will cancel each other out and the longitudinal components will add together to produce the propulsion (figure 156).

As Kahn considered it, wing motion was the resultant of several movments: a general displacement; a forward translational movement; a motion that closes on itself (orbital); and, finally, a deformation that makes the wing follow the bends in its trajectory.

One can get an idea of how this movement is broken down by considering the undulated path that the foot of a bicyclist traces. The foot advances on the road while turning around the hub of the sprocket (orbital motion). It also seems to oscillate about itself and to change form according to its trajectory (figure 157).

The forward motion of the wing, like that of the fish, would seem to result from its undulatory movement, like the "spinning" of a needle.

L. Bréguet's Theory

For L. Bréguet, the rowing-like beats of a bird's wing in horizontal flight did not serve, as certain people thought, to provide the lifting force directly. Rather, it was really to propel the bird, which was then kept aloft by the speed that the beating wings maintained.

The explanation and the analysis of the way flapping its wings horizontally propels a bird in calm air would then follow a course similar to the way in which the vertical pulsations of the wind cause the average aerodynamic resultant to become upright in a bird that encounters them passively.

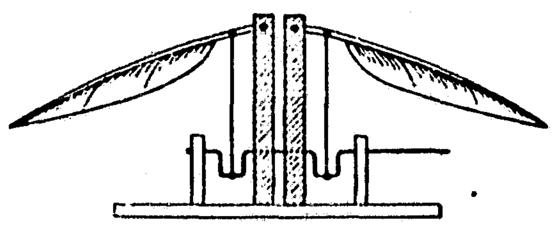


Figure 158
Equipment for Studying the Air Current Created by the Flapping of a Bird's Wing

A perfect reciprocity would then exist between the two phenomena. The flapping wing would cause a periodic oscillation in the vertical component of the aerodynamic speed, just like a vertical pulsation of wind with the same force and cycle as the beating wings.

According to this author, this implies that flapping flight is due to the existence of an air current possesing variations in vertical inclination and created by the alternating wings. The air current would neutralize resistance to the advance of the bird in the same way as occurs in surfaces in a wind tunnel. This has been called the Katzmayr effect.

Katzmayr made the following experiments in a wind tunnel. First an air current of theoretically constant direction was maintained in the tunnel. A wing that could oscillate around an axis parallel to its leading edge was then placed in the current. The author has observed that, in these conditions, the oscillation of the wing has the result of giving the wing a lower polar curve. The greater the angle of oscillation, the lower it is.

Resistance also increases significantly, and in proportion to the magnitude of the angle of oscillation. If, instead of making the wing oscillate about an axis parallel to the leading edge, it is made to beat in the manner of birds, the result is the same.

I attached two wings by their humeral heads to a horizontal axis supported by two columns. The wings were held close to the columns and connected to a bar linked to a crankshaft which could be turned by hand. (See figure 158.) The rotation of the crankshaft made the wings beat alternately upwards and downwards. I wanted to see if this flapping resulted in an oscillating movement of the ambient air. To achieve this, I used a double hot wire instrument, whose cylinder was placed at several positions around the wings. The instrument never recorded any curves providing convincing proof of the existence of such an oscillation of the wind. /98

I used a similar method when I attached a pigeon to a harness, as Marey did. I then fixed the double hot wire cylinder either in front or in back of the plane of the air. The natural beating has never given me any evidence of an air current with regular variations of inclination which would indicate the possibility of an oscillating wind. Moreover, in a horizontal air current, a swallow, as Marey pointed out, skims the water without rippling its surface. The largest species of birds also do this.

Another researcher, Weyham, has stated that he has often seen pelicans fly over the Nile during calm weather at a speed of 15 m/sec. The pelicans beat their wings barely 30 or 40 cm above the river, without agitating the water in any way.

Constantin's Theory

J. Constantin, who first observed the rocking of the rear of a bird's body, of which I have already spoken, experimentally studied the different possible effects of gravity on a plane. He then decided that birds, by successive soaring and swooping, caused a certain permanent pressure to be built up against their lower surface, proportional to their weight. This would give them part of the required lifting force.

To this first cause of lift, that obtained by lowering the wings is immediately added. At this moment, when the animal has not yet acquired sufficient speed, the force caused by lowering the wings provides an indispensable complement for keeping it aloft. It is the difficulty of obtaining these two primary sources of lift that makes some birds hesitate at the moment of takeoff.

A bird in the air would naturally feel an inclined upward propulsive force at the moment when its wings make their downward thrust, because of the position of its center of gravity. This is similar to the plane in figure 159, which is provided with a moveable weight and a propeller or float.

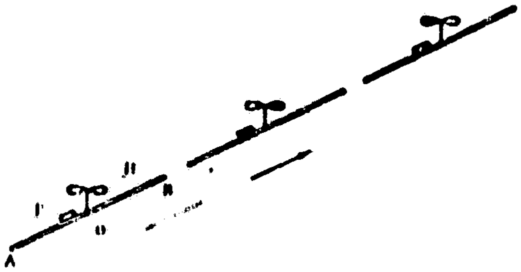


Figure 159
Plane AB Equipped with a Moveable Weight P and a Propeller H for Upward Propulsion (from Constantin)

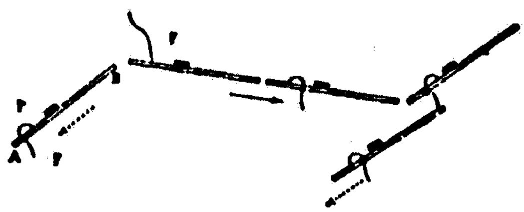


Figure 160
Plane AB Designed for Demonstrating the Action of the Rocking Motion of the Rear of a Bird (from Constantin)

However, this source of upward propulsion ceases with the downward stroke of the wings that produced it, and the bird would fall backwards while raising its wings. It is at this point that the rear to front rocking intervenes. The rocking is produced by a sudden induced tipping of the plane which causes it to change inclination (figure 160). In the case of the bird, this is done instinctively towards the end of its downward stroke.

During the period when the wings are being raised, this move- /99
ment ceases and the normal descending glide is resumed.

The ascending forward motion which was caused by the transformation of the vertical action of the wings is thus succeeded by a descending forward motion resulting from the rocking movement.

We shall end this survey of the literature here. Let us leave on the sidelines all the other theories based only on calculations and without experimental foundation, even though they are very numerous and sometimes interesting.

II. Experimental Research on Reaction to a Wingbeat

We are now going to try to give as precise, accurate, and detailed a report as possible of the experimental research that could shed light on the mechanism involved in flapping flight.

However, despite the modesty of this program, it must be stated that researchers came up against special difficulties in making observations from the very beginning. These were caused by the fact that the air is, in general, invisible, and that as a result we are not accustomed to "see" with our eyes the range of mechanical effects produced by the passage of a projectile, be it blimp, bird, or, finally, airplane. This is the circumstance that is at the origin of many of the errors of interpretation committed in regard to flight.

The first point to bring to light is this:

That which profoundly differentiates flight from other modes of displacement on the earth's surface, or even in rivers in oceans, is the low density and high compressibility of the supporting medium. In fact, the normal atmosphere does not offer any direct "support." It literally escapes from under any solid or flexible surface that attacks it.

However, the mechanical effects produced by the reaction of the air could engender an almost vertical upward impulsion sufficient to compensate or even exceed the reverse impulsion produced in the same period by gravity and the resistance to the progression of the moving object.

In the study of flapping flight, the following must all be simultaneously considered:

1) The inertia and weight of the primary moving body.

2) The secondary moving bodies (the wings) which make periodic orbital movements (in relation to the principal body.)

3) The inertia (and weight) and compressibility of the surrounding medium.

As we shall see below, there is no true direct support in the basic avian flapping cycle, if by that is meant reactions originating in solid bodies or that could be considered as such. The influence of the ambient milieu on the body in flight takes the form of only retarded, deferred, or indirect reactions.

Vertical Reactions

Some of these reactions can be precisely documented using cinematographic procedures. They are reactions having to do with vertical or horizontal oscillations of the animal's center of gravity and whose existence may be predicted from sensory data.

Conventional methods for determining the position of a bird's center of gravity already exist.

a) Determination of a Bird's Center of Gravity /100

I have personally used the methods employed by my predecessors for this purpose, although they have been criticized by some authors. I have also employed a personal method which attempted to manipulate the animal into a position identical to when it is in flight. The body and the head must form a straight line and the wings must be kept extended as in flight, i.e. elevated, level, or lowered. The animal was therefore first placed on a board with its neck elongated and its wings spread out horizontally. I then injected a solution of formaldehyde so as to give the wings a greater degree of rigidity. I thus obtained, without significant modification of the specific distribution, birds in flight position. By holding an individual by a clump of feathers on the back and seeing whether the bird tipped forward or backward, I could tell if the chosen point was in front of or in back of the center of gravity. After moving thus from point to point, there finally came a time when the animal was perfectly balanced in a horizontal plane. The exact transverse plane containing the center of gravity could be easily found in this manner. By suspending the bird by the beak or by a wing tip, a second plane containing the point in question could be discovered. Since the center of gravity also lies in the vertical plane passing through the major axis of the body, it could now be determined precisely.

By repeating the same procedure with the same bird after its wings had been raised or lowered, it was found that the center of gravity moves a few centimeters upward or downward in the vertical plane. We have seen that the wing is moved forward during a downward stroke and rearward during an upward one. The same procedure as before can be used to discover the position of the center of gravity for extreme attitudes of the wing. Experience has shown that the center of gravity undergoes both horizontal and vertical displacements.

It is thus easy to investigate changes in position of the center of gravity by using measurements taken from motion picture film. The purpose of this is to determine the magnitude of the oscillations of the body caused by flapping the wings.

b) Marey's Experiments

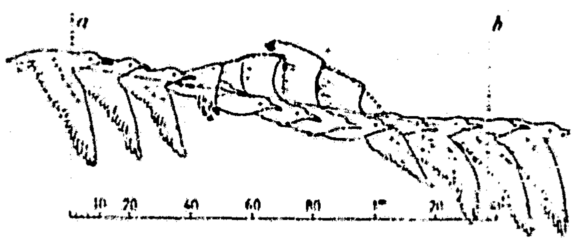


Figure 161
Vertical Oscillations of a Sea Gull's Eye when Descending

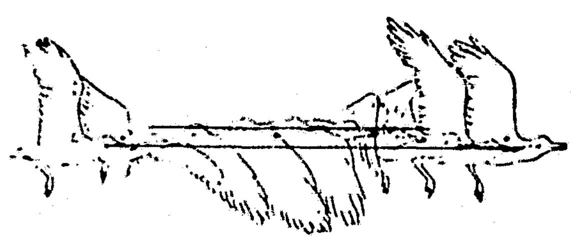


Figure 162
Path of the Eye and Center of Gravity of a Sea Gull in Flight

Marey made an intensive study of this question. He took a series of photographs of a sea gull in flight (figure 161). On each photograph he picked a well defined point, such as an eye, which was always visible in spite of the movement of the wings. By joining the position of the eye in the successive images with a dotted line, he created a winding curve. The eye is therefore alternately elevated and lowered during each flap of the wings.

Measurement of eye displacement above and below the axis of flight revealed that the oscillations had an amplitude of 0.09 meters, or 0.04 meters on each side of the axis. The positive and negative phases of the oscillations both had essentially the same duration. The positive, convex side upwards phase of the curve corresponded to the downward stroke of the wing. The negative, convex side downward phase occurred during the upward stroke.

All observers, even in Marey's time, were cognizant of these vertical oscillations, especially during the first moments of flight. The bird's body moves upward each time the wings are lowered. It descends during each elevation of the wings. Does this /101 mean that the mass of the bird experiences the same oscillations as a particular point of its body? The mass of a body should in fact be considered as located at its center of gravity. In a projectile of invariable form, the center of gravity is immobile, but this is no longer true for a body of irregular form whose different parts change position in relation to one another.

When a bird beats its wings, its center of gravity is displaced. It rises when the wings are elevated and descends when they are lowered. It is thus possible that the center of gravity could keep to a straight line while every point of the body, individually considered, describes a more or less complicated trajectory.

c) The Huguenard-Magnan Experiments

Experience seems to indicate that there really are oscillations of the center of gravity, but that they are of small magnitude. I made a series of curves of the displacement of the center of gravity of a pigeon flying in front of a set of reference lines. Its center of gravity had first been precisely determined by the method described above. Vertical displacements, although of fairly small amplitude, were indeed noted. Marey, and later Labouret, had already noticed them. In figure 162, due to Marey, the crosses indicate the positions of the center of gravity of a bird in flight. It may be seen that the center of gravity does not have as pronounced oscillations as those of the eye, which are contained within the two solid horizontal lines. In the first case, the oscillations have an amplitude of only 1 cm, while they have an amplitude of 4 cm in the second case.

In order to document the reaction of the trunk in the vertical direction to the beating of the wings, Huguenard and I tried to measure directly the acceleration of the animal in flight with the aid of an accelerograph that we designed. We attached this instrument to the back of a carrier pigeon capable of carrying an added load without difficulty.

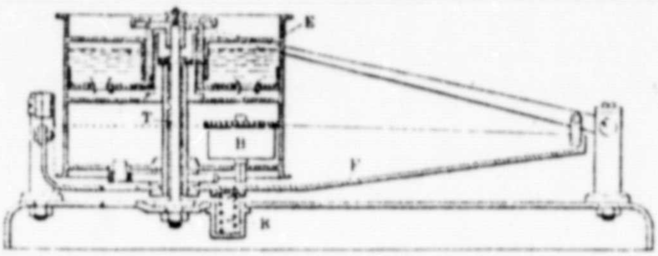


Figure 163
Design of the Huguenard-Magnan Accelerograph

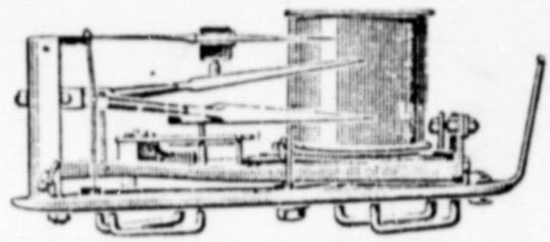


Figure 164
Accelerograph for Birds

The use of an accelerometer is limited, however, by the size of the perturbations caused by the mass of the instrument to the system that one wishes to study. To obviate this problem, we have set up an accelerometer arranged so that practically all of its mass is made up of moving parts. To do this we made all the parts whose functions require an elevated weight part of the mobile accelerometric mass. It is thus possible to reduce the weight of the instrument considerably and to adapt it to measuring acceleration in light systems.

Figure 163 represents an accelerometer of this type. The accelerometric mass is made up of the recording cylinder E, the device that rotates it, and the major part of the dampening mechanism. The rotation is produced here by a clock movement, whose barrel
is indicated by the letter B in the figure. A toothed pinion /102
meshes with a pinion attached to the frame member F which holds the hollow axis around which turns the cylinder. Through the hollow axis passes a shaft T which holds a light piston at one of its ends. The piston moves in a space set aside for it in the lower part of the recording cylinder and is filled with a liquid of suitable viscosity.

The other end of the shaft T is attached to the base of the instrument. The base also holds up a set of columns which support the frame member F by thin flexible plates. Frame member F gets thinner towards its right end in order to form an amplifying lever jointed at a tie rod. This rod guides the needle tracing the variations in acceleration in the direction of the axis of the cylinder. The center of gravity of the cylinder and frame member arrangement is placed approximately on the line perpendicular to the axis of the cylinder and passing through the flexible joint.

This makes the instrument sensitive only to the component of acceleration (here, vertical) parallel to the axis of the cylinder. Adjustment of the dampening mechanism is done by orifices cut into the piston which can be made to coincide more or less exactly with orifices cut into a stop valve, adjustable by means of a button. When the openings do not match up at all, maximum dampening is obtained.

The mass of liquid makes up a part of the mobile mass. The surface of the piston is chosen so that the pressure developed by the dampener in the liquid does not exceed a small fraction of the pressure of the atmosphere. The sensitivity of the instrument is adjusted by means of a detachable spring R held in place by the housing. The tension on the spring is reduced when greater sensitivity is desired.

The accelerograph that we constructed (figure 164) for use with birds has a form that has been slightly simplified, miniaturized, and streamlined. It measures 7 cm long, 3 cm wide, and 3 cm high and weighs 55 grams. The recording cylinder that it carries has a diameter of 2 cm, makes a complete revolution once every 6 seconds, and produces diagrams measuring 6 cm by 2 cm. On these diagrams is traced the vertical acceleration in the vicinity of the bird's center of gravity, the movement of a wing, and also the vibrations of a thin plate serving as a chronograph. The plate is kept vibrating by the mechanism recording the movement of the wing.

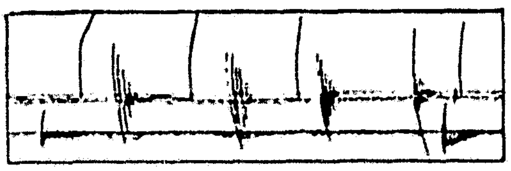


Figure 165
Recording of the Intrinsic Period of the Bird Accelerograph

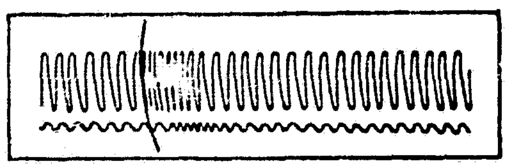


Figure 166
Calibration Curve of Bird Accelerograph

The extreme lightness of our instrument was achieved, as we have just said, by the use of the recording cylinder and clock movement as accelerometric mass. Because of this arrangement, 4/5 of the device's weight is used to absorb acceleration.

The small accelerograph possesses an intrinsic oscillatory period of 1/20 second (figure 165). Its starting sensitivity is 1 mm per m/sec^2 of acceleration. After having been calibrated statically, the accelerograph was placed on a plate equipped with an electric vibrator. (See figure 166.) The comparison of the acceleration due to the sinusoidal oscillations of the plate and of the tracings recorded by the accelerograph enabled the exactness of the previous calibration to be verified for a frequency of oscillation close to that at which a pigeon beats its wings (around 5 times per second.)

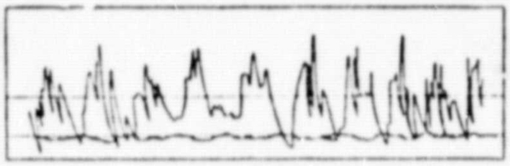


Figure 167
Recording of the Vertical Acceleration Caused by a Man Walking Normally

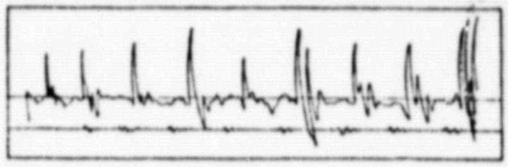


Figure 168
Recording of the Vertical Acceleration Caused by a Man Walking Asymmetrically

We used the accelerograph to record the acceleration curve produced by a human being with an asymmetric pace (figure 168). If this tracing is compared to that of a normal pace (figure 167), the difference is clearly visible.

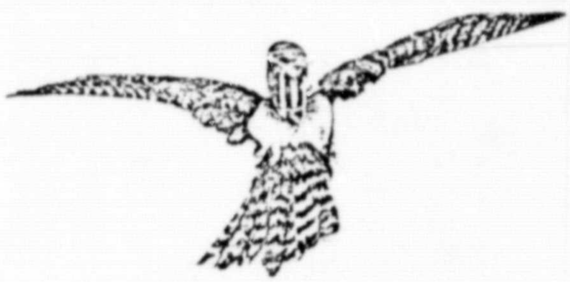


Figure 169
Accelerograph and Corset on the Back of a Falcon

We then attached the accelerograph to a kind of corset which /103
covered the body of a pigeon but left its neck, wings, and feet free (figure 169). A braided silk thread wound on a reel was tied to the pigeon's feet. It was used to measure the speed of the pigeon and to halt its flight after a predetermined trajectory was completed.

We then made various recordings that proved, from the beginning, that a pigeon taking off from the ground underwent considerable acceleration. This caused us to reduce the sensitivity of the accelerograph by half. Figure 170 reproduces a curve traced by the readjusted instrument of a bird taking wing after having been released at a height of 1.50 meters. The bird was flying away at a very low speed while very strongly beating its wings 6 to 8 times per second. The acceleration thus attained was 4 grams. Figure 171 shows a portion of the curve traced in a type of flapping flight that is less active than in figure 170. It is consequently closer to full flight. The strokes of the wings are less rapid and the amplitude smaller.

Figure 170
Recording of Vertical Acceleration Caused by A Pigeon Flapping its Wings during Takeoff

Figure 171
Recording of Vertical Acceleration Caused by A Pigeon Flapping its Wings in Flight

By working with different types of birds strapped to accelerographs of this type, curves are obtained whose elevations and descents correspond to the vertical acceleration occurring in flight.

It may be seen in figure 172 that the recordings differ according to whether they are made by rapid flappers, like wild ducks, or birds that flap more slowly, such as buzzards.

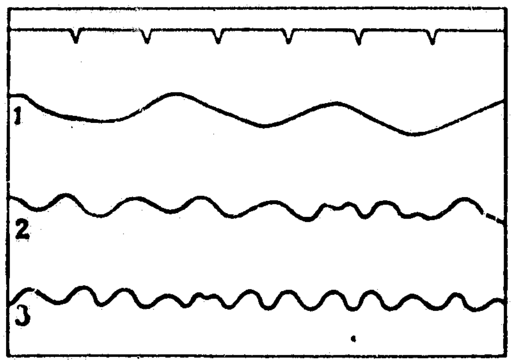


Figure 172
Recordings of Vertical Acceleration Caused by the Wings of 1) a Buzzard, 2) a Pigeon, 3) a Duck At the Top, Marks Made by a Jaquet Chronograph (1/5 second)

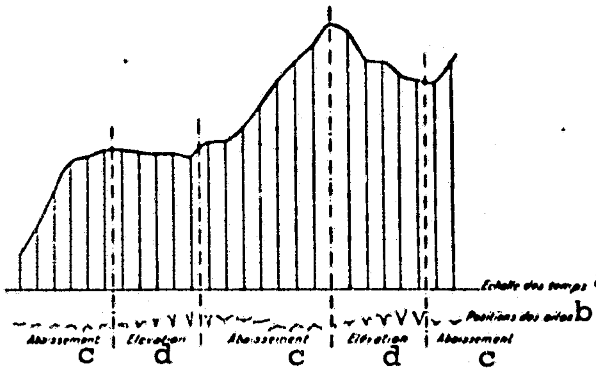


Figure 173
Vertical Oscillations of a Heron in Oblique Ascending Flight (from Oehmichen)

Key: a) Time scale
b) Position of wings
c) Descent
d) Elevation

It must be added that the vertical oscillations of birds in flight are easily noticeable in many individual birds, which may be seen jumping higher in the air at each flap of the wings.

Horizontal Reactions

/104

If the accelerograph is oriented horizontally rather than vertically when mounted on the back of a bird, the instrument will, if it is very sensitive, record fluctuations in horizontal speed instead of the vertical oscillations. In this arrangement, positive acceleration causes an elevation of the curve, whereas slowing down results in a descent.

The variation in horizontal speed can be made visible by another procedure, consisting of tracing the measurements made on the film of a bird flying parallel to a set of coordinate lines. The abscissa is the time in sixteenths of a second and the ordinate marks off the distance in meters between the bird's center of gravity in successive frames. The space between two points in the tracing then represents the amount the bird has advanced per unit time and, consequently, the speed of the animal at different instants. Figure 173 shows that a bird progresses by jerks and is projected forward immediately after the downward stroke of its wings is completed.

III. The Determination of the Cause of Reactions during Horizontal Flight

The vertical reactions to a bird may be easily explained. The wing, whose lower side is concave during a forceful downward stroke, compresses the air in a sort of pocket and succeeds for an instant in actually being supported by the air, which cannot escape.

In this situation, the bird's body lifts itself up like a man who supports himself on crutches resting on solid ground. This is what led me to say before that the mechanical metaphor for flight should be sought in the action of jumping, with the stipulation that in place of a solid support there must be substituted a basically mobile support that flees under the force of the shock.

The Action of the Pectoral Muscles

It must be added that the elevation of a bird's body is increased by the pectoral and thoracic muscles. These muscles are supported by the axis through the points of attachment of the wings, as Houssay stated. In fact, the body oscillates around such an axis in a rhythmic fashion. It beats around the same axis as the wings and at the same time. The entry into action of the muscles during the downward stroke in relation to this axis is clearly demonstrated by the elevation of the rear of the body. This elevation is brought about by the action of all the muscles in motion and initiates the rocking motion already examined.

The study of the contractions of the pectoral muscles clearly justifies this approach to the situation. If the contraction of the pectoral muscles is recorded simultaneously with the vertical oscillations of the bird (figure 174), as Marey has done for the duck and the buzzard, it may be seen that two vertical oscillations are produced for each flap of the wings. /105

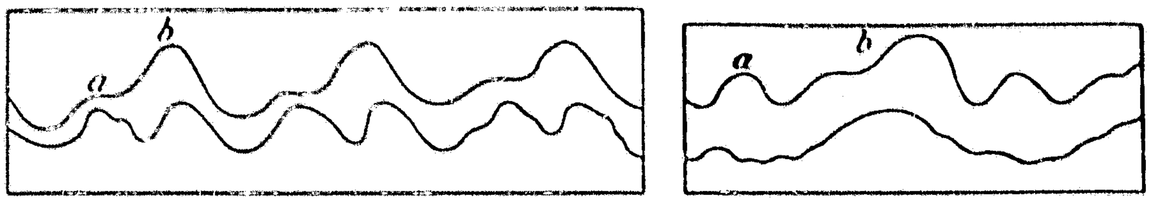


Figure 174
Simultaneous Tracings of the Contractions of the Pectoral Muscles (Top) and the Vertical Oscillations of the Body (Bottom) Left: a Duck, Right: a Buzzard (from Marey)

Part b corresponds to a downward stroke of the wings and part a to an upward one. By superposing the two curves, it becomes apparent that a vertical oscillation accompanies the raising of the wing and that another oscillation in the same direction corresponds to its descent. In the buzzard, it maybe observed that the oscillation related to the elevation (a) is much weaker.

The Form of the Air Flow during a Wingbeat

While it is easy to explain the vertical oscillations, it is more difficult to understand, *a priori,* the fluctuations in the speed of a bird and especially its progression in the air. Research, however, has partly revealed the cause of avian propulsion.

First of all there is the question of what becomes of the air struck by the wing, upon which it supports itself. We have seen that it does not seem to descend or curl back around the wing.

We are going to show that in reality it escapes at high speed along the trailing edge of the wing.

We owe the first experimental demonstrations on this subject to Muller. He constructed small spring powered motors which made a wing-like object beat with a small amplitude but with great force. He made the movements of the air caused by the beating visible in daylight through the use of smoke. He then noticed that the air escaped along the trailing edge, if the wing possessed a thick rim on one side similar to that often observed on the anterior edge of avian wings. The purpose of such a rim is to impede the escape of the air toward the front and to channel it toward the rear, which /106 is thin and flexible. (See figure 175.)

If the wing were thin and had no rim, the air would flow out in all directions. If, on the contrary, the rim existed all around the wing, the mass of air would only escape if the movement of the wing were violent and rapid enough to enable it to pass over the rim.

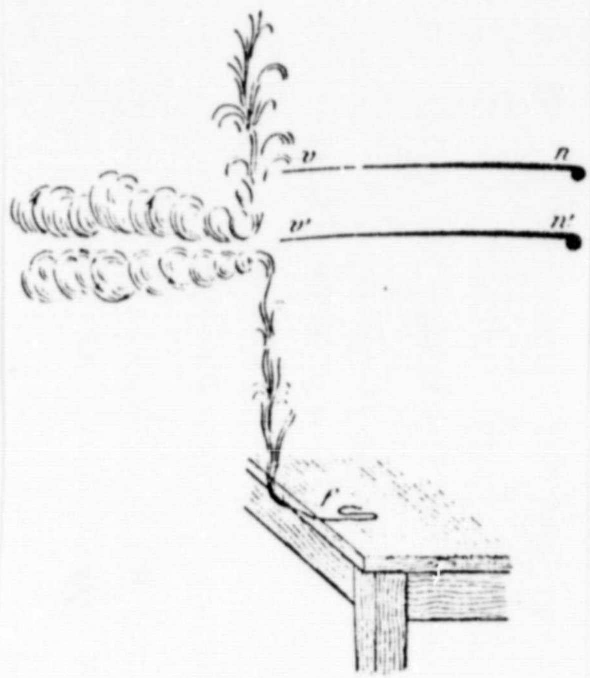


Figure 175
Movement of the Air under the Influence of a Stroke of the Wing Going from vn to v'n' (from Muller)

Experimental Models

Suppose that the humeral head of the wing of a large dried bird is held in the hand. The wing is then completely spread out and quickly lowered so as to strike the air with its lower surface while a slight frontward and downward inclination is maintained. A deviation of the arm toward the rigid edge will then be observed. It is, in fact, impossible to hit the air with the wing held flat and inclined downwards. The more force is exerted, the more the arm is deviated by the wing which is pulled toward its large edge.

This demonstrates that the forward movement of the wing during its downward stroke is automatic and due to the reaction of the air.

Let us recommence the flapping experiment between two lighted candles. It will usually be immediately evident that the candle next to the anterior edge of the wing will not display any agitation, although sometimes it is slightly attracted to the wing. The other candle will, on the contrary, vacillate in every direction, even when it is far from the beating wing. If the trailing edge of the wing is halted at the level of the flame, the candle will surely be extinguished.

Figure 176
Propulsive Mechanism in Birds
A, Flow of Air Toward the Rear
B, Reaction Toward the Front

Figure 177
Pline's Artificial Wing

These experiments clearly reveal the effect of wing flapping on the air. They prove that the air is not projected vertically, but that it is compressed in the hollow of the wing until it is forced out around the trailing edge and that the wing assumes a double curvature. The air escapes with great speed parallel to the plane of the wing. (See figure 176.) Another action also occurs parallel to the wing's plane at the same time. Around the entire front of the wing, the rim blocks the air from moving forward. This is the reaction that makes the bird progress and that carries the wing forward. It should be added here that the faster the wing is beating, the thicker is the mass of compressed air.

Pline was able to reproduce these experiments with a bamboo wing at the ends of which a cord was tied so as to stretch the bamboo into the shape of an arc. Two other small pieces of bamboo were curved into arcs and then attached to the main shaft and the cord. After fabric was glued to this skeleton, the demonstration of the rearward flow of air could be made almost as well as with a real bird wing. (See figure 177.)

<u>The Measurement of Air Flow Speed at the Trailing Edge</u> /107

It is possible to try to measure the speed of the air current that escapes from the trailing edge of a wing. To do this I suspended a live pigeon in a harness, as Marey used to. The pigeon could beat its wings freely but could not move its body vertically or laterally. I then placed a hot wire on the rear of the pigeon's wing, outside of the setup. The purpose of the hot wire, which was insufficiently compensated, was to measure the speed of the air current escaping from the trailing edge when the wing is at the end of its downward stroke. These experiments, to which I will return later on when trying to calculate the magnitude of the reaction, have shown me that the speed of the air certainly exceeds 15 m/sec, although I have not yet been able to determine the exact value.

In conclusion, it is worth remarking that the preceding experiment does not yield any evidence for a similar air current when the wing is thrust upward. The wing therefore does not press against the air during its upward stroke. This is because of the arrangement of its plane during this phase.

IV. The Cause of Ascending Flight

The preceding account approximately described the methods used by birds to achieve the required lift and propulsive force. The mechanisms involved in flapping flight as well as all the reactions sustained by birds' bodies may now be partly understood and explained. It is thus clear why the downward stroke of the wings lifts up the body of the animal and increases its horizontal translational speed, and why the wings of a bird are less well supported and its speed diminishes during the upward stroke.

It should be stated that, on the whole, this schema applies especially to the mode of flight that directly succeeds takeoff.

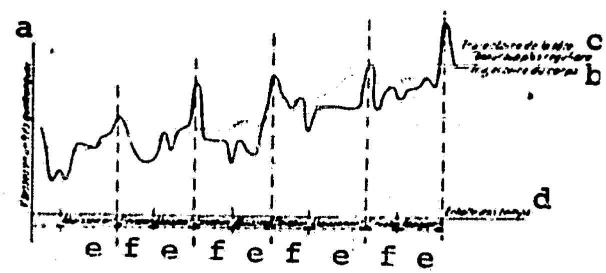


Figure 178
Path of a Point Close to the Center of Gravity of a Heron in Horizontal Flight (from Oehmichen)

Key: a) Speed in arbitrary units
b) Path of the body
c) Much more regular path of the head
d) Time scale
e) Descent
f) Elevation

When a bird takes wing, the mechanism involved in flapping the wings is still the same. The only difference is that as a result of the arrangement of the wings, which alternately beat fowards and backwards, the air current is directed downward in order to project the bird upward. The proof of this is furnished by the observation of birds like the pigeon, which at takeoff produce a wind along the surface of the earth that affects objects more than a meter away.

Vertical progression is similar to horizontal progression and is accomplished in leaps.

By following the successive positions of a point on the body of a heron in photographic enlargements, as Oehmichen did, one can see that the bird increases in altitude in the period after takeoff during the downward stroke of the wings. No altitude is gained while the wings are lifted and very often some is even lost.

The curve in figure 178 refers to two sets of data taken from /108
a filmed sequence. Time is marked off on the abscissa based on the interval between frames. The ordinate is the altitude corrected to take account of the progressive approach of the bird. The curve indicates the gain in altitude during the downward stroke and its loss during the upward one.

In contrast, everything seems to be regularized in full flight. Both the vertical reactions of the body and the horizontal variations are barely visible. The speed thus assumes a uniform appearance while the acceleration in the vertical direction varies only from 0.8 or 0.9 grams to 1.1 or 1.2 grams, as I have already shown.

RECOMMENDED READING

Bréguet, L. Le vol à voile dynamique des oiseaux [Avian Soaring], Paris (1925).

Constantin, "L'énigme de l'oiseau" [The Enigma of Birds], Notes (1922).

Katzmayr, "Ueber des Verhalten von Fugelfachen bei periodischen Anderungen der Geschwindigkeitsrichtungen", Z.F.M. (1922).

Kahn, L., "La propulsion animale dans les fluides" [Animal Propulsion in Fluids], Ass. tech. marit. et aéron. (June, 1929).

Pettigrew, La locomotion chez les animaux [Animal Locomotion], Paris (1887).

Oehmichen, Nos maitres, les oiseaux [Our Masters, the Birds], Dunod, Paris (1920).

When observing birds of various species in flight, one is quickly struck by the different ways they flap their wings. The general schema of flapping flight is always true to my description of it, but the frequency and the amplitude of wingbeats varies according to group. As a result, the forward speed varies too.

Difficulties immediately arise when trying to collect precise data on birds' flight speed and the frequency and amplitude of their wingbeats in nature. Most often, this latter information is impossible to obtain by simple observation. This is because our senses do not allow us to count more than 5 or 6 flaps per second or to estimate the angle that a wing passes through between the time of maximum elevation and the time of maximum descent.

The situation concerning the speed of birds is the same. There have been authors who believed that they could accurately determine the speed through simple observation. The figures they came up with in this manner were wildly inaccurate and totally at odds with reality. Others, of a more scientific spirit, have attempted to discover the speed of birds by timing them as they fly between two landmarks. They too often committed errors, although it is true that these were less serious. Their errors stemmed from the fact that they were not actually measuring the distance traveled by the animal as a function of time. Instead, they recorded an angular velocity from which they could draw no conclusions because they did not know either their distance from the bird or the angle they made with the two landmarks.

For these reasons, certain authors erroneously claimed that a swallow attained 241 km/h, a swift 316 km/h, and some falcons close to 400 km/h during dives. We shall see below that these figures do not correspond at all with the truth.

There exist several procedures for collecting these essential data. The most accurate is to use high speed movie cameras.

To determine the exact number of wingbeats per second, a bird is filmed at 100-200 frames/sec as it moves perpendicular to the axis of the lens. Also included in the camera's field of vision are a set of reference lines and a pendulum.

If a bird is filmed in the same way as it moves toward the camera, the amplitudes of the wingbeats may be measured by comparing the successive frames.

Lastly, the real flight speed of a bird may be measured by referring to the coordinate lines and the pendulum, which indicates the time between frames. The only other information that must be known is the length of the bird's body. The path of the bird in space may also be determined with these data.

I. Wingbeat Amplitude

/110

The films made of birds as they approach the camera clearly show that the amplitude and even the form of wingbeats vary continuously when both ascending and descending. Direct observation also gives an indication of this.

If a pigeon is observed during an oblique ascent, it will seem that the wings come together, first behind, then in front of the head. (See figure 179). The angle that each wing passes through during one wingbeat is almost always close to 160°.

When the bird descends at an angle in order to land, the situation is about the same, except that the amplitude of the flapping is often slightly reduced.

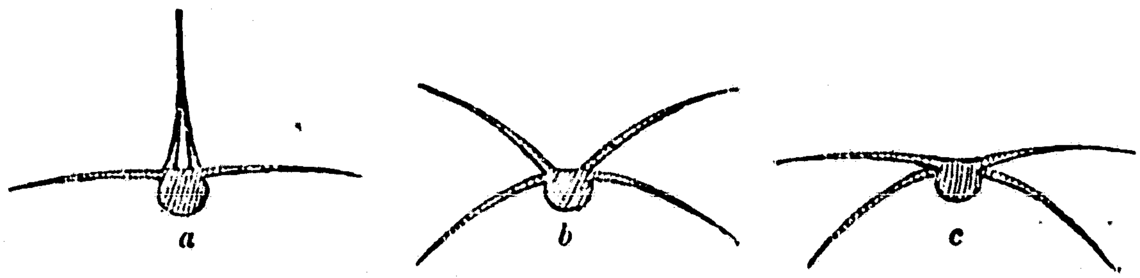


Figure 179
Different Orientations of the Angle of Oscillation of the Wings of a Pigeon
a, Takeoff b, Midflight c, At the End of the Flight (from Marey)

In contrast, when a pigeon is in midflight and moving horizontally, the successive frames of a film of its approach show that the wings no longer oscillate around the horizontal position by such a large amount. The total angle that they pass through ranges from 40 to 80° (figure 179), according to the energy that the pigeon puts into moving its wings.

Marey accurately observed this. He wrote that when a seamew takes off from the surface of the water, it first flaps its wings over a wide angle, at least 100 or 110°. Then, as it picks up speed, the extent of its wingbeats is reduced and their amplitude falls to 40°. The bird often continues to fly like this for a long time while skimming the water, neither gaining nor losing altitude and maintaining a perfect regularity in the beating of its wings.

The amplitude of birds' wingbeats depends on the species, as the following table shows. In this table, the angle given corresponds to the extreme positions occupied by the extended arm and forearm.

	Amplitude (deg.)		Amplitude (deg.)
Griffon Vulture	40-60	Seamew	40-90
Peregrine Falcon	60-100	Pigeon	40-80
Owl	40-70	Wild Duck	80-100

It should be added that amplitude is a function of a bird's speed. The faster the animal goes, the smaller it is, but in any case it never goes below 40°.

It may be concluded from the preceding numerical observations that a wingbeat of small amplitude has as much effect in horizontal flight as a wingbeat of maximum amplitude in ascending flight. Lift is supplied just as well in the first case as in the second despite the difference in energy produced by the bird. /111

This is solely because the bird has already attained such a high speed in horizontal flight that a slight atmospheric counterforce suffices to keep it aloft. Meanwhile, in ascending flight, the bird is taking off from the rest and is trying to gain both altitude and forward speed. It may thus be said that speed is advantageous to birds because it enables them to stay aloft with less effort.

II. Wingbeat Frequency

Numerous observers have tried to measure how often birds flap their wings by counting the number of wingbeats made during a known period of time, which is made as long as possible. Such a method cannot be used to acquire a large body of data because it can only be applied to species that beat their wings slowly and not at all to rapid flappers. It is impossible to count more than 10 wingbeats per second with the naked eye and is completely out of the question at frequencies of over 40 per second, as are attained by hummingbirds hovering above a flower.

To achieve accurate results, it is indispensable to employ high-speed movie cameras to simultaneously photograph the beating of the bird's wings, a network of coordinate lines, and also the oscillatons of a pendulum. All that is then necessary is to use enlargements to count the number of frames required for a complete wingbeat and to figure out the time taken up by one wingbeat by examining the movement of the pendulum.

Here is the average wingbeat frequency in midflight for a few species of birds:

	flaps/sec		flaps/sec
Griffon Vulture	1-2	Pigeon	3-6
Peregrine Falcon	4-5	Duck	9-10
Buzzard	2-3	Sparrow	12-14
White Stork	1-2	Weaverbird	15-20

	flaps/sec		flaps/sec
Pelican	1-2	Parakeet	15-20
Herring Gull	2-3	Gray Waxbill	16-20
Seamew	4-5	Hummingbird	30-40

Wingbeat frequency changes according to flight circumstances, justlike amplitude. In oblique or completely vertical climbs, or while hovering, the number of beats is considerable, although the exact number depends on the species. In contrast, during horizontal flight, the frequency is much smaller and the greater the speed the more it is reduced. It should be pointed out, however, that in midflight the wingbeat frequency also varies. If a bird is being pursued, it increases the number of beats it makes to gain speed. Similarly, if it has gained too much weight as a result of a large meal, it also increases its flapping to insure the proper amount of lift. Furthermore, wingbeat frequency is immediately augmented if /112 the wing surface is reduced for any reason. This had already been noticed thirty years ago by several writers.

Mouillard discovered that if the wing surface of a pigeon is increased by grafting new long remiges to the barrels of severed normal remiges, as falconers do, the animal's flight is markedly impaired. Its normal flapping motions now appear to tire it. Conversely, Mouillard reduced the depth of the wings of another pigeon by cutting its remiges. This pigeon had a hard time generating enough lift to keep itself aloft in calm weather. However, it had no trouble at all when the wind was blowing.

Marey once performed a different kind of experiment on some birds whose wing motion he was trying to record. These animals were loaded down with gradually increasing weights and the resulting increase in wingbeat frequency and amplitude were observed. According to Marey, a buzzard could still fly with a load of 125 grams, whereas a pigeon could only carry up to 60 grams.

Certain experiments seem to indicate that it is the vertical thrust exerted by the air on the underside of a bird's wing that determines wingbeat frequency. As a matter of fact, Marey observed that a bird slows down the frequency of its flapping after it has reached a certain speed. A well developed muscular sense seems to inform the animal of the amount of lift furnished by air resistance. When resistance becomes excessive, it impedes the muscular effort producing the downward stroke. The bird then delays its stroke until its diminishing speed reduces its lift to such an extent that a new beat is called for.

III. Birds' Speed

The speed of a bird in flight may be measured with a high degree of precision by using a movie camera, a network of coordinate lines, and an oscillating pendulum.

The Calculation of a Bird's Distance with a Movie Camera

The reconstruction of a bird's trajectory, and consequently of its speed, is deduced from the following data:

a) Focal length of the objective;
Size of the mesh;
Distance from the network,
which are constants of the apparatus.

b) Actual dimensions of the bird;
Dimensions of its filmed image,
which give the distance of the bird from the objective.

This timed reconstruction directly yields the direction and magnitude of the velocity.

The first result to deduce from an examination of the prints is the distance of the bird from the camera gun. If an image of the bird located near the center of the coordinate network is examined, its distance D is given by the equation:

$$D = \frac{d \times L}{m} \times \frac{m'}{\delta}$$

where:

d is the distance between the coordinate network and the camera gun; /113

L is the length of the bird;

m is the length of the sides of the squares of the network;

m' is the apparent length of one of these sides;

δ is the apparent length of the bird in the photograph.

There is a comment that should be made here. This concerns the errors in measurement that can be made as a result of distortions of the coordinate network caused by perspective. This occurs when the camera moves around its optical center.

With the rotational mechanism previously described, different parts of the network are not at the same distance from the optical center. The squares on the edges are further away than the central squares. They consequently appear on the film slightly deformed and a little smaller. However, the formula for the amount of distortion is easy to obtain and, moreover, the corrections are very slight.

Calculation of Birds' Flight Speed with a Movie Camera

The path traversed by the center of gravity, from its first position to its last, divided by the number of intervals, and then multiplied by 16 (if the film was taken at 16 frames/sec) yields the apparent speed u of a bird as seen in the enlargements. The real speed v in m/sec is then: $v = uL/\delta$.

In the case of a bird in linear flight in zero wind, it is best to make sure that the bird's trajectory and the network of corrdinate lines are parallel. One could use a second camera gun perpendicular to the first for this purpose. In practice, however, it is usually sufficient to examine the way in which the views of the bird vary to verify the existence of parallelism.

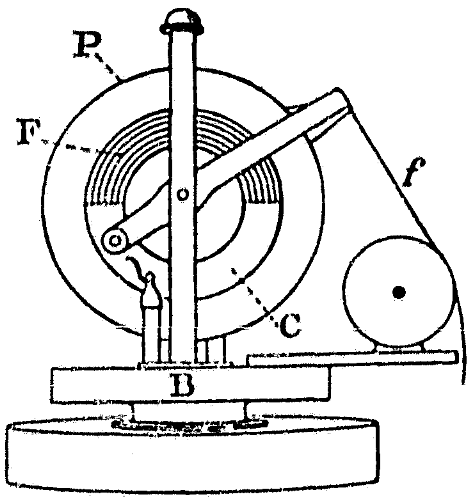


Figure 180
Apparatus for Measuring a Bird's Speed
P, Large Pulley; f, Thread
F, Fiber; C, Copper

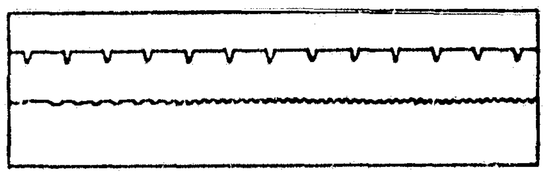


Figure 181
Impulses Produced by a Jaquet Chronograph (above) and by an Houssay-Magnan Apparatus (below)

The Houssay-Magnan Apparatus for Directly Measuring Birds' Speed

There is another procedure for measuring a bird's speed in flight which uses an apparatus (figure 180) composed of a pulley mounted with ball bearings on a horizontal axis. The framework supporting the pulley itself rests on ball bearings and is moveable about a vertical axis. Very fine, strong silk thread is rolled up around the pulley. The free end of the thread is attached to a bird by a system of laces. The animal unrolls the thread as it flies and the pulley's horizontal axis opens the contact of a Deprez signal /114
relay one time per revolution. The stylus of the relay then inscribes a mark on smoked paper each time the pulley makes a complete revolution (figure 181).

The length of thread unrolled by the bird can thus be measured. By marking off the smoked paper in fifths of a second with the aidof a Jaquet chronograph, all the data necessary to calculate the speed of a bird at each instant is present.

The results obtained in this manner should be considered as minimum values. This is because birds seem to show a certain reluctance to fly under these conditions. Surprise or annoyance caused by the unaccustomed situation in which they find themselves is enough to explain this attitude.

Marey's Studies

First of all, recall the figures given by previous authors obtained through direct observation.

Marey, taking account of the facts already discussed, remarked fifty years ago that voyages by train sometimes provided the occasion to evaluate the speed of birds in flight. This occurred when the birds flew parallel and in the same direction as the train.

The same author recalled that at the time, passerines were easily out distanced by express trains, whose normal rate of speed was 18 m/sec. Crows also flew slower than railroad cars went. Pigeons, however, accompanied them, and frequently passed them by. The swallows flew even more quickly and the old-fashioned trains were no match at all for the swifts.

Marey continued that the length of a trip accomplished in one stretch has been best determined for pigeons. He cited the obser-vatons of various authors on this subject. According to Aldrovande, one pigeon flew from Aleppo to Babylon, or 625 km, in 48 hours with-out traveling at night.

A famous pigeon named Gladiator once made the trip from Toulouse to Versailles, 530 km, in 6.5 hours.

One of Henri II's falcons, lost during a hunt in the Forest of Fontainebleau, was found the next day on the Isle of Malta. It had therefore flown 1,400 km in that period of time.

Finally, according to a well known pigeon fancier, Van Rossenbecke, the maximum speed of carrier pigeons is 25 leagues/hr. Furthermore, such birds could make the trip from Spa to Paris, a distance of 398 km, in 5 hours. This implies a speed of 80 km/hr or 22 m/sec.

The famous physiologist added that nothing is more variable than the length of a bird's flight, which depends on various circumstances. Certain passerines, which generally make only short flights, fly across oceans gathered in large flocks at considerable height, beyond the range of the eye. The quail, which is rarely observed to fly more than 300 meters at one time when it resides in our part of the globe, travels very long distances during its migration.

Personal Studies

Here are figures for some typical birds flying horizontally in calm weather, which I obtained through the use of modern methods of measurement. These figures, obtained by filmed observation, have an incontrovertible value. They represent the real speed of an animal, at least at the moment when the film was made. It is certain that they correspond to a flight in calm air since it was easy to check experimentally if there was a wind or not. The figures produced /115 by timing the departure and arrival of a bird released at a chosen point have less value because it is not known if there was a significant wind at the altitude at which the bird was flying.

Speed of Horizontal Flapping Flight, in m/sec

Albatross	15	Crow	10-12
Giant Fulmar	14	Goldfinch	8-9
Herring Gull	15	Sparrow	10
Griffon Vulture	17	Stockdove	22
Peregrine Falcon	28-30	Gray Partridge	20
House Martin	15-20	Capercaillie	15
Swift	35-40	Curlew	12-13

If a table were made of birds' frequency of flapping, it would immediately appear that the greatest speeds are incontrovertibly to be found in species that beat their wings fairly rapidly. Birds that beat their wings slowly, in contrast, fly at a slower speed.

On the other hand, if a pigeon is attached to a string and released, and if one pulls strongly enough on the strong to stop the bird in midflight, the bird will first fall and then beat its wings very vigorously to reestablish sufficient lift.

Up to here we have examined only the case of a bird flying near the ground in calm air. Actually, the wind plays an important part during flight. A moderate wind helps a bird a great deal both during takeoff and in midflight. Certain species even take advantage of it to fly more quickly. These include quails during their migrations, carrier pigeons during their trips, and falcons during their hunts. In contrast, when the wind is too strong, numerous birds have difficulty flying and often lose their bearings because of the skips they make in the air.

IV. The Various Ways Birds Fly

It now remains for us to examine the differences that exist in the ways in which various species fly.

Marey had already pointed out how simple observation shows that each group of birds has its own characteristic type of flight. Each type is difficult to define, but a trained eye recognizes it immediately.

With the analytical means at our disposal, we can see that the different types of flight are characterized in as clear a manner as anatomical forms, which is the feature that differentiates species of birds. There is nothing more fruitful to understanding the mechanism of flight than correlating anatomical and functional characteristics.

Takeoff

It has been known for a long time that birds at rest have differing procedures for taking wing even though most of them first face the wind, when there is one, to acquire preliminary speed. To this end, some run along the ground (vultures, stork, buzzards, etc.) or the surface of the water (albatrosses).

Other birds, in order to give their wings freedom of movement from the moment of liftoff, jump in the air to a fairly great height in relation to their size. Among these are the small waders, gallinaceaes, and passerines. Finally, there are some that drop down /116
from an elevated perch. These include vultures, falcons, storks, and swifts.

The point of such runs, jumps, and falls is to provide the initial speed necessary to generate a certain lift. The wings can then take up the task.

These are known facts which, along with those that follow, I have personally observed.

The Flight of Palmipeds

The majority of small-winged palmipeds, like ducks and auks, fly by rapidly beating their wings. I found the number of beats per second to range from 8 to 12, according to the species I was studying. For these birds, flapping flight is continuous. They rarely stop striking the air with their wings when in flight, which is one of the most rapid. Some palmipeds, whose wings are a little more developed than those of the ducks (e.g., swans, geese, and cormorans) progress by flapping their wings at a slightly lower frequency. They are capable of keeping their wings extended and motionless and of traveling a certain distance thanks to their acquired speed. Others, adapted more or less completely to an aquatic life, fly only rarely. These include grebes, loons, and particularly penguins.

The Flight of Gallinaceae

Almost all gallinaceae fly in a similar manner to geese. After a series of precipitous, rapid wingbeats, averaging about a dozen per second, they build up speed and fly off, flapping their wings repeatedly (figure 182). Every once in a while, they stop flapping and completely unfold their motionless wings. As they move forward in this position, they execute a true glide, which never lasts more than a short period of time (figure 183).

The Flight of Columbidae

The mode of flight of columbidae, or pigeons, is a little different. These birds flap at a fairly rapid rate, 3 to 6 times per second, on the average. They are also capable of gliding with their wings extended between two series of wingbeats. However, when they have attained sufficient speed, they can also fly with motionless flexed wings, which the gallinacea are basically incapable of. With the elbow slightly bent and the wing tips clearly thrust rearward, as is illustrated in figure 184, they considerably reduce their airfoil and shoot off through the air without losing much altitude. Their speed can be as high as 120 km/hr, while during flapping flight their speed varies between 80 and 90 km/hr. /117

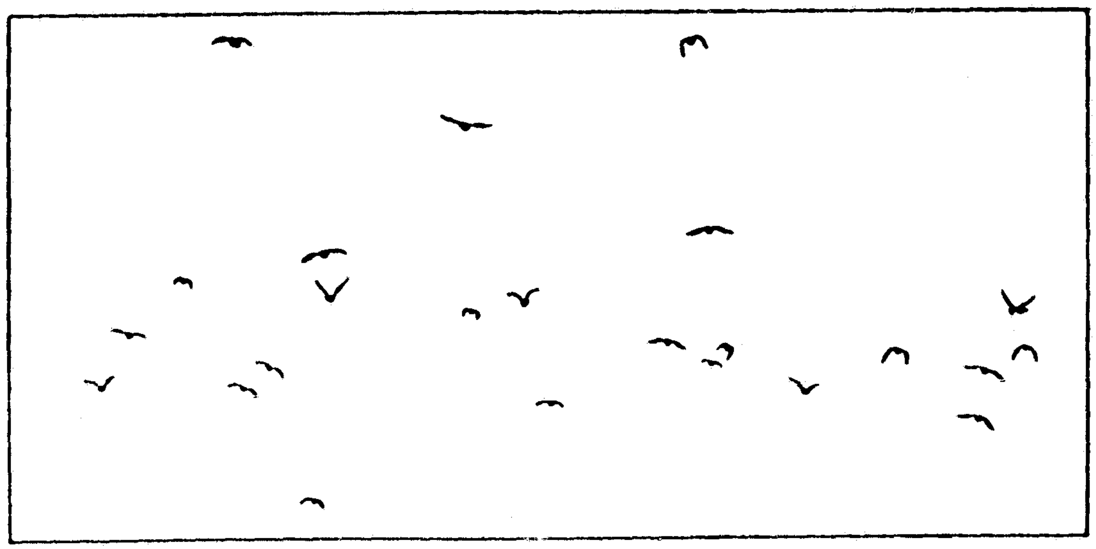


Figure 182
Red Grouse in Midflight

The Flight of Small Waders

Small waders fly through the air in an analogous fashion. Between periods of flapping at the rate of 5 to 10 beats/sec, they drift through the air pointing their wing tips rearward (figure 185). Their speed is highly variable. For the larger species it is 60 km/hr. It can even surpass 100 km/hr in smaller species such as plovers. Some waders well adapted to aquatic life, such as the coot, hardly ever take wing. When they do, their flights are always of short duration.

The Flight of Swifts

Other birds, such as swifts and swallows, usually fly exclusively by flapping their wings, with a frequency of 8 per second for the former and 3 to 4 per second for the latter. However, at times they do accomplish fairly long glides, thanks to their more developed airfoils. They are numbered amongst the most rapid of the flying vertebrates.

Figure 183
Grouse's Position when Gliding

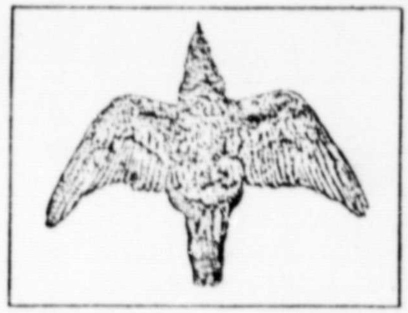


Figure 184
Wood Pigeon Flying off at Great Speed with Wings Bent, Ventral View

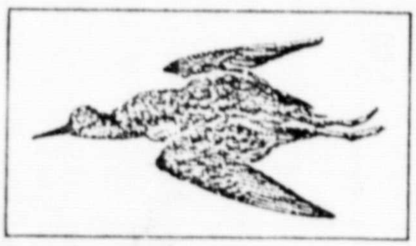


Figure 185
Ruff Gliding with Wings Bent

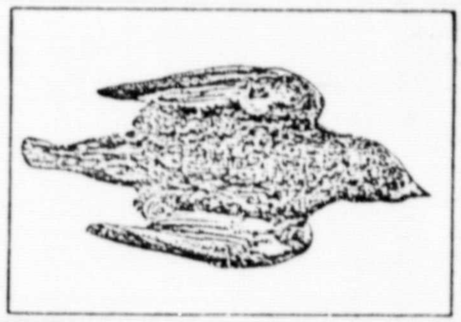


Figure 186
Greenfinch Drifting with its Wings Folded against its Body, Ventral View

The Flight of Small Passerines /118

The small passerines have a particular mode of flying, consisting of a period of rapid flapping followed by a period in which the wings are at rest. In the first period they progress as long as their wings strike the air, which is at a frequency of 8 to 20 beats/sec. Their trajectory follows an inclined ascending line. Then, when they think their speed is sufficient, they cease rowing, fold their wings up against their bodies (figure 186), and shoot through the air like an arrow, while simultaneously losing altitude. Their airfoil is not, however, reduced to zero at this time. It is six times smaller than during flapping flight itself. It thus only serves to balance the body until the moment when its decreasing speed obliges the animal to flap its wings so as not to fall. If a comparison can be used, the bird is hurtling through the air like a projectile and its trajectory obeys the laws of ballistics.

This is how the majority of small passerines fly. Their motion in the air is an undulated line of variable amplitude (figure 187). It is formed of inclined ascents during periods of flapping and of inclined falls when the wings are closed up.

Some passerines, such as orioles, are able to glide for a certain length of time because of their fairly well developed wing surface. They constitute a transition between species whose flight is undulated and the corvids, which beat their wings only 2 to 3 times pèr second. These latter birds are capable of gliding for a certain length of time with their large wings open.

Other passerines, such as the titmouse, the sedge warbler, the woodpecker, and the wryneck, can accomplish only short, unsustained, abrupt flights because their habitat is located in trees or reeds and the faculty of flight has become much less developed in them. They do not usually fly for very long and most commonly only leave a tree or a reed to latch onto another one. The ability to fly has just about disappeared in the wrens, which live almost continuously in the brush and whose flight is accomplished only with great effort, and in the wallcreepers, who fly in jumps like butterflies while going from one wall to another.

Lastly, I should add that the speed of the passerines is never great. The best fliers among them barely exceed 50 km/hr.

Figure 187
Undulated Trajectory of a
Passerine (from Oehmichen)

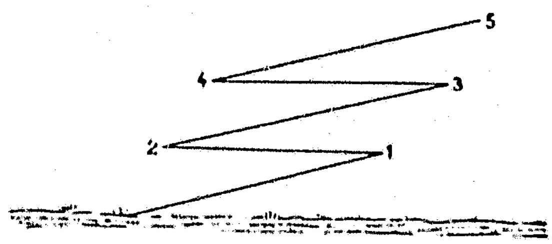


Figure 188
Trajectory of
a Falcon (from Huber)

Key: a) Direction of movement

The Flight of Raptors

Among diurnal raptors, the group composed of the falcons reveals a remarkable virtuosity in flapping flight. Falcons rise up against the wind by flapping repeatedly. The number of flaps varies from 3 to 4 for the peregrine falcons to 5 or 6 for the hobby, whose flight is similar to that of the swift. /119

They ascend, for example when they are pursuing a prey, at an angle of 15 to 20° with the horizon. This visibly requires great effort on the falcons' part. They are frequently obliged to interrupt their ascents and fly off almost horizontally in the direction of the wind. They thus end up directly above their point of departure without suffering a net loss in altitude. (See figure 188.)

After a falcon has zig-zagged to a sufficient height, it folds its wings up against its body and swoops down upon its prey at a dizzying speed. The falcons, particularly the kestrels, are capable of gliding in a remarkable fashion. The same is true of the goshawks and the sparrowhawks, moreover, whose mode of flight is similar to theirs. This group of birds of prey ranks among the most rapid birds.

Concerning the hobbies, I have seen them fly at speeds of more than 100 km/hr during horizontal flapping flight.

The Flight of Large Gliders

Lastly, in addition to the majority of birds of prey, whether diurnal (vultures, eagles, buzzards) or nocturnal, such as the large winged palmipeds (albatrosses, sea gulls, gannets) and certain waders (cranes, storks, herons, marabous), there are other groups possessing a large wing surface that perform rowing flight. Some do it only exceptionally, others more frequently. The number of wingbeats is always reduced to 2 or 3 per second, with fairly long separations between series of beats. Such long separations exist because these birds most often either glide with their wings open for considerable periods or else flex their wings rearward and fly off at a higher rate of speed. In the latter case, their displacement in space is more rapid than in the former. While the average speed is on the order of 40 km/hr, a speed of 50 to 60 km/hr can be attained when the wings are flexed.

In the course of the present study of flapping flight, I have only considered the wing surface and its movements. There is another organ that plays an important role in the rowers. This is the tail, which represents, contrary to what certain authors such as Mouillard think, a true tiller governing both depth and direction.

In rowing flight, the tail is constantly folded up, except at departure and during ascents, descents preceding arrival, and turning movements. When moving forward horizontally, the tail's surface is always reduced to a minimum.

I have not dwelt on how a bird in flight changes direction, either. Generally, a right turn (for example) in midflight is performed by beating the left wing more broadly. A descent in the midst of a turn is accomplished by tucking in one wing while extending the other. The bird thus pivots around the tucked-in wing.

It can be seen from this report, which perhaps merited a fuller development, that variations exist in birds' rowing and gliding ability. However, there is in fact no reason to separate rowing from gliding flight, as has been done up to now. They are actually two phases of a single mode of airborne locomotion. Which of these phases is more often used by an animal in flight depends on its conformation and, consequently, on its aeronautical characteristics.

V. Gliding Flight

Gliding flight, whatever its duration, should not be confused with soaring flight. During gliding flight, a bird of prey, for example, extends its wings at right angles to the axis of its body and drifts through the air or describes successive circles, always while losing altitude. It performs this flight even in calm air. /120
Gliding birds behave like an airplane with a large airfoil which, with its engine shut off, descends slowly along a path whose inclination depends on its characteristics and profile. The work necessary for lifting and moving a bird in rowing flight is provided by flapping its wings. When flapping stops, lift is provided in circumstances varying with the magnitude of the wing surface. However, descent begins along a trajectory whose inclination depends on the aerodynamic efficiency of the bird.

Here is what Painlevé wrote on the subject of gliding flight:

"The various types of flight made in the absence of wingbeats seemed for a long time to be inexplicable because a persistant, serious error was distorting the laws of gliding. More precisely, air resistance encountered by a moving thin plane was considerably underestimated. Let us imagine a model glider consisting of a solid plate, whose thickness and surface roughness we will assume is negligible.

"Suppose that this plate falls vertically in still air while remaining horizontal. It encounters a resistance originating in the fluid. This resistance is directed vertically upwards and has been found to be basically proportional to the square of the speed of descent. For example, if at a speed of 1 m/sec, the air resistance impeding the plate is 1 kg, at 5 m/sec the resistance will be 25 kg. If the plate also weighs 25 kg, air resistance will balance the weight of the plate as soon as the speed of descent reaches 5 m/sec, and the plate, no matter how far it falls, will remain at this speed.

"However, suppose that the plate (still in a horizontal position) is controlled so as to descend at an angle. It will then have both a horizontal and a vertical speed at the same time.

"Air resistance will always be perpendicular to the (perfectly smooth) plate. It is therefore vertical and directed upwards. However, some simplistic, valueless reasoning has caused it to be assumed since Newton that the resistance is completely independent of the horizontal speed. It supposedly depends only on the vertical speed of descent, and is proportional to its square.

"If such a law were correct, the phenomenon of gliding would not exist. By this I mean that the angle of the fall would not be a factor in attenuating the vertical speed. In the numerical example chosen above, the plate would still arrive on the ground with a speed of 5 m/sec, as in the case of a vertical fall.

"However, this law is in complete contradiction with experience. It has been found that, on the contrary, for very oblique descents, air resistance is proportional not to the square of the vertical speed, but simultaneously to both the vertical and horizontal speeds. The air resistance corresponding to a very low rate of vertical speed could counterbalance the weight if the horizontal speed is great enough. Thus, in the preceding numerical example, the weight and air resistance would be in equilibrium if the glider had a horizontal speed of 25 m/sec and a vertical speed of only 1 m/sec.

"In relation to this, let us consider a bird that is released at an appropriate height in still air. After dropping briefly, it will descend with its wings horizontal and motionless along a straight line with a speed and inclination depending on the manner in which it chooses to control its fall. If a bird were really comparable to the infinitely thin and perfectly smooth model glider, it could make its vertical speed be as small as it desired. In reality, because of the thickness of its body and of friction, the plane of its wings has to lean slightly forward during glided descent instead of being horizontal. No matter how agilely the bird maneuvers, the slope of the fall cannot be reduced below a certain limit, no more than its vertical speed /121
can be. This limit characterizes the aerodynamic efficiency of the glider made up of the bird and its outstretched wings. The lower the limit is, the closer the bird approaches the model glider and the more remarkable is its efficiency."

In addition to what is properly called gliding flight, there exists another sort of flight also, but incorrectly, called gliding by some people. This is soaring. It may be considered that soarers glide, but they do not lose altitude; in fact, they gain it at every instant. Even so, they do not develop any propulsive force with their muscles. In this sense they do not beat their wings for considerable lengths of time. However, muscular work still occurs, as we will see below.

RECOMMENDED READING

Huber, Observations sur le vol des oiseaux de proie [Observations on the Flight of Birds of Prey], Geneva (1784).

Magnan, A. "Les caractéristiques des oiseaux suivant le mode de vol" [The Characteristics of Birds According to the Mode of Flight], Ann. des Sc. Nat. Zool. (1922).

Marey, Le Vol des oiseaux [Bird Flight], Masson, Paris (1890).

Mouillard, L'empire de l'air [The Realm of the Air], Paris (1880).

Oehmichen, Nos maitres, les oiseaux [Our Masters, the Birds], Dunod, Paris.

Painlevé, P. "Le vol à voile" [Soaring], Revue de Paris (1923).

Pycroft, N.P., Birds in Flight, London (1922).

The existence of soaring, a special mode of flight practiced by certain groups of birds, was discovered through the observations of naturalists. They have been able to further specify that, by means of soaring, large birds are usually able to transport themselves in any direction supported by their rigid, immobile wings. Soaring birds can also make great circles in the air, rise to great heights, and even more forward, sometimes climbing, sometimes falling through the air, for long hours without flapping once.

At a time when observation was the only means available, some naturalists tried to discover the basis for soaring in the constitution of the bird itself. However, more curious spirits did not take long to notice that there was an obvious correlation between soaring and the presence of wind. From this moment on, the wind became the starting point for theories on this mode of flight. Such theories are innumerable, moreover, and I shall not analyze them here. I will instead limit myself to explanations arising from current experimental research.

It has often been written that soaring birds occupy only a small portion of the globe and that this was the reason it was so difficult to study soaring and to describe with certainty the maneuvers executed by the species performing this kind of flight.

Contrary to this baseless assertion, soaring birds could be found everywhere if it were not for faulty observation. This includes on land just as well as at sea, and cold regions as well as temperate and tropical ones. If these birds' activity is not observed more frequently, it is because people do not go to the places where they are found. In the same way as there are points on the globe where humans do not live, there are spots where soarers do not live. This is not because the lack of favorable winds makes it impossible for them to fly in these localities. Rather, they cannot find the living conditions or food required for their survival.

In order to see soarers engage in their favorite form of flight, one must go to the regions where they are well established. Even then, it is necessary to observe the birds of these regions in flight attentively in order to be able to distinguish true soaring. Many people have watched sea gulls along coastal cliffs, for instance, without suspecting that these palmipeds were simply performing feats of soaring.

All one has to do is to walk along the coast anywhere between Le Havre and Calais, especially in autumn and winter, i.e. outside of the breeding season, to find the common gull. Particularly if there is a wind, it can be seen balancing gracefully in the air and drifting above the edges of cliffs for long periods, practically without moving its wings.

I have many times had the chance to study soaring birds during my travels. I have not been content just to observe soaring in order to describe in detail the maneuvers involved or to note /123
the changes in shape that the wings and the tail undergo. I not only sought to become acquainted with how soaring flight unfolds, to ascertain its characteristic movements and the actual sequence of such movements, I have also attempted to determined, with the aid of the appropriate instruments, the nature of the winds in which soarers maneuver. In addition, I have tried to measure soaring birds' forward and ascending speed, the diameter of the circles they make in the sky, the height to which they climb, and their angle of descent.

A theodolite with a micrometric sight could be used to collect the necessary information, as I have done formerly. However, it is preferable to make use of a movie camera or even the camera gun and coordinate network set up about which we have spoken previously. If the average wingspread or body length, which vary little from individual to individual, is also known, it is possible to make a good enough approximation by measuring successive film enlargements of the distance of the bird from the objective, its height above the ground, the trajectory it describes in the air, and its horizontal and ascending speed.

I. Soaring in Ascending Obstruction Currents

The characteristics of the wind in which a bird maneuvers can be determined, although it is not always easy, with such instruments as hot wire instruments, sounding balloons, and smoke apparatus, which have been described previously. I have thus observed that the layers of wind that strike a cliff, especially frontally, are forcefully rejected upward. This has the effect of creating an ascending current whose area of greatest intensity is located in front of the upper edge of the cliffs, as has already been seen.

The Flight of Sea Gulls

It is in this zone that common gulls are seen along the cliffs of the English Channel. Some, their wings almost completely extended and thier beaks pointed forward, mount up almost vertically in the air. First their climb is rapid, then it slows down as they rise from in front of the edge of the cliff to a variable height above it. Their speed, which is at first 1 m/sec in a wind of 10 meters, is reduced little by little and ends up having a value of only a few centimeters. The gulls thus in certain cases attain a fixed altitude which they hold to as if stuck to the sky. They then slip through the air in the direction from which the wind blows, as if they were sliding down the slope of the layers of air obstructed by the cliff. They thus return to the most favorable zone of the ascending current to start the cycle anew.

During their ascents, sea gulls do not flap their wings at all, in the true meaning of the term. They merely influence the air flow, sometimes on one side, sometimes on the other, by lowering the hand s[illegible] of their wings as required to reestablish their balance. T[illegible] lowering is sometimes so great that the hand wing in action appears to abruptly make a 90° angle with the rest of the wing. (See figure 189.) The result of this special maneuver is a sort of lateral balancing of the bird, comparable to that of a tightrope walker.

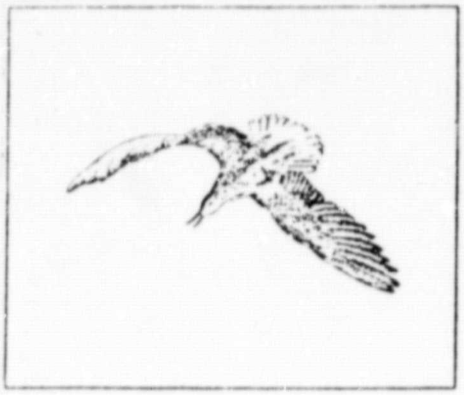


Figure 189
Sea Gull Lowering its Left Hand Wing to Reestablish Equilibrium

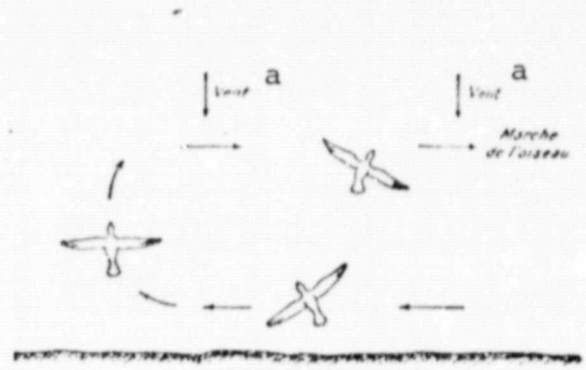


Figure 190
Maneuvers of a Difting Sea Gull

Key: a) Wind
b) Direction of bird

Not only can sea gulls move vertically in a zone of ascending current, they can also move horizontally.

To do this, they tack against the wind to maintain the right height and they maneuver in such a way as to follow the top of the cliff. They face the wind and strive to keep their beaks constantly facing the wind. Their bodies are slightly tipped, with the long axis directly downward. They then fly sideways along the cliff and continuously manipulate their tails so as to follow a path almost parallel to the upper edge of the cliff.

To achieve this, they direct the axis of their bodies so that the front part is pointed to the right if they are moving right- /124
ward (figure 190) or to the left if they are moving leftward. In addition, the sea gull never changes direction by banking. It finds it sufficient to alter the orientation of the axis of its body when it wants to change course. Its speed in these circumstances can be as high as 20 m/sec. On the average, it oscillates between 10 and 12 m/sec.

In contrast, once the wind dies down, the sea gull begins to descend. It now has only one way to stop falling. This is to beat its wings.

It can be stated that all sea birds are able to take advantage of rising obstruction currents. Those that nest on steep rocks, like the gannets at Saint Kilda or certain wandering albatrosses at Tristan da Cunha, know how to utilize such winds to gain altitude.

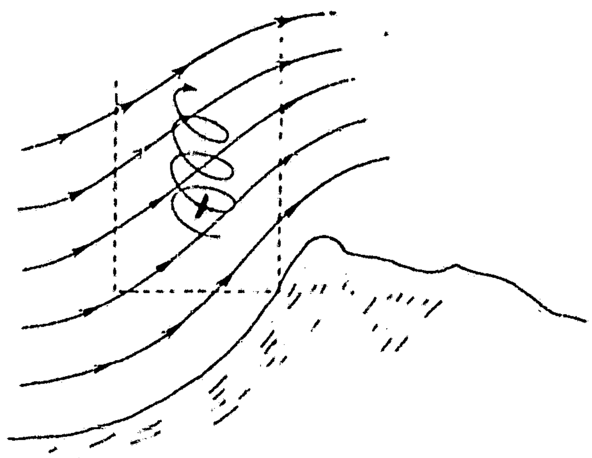


Figure 191
Circular Flight of an Eagle in a Rising Mountain Current

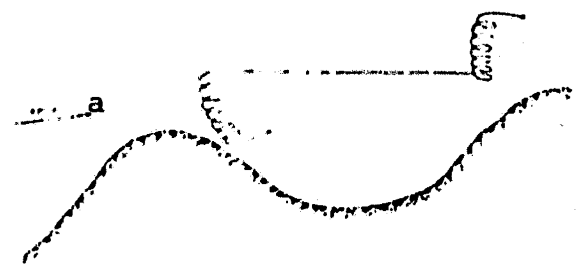


Figure 192
Path of a Buzzard Soaring in a Rising Current Existing before and behind Cliffs

Key: a) Wind

The Flight of Eagles

The truth is that a rising current is a source of soaring and is at the origin of some of these flights. Many birds readily use them every time they have the chance, in order to facilitate their flight. Some even devote themselves to soaring by means of rising winds, perhaps in preference to any other.

Such is the case for many raptors. Thus, they are encountered in localities where the conditions necessary for soaring in rising winds are found. This is in areas where either vertical or steep cliffs or mountains with sharp precipices exist in addition to regular, or at least frequent, propitious rising currents. The /125
more the terrain is uneven and the wind is regular but not too strong, the more the air is filled with soaring raptors. They can be seen climbing to great altitudes and making large circles in the air (figure 191).

Eagles use rising currents in other localities besides mountainous regions. Particularly in Soctland, they can be found at the edge of forests where there are deer, which they seek to make their prey. In sections where the wind has a high enough vertical component, they hold their wings greatly spread out. The large remiges are distinctly separated and even turned slightly upward, especially at the tips.

In the hilly regions of Europe, other species of birds exist that soar by making use of rising currents. Spain and Sardinia are still inhabited at the present time by bearded vultures whose flight appears less graceful than that of eagles and seems slower, in general. They can be seen gliding in rising currents, sometimes flying in circles when the currents occupy only a small area.

The Flight of Buzzards

I have frequently witnessed buzzards flying over greatly protruding terrain in the Vosges. They fly upwards on the windward side of a summit and, in a wind of 6 m/sec, make successive circles up to 100 meters above the crest. They then start to glide to reach another peak and begin to gain altitude again in spots where there are rising currents.

I once saw a buzzard circling above the lee slope of a hill separated by a large valley from another hill (figure 192). One would think that at this location the layers of air would possess a descending component. I realized that on the contrary, there was an ascending current along the lee slope whose speed attained 7 m/sec at the summit of the protrusion. At this point, it joined up with the rising current formed on the windward slope. The exceptional leeward rising current was due to eddies engendered behind the hill. It rose as it followed the lee slope and then reinforced the normal rising current.

The circles made by buzzards barely reach 20 meters in diameter. They are completed in 8 to 9 seconds, which implies a speed of 7 or 7.50 m/sec. Buzzards soar even in relatively weak winds. I have seen them climb to 100 meters in front of a forest struck by a wind of 4 m/sec.

As a matter of fact, a simple curtain of trees suffices to produce a rising current which kestrels, for instance, know how to take advantage of for stationary flights several meters above the tops of the trees. In a wind of 5 meters, these small raptors can maintain an almost immobile position facing the wind. Their wings do not flap at ll. Their only motion is a slight lateral balancing to counteract momentary disequilibria.

The Flight of Condors

It is also interesting to note that there are soaring birds able to use wind reflected from obstacles on all continents. It can even be stated that everywhere on earth that windy stretches of uneven ground are found, it is certain that soarers will be encountered, so long as the conditions for their continued survival are present.

In the Andes of South America, there are gigantic walls that give rise to very strong rising currents. The condors there take /126
advantage of such currents for both soaring and moving about.

The condors nest at an altitude of 3 or 4,000 meters. They therefore usually soar at very great heights, making circles of more than 60 meters in diameter with their heads in constant motion. Their flight tends to be very slow. According to the observations that I have come across, it seems that their speed is less than 12 m/sec. Condors do not live only in the high mountains of the Andes. They are also found along the coast, at locations where high cliffs create rising currents favorable to soaring.

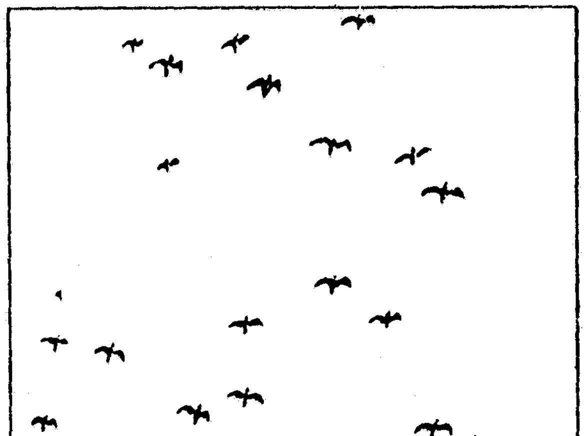


Figure 193
Sea Gulls Soaring in a Rising Current behind a Moving Ship

Flight Behind Ships

Sea gulls also receive lift from rising obstruction currents when, as if suspended above the prow of a ship by a magic wire, they keep their balance without moving their extended wings as they accompany boats (figure 193). The rising currents are here due to disturbances created behind a ship by masses of air displaced by its forward motion.

Flight Above Waves

Sea birds also soar with the help of rising currents arising when the wind encounters a swell. Certain species seem to have particularly specialized in this kind of flight. Remaining constantly far out at sea, marine palmipeds cross oceans by flying above the waves, when there is a wind, practically without resting.

In the course of their airborne circuits, such marine soarers make use of the rising currents produced when horizontal wind comes up aginst slower moving waves or when wave motion occurs in gentle or nonexistent wind. The rising current can thus be located either on the windward or leeward wide of waves.

Such is the case of the Cory's shearwater, which is found only /127
on the high seas, particularly between Corsica and the Balearic Islands. It lands on the coast only during breeding season.

When the wind is still, the Cory's shearwater is difficult to catch sight of during a Mediterranean cruise because it is floating on the water and stays far from ships. However, as soon as the wind rises and produces breakers on the surface of the sea, the shearwater springs from the surface of the waves by beating them with its feet and tail. Its speed increases little by little and soon, like a seaplane, it leaves the water and starts to soar. It then climbs to a height of between 1/2 and 1 meter above the windward slope of the wave. This is the point where experience has shown that the air current has the greatest rising component. The shearwater's flight almost always takes place parallel to the crest of the wave and almost always at the same distance away from it. The shearwater most commonly faces the wind and its wings are spread out at a right angle to its body. It therefore flies sideways at the same time as forward. This allows it to remain in the rising current's most propitious zone, which constantly changes position as the wave advances. The shearwater then glides between two waves and catches up with another crest along which it moves. (See figures 194 and 195.)

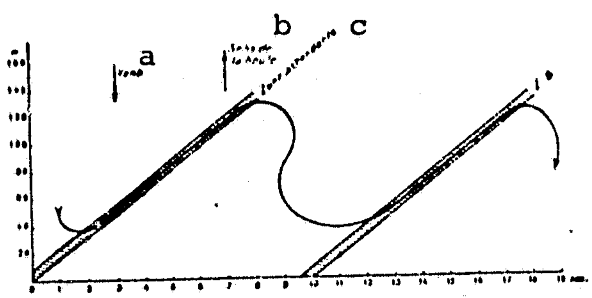


Figure 194
Path of a Shearwater
along the Crests of
Advancing Waves

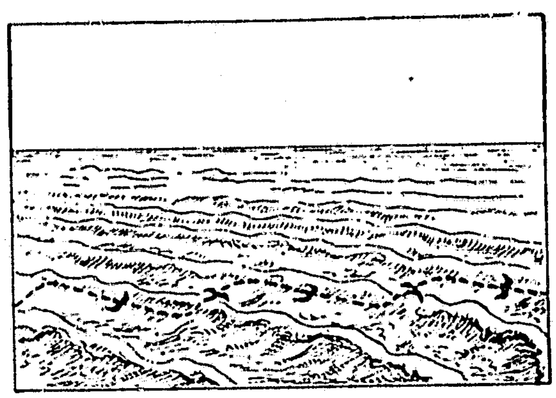


Figure 195
Maneuvers of a Shearwater
along the Crests of Waves

Key: a) Wind
b) Direction of swell
c) Rising zone

Other birds, such as the storm petrel and the cape petrel, make similar flights in the same circumstances.

II. Soaring in Rising Thermal Currents

Soaring birds are also encountered in regions where rising obstruction currents are less common, for example in warm regions and deserts. I have experimentally observed that the soaring birds of these areas ascend in zones where there are rising thermal currents sufficient to lift them. Among such soarers, let me cite the vultures, kites, eagles, pelicans, and the adjutant cranes and marabous.

In the course of a day, numerous soarers, vultures and kites, can be seen in these zones. They climb through the air with their wings and tail spread wide while making successive circles. They thus remain within the most propitious region and can attain very high altitudes.

From their high point, they slip down through the air. As they cross beaches where the current is descending, they follow a straight, inclined path downward until they reach a new column of /128
rising air. (See figure 196.)

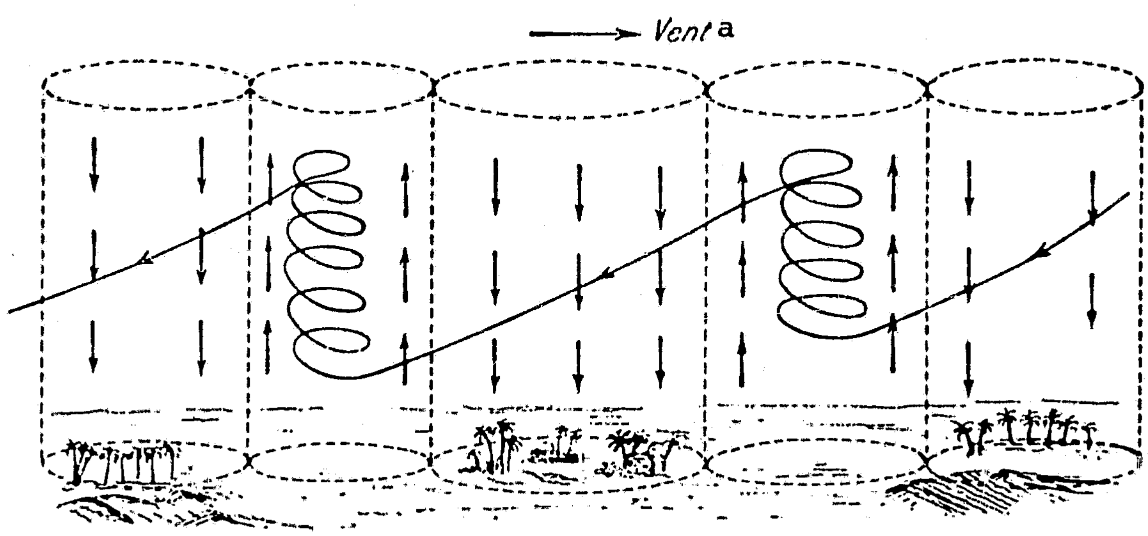


Figure 196
Path of Vultures Soaring in Rising Thermal Currents

Key: a) Wind

The Flight of Vultures

In the course of my travels in North Africa, I have often studied the flight of griffon vultures. These birds particularly inhabit deserts. They need to glide high up in the air to insure their survival because they live chiefly off the carcasses of dead animals, which are not to be found just anywhere. They climb to great heights to discover their prey with the aid of their sensitive eyesight.

In his time, Mouillard considered vultures as the archetypal soarers. He did not separate them from marine soaring birds in regard to their manner of using the wind. This was true even though he recognized that the former were wide-winged slow gliders while the latter constituted a family of narrow-winged soarers. He also knew that vultures are not designed to move in rapid air currents, although such speeds are perfectly acceptable to other families of skilled flyers.

Griffon vultures have one of the most characteristic ways of flying. My observations in North Africa have led me to some very definite conclusions. Since 1906 I have noticed that soaring does not begin in arid regions until a specific hour, around 8 or 9 o'clock in the morning, according to the season.

On several occasions, I was able to get a good view of how vultures set about leaving the ground. They have to make a considerable effort, even when they are not stuffed with food and are reduced to taking off from the sand by running a variable distance and using their wings to assist them. After a certain distance, the feet leave the ground more and more and the flapping of the wings becomes more precise. Then, they begin to ascend while beating their wings at a rate of 2 or 3 times per second. The flapping slows down twenty meters from the ground and at 50 or 60 meters it almost ceases, when the bird has achieved the necessary support. Vultures then circle into the sky, but it is not until 100 meters above the sand that their flight takes on the majesty characteristic of them. At this point, flapping has stopped completely. The slow ascent is continued up to more than 1000 meters. The circling bird holds its inside wing a lot lower than the other. The resulting inclination of the bird about its horizontal axis seems to be invariable. The griffon vulture keeps its tail spread wide and sometimes inclined in /129
relation to its major axis. Its wings are v-shaped in both the horizontal and vertical planes.

When gliding at constant altitude, the wings are in a horizontal plane passing through their points of attachment to the body (figure 197). However, when circling, the two wing tips are elevated above the horizontal plane (figure 198). The wing in this case has an elevated dihedral, according to the term used in aviation. The angle thus formed is approximately 170°. This arrangement of its airfoils gives the bird a certain transverse stability.

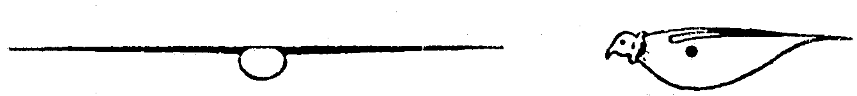


Figure 197
Silhouettes of a Griffon Vulture when Gliding, Frontal and Lateral Views

Figure 198
Silhouettes of a Griffon Vulture when Soaring in Circles, Frontal and Lateral Views

Figure 199
Silhouettes of a Griffon Vulture Soaring with Flexed Wings Frontal and Lateral Views

In simple gliding, the major axis of the vulture's wing is most often perpendicular to the vertical plane passing through the longitudinal axis of the bird. When circling, the wing tips are thrust forward so that the straight line passing through them also passes near the animal's beak (figure 200). In fact, they form a new dihedral angle in a plane that is virtually horizontal. The angle measures approximately 160°.

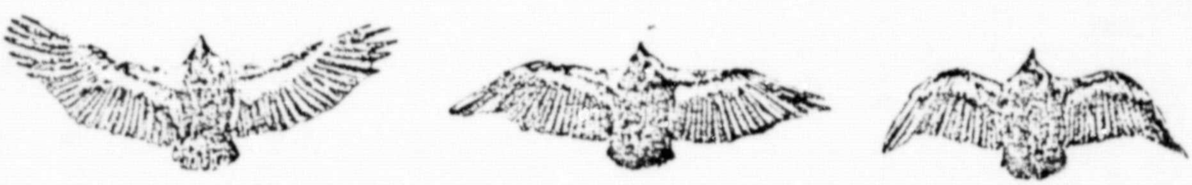


Figure 200
Wing Configuration of a Griffon Vulture
Left: Soaring in Circles; Center: Soaring with Flexed Wings
Right: Gliding with Very Flexed Wings

The result of such an arrangement is that the wing's center of thrust passes to the front of the bird's center of gravity, thus creating a torque that tends to elevate the front of the bird (figure 198). That is actually what happens, for a vulture ascending in circles does in fact have its body tilted slightly upward.

However, this does not mean that the wings remain motionless during the entire ascent. The remiges of the hand wing fan out and are often separated by a space equal to five widths of the large quills. In addition, the remiges are twisted upward and in certain conditions their tips noticeably vibrate. These vibrations are passive and depend upon the vibrations of the air current itself.

The tail, which is also most often fanned out, provides all necessary steering corrections during this period.

An examination of films of vultures in flight has revealed that they complete an entire circle of 50 meters in diameter (figure 201) in 13 to 15 seconds. Their flight speed is therefore 10 to 11.5 m/sec. When there is no horizontal wind or only a weak one, which does not occur very often in the countries that I visited, the ascent of the birds is slow. It has a very gentle slope and hardly exceeds 1 meter with each circle.

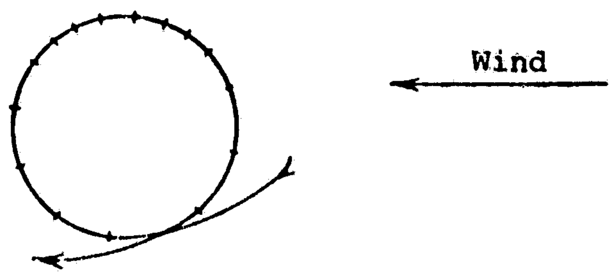


Figure 201
Circles Described by Soaring Golden Vultures, with Time in Seconds (from Hankin)

When the wind is blowing at the same time as the air has been heated up and is rising, there is a marked ascent of the horizontal wind where it intersects zones of thermal currents. As I have already indicated, these zones are stretched into columns with an elliptical cross section. Their major axis, which is sometimes several kilometers long, is parallel to the direction of the wind. In such zones, vultures /130 fly with ease. They follow linear trajectories and advance against the wind at a speed depending on that of the air current encountered.

This last mode of flight is characterized by a flexing of the wings, and the ends of the large remiges are now pointed toward the tail (figure 200). The wings no longer form a dihedral, but are not flat, either. They have a double curvature, which gives the soaring bird the appearance of a circumflex accent or a U when viewed from in front (figure 199).

One of the first things that one notices when observing flexed wing flight is that a bird's speed increases as the amount its wings are flexed increases.

What is more, this mode of flight is carried out by vultures over great distances without any noticeable change in general direction, loss of altitude, or wing movement.

What we have just said about the griffon vulture can be applied to all the others. They all soar in the same way, by means of rising thermal currents, including the condors.

Egyptian, turkey, and black vultures (figure 202) fly through the air in a similar fashion. The hooded vulture of central Africa has a flight that resembles that of the griffon vulture, even though it is of smaller size. Idrac made a careful study of this bird and also of the kite in Senegal. He noticed that the hooded vulture circles in areas where the wind has an ascending component and that in these areas there was always a high density of birds. He found that the speed of the kite was 7 m/sec and that of the hooded vulture was 8 m/sec.

The Flight of Kites

The kites seen frequently in North Africa are some of the best soarers, like their cousins in India. Their flight is more varied and demonstrates a remarkable agility in the air. They closely resembles the true soarers in the sense that they do not flap their wings at all for considerable periods of time.

Kites perform very graceful circling flights in the morning, as /131 soon as the sun begins to send out its rays, and especially when there is a light wind. They first make an inclined takeoff using flapping flight. They then start to circle around, sometimes with their wings well extended and the tips pointed slightly forward, sometimes by rowing slowly in the part of their circuit where they are facing the wind. Later, they stop flapping altogether and they climb into the sky with an astonishing slowness, regularity, and stability.

At this moment their soaring ability truly equals that of the griffon vultures. Their wings are absolutely motionless. Changes in direction are made by inclining the wings. Only the tail is in continual movement, for purposes of banking.

Even though it makes no effort to propel itself, the kite gains altitude with each circuit. The increase in altitude is obviously made in the part of the circle in which the bird is facing the wind. However, the flight of the kite is differentiated from that of the vulture in that as it climbs the kite is clearly carried along by the wind to an increasing degree as the wind's strength increases. (See figure 203). The kite makes circles about 20 meters in diameter. The centers of the different circles are located on a line following the direction of the land and are distant from each other by 2 to 6 meters. Since each circle is completed in 8 to 9 seconds, the flight speed varies from 6.50 to 7.50 m/sec.

Whenever kites circle, they are in a cylindrical or elliptical zone having an ascending component.

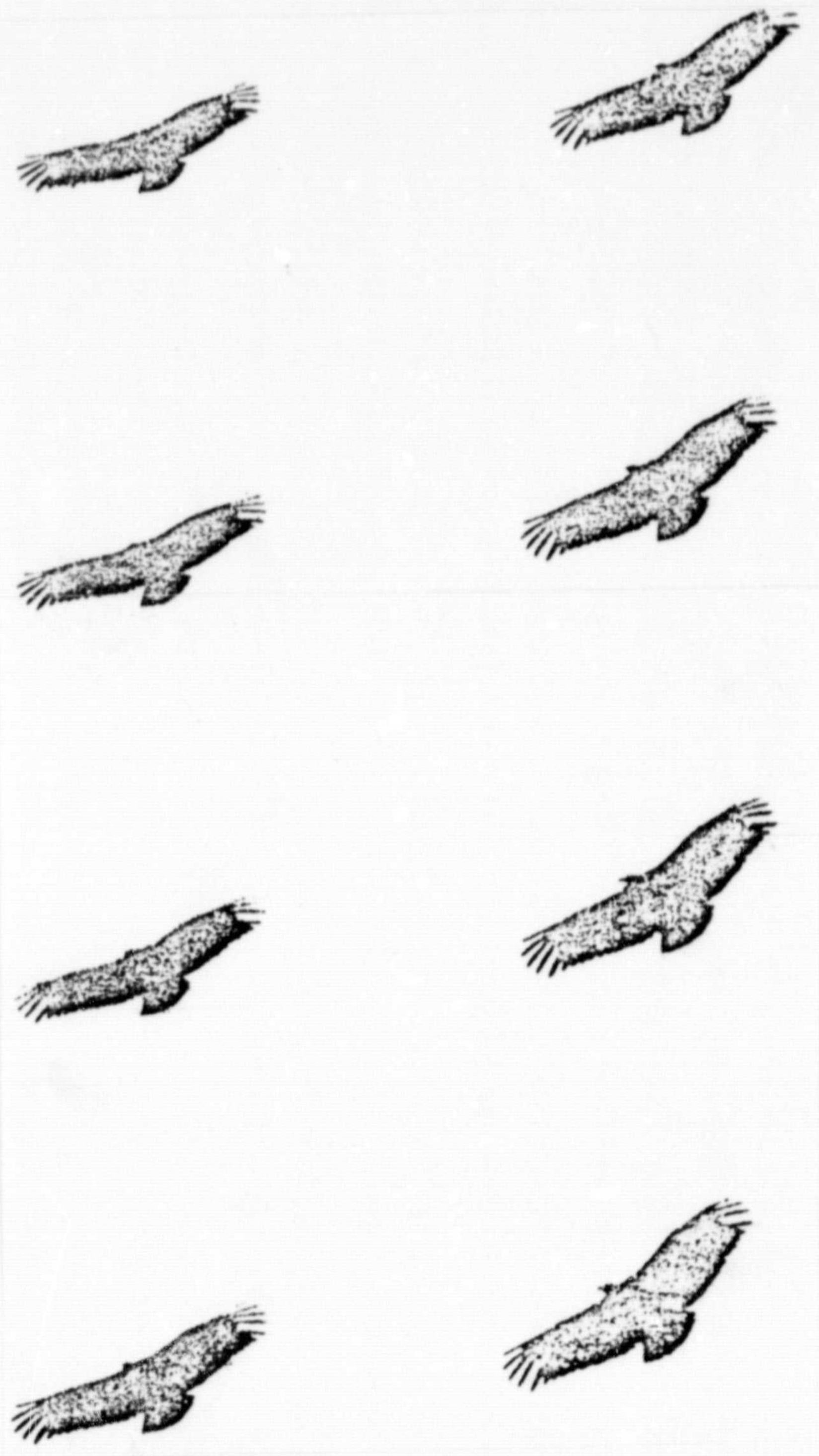


Figure 202
Film of a Black Vulture (Catharist atrata Bartr.) in Flight Circling in Rising Thermal Currents without Beating its Wings (Film by Idrac) 16 Frames a Second (Read from Top to Bottom and from Left to Right)

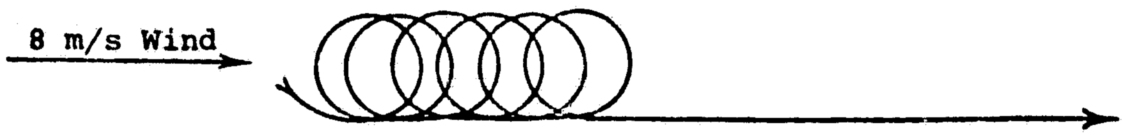


Figure 203
Path of a Circling Kite Carried Along by Rising Thermal Currents
(from Hankin)

The Flight of Marabous and Pelicans

The pouched marabou that is found in great numbers in Africa is, despite the ridiculous form that it presents on the ground, one of the kings of soaring. Its style of flight resembles that of the griffon vulture. As a matter of fact, the two are frequently seen together as they both are lovers of carrion. When the marabou takes wing in a wind of 5 to 6 m/sec, it first rises with the aid of powerful wingbeats until it reaches a height of some thirty meters. It then gradually stops flapping and starts to turn without the least effort in zones of rising currents. It makes circles of about 60 meters in diameter. Meanwhile, it spreads its wings and tail wide and its remiges fan out. (See figure 204). The dihedrals formed by its wings in the vertical and horizontal planes are less acute than in griffon vultures.

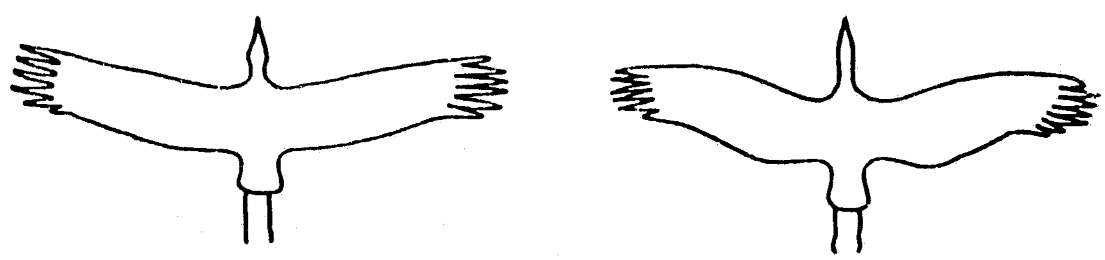


Figure 204
Silhouettes of Marabou or Adjutant Crane
Left: Circling; Right: Drifting with Flexed Wings

The marabou, like the vulutre, retracts its head into its shoulders, but its pouch dangles as a result of the folding of the neck and is balanced in the wind. When they are flying with the wind, the marabous lose a little altitude. This can be seen by an observer a short distance away. They too turn in circles, sometimes for as long as one or two hours, until they are so high as to be practically invisible. It is entirely possible that they can climb in this manner at least up to 1,500 meters on hot days. /132

The marabou does engage in flexed wing flight (figure 204). However, the flexing is never very pronounced, as is the case with the vulture.

The pelicans living on the shores of central African lakes start their flights by rowing like the preceding birds. They then climb up to great heights without flapping their wings. They can be seen turning round and round for hours, their head retreacted between their shoulders and their wings slightly flexed (figure 205). They go down and then back up again without flapping once.

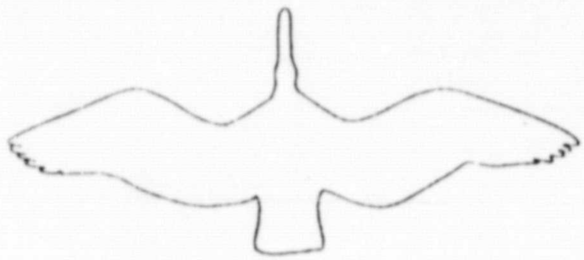


Figure 205
Silhouette of Pelican
Soaring with Flexed Wings

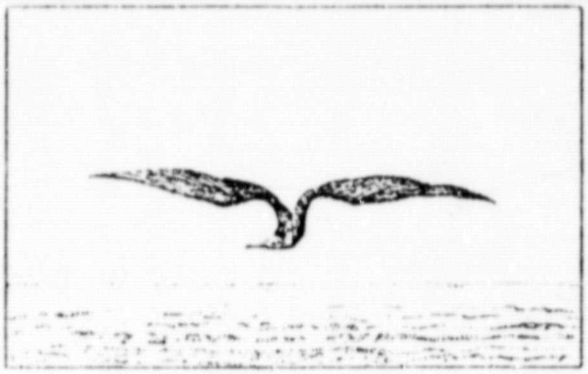


Figure 206
Frigate Bird Soaring

Flight Below the Clouds

Any cloud blocking off the sun for a significant length of time on a warm, fair day interrupts the circling flight of all the birds I have mentioned fairly rapidly. The vultures and other birds that turn tirelessly high off the ground without losing altitude soon begin to descend. As soon as the natural screen has disappeared, the soarers begin to circle anew and gain height.

However, on some stormy or clouded over hot days a special type of soaring can be observed. A bird beats its wings for a time and flies around as if it is looking for something. Then it suddenly stops flapping and rises several hundred meters without the least movement.

I have noticed the phenomenon in sea gulls at Cherbourg's roadstead. Sea gulls leaving the beach are suddenly lifted up upon arriving at the basin as if by an elevator to 500 or 600 meters in altitude. They then swerve and slide through the air back to the beach.

I have noticed that when they ascend like this, there is a storm cloud above them that seems to suck them up.

The Flight of Frigate Birds

Up to this point I have been describing the soaring of land birds by means of thermal winds. Certain marine birds also make use of rising thermal currents which form above the sea just as much as above the land in all tropical regions. Such is the case of the frigate bird and the tropic bird. They are classed among the skilled soarers and even though they most commonly live near the coast, are capable of traveling several hundred kilometers out to sea. /133

The frigate birds are all confined to the tropical islands and coasts of the southern hemisphere. Although they are one of the great masters of flight, they prefer to rest on rocks or in trees because of the diffiuclty they have in taking wing as a result of their small feet. The frigate bird launches itself from its high perch at the break of day. After flapping several times, it makes great circles in the air with its wings outstretched and climbs upward. It thus attains great heights without flapping its wings, as it were.

The frigate bird's wings are often M-shaped (figure 206). As long as it flies in this manner, it appears to be swimming in the air. At times it seems to be pinned to the sky like someone's kite. There is no visible movement of its wings. Its tail alone appears to be fanned out and deeply slotted.

III. Soaring in Horizontal Winds

There exists a soaring bird that for a long time has inspired admiration and surprise in the navigators who had the luck to encounter it. This is the wandering albatross, which has a wingspread of 3.50 meters and weighs 9 to 10 kg. It lives in the vast expanses of the Pacific and the southern Atlantic between 30° and 60° south latitude. Essentially a marine bird, it rests on the water at night. During the day it flies continually in quest of food.

It lives with its smaller cousins, the sooty and black-browed albatrosses, in regions of extremely unsettled weather--in the south seas storms are very frequent. All those who have landed on any of the scattered southern islands have noticed how rarely the weather is calm.

It is certain that in the south seas high winds, attaining 20 m/sec, are frequent. They usually blow from the southwest and make the water very rough. They also exhibit variations of speed and vertical and horizontal oscillations.

All albatrosses can use these currents to keep themselves aloft and move from one place to another. They make very extended flights which are always undertaken in midocean at a great distance from land. The extent of their flights can be estimated as a result of the capture of an albatross with a 3.05 meter wingspan at Cape Horn in 1917. This albatross had been banded at Kerguelen Island. It had therrefore traveled a distance of 13,000 km.

In the absence of any wind, the albatrosses alight on the water, where they move around by beating their wings, rapidly tiring themselves out. In calm weather, these birds also have difficulty taking off from the water. They are obliged to run with the waves in order to take wing.

The Flight of Albatrosses

During a voyage to South Georgia, Idrac studied how albatrosses fly. He has given a detailed description of the maneuvers made by these birds in order to soar. Idrac says that, provided there is enough wind, albatrosses soar outside of rising currents, far from the distrubances created by boats, and even when the wind and the waves have almost the same speed.

They first skim the surface of the water, usually between two waves, and preferably on the lee flank of a wave, and make a banking turn. After they have turned themselves around so as to pretty much face the wind (figure 207), they immediatley start climbing in a straight line until they reach an altitude of 10 to 15 meters. They /134
then make another sharp turn, either to the left or the right. This is followed by a descent with the wind at their rear or side which leads them back to the vicinity of the ocean surface. There they start over agin in an infinite cycle. (See figure 208). Idrac has pointed out that albatrosses begin soaring in a wind of around 1.50 to 5 meters in the layer just above the water. It is here that albatrosses change course. Another point is that the maximum height to which the birds climb is greater in high winds than in weak ones. The height attained varies from 8 to 15 meters, with the aerodynamic speed of large albatrosses being 22 m/sec and ranging from 11 to 28 meters. Lastly, the time required for the maneuver is fairly constant: from 10 to 11 seconds for the wandering albatross and from 7 to 9 seconds for the black-browed albatross.

Thanks to the films taken during the Scott expedition that Javouhey has made available to me, I have been able to analyze the maneuvers of the wandering albatross myself. (See figure 209).

My study of this documentary evidence has enabled me to see first of all how albatrosses maneuver.

All of a sudden they ascend against the wind until they reach a height that does not exceed 18 meters in the films. (See figure 210). They then make a very wide U-turn 35 to 40 meters in diameter (figure 211). As soon as they are flying with the wind, they make a dive and then glide randomly until they approach the surface of the sea (figure 212). The albatrosses then begin their displacement anew with another wide banking turn, most commonly along the lee slope of a wave. They ascend once again and repeat the same maneuvers. While flying in this manner, their wings remain motionless and are extended to a degree that depends on the force of the wind. Their tail fans out, with the feet thrust rearward below the rectrices and sticking out from under the tail like two oars.

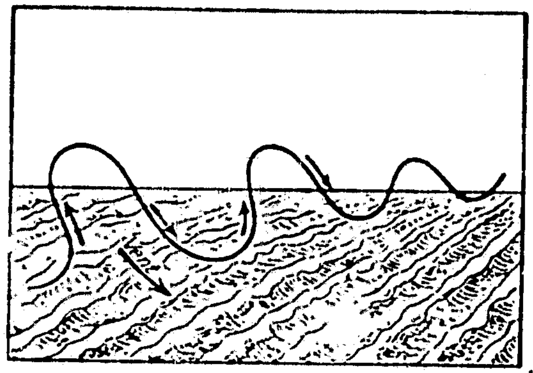


Figure 207
Path of Wandering Albatross
Soaring above the Sea

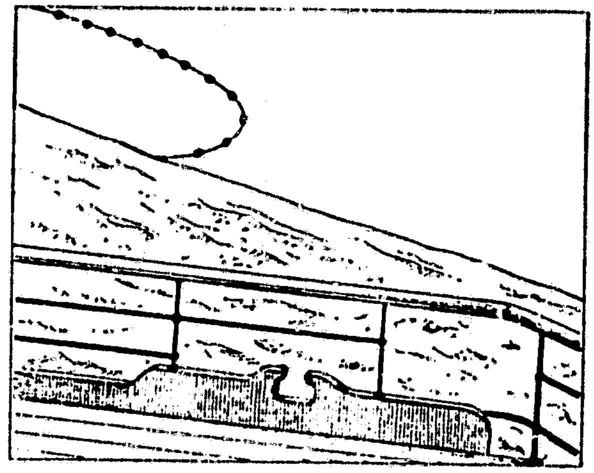


Figure 210
Path of Albatross Gaining
Height against the Wind

Figure 211
The Abrupt Changes of Course
of an Albatross as it Skims
the Waves and as its Ascent Peaks

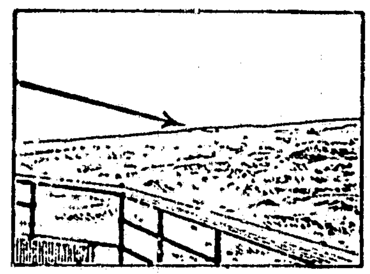


Figure 212
Descent of Albatross
Gliding with the Wind

When albatrosses make banking turns their outstretched wings form a single plane.

The flight of albatrosses is relatively rapid. Duirng the periods of gliding with the wind, they frequently exceed 25 m/sec, while in other parts of the circle the speed is about 15 m/sec.

Albatrosses can thus maneuver in any direction during rough weather.

The albatross barely climbs higher than 5 to 6 meters above the waves. However, when soaring by means of rising currents created by swells, it reaches greater heights. Some authors claim that outside the zone of rising currents it attains a height of 20 to 30·

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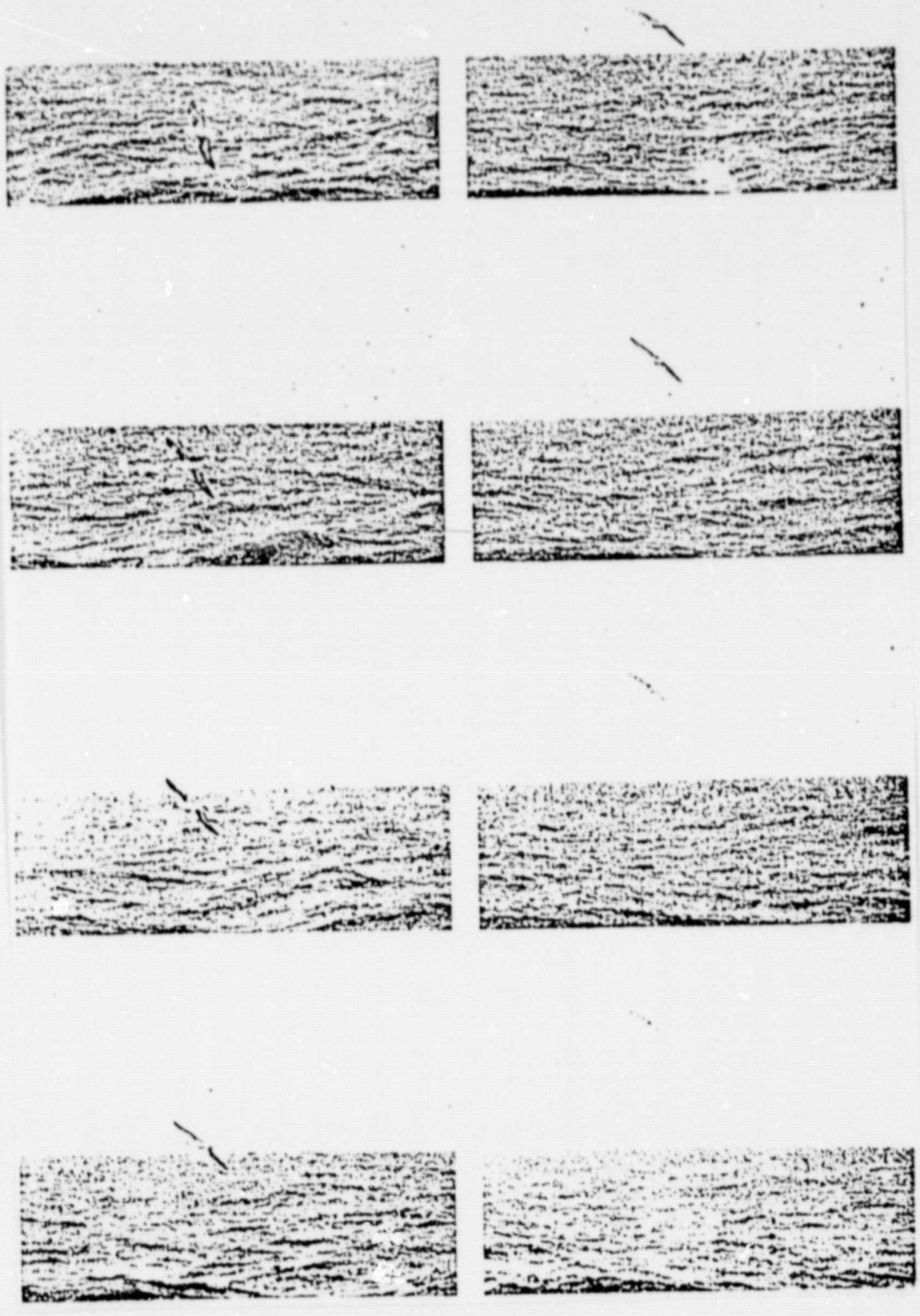

Figure 208
Film of the Maneuvers of a Wandering Albatross (Diomedra exulans I.)
Soaring in the South Seas (Film by Idrac)
The Time between Frames is 1/3 Second
(Read from Top to Bottom and from Left to Right)

Figure 209
Film of a Wandering Albatross Changing Course near the Surface of the Water, along the Lee Side of a Wave (by Scott) 16 frames/sec (Read from Top to Bottom and from Left to Right)

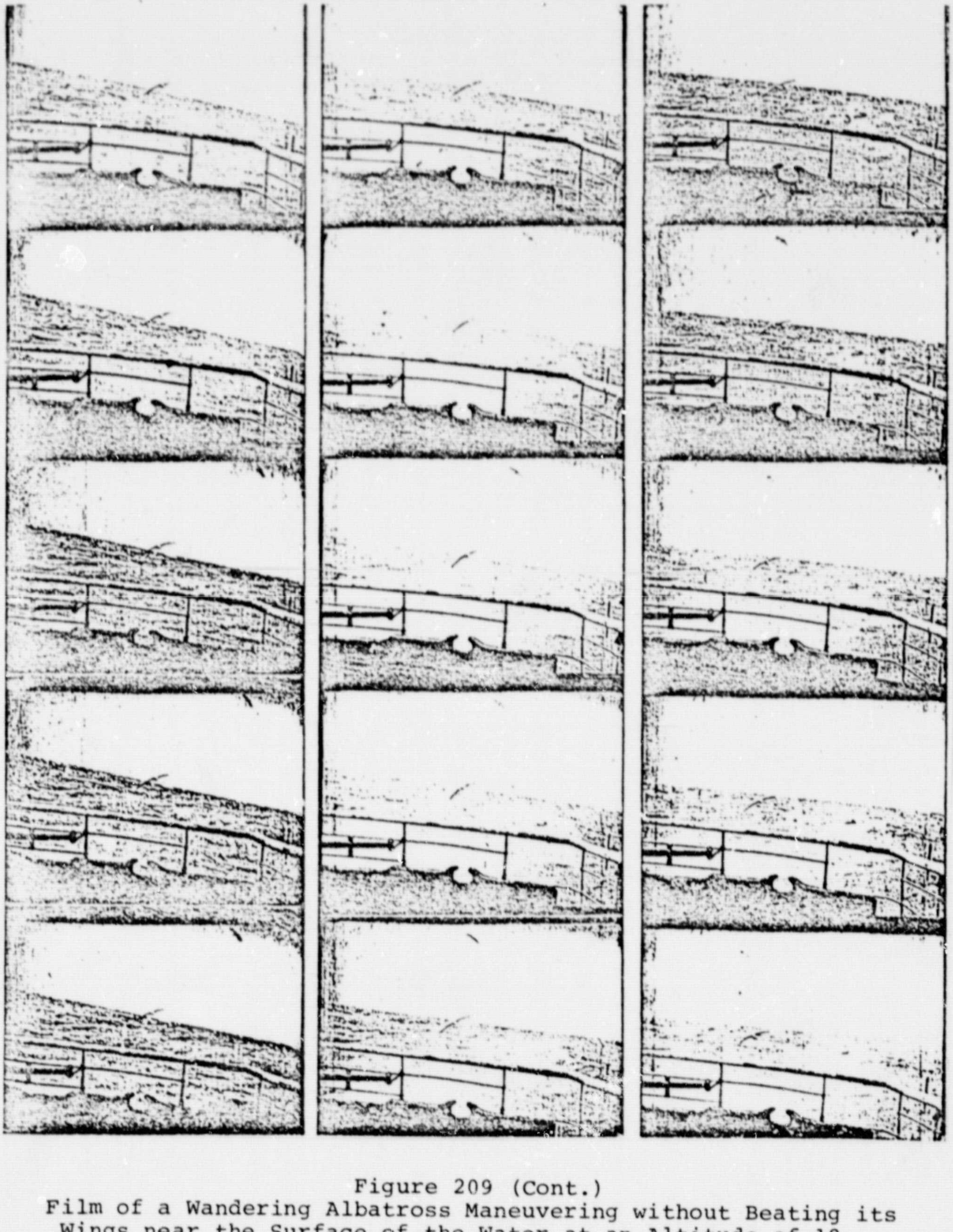

Figure 209 (Cont.)
Film of a Wandering Albatross Maneuvering without Beating its Wings near the Surface of the Water at an Altitude of 18 meters (Film by Scott) 16 frames/sec (Read from Top to Bottom and from Left to Right)

meters above the water, occasonally more than 30 meters. The bird makes use of the energy of the wind to soar in these circumstances. It flies into the air current, which increases in strength in a direction opposite to its own movement, and it gains altitude as it loses speed. However, the albatross does not continue climbing until it has lost all speed. Before this happens, it makes a U-turn and recovers speed. The U-turn takes 10 seconds to complete. The albatross can continue its flight in this manner for hours on end. With its wings absolutely motionless, it climbs agianst the wind and descends with it. Sometimes it turns alternately to the right and the left so as to describe an undulated line. The bird thus continuously builds up potential energy which it then transforms into kinetic energy as it drifts through layers of air. /135

During this mode of flight, whether in circles or undulated lines, the wings are set in a particular fashion. When an albatross ascends against the wind, its wings are generally curved to form a circumflex accent. At this moment it is flexing its wings while the speed of the wind is increasing. Furthermore, it is sometimes observed that the tips of the hand wings are bent upwards somewhat in the course of the ascent. Albatrosses only spread their wings out during relatively calm periods and especially when turning. Their wings at these times are straight and lie in a single plane. The preceding description applies to all albatrosses, but particularly to wandering and black browed albatrosses. These two fly at a low rate of speed, 18 m/sec, and the period of their cycle of maneuvers is on the order of 7 seconds. The flight of the sooty albatross is perhaps even closer to perfection than that of the two others. In addition, it very frequently reaches greater heights. It is not uncommon to see it pass above boats in the course of its circuit. Even so, it never exceeds a height of 50 meters above the sea. Lastly, it often flies with flexed wings against strong winds blowing over an almost calm sea. This is shown in the photograph in figure 213.

The Flight of Petrels and Fulmars

There is another bird, the giant fulmar (figure 214), whose style of flight merits attention. It can be seen making great circles along shorelines with its wings held more stiffly than the albatross's. It is in search of carcasses for food, which it cuts up like a vulture. No matter how long one observes it, no movement of the wings will ever be visible. It makes free use of rising currents reflected by obstacles, but it can ascend just as well against the wind until it is completely motionless and stalling. It then makes a wide circle and regains speed as it descends almost to the water. There, it turns to face the wind anew, so as to gain height. This maneuver last 9 seconds.

Certain well outfitted birds living off the coast of Scotland, the Hebrides, and Iceland, like the arctic fulmar, perform feats of soaring far from ships or the coast. Their maneuvers are identical to those of the albatross in the Antarctic Ocean (figure 215). They follow a twisting line made up of ascents of less than 15 meters, descents, and sharp turns as long as the wind is less than 6 meters. The period of their cycle of maneuvers is about 7 seconds. /136

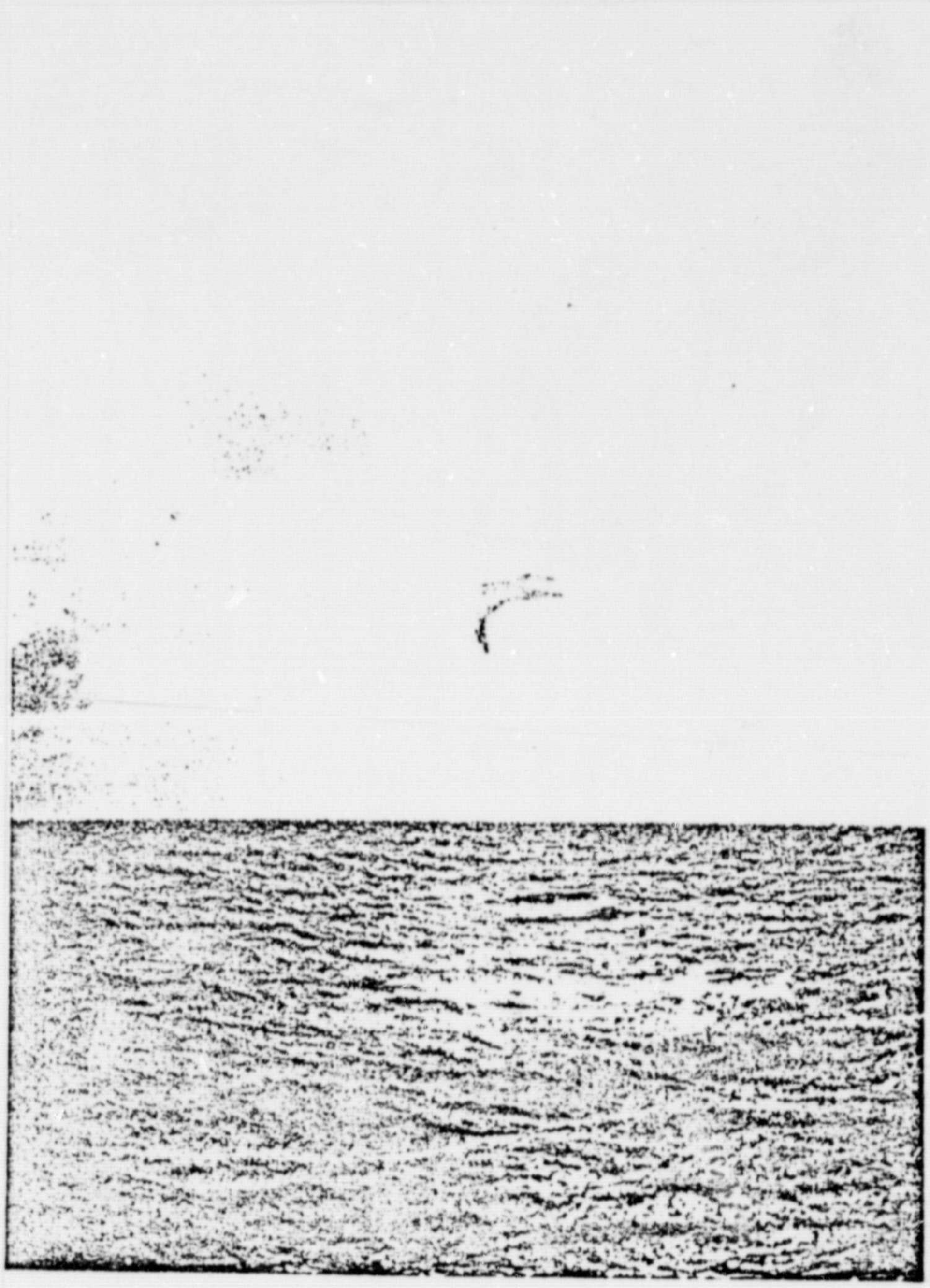

Figure 213
Sooty Albatross (Phoebetria fuliginos Gm) Moving without Beating its Wings against a Moderate Wind Blowing over an Almost Calm Sea

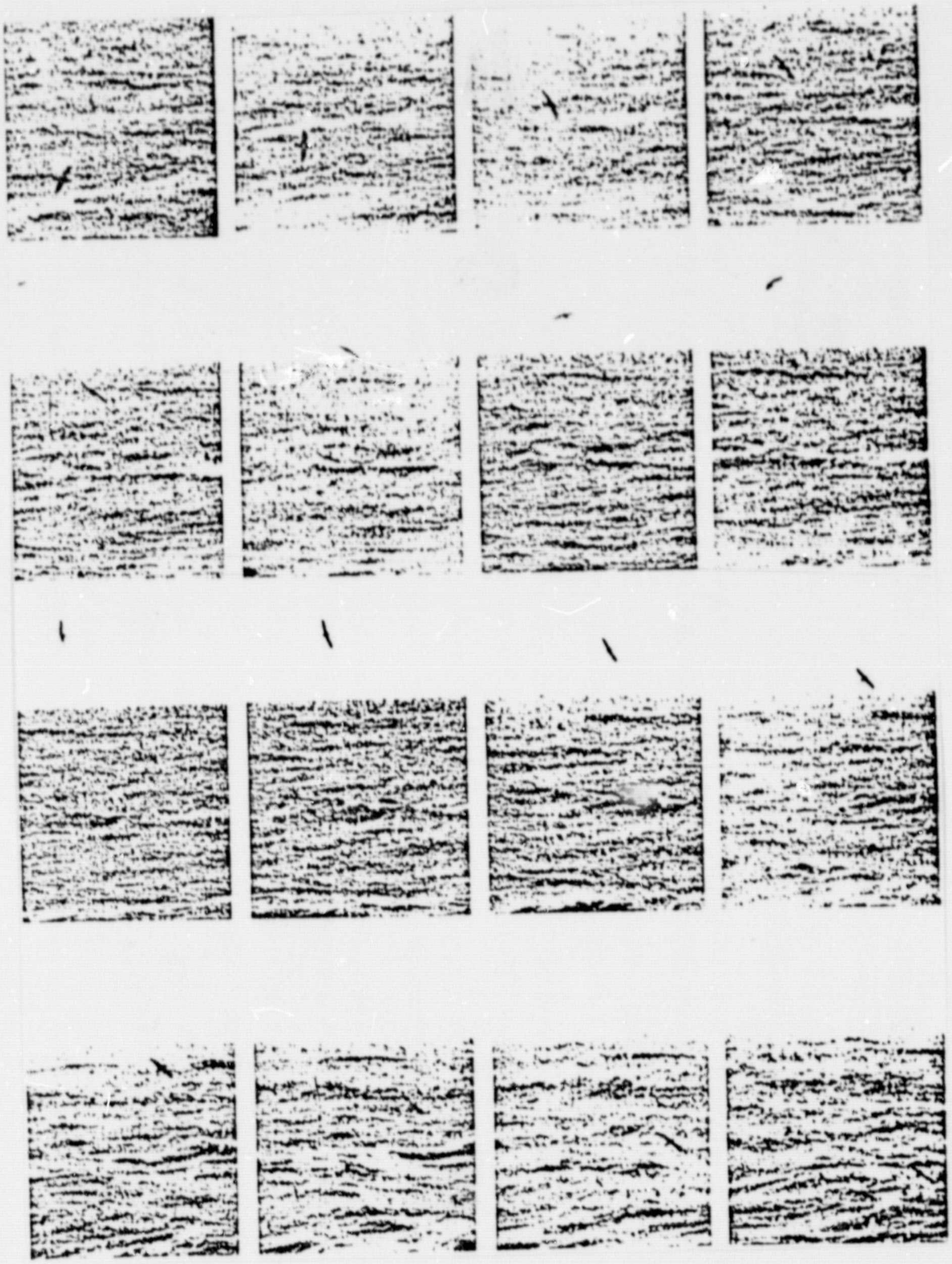

Figure 214
Film of a Giant Fulmar's Periodic Maneuvers (Macronectes Giganteus Gm) above the Sea (Film by Idrac) Frames Separated by 1/3 Second (Read from Left to Right and Top to Bottom)

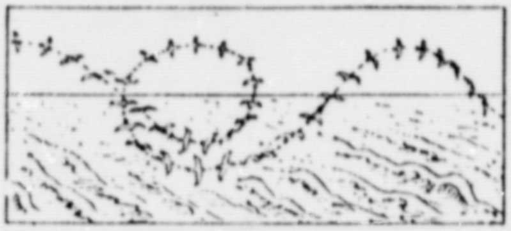

Figure 215
Path of Soaring Arctic
Fulmar (from Idrac)

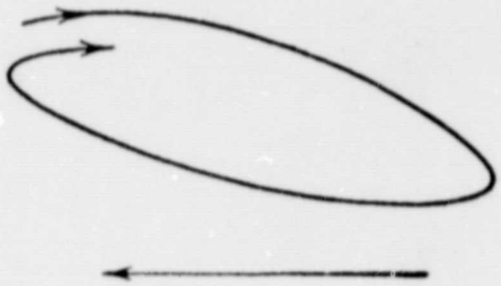

Figure 216
Path of a Soaring Gannet

The Flight of Gannets

I have had the opportunity to study the flight of gannets in the Atlantic several times. Gannets perform a series of ascents and descents like other marine species. These are also in the form of circles or along a more or less twisty path.

At the moment when the wind rises gannets turn to face it and with its aid they increase their altitude without ever flapping their wings. They can gain 6 to 10 meters in this way, depending on the force of the wind. They then drift back down, keeping the wind always to their rear (figure 216).

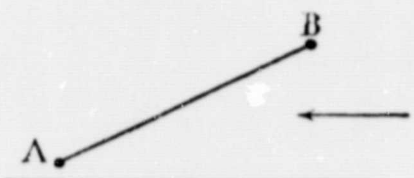

Figure 217
Inclination of a Gannet's
Path when Soaring in
Circles

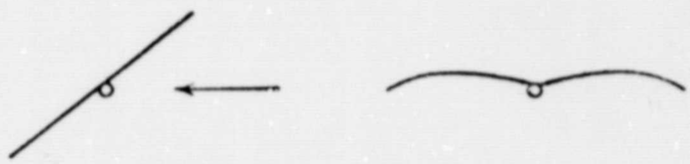

Figure 218
Form of a Gannet's Wings
Left: when Banking
Right: when Ascending against
the Wind

The circles made by gannets have an average diameter of 35 meters and take about 9 seconds to complete. The climbing angle is generally about 20° (figure 217). When ascending, the wings are flexed a bit and viewed from in front have the form of a circumflex accent. When banking, they are, on the contrary, flat (figure 218).

The flight of flocks of gannets over calm seas and at a height where the rising current engendered by the swell is no longer detectable can yield some interesting observations. I have often witnessed trips made against the wind by a hundred of these birds crowded

Figure 219
Large Numbers of Gannets
Soaring Against the Wind

together. They can be seen slowly climbing the stream of air, each repeating the same movements, either all at once or with some interval of time between them. This depends on their vertical or horizontal distance from each other.

Figure 219 illustrates my observations very clearly. All the gannets are flying against a wind blowing from right to left. They are located at a variable height in a zone ranging from 10 to 100 meters above relatively calm seas. The picture includes both ascending and descending gannets. The ascending ones are climbing against the wind tilted upwards with their wings flexed. The descending ones drift through the air with their wings and necks extended. /137

<u>The Three Known Types of Soaring</u>

The following conclusions can be drawn from this report. There are three types of soaring:

1) Soaring by birds using the rising currents created by obstacles. This is undertaken by:

Sea gulls above cliffs or behind ships;
Raptors in the mountains;
Shearwaters above the crests of waves.

2) Soaring of birds using rising currents resulting from solar heating or existing under clouds. This is practiced by vultures and kites above deserts and by frigate birds and sea gulls above the ocean.

3) The soaring of marine birds like the albatross, which maneuver in horizontal winds having variations of speed and inclination.

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The study of the varieties of flapping flight and soaring mentioned in previous lessons has laid the basis for classifying birds into twenty groups. As we shall see, each of these groups is characterized by very clear differences in its manner of flying. Here is the list of groups.

The Classification of Birds

I. Diurnal Soaring Raptors -- Land birds who do not flap their wings very often and most commonly soar with the help of rising thermal or obstruction currents. Excellent gliders (average speed 30 to 40 km/hr).

Vultures, eagles, buzzards, harriers, kites.

II. Soaring Palmipeds -- Sea birds who beat their wings extremely rarely and soar for hours on end by using winds of uneven speed and inclination or that are rising.

Albatrosses, giant fulmars, arctic fulmars, gannets, black-backed sea gulls, frigatebirds, tropicbirds.

III. Soaring Waders -- Usually lake or marsh birds whose slow flapping flight is frequently interrupted by fairly long glides and who soar by using winds having a rising component (average speed: 45 km/hr).

Marabous, cranes, storks, spoonbills, egrets, herons.

IV. Rowing/Soaring Palmipeds -- Marine or coastal birds who travel by means of moderately frequent wingbeats (2 to 6 per second), glide remarkably well, and are capable of soaring with the aid of rising currents along cliffs or waves (average speed: 50 to 70 km/hr).

Sea gulls, Cory's shearwaters, storm petrels, cape petrels.

V. Nocturnal Rowing/Gliding Raptors -- Land birds who fly slowly and quietly with infrequent wingbeats (1 to 3 per second) and are able to glide remarkably well (average speed: 30 to 40 km/hr).

Eagle owls, shorteared owls, screech owls, other owls.

VI. Rowing/Gliding Corvids -- Land birds who fly and flap slowly. Their wingbeats (1 to 3 per second) frequently cease altogether and are replaced by a period of gliding. Some of these birds occasionally make use of rising winds in attempts at soaring (average speed: 40 to 50 km/hr).

Crows, rooks, choughs, magpies, jays.

VII. Rowing/Soaring Passerines -- Land birds who fly very rapidly /140
and are capable of substantial periods of gliding punctuated by

rapid, often intermittent wingbeats (8 to 10 per second). They can also soar. (Average speed: 60 to 150 km/hr.)

Nightjars, swifts, and swallows.

VIII. Diurnal Rowing Raptors -- Rapidly flying land birds sometimes capable of performing short glides or soaring above wooded groves. However, their only means of ascent and progression is more or less rapid flapping (3 to 7 times/sec) (average speed: 80 to 100 km/hr).

Goshawks, sparrowhawks, falcons.

IX. Long Distance Rowing Passerines -- Represented by the majority of small land birds, who generally flap their wings rapidly (6 to 20 beats per second) and then fly off like arrows with their wings partly retracted, only to start flapping anew. The resulting flight is undulated to a certain degree (average speed: 40 km/hr).

Larks, wagtails, shrikes, nightingales, orioles, blackbirds, thrushes, starlings, finches, sparrows, goldfinches, buntings, crested wrens.

X. Short Distance Rowing Passerines -- Includes birds adapted to arboreal life, such as titmice and woodpeckers, whose flight is most often of short duration, and species like wrens that have almost lost the ability to fly.

XI. Vibrating Passerines -- Whose lift is supplied by vibrating their wings (30 to 40 beats a second).

Hummingbirds.

XII. Terrestrial Rowing Waders -- Who rapidly flap their wings (5 to 10 wingbeats/sec) and only glide for short distances (average speed 60 to 80 km/hr).

Great bustards, little bustards, great plovers, golden plovers, woodcocks, lapwings.

XIII. Waterside Rowing Waders -- Who progress by rapidly beating their wings (5 to 10 beats per second) sometimes punctuated by periods of gliding performed with the wings flexed and the wingtips pointed rearward (average speed: 60 to 80 km/hr).

Curlews, snipes, ruffs, sandpipers, godwits, avocets.

XIV. Rowing Columbidae -- Rapid flying land birds who produce their lift and propulsion by means of repeated wingbeats (3 to 8 per second), and are able to glide for awhile when their speed is sufficient. They can also drift through the air with their flexed wings thrust rearward. (Average speed: 80 to 100 km/hr).

Pigeons, turtledoves.

XV. Rowing Gallinaceae -- Land birds who progress by interspersing periods of rapid flapping (6 to 13 times a second) with periods of gliding with their wings outstretched. Their glides carry them 50 meters or so (average speed: 60 to 80 km/hr).

Capercaillies, ptarmigans, grouses, hazel grouses, partridges, quails.

XVI. Swimming/Rowing Palmipeds -- Aquatic birds able to dive and move rapidly through the air. They fly by energetically beating their wings (5 to 12 times a second) in a continuous manner. Except for swans and geese, they almost never glide. (Average speed: 100 to 120 km/hr)

Swans, geese, ducks, teals, pochards, scoters, cormorants, many shearwaters.

XVII. Diving/Rowing Palmipeds -- Birds adapted to aquatic life, /141
but for the most part still able to perform flights of some duration by means of rapid flapping (average speed 40 to 50 km/hr).

Mergansers, grebes, loons, guillemots, puffins, little auks.

XVIII. Diving/Rowing Waders -- Birds who are adapted to aquatic life to some extent and generally capable only of short flights.

Coots, waterhens, rails.

XIX. Diving/Rowing Passerines -- Birds who fly with the aid of rapid flapping (8 to 10 times a second) and who are admirable divers.

Kingfishers.

XX. Running Birds -- Incapable of flight.

Rheas, ostriches, penguins.

Notice that the groups represent practically all the orders or sub-orders of the class to which birds belong.

Having said this, I will now report on my own research on birds' organs and their relation to their mode of flight. I shall try to draw out all the useful information contained in this study. The conclusions following from an examination of avian characteristics can be a fertile source of ideas in airplane design and construction. They are above all a means of achieving a better understanding of the aerodynamic conditions encountered during flight.

As we shall see, the various bird groups possess different features. Their wingspread, aspect ratio, wing area, and caudal area are far from having relatively equal dimensions. The differences even extend to the various groups of soaring birds, and depend on the winds they utilize.

Body Length

The fundamental point of comparison in all that follows is weight, to which all other data will be related. According to the laws of geometric similarity, weight increases in proportion to the cube of linear dimensions, length, width, etc. Meanwhile, birds' flesh has roughly the same density as ours. The cubic root of weight is therefore the variable we will most often turn to for comparing lengths, the square root of surface areas, etc.

One of a bird's dimensions has seemed to me important to study. This is body length, which corresponds to the length of an airplane's fuselage. I measured a bird's length from the tip of its beak to the end of its tail while in flight position, with its neck elongated. The length in and of itself has no value because of the extremes of size observed in birds. I therefore divided it by the cube root of the weight P expressed in grams so as to have dimensionless and comparable ratios. I found that, proportionally speaking, body length does not vary appreciably in birds and that it is related to the size of the neck and tail. The animal's fuselage is shortest in groups where both neck and tail are small. It is greatest by one or two fifths when one of these organs is much more elongated than usual. Such is the case of waders like the herons, who possess a long neck. Another example is passerines like the swifts, who have large tails.

Wingspread

The wing dimensions themselves, length and width, have not been the focus of much attention. Only wingspread, which is the maximum distance between the two wingtips, has been the object of study by some authors.

If birds are ranked by the ratio of wingspread in centimeters /142 to the cubic root of weight, it becomes obvious that soaring or gliding birds have the greatest relative wingspread and that in contrast all rowing birds have a much smaller one. In other words, birds with the highest wingbeat frequency have the smallest wingspread. An example is gallinaceous birds, who make up to thirteen beats per second and have half the relative wingspread of the soaring palmipeds:

Group	Body Wt. (gr)	Ratio of Wingspan to $\sqrt[3]{P}$	Ratio of Wingspan to Real Body Length	RATIO Hand Wing Length to $\sqrt[3]{P}$
Soaring Palmipeds	2 552,7	14.7	2,38	4,1
Diurnal Soaring Raptors	1 869.5	14,2	2.36	4.4
Rowing/Soaring Palmipeds	697,1	14,1	2,25	4,3
Nocturnal Rowing/Gliding Raptors	466.4	13,7	2,59	4
Rowing/Soaring Waders	2 301,6	13,3	1,86	3,6
Rowing/Soaring Passerines	46,7	12,4	1,96	4,4
Dirunal Rowing Raptors	423,7	12,2	2,15	3,9
Rowing/Gliding Corvids	272	10,9	1,78	3,7
Waterside Rowing Waders	176,9	10,7	1,84	3,2

Group	Body Wt. (gr)	Ratio of Wingspan to $\sqrt[3]{P}$	Wingspan to Real Body Length	RATIO Hand Wing Length to $\sqrt[3]{P}$
Terrestrial Rowing Waders	1 578.1	9.8	1,89	2,8
Rowing Columbidae	326,3	9,5	1,80	3,1
Rowing/Swimming Palmipeds	1 380	9,5	1,72	2,7
Long Distance Rowing Passerines	33,1	9,5	1,64	3
Short Distance Rowing Passerines	23,9	9,3	1,58	2,9
Vibrating Passerines	2,85	9,2	1,53	3,6
Diving/Rowing Waders	260	8,8	1,63	2,3
Diving/Rowing Passerines	36,4	8,7	1,52	2,5
Diving/Rowing Palmipeds	736,5	8,5	1,60	2.2
Rowing Gallinaceae	861,2	7,6	1,53	2.2

[Commas in tabulated material are equivalent to decimal points.]

It is also of interest to measure the length of the hand wing. This is the distance between the carpal joint and the tips of the primary remex.

It has been found that the hand wing is longest in soarers and certain rowers who make abrupt wingbeats to attain a high rate of speed and have a facility for gliding. Examples of the latter group are swifts, hobbies, and terns. Hummingbirds are also in this category. The hand wing is much smaller in continuous rowers. It is shortest in gallinaceae, in which it is half the s[illegible] that it is in soarers.

It is precisely because their wingspread and hand wings are small that most rowing birds cannot soar. They are obliged to flap their wings more or less constantly. In general, the shorter the wings have become, the larger wingbeat frequency is.

Aspect Ratio

The findings on the subject of wing width are no less interesting. In order to have comparable data, I measured the width of wings at the hand joint and then compared it to actual body length and the cube root of weight. I also endeavored to discover the wings' aspect ratio, which plays an important role in the design of modern aircraft, by dividing the wingspread by the width of the wings. Here are the average results: /143

Group Series A	Body Weight (gr)	Wing Width to Body Length	Wing Width to $\sqrt[3]{P}$	Aspect Ratio
Nocturnal R/G Raptors	496,4	0,46	2,49	5,5
Diurnal Soaring Raptors	1 869,5	0,40	2,46	5,7
Rowing/Gliding Corvids	272	0,39	2,47	4,4
Diurnal Rowing Raptors	423,7	0,37	2.15	5,7
S.D. Rowing Passerines	23,9	0,37	2,20	4.2

Group	Body Weight	Wing Width to Body Length	Wing Width to $\sqrt[3]{P}$	Aspect Ratio
L.D. Rowing Passerines	33,1	0,35	2,13	4,5
Rowing Columbidae	326,3	0,33	1,75	5,4
Rowing/Soaring Paseerines	46,7	0,30	1,96	6,3
Rowing Gallinaceae	861,2	0,29	1,50	5,1
Terrestrial Rowing Waders	1 578,1	0,28	1,52	6,4
Vibrating Passerines	2,85	0,22	1,32	6,9
<u>Series B</u>				
Rowing/Soaring Waders	2 301,6	0,30	2,19	6
Rowing/Soaring Palmipeds	697,1	0,28	1,77	7,9
Diving/Rowing Waders	260	0,28	1,59	5,6
Diving/Rowing Passerines	36,4	0,27	1,57	5,5
Waterside Rowing Waders	176,9	0,25	1,51	7
Soaring Palmipeds	2 552,7	0,25	1,59	9,7
Swimming/Rowing Palmipeds	1 380	0,22	1,31	7,2
Diving/Rowing Palmipeds	736,5	0,20	1,10	7,8

[Commas in tabulated material are equivalent to decimal points.]

The birds in the preceding table happen to be divided into two series as far as width and aspect ratio go:

1) Series A, in which the wing is wide or fairly wide and the aspect ratio small. Included here are rowing/soaring land birds, rowers, and soarers using ascending winds.

2) Series B, made up of aquatic or shore birds accustomed to living in regions where large air currents are prevalent and to using a strong horizontal wind either for help in flying or for actually soaring. In this series, the individuals have a narrow wing and a large aspect ratio, no matter what their habitual mode of flight is. In such circumstances, the action of the air currents seems to be the cause of the reduction in wing width, or rather of the fact that a narrow wing is necessary for maneuvering in such an environment. This is certainly true for soaring palmipeds. The more one of them is used to stiff winds, the narrower its wings are. As for rowing/soaring passerines, another reason must be found for their wing configuration, which is close to that of maritime soarers. We will return to this question later on.

There is a way to illustrate graphically the differences between the various groups of birds. To do this, I made photographs of birds with their wings outstretched and reduced them so as to give them the size they would have if they all weighed the same. Figures 220-224 depict in a striking fashion the variations in windspread, wing width, and aspect ratio. The nature of the differences can thus be better appreciated from this rigorously precise procedure.

Figures 220-224: Birds' center of gravity and characteristics, according to flight mode, ventral view. Dimensions are changed to what they would be if each bird weighed a gram and was reduced by a third. (Center of gravity: black or white dot.)

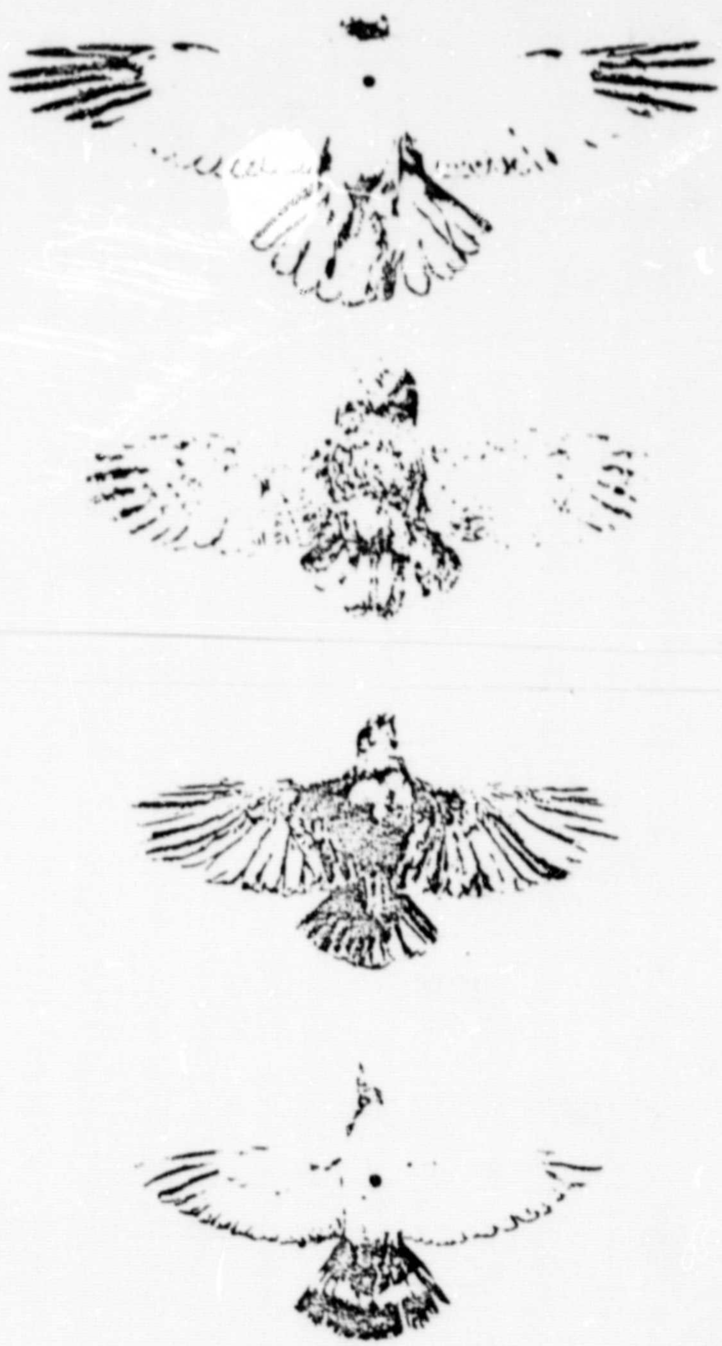


Figure 220

1. Hen Harrier (Circus cyaneus L.) (Diurnal Soaring Raptor)
2. Tawny Owl (Strix aluco L.) (Nocturnal Rowing/Gliding Raptor)
3. Redbilled Chough (Pyrrhocorox pyrrhocorox L.) (Rowing/Gliding Corvid)
4. Ringdove (Columba palumbus L.) (Rowing Columbida)

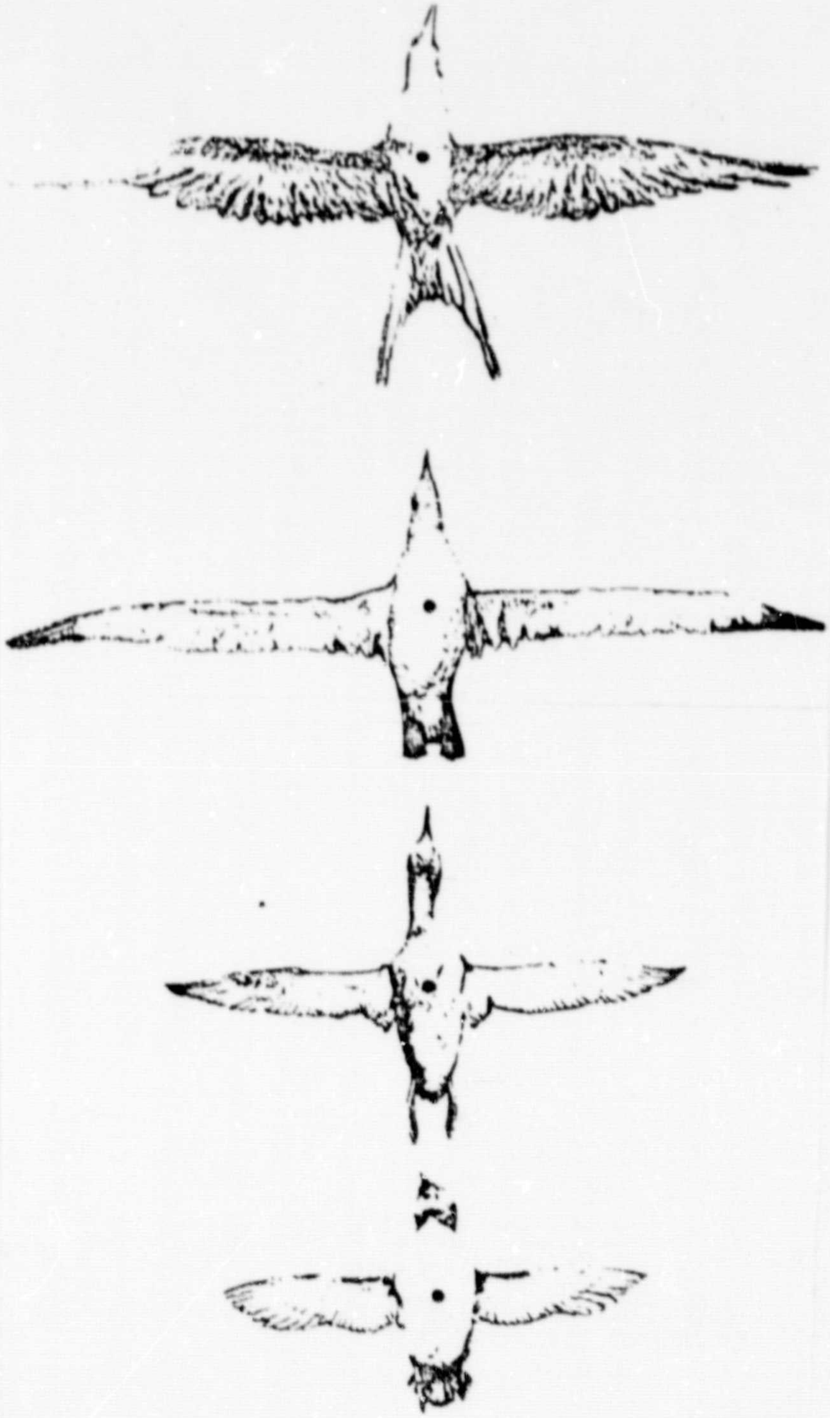


Figure 221

1. Frigatebird (Fregata aquila L.) (Soaring Palmiped)
2. Wandering Albatross (Diomeda exulans L.) (Soaring Palmiped)
3. Blackthroated Diver (Gavia arctica L.) (Divisng/Rowing Palmiped)
4. Southern Puffin (Fratercula arctica L.) (Diving/Rowing Palmiped)

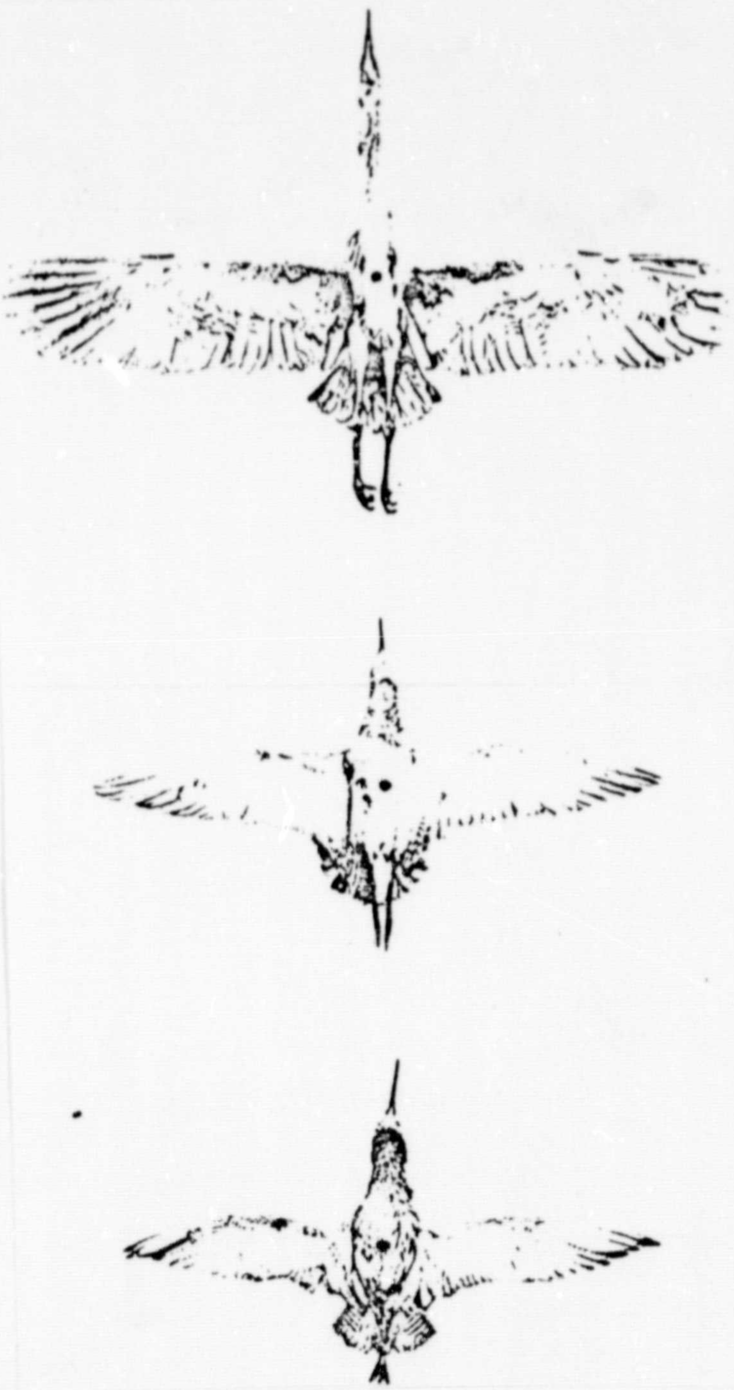


Figure 222

1. Common Heron (Adrea cinerea L.) (Rowing/Gliding Wader)
2. Ruff (Machetes pugnax L.) (Waterside Rowing Wader)
3. Curlew (Numenius arquatus L.) (Waterside Rowing Wader)

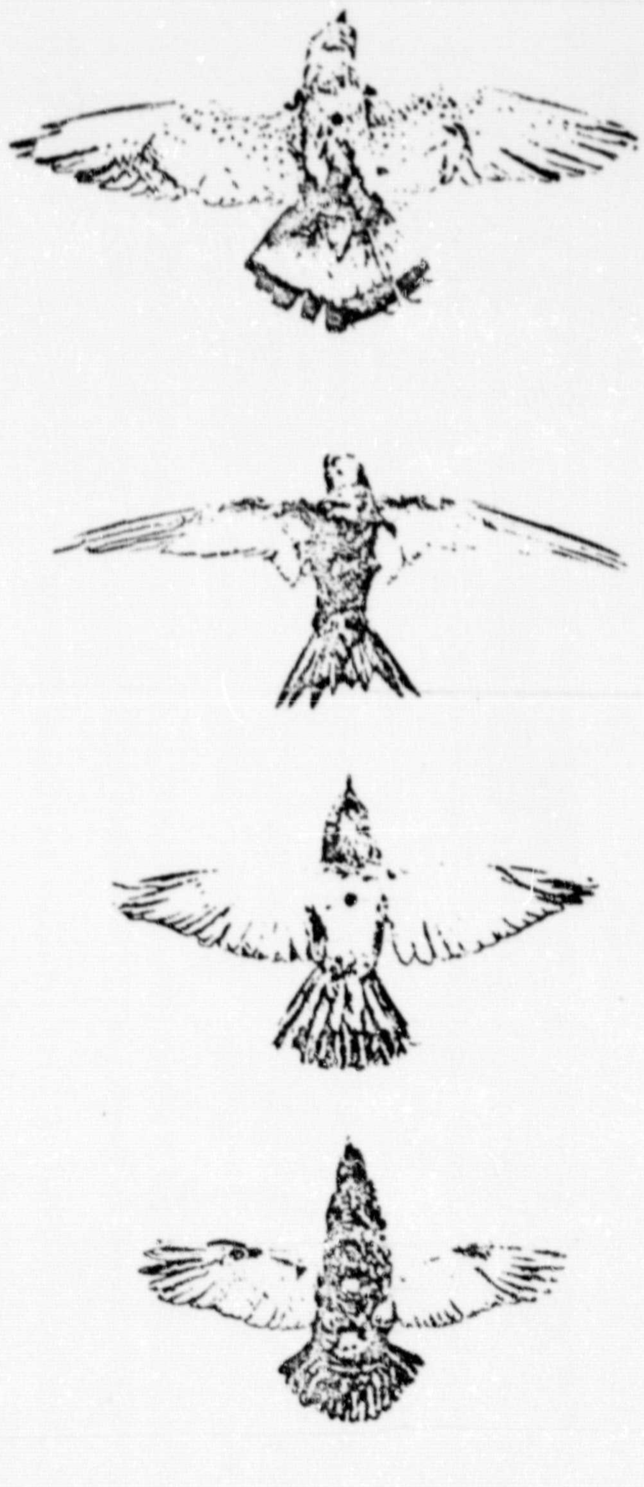


Figure 223

1. Kestrel (Falco tinnanculus L.) (Diurnal Rowing/Gliding Raptor)
2. Common Swift (Apus apus L.) (Rowing/Gliding Passerine)
3. Blueback (Turdus pilaris L.) (Long Distance Rowing Passerine)
4. Capercaillie (Tetrao urogallus L.) (Rowing Gallinacea)

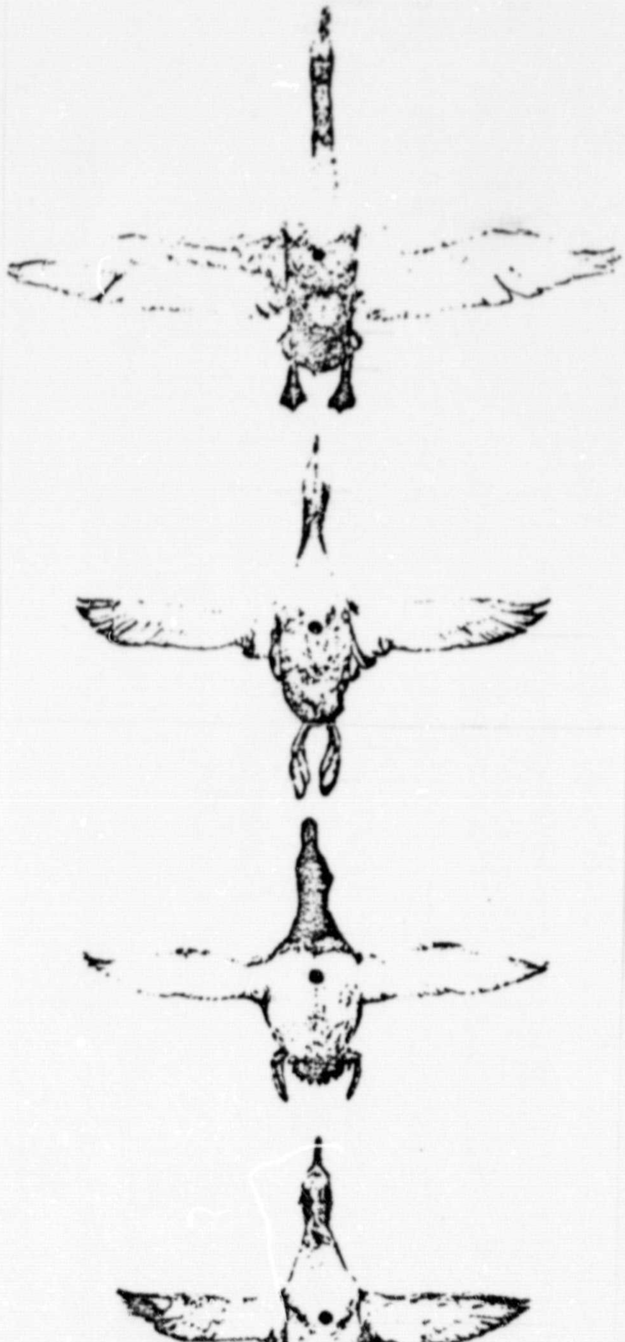


Figure 224

1. Wild Swan (Cygnus cygnus L.) (Swimming/Rowing Palmiped)
2. Rednecked Grebe (Colymbus griseigena Bodd.) (Diving/Rowing Palmiped)
3. Common Pochard (Nyroca marila L.) (Swimming/Rcwing Palmiped)
4. Smew (Mergus albellus L.) (Diving/Rowing Palmiped)

Each group of birds is therefore distinguished by its dimensions and, consequently, by a particular wing configuration.

An examination of the preceding figures reveals the principal wing shapes encountered in birds.

I consider an elliptical form to be typical of wings. It can be found in diurnal soaring raptors (figure 220) with the peculiarity that the wing tips are cut into strips. This is the result of an abrupt narrowing of the ends of the large quills. Interdigital spaces of variable size but similar shape are thus left between them. The free end of the wing is also slotted in waders possessing large airfoils (figure 221), who often perform feats of soaring, and in a few nocturnal rowing/gliding raptors (figure 220), who fly by slowly rowing or silently gliding.

There are birds with almost round wings. Some, like the wall-creepers, fly along rocks like butterflies; others, like the wrens, hardly fly at all.

In contrast, the rapid flapping groups have wings which thin out to an extent depending on the speed at which they flap. Their wings thus assume a somewhat pointed shape. In columbidae, gallinaceae, and most passerines, the hand wing, i.e. the upper part beyond the hand joint, is the only tapered section. The wing then takes on an oval shape, with the big end close to the body. Furthermore, the large remiges of the gallinaceous group (figure 223) narrow at the tips, leaving slots between them, as in the soaring raptors. An exception to this is the quail, who flies in short bursts and whose wings taper considerably, too.

In diurnal rowing raptors (figure 220), who flap their wings to provide forward motion, the wing becomes more pointed as wingbeat speed increases. The whole gambit of wing configurations, from the pointed region being confined to the hand wing in goshawks to the scythe-shaped wing of the rapidly rowing hobbies, is found in this group. The flight of swifts and swallows is similar to that of hobbies, and these rowing/soaring passerines also have a highly tapered wing that becomes more pointed as its movements increase (figure 223).

Wing shape is so closely determined by how fast a bird flaps that hummingbirds, who row so quickly that their upper members seem to vibrate, also have wings resembling scythes.

The pointed form is also encountered in other groups including almost all palmipeds and most of the waders (figure 224). However, there is not just a single cause of tapering. For some birds it depends on speed, but it also arises from the action of the air currents through which a species flies. The result is to diminish the wing depth to such an extent that certain soarers, like the albatross (figure 221), support their bodies with airfoils comparable to narrow rods.

All water and coastal birds flying in these conditions have narrower wings than those of land birds. This is true whatever their mode of flight, rowing or soaring. It can only be atmospheric conditions that cause the transformation since waders living on the plains, as well as lapwings, woodcocks, and bustards, are provided with much less tapered wings than those of their cousins living at the edge of bodies of water and having an appreciably equal wingbeat frequency.

I have carried out experiments proving that the above explanation of the variation of wing shape is correct. By modifying the configuration of birds' wings, I could see that wing shape is in fact due to the action of the ambient milieu and the manner in which wings move, which causes reactions having the result of partly or totally tapering the wings. /145

Wing Cross Sections

Avian wings have other characteristic features. Whatever their shape, their lower surface is always concave in every direction. The wing is composed, as I have said, of a plane underlying the upper limb's bony and muscular masses and on the average equal to a third of the wing width in narrow winged birds and a quarter of the wing width in wide winged ones.

Figure 225
Average Wing Curvature
in a Soaring Raptor

Figure 226
Average Wing Curvature
in a Soaring Palmiped

The remiges come next. They are always arched downwards and make an angle with the first plane that decreases as it approaches the body. For most birds this angle is very large, as can be seen in figure 225.

In contrast, the angle is much smaller in aquatic species, who live in strong air currents. It is always less than 140° according to my own research. Great soaring birds like albatrosses (figure 226) and gannets exhibit angles on the order of 120° around the elbow. The wing thus looks like it curves very strongly downward in this area. Given its narrowness, it resembles a gutter, and the wind's action on it is very effective. The angle increases as the wingtip is approached. My studies indicate that the lower surface of the wing is only slightly concave in the hand section. The curvature becomes pronounced near the carpus and increases further the nearer one gets to the body. This is true for all birds, whatever the magnitude of wing curvature.

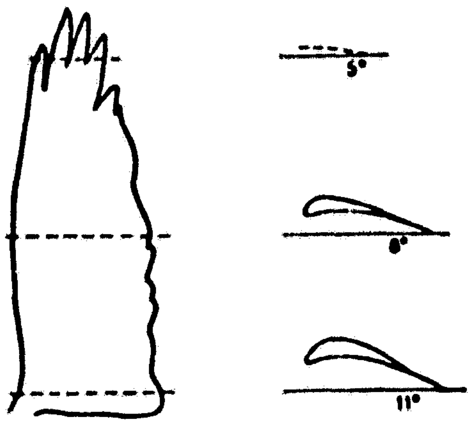


Figure 227
Bearded Vulture Wing with Cross Sections Showing Various Curvatures and Angles of Incidence

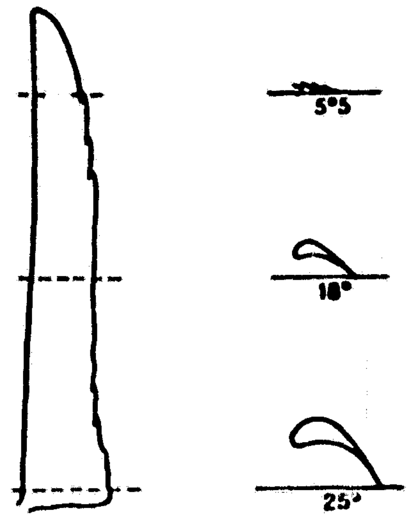


Figure 228
Soaring Albatross Wing with Cross Sections Showing Various Curvatures and Angles

The variable magnitude of the curvature is shown for a raptor in figure 227 and for a palmiped in figure 228.

Wing Feathers /146

Taking a look at feathers, one sees that the remiges of raptors and soaring waders, as well as those of pelicans, all birds specializing in using ascending winds in similar regions, have a special appearance. The primary remiges are wide at the base, but the barbs get narrower at the tips (figure 229). This is why there are slots between remiges. In contrast, the secondary remiges have well developed barbs with pretty much the same length everywhere (figure 230).

The wing feathers of marine soarers, rowing raptors, small waders, and ducks are different: The primary remiges are tapered and remind one of a pointed knife (figure 229). They are never separated from each other and instead are massed together so as to act like a single remex. The secondary remiges are, in contrast, little developed (figure 230). In addition, they appear proportionally smaller than in soaring raptors.

Notice also that the primary remiges of land soarers are more /147
curved than those of marine soarers (figure 231). The narrowed part of the large plumes curves downward at rest much more in the former birds than they do in the latter.

On the other hand, the secondary remiges of marine soarers are much more arched than those of land soarers. Their curvature resembles the general curvature of the wing (figure 232).

Wing Thickness

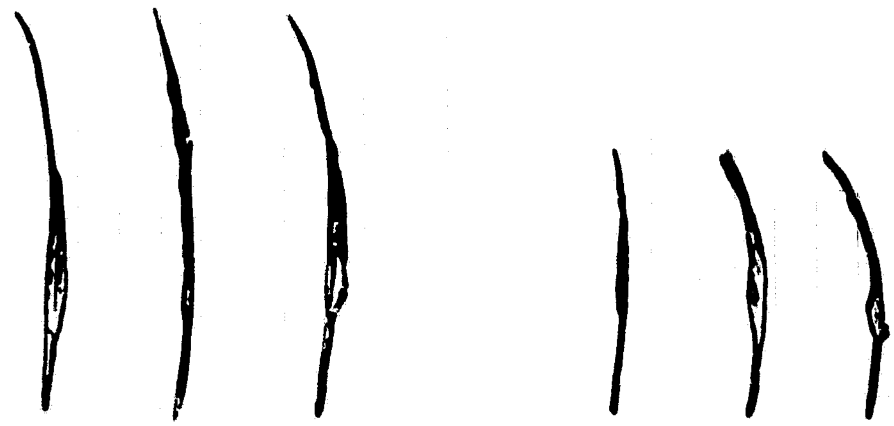
The thickness of bird wings varies by group and, therefore, flight mode. Cross sections of a wing at the middle part of the arm reveal a rounded anterior edge, a concave lower surface and an upper curvature that rises steeply at first and then descends more gradually. The highest point of the upper curvature is located at the thickest part of the wing. This is where the mid-frame member is found. It is more elevated at the elbow than at the hand joint. .

Figures 229 & 230
Remige Length in Soaring Birds
with Dimensions they would have if All the Birds Weighed the Same
Left: Primary Remiges: 1, Eagle; 2, Gannet; 3, Albatross
Right: Secondary Remiges: 1, Eagle; 2, Gannet; 3, Albatross

Such an arrangement gives the wing a characteristic configuration. Its thickness decreases from the point of attachment to the wing tip and from the midframe member to the following edge, where the wing is thin.

An examination of their wings will prove that soaring birds have very thick ones compared to other birds, with albatrosses having the thickest of all. In contrast, gallinaceae and rowing /148
palmipeds have the thinnest wings. Figure 233 very graphically displays the wing cross sections of the principal avian groups.

Lastly, bird wings change shape in certain characteristic ways during flight. They undergo a double curvature in all birds, whether they are gliding or flapping (figures 234 and 235).



Figures 231 & 232
Curvature in Soaring Bird Remiges Reduced to the Same Length
Left: Primary Remiges: 1, Eagle; 2, Gannet; 3, Albatross
Right: Secondary Remiges: 1, Eagle; 2, Albatross; 3, Gannet

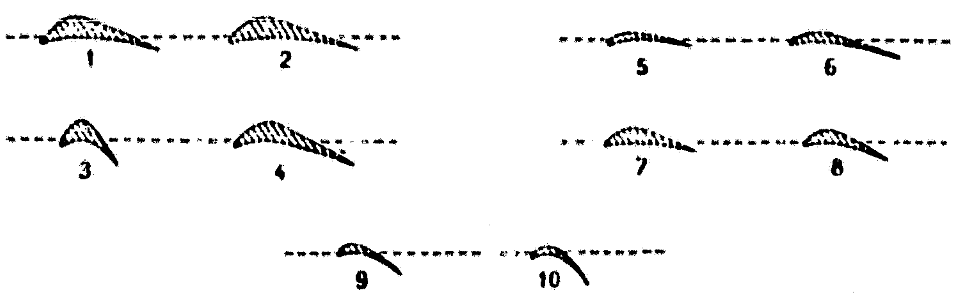


Figure 233
Schematic Wing Cross Section Showing their Relative Width and Thickness as well as Curvature According to Flight Type
1, Bearded Vulture; 2, Eagle Owl; 3, Wandering Albatross; 4, Common Heron; 5, Common Swift; 6, Yellow Bunting; 7, Ringdove; 8, Black Grouse; 9, Common Pochard; 10, Rednecked Grebe

Figure 234
Transverse Cross Section through the Carpus of an Outstretched Albatross Wing
Left: Standing on its Feet; Right: During Gliding Flight

Figure 235
Transverse Cross Section through the Carpus of an Outstretched Kite Wing
Left: Standing on its Feet; Right: During Gliding Flight

Wing Size

Among the organs of flight, wings stand out as most important. Wing size has therefore been the subject of much work. The ratio of wing surface area to body weight, S/P, has particularly attracted scientists' attention over the years. Even though such a ratio probably does not have a great significance (we shall return to this point later), it has been adopted by many authors. This is why we are going to present the findings concerning it first.

In taking up the study of avian wing size, I did not calculate wing area geometrically, as almost all my predecessors had done. Rather, I spread bird wings out over graph paper and traced them as accurately as possible. This was done in such a way that the separation between remiges was close to what it was in nature. I then drew their contour, including the slots frequently encountered on the ends of some wings. I thus obtained a figure for the real wing surface area that was very close to reality.

I first divided the real wing area expressed in cm^2 by body weight expressed in grams and then sought to discover what the area per kg of animal was. Here are the figures I obtained for the various groups.

	Av. Body Weight (gr)	Wing Area per kg (dm^2)
Soaring Palmipeds	2 552,7	21,7
Rowing/Soaring Waders	2 301,6	21
Diurnal Soaring Raptors	1 869,5	26,6
Terrestrial Rowing Waders	1 578,1	17,1
Swimming/Rowing Palmipeds	1 380	8,9
Rowing Gallinaceae	861,2	10,2
Diving/Rowing Palmipeds	736,5	9,2
Rowing/Soaring Palmipeds	697,1	30,7
Nocturnal Rowing/Gliding Raptors	466,4	40,5
Diurnal Rowing Raptors	423,7	29,2
Rowing Columbidae	326,3	18,2
Rowing/Gliding Corvids	272	32,2
Diving/Rowing Waders	260	19,5
Waterside Rowing Waders	176,9	25,9
Rowing/Soaring Passerines	46,7	57,2
Diving/Rowing Passerines	36,4	29,6
Long Distance Rowing Passerines	33,1	51,6

	Av. Body Weight	Wing Area per kg.
Short Distance Rowing Passerines	23,9	57
Vibrating Passerines	2,85	54

[Commas in tabulated material are equivalent to decimal points.]

An examination of this table might lead to the conclusion that there is an inverse relationship between wing area per kilogram and body weight. However, further examination quickly reveals that the relationship does not vary in a simple fashion. At most, one can make the approximate generalization that the largest birds have the least wing area per kilogram while the smaller ones have the most. Such an approximation would be, moreover, partly at odds with current observations. For example, when comparing a quail and an owl, it seem obvious that the owl has more extensive wings, yet this is contrary to the relationship I have just mentioned. Let us say right off that this result has no meaning. It is the consequence of mathematical artifices. In fact, the ratio: /149

$$\frac{\text{Wing Area}}{\text{Body Weight}} = \frac{KI^2}{K'I^3} = \frac{K}{K'I}$$

is not dimensionless. It is still a function of one of the bird's linear dimensions. The larger this dimension is, the smaller is the ratio in question.

In the organometric research I carried out on wings, I preferred to make an innovation and relate real wing area in cm^2 to body surface area calculated by the formula $\sqrt[3]{P^2}$ (P in grams). Ratios of relative surface areas are obtained in this way. They are easier to compare, dimensionless, and of incontrovertible value.

Here are the average results I found for the different groups:

	Av. Body Weight (gr)	Ratio Wing Area to $\sqrt[3]{P^2}$
Diurnal Soaring Raptors	1 869,5	25,9
Nocturnal Rowing/Gliding Raptors	466,4	24,7
Rowing/Soaring Waders	2 301,6	22,6
Rowing/Gliding Corvids	272	19,1
Diurnal Rowing Raptors	423,7	18,8
Rowing/Soaring Passerines	46,7	17,9
Rowing/Soaring Palmipeds	697,1	17,8
Soaring Palmipeds	2 552,7	16,9
Short Distance Rowing Passerines	23,9	14,3
Long Distance Rowing Passerines	33,1	14,2
Waterside Rowing Waders	176,9	12,6
Terrestrial Rowing Waders	1 578,1	12,1
Rowing Columbidae	326,3	12,1
Diving/Rowing Waders	260	10,4
Diving/Rowing Passerines	36,4	9,9
Swimming/Rowing Palmipeds	1 380	9,3
Rowing Gallinaceae	861,2	8,1

	Av. Body Weight	Ratio Wing Area to $\sqrt[3]{P^2}$
Vibrating Passerines	2,85	7,7
Diving/Rowing Palmipeds	736,5	7,2

[Commas in tabulated material are equivalent to decimal points.]

Notice that the average ratio of wing area to body surface varies considerably from one type to another. The range is from 7.2 to 25.9. It can be made even greater if the extreme values are included. The relative area of the penguin's atrophied wing is only 0.4, while that of the Montagu's harrier is 33.9.

I also sought to determine the bird's real body surface area so as to counteract objections that could be raised concerning the use of fictitious body areas in my calculations. To accomplish this, I applied a new method, used for the first time anywhere by a coworker and me. /150

I made up a batch of heavy paint by thoroughly mixing 26 gr of ceruse with 100 gr of linseed oil. I coated the body of a plucked animal with this paint. All I had to do was to weigh the featherless body before and after painting to have the exact weight W of the paint used. If previously the same thing had been done to a 100 cm^2 square of skin, the surface area S in square centimeters can be found.

By dividing real wing area by S, ratios identical to those in the preceding table are obtained. The order of the birds is practically the same, as the following table proves:

Bird	Body Weight (gr)	Gr. of Ceruse Applied	Real Wing Area (cm^2)	Relative Wing Area
Griffon Vulture	7 269	75	7 252	96
Marabou	7 030	87	8 270	95
Kestrel	245	7,50	708,2	94
Jackdaw	253	8,50	606,5	78
Bullfinch	21,4	1,80	95	52
Gray Partridge	387	10	435	43
Sandpiper	133	6	306	61
Mallard Duck	1 105	21	936	39

All the evidence therefore indicates that different birds carry different amounts of flying equipment. Those who have the greatest relative wing area are the soarers or accomplished gliders. They are in fact able to fly or glide over long periods of time precisely because they are well decked out. However, it sould be pointed out that the great soarers, like the palmipeds, who make use of stiff, gusty horizontal winds have smaller airfoils than the soaring raptors who use rising thermal currents and need more extensive wing surfaces for the sake of efficiency. The difference in relative area results from the fact that although the relative wingspreads are the same, the relative widths are very different.

In addition, nocturnal raptors, even though they are rowers and gliders, possess wings of a size almost equal to that of soaring raptors. The rowing raptors, in contrast, have smaller wings, and this is the reason that they are obliged to row.

Groups having an average or small relative wing area are all composed of rowers who can sometimes glide over short distances when their speed is sufficient (gallinaeeae, columbidae), or of birds who are only able to keep themselves aflight by continually flapping their wings (rowing palmipeds). The hummingbirds, who only stay in the air by vibrating their wings, have one of the smallest wing surfaces. Lastly, I sould add that within groups the ratios are fairly close together, as can be noticed by examining the individual figures. For example, there are no soaring raptors possessing a relative wing area less than 17. It can therefore be surmised that below this point, true gliding becomes difficult and that more or less continuous flapping flight is the only mode possible. Such flight becomes more and more impaired and short as wing area is reduced.

By studying figures 220 to 224, one can get a good idea of the differences that exist between different groups of birds.

Avian Load /151

In the meantime, there is a characteristic, known in aviation as load, which represents the number of kilograms supported per square meter of airfoil (P/S) and which our conclusions have not taken into account.

Load, being the ratio between a weight and an area, is not a pure number. It is affected by a linear dimension of the apparatus or animal under consideration and consequently can be used legitimately only to compare apparatus and animals of the same size.

The comparison is very interesting to make for airplanes of the same weight. However when trying to compare directly the load of a 10,000 kg airplane with that of a 1,000 kg machine or that of a bird 100 times smaller, or that of an eagle to that of a hummingbird, one risks making very gross errors. One might be induced to conclude, for example, that the largest birds are the least adept at flight. This is the opposite of what was decided for the ratio S/P and is manifestly incorrect.

For making comparisons with airplanes it might be useful to list the magnitude of the loads. In each group, I averaged the total weight of the member species and the average loads supported per square meter. I thus obtained the first two columns of the following table:

	Av. Wt.	Load P/S	K	$\sqrt[3]{K}$	$\sqrt[3]{K} \cdot \frac{P}{S}$
	gr.	kg par m²			kg par m²
Soaring Palmipeds	2 552,7	7	1,00	1,00	7
Rowing/Soaring Waders	2 301,6	5,3	1,10	1,03	5,4
Diurnal Soaring Raptors	1 869,5	4,4	1,36	1,10	4,8
Terrestrial Rowing Waders	1 578,1	6,9	1,61	1,17	8
Swimming/Rowing Palmipeds	1 380	11,6	1,85	1,22	14,1
Rowing Gallinaceae	861,2	11	2,96	1,43	15,7
Diving/Rowing Palmipeds	736,5	12,7	3,46	1,51	19,1
Rowing/Soaring Palmipeds	697,1	5	3,66	1,54	7,7
Nocturnal R/G Raptors	466,4	2,8	5,47	1,76	4,9
Diurnal Rowing Raptors	423,7	3,8	6,02	1,81	6,8
Rowing Columbidae	326,3	5,5	7,82	1,98	10,8
Rowing/Gliding Corvids	272	3,2	9,38	2,10	6,7
Diving/Rowing Waders	260	6	9,81	2,14	12,8
Waterside Rowing Waders	176,9	4	14,42	2,43	9,7
Rowing/Soaring Passerines	46,7	1,8	51,65	3,79	6,8
Diving/Rowing Passerines	36,4	3,3	70,12	4,12	13,5
L.D. Rowing Passerines	33,1	2,1	77,35	4,26	8,9
S.D. Rowing Passerines	23,8	1,8	106,80	4,74	8,5
Vibrating Passerines	2,85	1,8	895,61	9,63	17,3

[Commas in tabulated material are equivalent to decimal points.]

Since the animals are ordered by decreasing average weight, it would be natural, according to what we have explained, to expect a decreasing load capacity also. Now, a clear decrease in load does not occur. There must be a phenomenon that the mathematical artifice already mentioned has not completely covered up. It must therefore be uncovered and drawn into the light.

As I have said, load comparisons between animals of the same size are legitimate. Now, suppose that all our birds have the same density, which is not far from the truth, and the same or similar shapes, which is not at all true. Let P_1, P_2, P_3......P_n represent the different average weights. The quotients $P_1/P_1 = K_1$, $P_1/P_2 = K_2$, $P_1/P_3 = k_3$.......$P_1/P_n = K_n$ yield numbers K such that if one multiplies P_α by K_α, P_1 is obtained. /152

In the same way, with the hypotheses already made, if one multiplies a surface area S_α by the coefficient $\sqrt[3]{K_\alpha{}^2}$, the result should be S_1, the surface area of the first group of birds.

Again in the same way, if the length L_α is multiplied by the coefficient $\sqrt[3]{K_\alpha}$, the result should be L_1, the same dimension as in the first bird group.

Given the above, the load P/S is a certain number N multiplied by a linear dimension L. If birds were similar to each other and if the law were exact, one would then have as general rule:

$$P_1/S_1 = (K_\alpha P_\alpha)/(K_\alpha{}^{2/3} S_\alpha) = \sqrt[3]{K_\alpha} \cdot (P_\alpha/S_\alpha)$$

I thus calculated the K coefficients and then $\sqrt[3]{K}$, and multiplied each load by the corresponding coefficient and found, finally, the numbers in the last column of the preceding table, which gives the loads supported by the wings of different orders of birds reduced to the same size.

The loads are not at all equal. Their comparison allows the following list to be made up:

Group	Load/ m^2 of wing surface (kg)	Group	Load/ m^2 of wing surface (kg)
Diurnal Soaring Raptors	4.8	L.D. Rowing Passerines	8.9
Nocturnal R/G Raptors	4.9	Waterside Rowing Waders	9.7
Rowing/Soaring Waders	5.4	Rowing Columbidae	10.8
Rowing/Gliding Corvids	6.7	Diving/Rowing Waders	12.8
Diurnal Rowing Raptors	6.8	Diving/Rowing Passerines	13.5
Rowing/Soaring Passerines	6.8	Swimming/Rowing Palmipeds	14.1
Soaring Palmipeds	7	Rowing Gallinaceae	15.7
Rowing/Soaring Palmipeds	7.7	Vibrating Passerines	17.3
Terrestrial Rowing Waders	8	Diving/Rowing Palmipeds	19.1
S.D. Rowing Passerines	8.5		

This is still identical as a whole to the listing furnished by the study of relative wing area. It is the soarers and rowing/gliders whose wings support the smallest load. The heaviest loads are supported by the wings of the large rowers and the vibrators.

Lastly, it is interesting to note that if contemporary airplanes were reduced by an analogous procedure to the same size as above, i.e. to the dimensions of a bird with a one-meter wingspan, one would see that certain avian groups carry a considerably greater load than modern-day aircraft. Thus, a machine with a wingspan of 10 meters carrying 40 kg/m^2 reduced to a one meter wingspan would carry only 4 kg/m^2. In contrast, a diving/rowing palmiped with a 10 meter wingspan would support 101 kg/m^2. /153

Altitude and Wing Surface

Birds not only remain aloft and move forward by moving their wings, they also ascend up to varying altitudes.

The altitudes attained by birds are, as a whole, poorly known. It is almost impossible to determine the platform, or maximum attainable height, of small birds. A movie camera or even an observer rapidly loses sight of them. The situation is the same for large, very high-flying species, like vultures.

This is why the published data are frequently imprecise or even totally off the wall.

Some progress has been made by especially curious balloon and airplane pilots and mountain climbers who had gotten into the habit of making observations during their ascents. By noting birds that were flying near or above them and by measuring the altitude with a barograph, they have established that such and such a species can fly to such and such a height. They have also noted that never have they encountered certain birds above a given height.

Here is a list of these observations:

Bird	Maximum Observed Altitude (m)	Bird	Maximum Observed Altitude (m)
Condor	6.000	Swan	2.000
Bearded Vulture	4 à 6.000	Lapwing	2.000
Griffon Vulture	6.000	Mallard Duck	1.800
Eagle	4.500	Stork	1.500
Kite	4.000	Lark	1.200
Falcon	3.000	Quail	1.000
Sparrowhawk	3.000	Crow	900
Goose	3.000	Swallow	7 - 800
Pigeon	2.500	Nightingale	100
Buzzard	2.500	Woodcock	50 - 80
Heron	2.000		

[Periods in tabulated material are equivalent to commas.]

It appears correct to conclude from these data that birds with a large relative surface area are the ones who attain the highest altitude, whereas those with a smaller wing surface cannot climb to much more than 2,000 meters. This seems logical enough since it is known in aviation that an airplane's platform is partly dependent on the size of its wings and that in theory wing area must be augmented the higher one goes to maintain constant lift. This is because of the reduction in air density with increasing altitude. /154

Wing Weight

Bird wings, whose characteristics vary from group to group, are put in motion by the action of the large and small pectoral muscles, as we have already seen. The function of the former is to lower the wing, while the latter serves to raise it in the course of a wingbeat.

Before taking up the study of these muscles, and consequently of the avian motor in the different modes of flight, it is useful to take a look at relative wing weight. This weight could have an effect on the effort required by a bird to make its wings move.

There are two points to consider concerning wing weight. They are the ratio of real wing weight to body weight and the ratio of wing weight to wing area, which will inform us of their lightness or heaviness. It is in fact very important to determine whether wings are massive or light relative to the extent of their surface.

In order to present an introduction to the subject, I am going to start off by considering the average relative wing weight, i.e., the weight of the wings per kilogram of animal, for each group characterized by a different mode of flight. The results I obtained are summarized in the following table, which orders the bird groupings according to the relative weight of their wings:

Group	Body Weight (gr)	Relative Weight of Whole Wings (gr)	Relative Weight of Plucked Upper Limbs (gr)	Relative Weight of Wing Feathers (gr)
Diurnal Soaring Raptors	1 869,5	214,5	148	66,5
Nocturnal R/G Raptors	466,4	195,4	142,1	53,3
Rowing/Soaring Waders	2 301,6	186,6	129,1	57,5
Diurnal Rowing Raptors	123,7	183,7	130,6	53
Soaring Palmipeds	2 552,7	172,1	123,2	49,2
Rowing/Soaring Palmipeds	697,1	162,5	107,6	51,9
Rowing/Soaring Passerines	46,7	151,3	113,1	41,2
Rowing/Soaring Corvids	272	147,1	101,9	42,2
Rowing Columbidae	326,3	141,2	107,5	33,7
Terrestrial Rowing Waders	1 578,1	121,2	90,5	33,7
Swimming/Rowing Palmipeds	1 380	117,1	88,5	28,8
Waterside Rowing Waders	176,9	115	81,1	33,9
L.D. Rowing Passerines	33,1	109,9	81	28,9
S.D. Rowing Passerines	23,9	103,2	76,2	27
Diving/Rowing Passerines	36,1	103	81	22
Rowing Gallinaceae	861,2	90,7	68,3	22,3
Diving/Rowing Palmipeds	736,5	87,2	65,9	21,3
Diving/Rowing Waders	260	79,2	57,9	21,2
Vibrating Passerines	2,85	62	47	15

[Commas in tabulated material are equivalent to decimal points.]

At first glance, it appears from this table that relative wing weight varies similarly to the way wing area does. The soarers and rowing/gliders with large wing surfaces have the highest wing weight per kilogram of animal. It is equal to a fifth of the body weight in soaring and nocturnal raptors and to a sixth of the body weight in soaring palmipeds. In contrast, rowers with a small airfoil have the lightest wings compared to body weight. Body weight is ten times that of the wings in passerines and gallinaceae. For vibrating passerines, it is sixteen times greater. /155

It is fairly difficult to directly grasp the relationship between wing size and weight because it is pretty rare to find birds with approximately the same wing area belonging to different groups. However, I have been able to gather together a few species in this situation. The area and real weight of their wings are given in the following table:

Bird	Wing Area	Wing Weight
First Series	cm^2	gr.
Capercaillie (Rowing Gallinacea)	1 081	206
Red throated Diver (Rowing Palmiped)	1 116	184
Little Bustard (Rowing Wader)	1 040	120
Cory's Shearwater (Soaring Palmiped)	1 080	98
Common Gull (Rowing/Soaring Palmiped)	1 040	92
Carrion Crow (Rowing/Gliding Corvid)	1 090	85
Montagu's Harrier (Soaring Raptor)	1 130	60
Longeared Owl (Rowing/Gliding Raptor)	1 082	50
Second Series		
Quail (Rowing Gallinacea)	172	7,60
Jack Snipe (Rowing Wader)	178	6,40
Crossbill (Rowing Passerine)	167	5,82
Swift (Rowing/Soaring Passerine)	165	4,90

Although the wing areas are not exactly the same, it is evident that wing weight varies from group to group for wings of nearly the same area. Thus, the capercaillie has wings that are four times heavier than the longeared owl's in spite of the fact that they are of equal size. Similarly, the quail has heavier wings than the swift.

However, it is difficult to use this method to decide on the relative lightness of wings in all the avian groups characterized by different modes of flight. Another procedure is called for. To this end, I calculated the average ratios between wing weight and area for the different groups. In the same way as in the study of wing loads, I multiplied the ratios by the coefficients $\sqrt[3]{K}$ contained in the table on page 214. They are applicable here because the average body weights are still the same.

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Group	Wing Weight per m^2 of Wing Area $\left(\sqrt[3]{K}\,\frac{P}{S}\right)$	Group	Wing Weight per m^2 of Wing Area $\left(\sqrt[3]{K}\,\frac{P}{S}\right)$
S.D. Rowing Passerines	952	Rowing/Soaring Passerines	1 137
Nocturnal R/G Raptors	976	Waterside Rowing Waders	1 176
Rowing/Gliding Corvids	1 022	Rowing/Soaring Palmipeds	1 185
Rowing/Soaring Waders	1 028	Soaring Palmipeds	1 223
Diving/Rowing Waders	1 041	Diurnal Rowing Raptors	1 250
L.D. Rowing Passerines	1 053	Diving/Rowing Passerines	1 429
Terrestrial Rowing Waders	1 073	Rowing Gallinaceae	1 477
Diurnal Soaring Raptors	1 086	Rowing Columbidaea	1 554
Vibrating Passerines	1 097	Diving/Rowing Palmipeds	1 638
		Swimming/Rowing Palmipeds	1 643

There are thus birds with heavy wings. There are birds with light wings; the rowing passerines and the waders are in this category. The nocturnal raptors are, too, which is the reason why they do not seem to expend great effort when flying even though they row frequently. In addition, they can fly silently thanks to the lightness of their flying apparatus. The soaring raptors have much lighter wings than soaring palmipeds, while diurnal rowing raptors, which flap their wings energetically, have heavier ones than soaring raptors. It certainly seems that all the birds that fly by means of continuous energetic flapping have heavy wings. They probably need them for increased wingbeat efficiency. In these birds, the weight of the wings in relation to their surface area is at least one and a half times greater than in other groups.

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I. The Pectoral Muscles

It seemed to me useful to investigate birds' pectoral muscles to see if they did not differ in weight by type of flight. I thus tried to penetrate the problem down to the fine details. The studies I carried out on the pectorals' relative weight, or the weight per kilogram of animal, have led me to conclusions different from those of my predecessors, as can be seen in this table:

Group	Body Weight (g)	Relative Weight of Pectoral Muscles	Relative Weight of Large Pectoral	Relative Weight of Small Pectoral
Nocturnal R/G Raptors	466,1	119,7	113	6,7
Soaring Palmipeds	2 552,7	130,1	122,3	8,1
Diurnal Soaring Raptors	1 869,5	111,7	131,7	7
Rowing/Gliding Corvids	272	112,6	131,5	11
Rowing /Soaring Palmipeds	697,1	143	130,8	12,1
Diurnal Rowing Raptors	423,7	168,2	159,9	8,3
Rowing/Soaring Waders	2 301,6	170,4	155,7	14,6
Diving/Rowing Passerines	36,4	186,2	165,2	21
Rowing/Soaring Passerines	46,7	190,1	172,5	17,9
L.D. Rowing Passerines	33,1	195,9	178,6	17,3
Swimming/Rowing Palmipeds	1 380	198,3	177,5	20,7
Waterside Rowing Waders	176,9	233,1	202,8	30,3
Terrestrial Rowing Waders	1 578,1	236,1	206	30,1
Rowing Gallinaceae	861,2	259,6	197,5	62,1
Rowing Columbidae	326,3	273,2	233,7	39,5
Vibrating Passerines	2,85	341	300	41
Diving/Rowing Waders	260	128,3	111,3	17
Diving/Rowing Palmipeds	736,5	145,7	121,3	21,4
S.D. Rowing Passerines	23,9	153,8	139,6	14,2
Running Birds	10 555	5,7	»	»

[Commas in tabulated material are equivalent to decimal points.]

It is readily apparent that groups differ in muscle mass just as they do in wing size. The difference is that the birds with relatively the most extensive wings are the ones with the smallest musculature. Now, it is known from physiology that the work a muscle is capable of is proportional to its weight. It is in fact observable that the larger a muscle is, i.e., the more fibers it contains, the stronger it is. /158

From the study I carried out on the wing and the pectoral muscles, it turns out that soaring and rowing/soaring birds as a whole have the greatest relative airfoil and the smallest relative pectoral msucle weight. In contrast, the rowers exhibit a small wing surface linked to large pectoral muscles. The pectorals' relative weight varies by a factor of 4 in the carinates. In the true soarers it oscillates between 100 and 130, while it surpasses 200 and often even 300 in the rowers, whose source of propulsion is sometimes equal to a third of their weight.

As a whole, wing area and weight thus vary inversely with pectoral muscle size as one moves from a group characterized by one mode of flight to another group characterized by another mode.

Looking now at the relative quantity of large and small pectorals, it is apparent that, generally speaking, birds with the lightest depressor muscles have small elevator muscles and large wings. In contrast, groups possessing large depressors have large elevators and small wings.

Depressor Weight

It should be noted that the evident inverse relationship between the weights of the various pectoral muscles and wing area is not absolute. There are groups such as the rowing raptors and the rowing/soaring passerines whose pectoral muscles, particularly the depressors, are relatively large even though their wings are fairly extensive also. All these facts are easy to explain. The rowers: passerines, waders, palmipeds, gallinaceae, and columbidae, have moderately to very small airfoils. They cannot remain aloft except by rapidly flapping their wings. Their depressor muscles have thus developed because of the muscular effort required by this mode of flight.

Among the birds displaying well developed wings are the hobbies, common terns, and swifts. However, these gifted gliders often fly in a manner similar to ordinary rowers, with the aid of rapid and repeated wingbeats. They all have very pointed wings and consequently enlarged depressor muscles. Meanwhile, closely related species with slightly larger wings, such as the kestrels, seamews, and house martins, possess less voluminous muscles because their wingbeats are two or three times less frequent.

In contrast, all groups that fly with little or no wing motion have relatively small depressors.

This is the way diurnal soaring raptors and soaring palmipeds fly. However, their depressors have not atrophied despite the absence of wingbeats during soaring. As I have explained, the depressors work during gliding to keep the body in an appropriate position and make it oscillate about the wing axis.

Given that wing shape is related to flight mode and that it also depends on the speed of flapping, the weight of the large pectoral muscle has a direct relation to the number and rapidity of the wingbeats. This is true in every bird group.

The effect of flapping on wing shape and motive power is so clear that it is possible to predict the nature of a bird's muscles simply by observing how it flies.

Finally, let us add that species who make only short flights have very reduced depressor muscles. Such is the case of the group made up of arboreal passerines, who usually only flutter from tree to tree. Also in this situation is the diver group. These aquatic birds rarely leave the water for the air. As a result of the minimal amount of work required of them, their depressors are even smaller than arboreal passerines'. The wren, for example, almost never flies and lives in bushes and holes like a mouse. Its muscles weigh less than those of all other flying creatures. In rheas, who do not fly at all, the weight of the depressor muscles is almost twenty times smaller than in soarers. This confirms the theory of the effort needed to support the body during flight. It is precisely because its engine is too small that the rhea cannot leave the ground, and not because of an insufficient wingspread, which is as great as in many able fliers. /159

Elevator Weight

Let us now look at the results of a study of the small pectoral [supracoracoideus] muscle.

Soaring birds only engage in rowing flight to ascend and to maintain altitude in the absence of wind. Most often, they use rising or horizontal winds to soar, or they glide through the air with outstretched, motionless wings. In all cases, the muscular effort made by the large pectoral is minimal, and their power is reduced because of it. The same reasoning can be used for the small pectorals in soarers. They are of small volume becuase most of the time the wings are motionless and because the wings' upstroke can be considered an automatic result of their large wing surface. Among birds with a small airfoil, the weight of the small pectorals is, on the contrary, ten times greater than in soarers. In addition, their elevator muscles average close to twenty times smaller than the depressors. One anomaly is gallinaceous birds, who make rpaid and repeated wingbeats. Their elevators are only three times smaller. However, the elevators of birds in this latter group are more voluminous than those of swifts because in

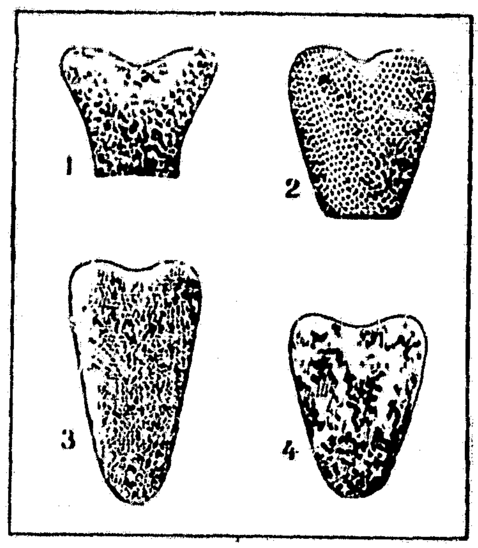


Figure 236
Relative Size of Pectoral Muscles According to Flight Mode
1, Buzzard; 2, Mallard Duck; 3, Northern Guillemot; 4, Ringdove

swifts the series of wingbeats are only several seconds long and are separated by periods of gliding.

Raising the wing therefore requires a considerable effort when the airfoil is minimal. This is true even for birds who fly rarely, such as certain divers, or almost never, like wrens. Their depressors are partly atrophied, but their elevators have remained voluminous enough to allow them to thrust their wings upwards in the course of the rare occasions they leave the ground.

The weight of the muscles is not the only thing influenced by the type of flight. Their dimensions are also affected.

I have reproduced in figure 236 the photographs of four large pectoral types found in birds. Their dimensions have been altered to those they would have if all the birds had the same weight.

Lastly, as I indicated during my first lesson, depressor muscles, in particular, constitute a veritable wing stress indicator. They enable a bird to know at every instant the stress acting on /160
its wings from the pull exerted on these muscles by the elevation of the wing. Among the sources of the pulling force are the action of the air or of ascending winds.

Pectoral Weight per Square Meter of Wing Surface

It seemed to me interesting to discover more exactly what the relationship was between pectoral muscle weight and wing area. I thus investigated the muscle weight corresponding to a square meter of wing surface for each bird. However, as I have already remarked. the ratios obtained by dividing a weight by an area are of no value since they are the result of a mathematical contrivance. One will find that, generally speaking, the largest birds naturally have the largest ratios, and the opposite will also be true. By using the procedure I used for evaluating wing loading, I was able to obtain figures pertaining to birds of equalized size. To do this, I multiplied each real ratio of pectoral muscle to wing area by the desired coefficient and I found the following weights:

	Ratio of Pectoral Muscle Wt to Wing Area (per m^2) $\sqrt[3]{K \frac{P}{S}}$ kg		Ratio of Pectoral Muscle Wt. to Wing Area (per m^2) $\sqrt[3]{K \frac{P}{S}}$ kg.
Nocturnal R/G Raptors	0,610	Diving Rowing Passerines	2,140
Diurnal Soaring Raptors	0,690	Waterside Rowing Waders	2,270
Soaring Palmipeds	0,900	Swimming/Rowing Palmipeds	2,700
Rowing/Soaring Waders	0,930	Rowing Columbidae	3,000
Rowing/Gliding Corvids	0,970	Rowing Gallinaceae	4,170

	Ratio of Pectoral Muscle Wt. to Wing Area (per m^2)		Ratio of Pectoral Muscle Wt. to Wing Area (per m^2)
Rowing/Soaring Palmipeds	1,070	Vibrating Passerines	6,100
Diurnal Rowing Raptors	1,110		
Rowing/Soaring Passerines	1,340	S.D. Rowing Passerines	1,280
L.D. Rowing Passerines	1,850	Diving/Rowing Waders	1,610
Terrestrial Rowing Waders	1,180	Diving/Rowing Palmipeds	2,910

[Commas in tabulated material are equivalent to decimal points.]

The order of the list is very close to that resulting from the study of the amount of muscle per kilogram of animal, but it indicates that pectoral weight per square meter of airfoil is very great in rowers. If one kg of muscle per m^2 is used as a unit of power, it will be found that the strength needed to move a square meter of wing is greatest in hummingbirds and gallinaceae because of the number of wingbeats per second. It is ten times smaller for rowing/gliding birds, and is only a third or a quarter less in large rowers, like the pigeons, small waders, and ducks, who flap their wings only a little less frequently than the gallinaceae.

Heart Weight

I thought that it would be useful to study birds' hearts. Like Parrot, I theorized that the heart hypertrophies to an extent depending on several factors, among which muscular effort seemed to me most important. In birds, the greatest muscular effort is made by the pectorals. The variation in heart weight must consequently parallel that of the pectoral msucles.

I weighed bird hearts completely drained of blood. The figures arrived at were divided by animal weight so as to have comparable results. Here are the averages obtained for the various groups: /161

Group	Heart Wt. per kg of Animal	Group	Heart Wt. per kg of Animal
Nocturnal R/G Raptors	6,9	L.D. Rowing Passerines	13,3
Diurnal Soaring Raptors	7,8	Terr. Rowing Waders	14,3
Rowing Gallinaceae	8,2	R/S Passerines	14,4
Soaring Palmipeds	9	Waterside Rowing Waders	14,5
Rowing/Gliding Corvids	9,8	D/R Passerines	17,8
R/S Palmipeds	9,9	Vibrating Passerines	20,1
Diurnal Rowing Raptors	9,9		
Rowing/Soaring Waders	10	Diving/Rowing Waders	8,6
Swimming/R Palmipeds	11,1	D/R Palmipeds	10,3
Rowing Columbidae	13,2	S.D. Rowing Passerines	12

[Commas in tabulated material are equivalent to decimal points.]

An examination of this table will show that heart weight has a direct relation to pectoral muscle weight or, more exactly, to the effort made during flight. The raptors, soaring palmipeds, and corvids, who have small muscles, have a small heart. The gallinaceae, ducks, waders, passerines, who have powerful pectoral muscles, have more hypertrophied hearts.

Power in Birds

There is much interest in estimating the power of a living engine and, in particular, determining the power expended in flight by birds. A certain number of authors, such as Navier, have tried to calculate, among other things, the work accomplished during flight. Their results were invalid because they based their calculations on inaccurate data. At the present time there are no precise figures on this subject because of the lack of appropriate research apparatus.

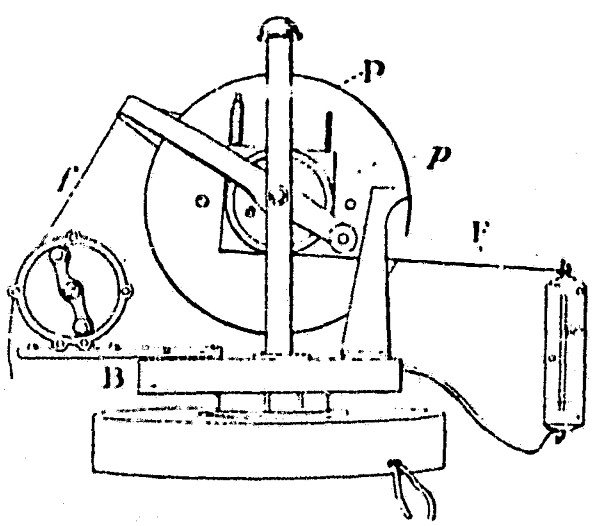


Figure 237
Magnan Apparatus for Studying Birds' Pulling Capacity

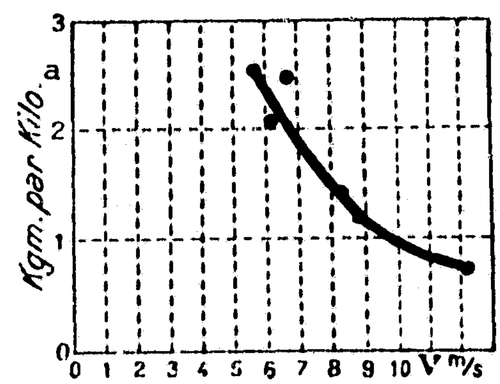


Figure 238
External Power Curve of a Pigeon in Flight

Key: B) Base
F) Lower jaw of brake
f) Upper jaw of brake
P) Large pulley
p) Small pulley
a) Kilogram-meters per kilogram

Even though it is not yet possible to evaluate the power required by flight, it is easier to measure the extra work that can be demanded of a bird. We have studied this question by employing /162 new equipment. For this purpose I used a modified version of the apparatus F. Houssay and I designed in 1912 for determining the flight speed of birds, which was already described above.

A smaller wooden pulley was attached next to the large pulley. A steel-shoed Prony brake was then mounted with two screws on the smaller pulley (figure 237). One of the screws is used to apply the brake through the intermediary of a coil spring. The brake's lower jaw holds a lever arm at the end of which the free part of a spring scale is attached. The fixed part is linked to the base of the apparatus.

If the spring is tightened to close the brake shoes at the same time as a bird in flight pulls on the thread and puts the larger pulley in movement, the animal has to make an effort that varies according to the friction of the shoes on the small pulley. The intensity of this effort can be measured directly by reading the graduations on the scale or by allowing the scale needle to move along a cylinder to make a recording.

From the diameters of the two pulleys, the length of the lever arm linking the small pulley to the scale, and the equilibration of the brake, the pulling force made by the bird can be exactly determined. The animal's speed is recorded at the same time, and with it all the elements necessary to calculate the external power developed by the bird are present: $P = F \times V$, where F is the pulling force in kilograms and V is the corresponding speed in m/sec.

Huguenard, Planiol, and I have recorded the speed and pulling force of carrier pigeons at a predetermined point in their flight. Here are the results obtained:

Pigeon #	Pigeon Wt.	Speed	Pulling Force	Extern. Power	Extern. Power per kg of animal
	kg.	m./sec.	kg.	kgm.	kgm.
137	0,490	5,76	0,225	1,29	2,63
137	0,490	6,08	0,165	1	2,04
118	0,510	6.72	0,1875	1,26	2.47
190	0,400	8,32	0,0825	0,68	1,40
118	0,510	8,96	0,072	0,64	1,25
190	0,490	12,16	0,030	0,36	0,73

[Commas in tabulated material are equivalent to decimal points.]

We also drew the pigeons' specific external power curve with speed in m/sec as the abcissa and power in kilogram-meters per kilogram of animal as the ordinate (figure 328). Based on the table and graph, the maximum power developed by carrier pigeons in our experiments was 2.6 kgm per kg of animal. This is equivalent to 1/30 metric horsepower, which for a 2,000 kg airplane would correspond to an excess power capacity of 69 metric hp.

It might be possible to learn about the power capacity of birds by making them fly with greater and greater loads. The acceleration produced by their wingbeats could then be recorded and the birds filmed as they fly.

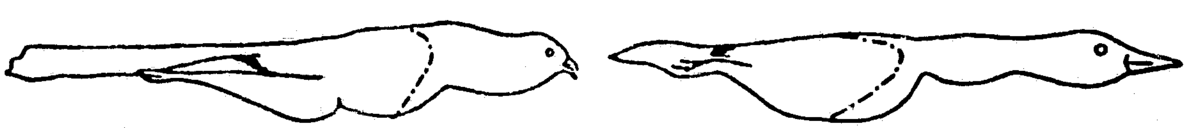
Such experiments have not yet been systematically carried out. Meanwhile, it is known that if 100 grams are attached to the tail of a 350 gram pigeon, it can still ascend at an angle of 11°. With such a load, a pigeon situated at 0.90 meters rose to 3.30 meters and then climbed to more than 12 meters. Pigeons fly with difficulty when carrying a weight of 200 gr. This would indicate that under these circumstances the excess power capacity of a pigeon is not greater than 200 grams, or 70% of its weight.

II. Avian Body Shape /163

Just as the characteristics of birds are closely linked to their manner of flying, their body is also a result of an adaptation to airborne locomotion, and sometimes to a particular life-style, in addition.

The Midframe Member

Alix, without specifying further, had remarked that a bird's trunk is egg-shaped, with the large end pointed forward.



Figures 239 & 240
Midframe Member (Dotted Line) of a Raptor (Left) and a Palmiped (Right)

I searched to find the form of the midframe member in birds by studying their vertical and horizontal projections. These are the lines projected by a bird when it is lying on its side in the first case, and on its back in the second. I have discovered that the midframe member has the shape of a parabolic curve whose apex points toward the head in an animal lying on its side and is located at the thickest point of the body, the middle part of the shoulder joint. When a bird is lying on its back the summit is pointed in the opposite direction, toward the tail, and is situated on the ventral line. The ventral point is forward on the body of birds of weak motive power (figure 239) and is much further to the rear on birds having a large engine (figure 240). This is shown in the following table, in which the real distances between the ventral point and the line passing through the anterior edge of the wings has been divided by the cube root of the bird's weight.

Buzzard	0.40	Gray Laggoose	0.65
Sparrowhawk	0.45	Partridge	0.80
Seamew	0.50	Guillemot	0.80
Eagleowl	0.50	Mallard Duck	0.85

Body Height

I also sought to learn about body height and width with a set of outside calipers. The ratio of width to height has some interesting features.

When the ratio is greater than 1, the width is larger than the height. When it is less than 1, the opposite is true.

This study showed that terrestrial soaring and rowing/soaring birds, whose ratio is greater than 1, have a body that is flattened in the horizontal plane (figure 241). The same goes for truly aquatic birds, such as soaring palmipeds, ducks, and divers. On the other hand, the ratio is smaller than 1 in columbidae, gallinaceae, and waders. These last birds have large pectoral muscles and an elevated breast bone. That is the reason for the increase in body height. In rowing palmipeds, the flattening of the body in the horizontal plane, in spite of the well-developed pectorals, is due to the action of the water, which has elongated the pectoral /164
muscles and thus reduced their height. The results are very apparent in figure 241.

The Center of Gravity

I determined the locations of birds' centers of gravity by the method already described. The positions are marked on figures 220 to 224.

The center of gravity of birds in gliding position is always pretty much located in the transverse plane perpendicular to the major axis of the body and passing through the line of greatest height. It is thus located far forward in soaring and rowing/soaring birds. In rowers it is much further rearward. It always corresponds to the anterior third of the wings for the first group and, as their flying and soaring ability improves, it gets closer to the anterior sixth.

1. Goshawk
2. Eagle-owl
3. Seamew
4. Rook
5. Plover
6. Mallard Duck
7. Partridge
8. Ringdove

+ = major axis
• = center of gravity

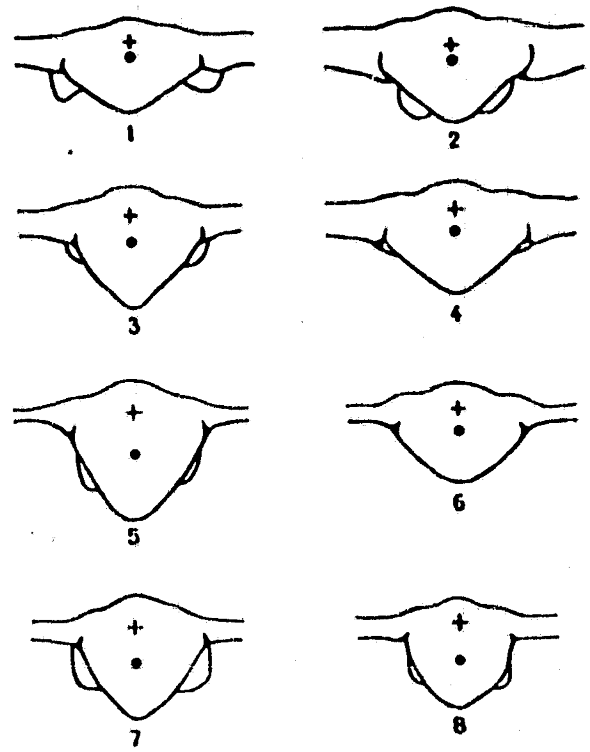


Figure 241
Relative Body Height in Various Birds

Rowers, on the contrary, have a center of gravity located even with the wings' middle region. The worse fliers they are, the closer their center of gravity is to the line joining the wing centers.

Furthermore, the center of gravity is always on the dorsal side of the midpoint of the line of maximum height in the body. The exception to this is certain birds with large pectorals, like the gallinaceae, in whom it is below the midpoint. (See figure 241.) In all birds, the center of gravity is in a horizontal plane below the one passing through the axis of the body, as the same figure shows.

Lastly, the center of gravity is well in front of the line determined by the wing centers of accomplished gliders and is even with this line in rowers.

III. Avian Stability /165

We are going to end this lesson by studying avian stability. This is a very interesting question. Unfortunately, there is very little information obtainable on it.

What strikes an observer watching a bird glide in calm weather is that its displacement most often follows a straight line. When there is a wind, its movement is observed to be stable, i.e., when pushed off its path by a gust, it rapidly returns to its former trajectory.

It is thus evident that a bird's motion is not constant, since its progress can be disturbed by oscillations around its three principal axes, just like what happens to a dirigible.

Such an aeronaut can pitch, i.e., oscillate in the vertical plane about the transverse axis passing through the center of gravity, yaw, i.e., oscillate about the vertical axis, and roll, i.e., oscillate about its major axis.

Corporal Weight Distribution

In a gliding bird, the longitudinal axis, Gx in figure 242, is the major axis in the plane of symmetry. The axis Gz is the minor axis in the median plane. In the bird's usual flight position, it is vertical. Lastly, the axis Gy is perpendicular to the plane of symmetry. It is the transverse axis.

A bird, when it is gliding in a straight line, should automatically, or by the appropriate maneuvers, put up the least

possible resistance to moving forward. This occurs when its major axis is parallel to its trajectory and when its plane of symmetry is held vertical.

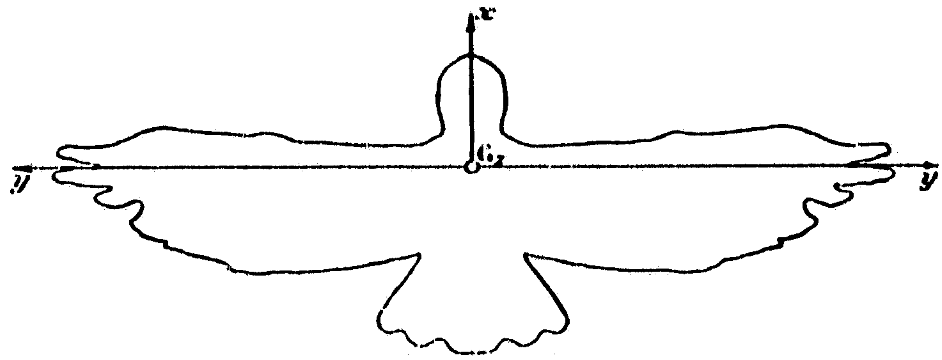


Figure 242
Axes of a Bird

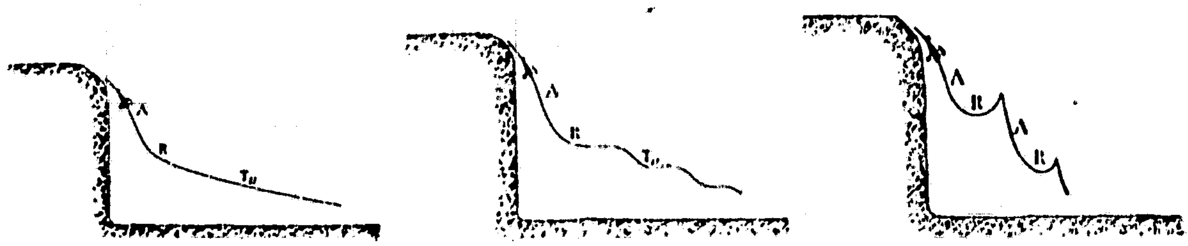


Figure 243	Figure 244	Figure 245
Path of a Well-Centered Glider	Path of a Less Well Centered Glider	Path of a Poorly Centered Glider

Key: A) Swoop — Tu) Uniform trajectory
R) Flattening out — To) Undulated trajectory

If a small well-centered glider, i.e. one whose weight is well distributed, is dropped from a certain height, it will swoop until it achieves its maximum flight speed. It then noses up and follows a straight, somewhat slanted line (figure 243).

If the glider is less well centered, it noses up more. Its speed diminishes, and it performs a new swoop to once again attain its maximum speed. It thus describes a twisting trajectory (figure 244). If the glider is very poorly centered, it noses up so as to be almost vertical after the swoop. It then makes a loop, then a vertical dive and the phenomenon starts over again (figure 245).

To stop the glider from nosing up like this, the front must be weighted down. This has the effect of reestablishing proper balance.

In birds, such automatic nosing up in calm air is never observed during gliding because they are well-centered. However, birds do not have a rigid form like gliders. They can, as we have seen, change the position of their wings during flight. Thus, good gliders hold their wing tips in a forward position when they are moving slowly. This moves the center of gravity forward a little. When they are gliding rapidly, they flex their wings so that the hand joint is very far forward and the wingtips are pointed rearward. The center of gravity is then pushed forward even more, which is equivalent to loading the animal down in front. Moreover, birds can also change the position of their center of gravity along their major axis by lengthening or shortening their necks and by changing the position of their feet under their bodies. /166

Furthermore, birds have at their disposal a caudal surface of varying size.

The Caudal Surface

Birds' tails are mechanisms for establishing balance while flying through the air as well as acting as a brake when landing. They are generally shaped like a sector of a circle. The point is located where the retrices intersect, and the external curvature varies in magnitude. A few species possess a bifurcated tail that is always in motion because of the incessant veering undertaken by the birds. Such movements are the cause of the changes noticed in the tail configuration of kites, American swallow-tailed kites, swifts, terns, swallows, frigatebirds, etc., all of whom perform a type of flight involving numerous rapid maneuvers.

Some interesting information can be drawn from the study I made of birds' tail dimensions. I weighed the rectrices, measured their length, and calculated the tail area by spreading them out while taking care that the feathers remained imbricated as in nature. I related this data to body weight, length, and surface area, so as to have comparable figures. I also determined the ratio between wing area and tail area.

Since I only studied birds whose tail played no ornamental role, the following average ratios retain their total import from the point of view of flight.

We will see, by examining the following table, that there exist two distinct series of birds:

1) Series A, formed by species flying above dry land, in whom the various ratios involving the tail are always fairly large, even though they vary somewhat. On the contrary, the ratio of wing area to tail area is fairly small. Tail length also seems to be linked to wingspread. The tail is large in birds with elongated wings, but it is usually smaller in birds having short wings. This is the reason why the gallinaceae have relatively poorly developed tails.

2) Series B, made up of birds used to flying in watery regions, and who have to deal with strong air currents. Their tails are small, while the ratio of wing area to tail area is very great. /167

	Body Wt.	RATIO Tail Length to $\sqrt[3]{P}$	RATIO Body Length to Tail Length	Tail Wt per kg of Animal	RATIO Tail Area to $\sqrt[3]{P}$	RATIO Wing Area to Tail Area
	gr.					
Series A						
Vibrating Passerines	2,85	2,3	2,5	10,5	5,8	1,3
Diurnal Rowing Raptors	423,7	2,5	2,2	11	6,5	2,8
Rowing Columbidae	326,3	1,9	2,7	8,5	4,2	3,1
Rowing/Gliding Corvids	272	2,4	2,5	8,2	6	3,1
L.D. Rowing Passerines	33,1	2,3	2,5	6,6	4,4	3,3
Rowing/Soaring Passerines	46,7	2,7	2,1	8,8	5,7	3,4
S.D. Rowiong Passerines	23,9	2,3	2,5	5,9	4,2	3,5
Rowing Gallinaceae	861	1,1	3,5	2,8	2,2	4,3
Diurnal Soaring Raptors	1 869,5	2,5	2,4	9,5	7,2	4,4
Nocturnal R/G Raptors	466,4	2	2,5	5,2	4,1	5,5
Terrestrial Rowing Waders	1 578,1	1,2	4,	1,8	1,8	6,8
Series B						
Rowing/Diving Passerines	36,1	1,1	5	1,6	1,8	5,4
Rowing/Soaring Palmipeds	697,1	1,8	3,4	3,8	2,9	5,9
Coastal Rowing Waders	176,9	1,3	4,2	2,2	2	6,2
Soaring Palmipeds	2 552,7	1,8	3,5	4,5	2,3	8
Swimming/Rowing Palmipeds	1 380	0,9	5,7	1,4	1,1	8,6
Rowing/Soaring Waders	2 301,6	1,3	5,1	2,2	2,3	9,9
Diving/Rowing Palmipeds	820,9	0,8	6,7	1,2	0,7	11,1
Diving/Rowing Waders	260	0,9	6	0,9	1	12,3

[Commas in tabulated material are equivalent to decimal points.]

On the whole, the way the groups are ranked is similar to the order of their aspect ratios. Figures 220 to 224 illustrate this very clearly.

The large tail of soaring raptors plays an important role in soaring. It constitutes a third wing in the sense that it supplies lift. It aids the animal to stay aloft while circling and at the same time assures its longitudinal stability. Its ablation has the effect of unbalancing the bird's flight.

In marine birds the caudal surface is much reduced because of the action of strong air currents. However, the tail is nevertheless one of their most important organs. My observations have shown me the major role played by the tail in the course of maneuvers performed by marine soarers. Constantly extended during flight, the tail is used to initiate either ascents or glided descents, as the animal desires.

The tail is very large and well-developed in rowers such as the hobbies, swifts, and hummingbirds, whereas it is much smaller in such aquatic birds as soaring palmipeds. This supports the distinction that can be made between factors causing the almost identical narrowness in the wings of both groups. It confirms that the action of air currents is at the source of the reduction in wing width and tail length among aquatic birds.

Lastly, notice that diving birds have extraordinarily small tails. They are smaller than the tails of other birds who frequent marshes and shores but do not lead an aquatic life. It is known that fishes have a tapered posterior end and that the tapering of their hull is a consequence of the action of the water. /168

I have shown that molding by water happens to diving birds in an identical fashion. The posterior part of their bodies becomes tapered and their rectrices are reduced in length and weight, often to the point of disappearing completely. That is as true for palmipeds and waders as it is for such diving passerines as kingfishers, whose tail has a relative length of 1.1, compared to an average of 2.3 in other passerines (figure 246).

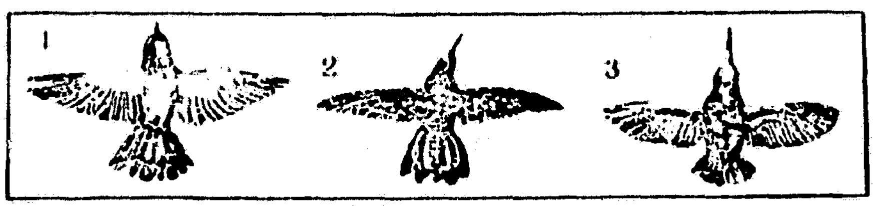


Figure 246
Relative Caudal Areas of: 1, Blueback; 2, Hummingbird; 3, Kingfisher

The Action of the Wind

Birds seem well balanced for gliding, and they follow a linear downward trajectory, as we have seen.

Rolling and yawing are never observed during glides in still air.

As soon as a wind comes up, especially if it is fairly strong, the situation changes. Flights are then observed in which the animal oscillates markedly in the vertical plane (pitches), and oscillates laterally or rolls. The passage of disturbances stronger on the left than on the right side of a bird is enough to make it perform balancing maneuvers similar to those of tightrope walkers.

To regain lost longitudinal and lateral equilibrium, a bird first resorts to its caudal surface, which it can augment or diminish at will. In addition, the tail can be raised or lowered. This enables a gliding or soaring bird to remain on a linear trajectory. As for countering a loss of lateral balance, a bird's wings can be banked to one side or the other at will. This area can also be increased or decreased. Finally, a bird can lower its hand section to stop rotation around its major axis. This is something airplanes cannot do.

Birds are thus wonderfully rigged for maintaining a satisfactory flight stability and an impeccable straightness of flight trajectory.

All this is only from observation, and almost nothing else is known about the balance of birds in flight. It is widely recognized that they manipulate their wings and tail to create eccentric forces that act on the body as a whole. It is further known that the action of the air on the wing and tail surfaces creates a horizontal torque parallel to the trajectory of a bird's major axis that forces its median plane back to a vertical position.

When a bird moves rapidly in still air, the action of external forces is significant enough that it can to a large extent dampen the nascent oscillations. When the bird moves more slowly, these forces are weaker and generally no longer suffice.

The Moment of Inertia

Air resistance exerts a dampening influence on the oscillations of a bird's body and causes its trajectory to more and more closely approximate a straight line. Do not forget, however, that in addition to this useful influence there is the baneful influence of /169
the moment of inertia, which increases oscillatory amplitude, especially when there are sources of perturbation and thus of heightened instability present.

There have never been any experiments done to gather information on this question or to establish a suitable theory of balance for a bird in flight.

I have begun research aimed at determining birds' moments of inertia.

In a rotating bird suspended from a post by a string attached to its center of gravity, the period is linked to the bird's moment of inertia about the axis of rotation passing through its center of gravity. Knowing the period thus allows one to deduce the magnitude of the moment of inertia. The duration of a complete oscillation of a material body suspended by a torsion wire around which it turns is:

$$t = 2\pi\sqrt{I/c},$$

where I designates the moment of inertia, and c is a constant depending on the wire employed.

To determine a bird's three moments of inertia in relation to the three principal axes passing through its center of gravity experimentally, I operated in the following fashion:

I constructed a circular alùminum plate which had been lightened considerably by cutting out numerous holes. Four copper wires were fixed to this plate, which only weighed 100 gr. The four wires were in turn attached to another wire hanging directly over the center of the plate. This last wire served to suspend the apparatus from a cross piece. I first made the system oscillate and noted its period of oscillation. I then placed two 100 gr weights 10 cm from the center of the plate and measured the oscillatory period anew. With that completed, I undertook the study of different birds' moments of inertia in relation to their three axes. Each animal was prepared as for the determination of centers of gravity and was placed on the plate stomach up and wings spread out. In this way, its center of gravity was located on the axis of rotation. (See figure 247.) The animal was then attached below the plate so that first its major axis and later its wingspan were positioned on the axis of rotation (figures 248 and 249). Oscillating the system in each of the three cases yielded the periods leading to the magnitude of the moments of inertia about the three axes Gx, Gy, and Gz passing through the center of gravity.

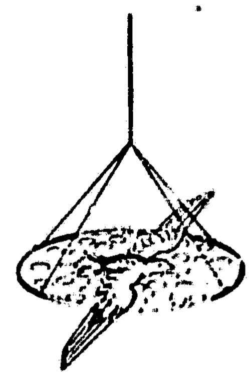


Figure 247
Equipment for Measuring a Bird's Moment of Inertia in Relation to the Vertical Axis

If t is the duration of an oscillation of the empty plate, t_o the oscillatory period with two 100 gr weights 10 cm from the center, and θ the oscillatory period when supporting a bird, the following three equations hold true:

$$t^2 = 4\pi^2 I/c, \qquad t^2 = 4\pi^2 (I + I_o)/c, \qquad \theta^2 = 4\pi^2 (I + M)/c$$

with I the plate's moment of inertia, I_o that of the plate with two 100 gr weights, and M that of the bird under study.

By eliminating I and c we obtain:

$$M = I_0 \frac{\theta^2 - t^2}{t_0^2 - t^2},$$

which can be used to calculate M in each case.

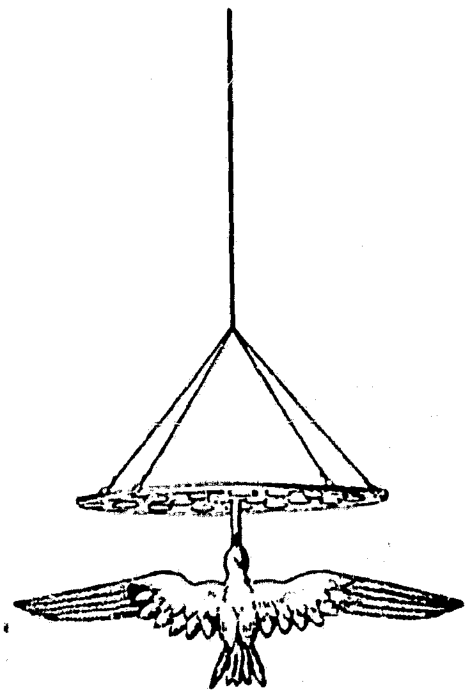


Figure 248
Arrangement for Measuring a Bird's Moment of Inertia in Relaton to the Longitudinal Axis Gx

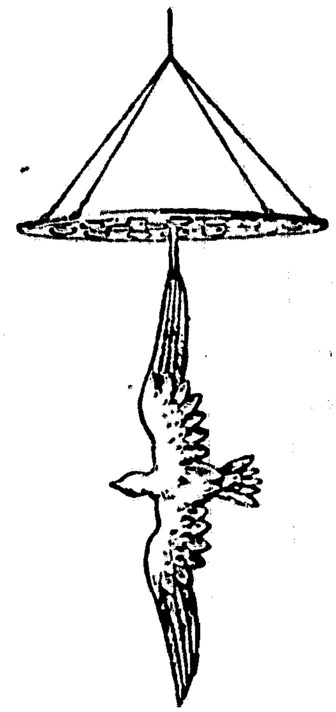


Figure 249
Arrangement for Measuring a Bird's Moment of Inertia in Relation to the Transverse Axis Gy

To make a useful comparison of the various moments of inertia, the ratio of the fifth root of each moment measured to the cube root of the bird's weight is calculated. /170

It might be objected that the air slows down a bird's oscillations, particularly about its major axis, because of the breaking effect of the wings and that the work should be done in a vacuum. Research currently under way has shown, meanwhile, that accomplished soarers have larger moments relative to their major axes than rowers. They are consequently more easily thrown off balance by disturbances.

RECOMMENDED READING

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Lesson Twelve: Motorless Flight in Rising Obstruction Currents /171

An international conference on soaring took place recently (1930) at Darmstadt. Many very interesting papers were read at this conference, which was attended by such German scientists as Karman, Goergii, Hoff, and Pröli.

I went to Darmstadt as a representative of the Ministre de l'Air [Minister of Aviation], the Collège de France, and the Comité français de propagande aéronautique [French Committee on Aeronautical Information] headed by Marshal Lyautey. In this capacity I delivered a lecture on air turbulence.

What is perhaps most striking in such a conference is that human attempts at soaring have not just laid the basis for such remarkable sporting performances as those of the German Kronfeld, who clibmed to 2,160 meters above his point of departure and made a trip of 150 km in his motorless aircraft "Wien." They have also resulted in very important scientific studies and technical progress. Indeed, without this progress no sporting performances would have been possible.

Careful studies have led not only to well designed, highly efficient airplanes, but also to a deeper knowledge of the atmosphere through which gliders as well as powered aircraft maneuver. Only ten years ago, the properties of the atmosphere did not interest technicians any more than if they didn't exist at all. We are now beginning to understand how great is the influence of atmospheric movements on motorized aircraft. This influence can be very undesirable at times since certain atmospheric disturbances accelerate airplanes as much as classic acrobatic maneuvers do. All this progress we owe to the study of soaring.

As we saw during the introductory lesson, while some nineteenth-century engineers sought to build motorized craft to carry them through the air, other researchers attempted to unlock the secrets of bird flight. They tried to imitate the birds by slipping through the air without any motive force besides their own weight and that of their apparatus. /172

All of us have witnessed how a pilot confronted with an engine breakdown in midflight attempts to land properly. He allows his craft to descend under the effect of its weight and tilts its wings to make the best possible use of air resistance. This is what is called "gliding descent" and is practiced all the time by birds wishing to land on the ground. Through the action of their weight, both airplanes and birds conserve speed while they maneuver to approach the earth. In calm weather, an airplane with an engine that has stalled at a given height can thus land within a circle whose radius becomes greater as the airplane's aerodynamic efficiency [lift/drag ratio] increases. (See figure 250.) However, the fact is that under these circumstances, airplanes and birds lose altitude when gliding in still air. They descend constantly.

Figure 250
Three Gliders Descending in Calm Air with Efficiencies of 3, 4.5, and 6, Respectively

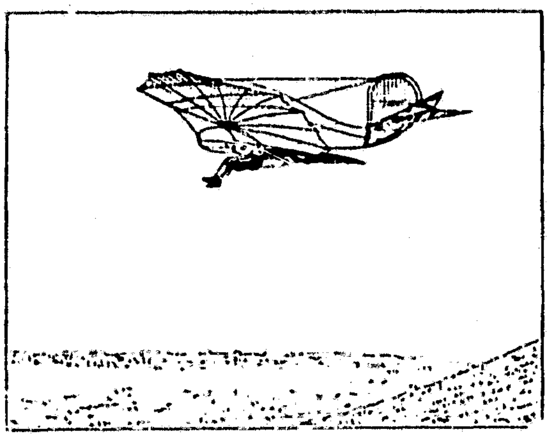

Figure 251
The Lilienthal Glider (1893)

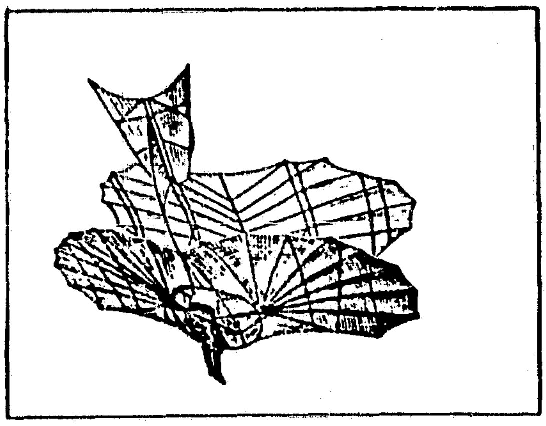

Figure 252
The Lilienthal Glider (1895)

Nineteenth-Century Attempts at Motorless Flight

Among the men who have tried to imitate birds, the German Otto Lilienthal stands out. An aircraft constructor in Berlin, he undertook a conscientious study of birds and of the environment in which they flew. He fabricated well-braced artificial wings attached to two horizontal rudders forming a tail and a large vertical rudder (figure 251). The wings were made of a wicker framework over which a light fabric was stretched. Lilienthal tried to use this glider for soaring. Securely fastened to the center, with his legs hanging down, he launched himself against the wind from the top of a small tower. His method of maintaining balance was to change the inclination of his body under the wings. He succeeded in making some remarkable flights, including a few exceeding 300 meters. However, he never did more than glide; soaring remained beyond him.

In 1896 Lilienthal wanted to perform some new tests on a biplane glider (figure 252). In the course of his thousandth experiment he fell 80 meters and died. Despite this tragic accident, Lilienthal's experiments excited a few followers. A Frenchman living in New York, Chanute, did similar experiments and built the first stabilizers (figure 253). One of Lilienthal's students, Pilcher, also continued his teacher's experiments (figure 254), but he too was killed, in 1899. Also in 1899, Captain Ferber carried out a series of airborne experiments on glider equilibrium (figure 255).

All these experiments yielded useful information. Two Americans, the Wright brothers, bicycle makers in Dayton, were thus able to perform the first human-bird test flights. They made numerous flights in a biplane glider they constructed (figure 256). Thanks to some successful modifications they then created the first powered airplane.

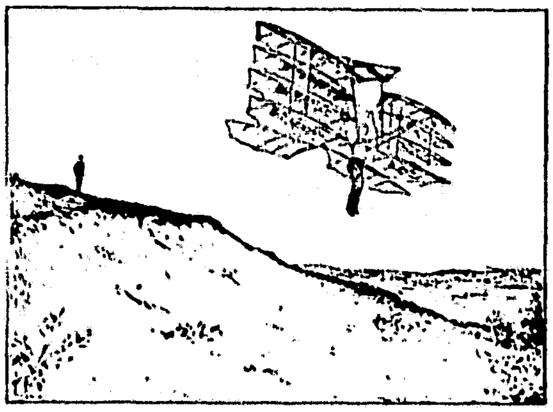

Figure 253
The Chanute Glider

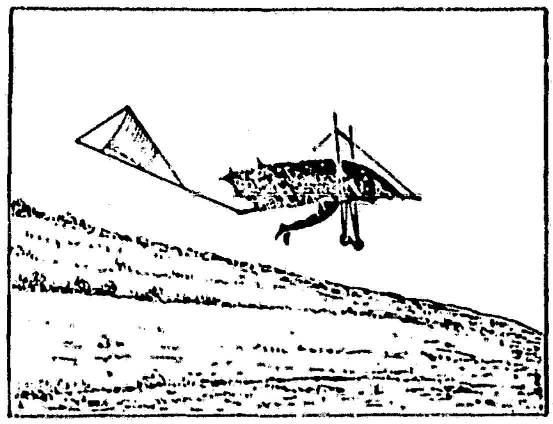

Figure 254
The Pilcher Glider (1899)

/173

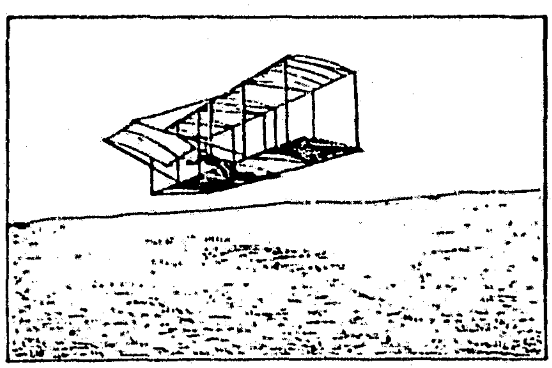

Figure 255
The Ferber Glider (1899)

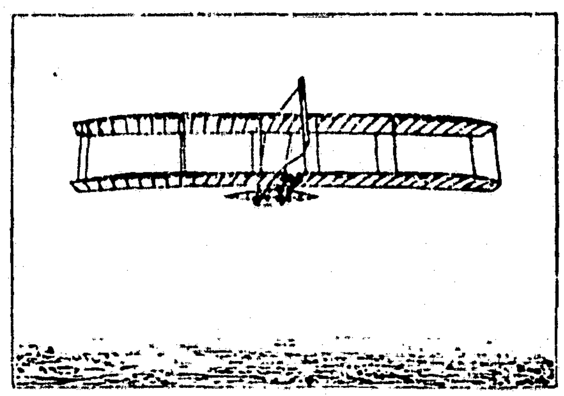

Figure 256
The Wright Glider (1902)

From that time on, most engineers concentrated only on improving motorized airplanes. Meanwhile, a few, like the German Harth (figure 257) and myself, nevertheless continued to be interested in soaring and devoted themselves to trials of powerless aircraft of their own design.

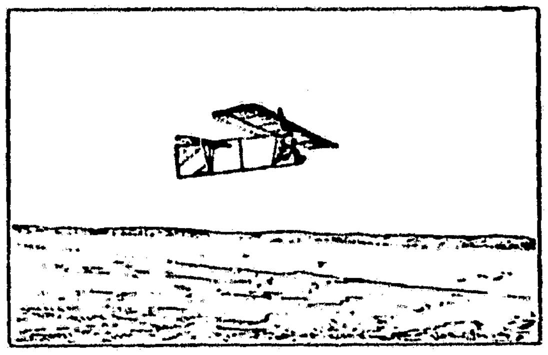

Figure 257
The Harth Glider (1914)

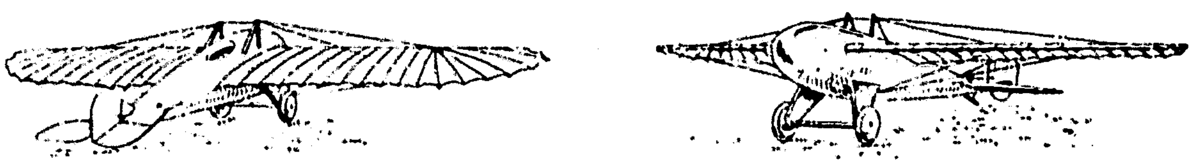

Figure 258
The Magnan Glider (1914)

The glider I designed was patterned after soaring raptors. (See figure 258.) I presented the results of my experiments to the Congrès des Sociétés savantes [Congress of Learned Societies] on August 16, 1911. The airplane was designed to weigh 150 kg including the pilot, and could weigh as much as 200 kg when carrying experimental apparatus. Here are some of its dimensions:

Wingspread	11.90 m
Average Wing Width	1.82 m
Total Length	4.75 m

Wing Area	15.20 m^2
Tail Area	2.5 m^2
Load per m^2	9.8 kg

The vehicle had oval, almost rectangular, flexible wings, the exact form that the wings of soaring raptors have. They were also very thick, especially in the half closest to the fuselage, and had a gutter-like curvature of large radius. In these ways they also resembled soaring raptors' wings. I still think that this kind of motorless aircraft is the most appropriate for flights in rising winds and is better suited than the high aspect ratio craft developed by the Germans.

For these soaring experiments, I also invented an apparatus to indicate automatically if the aircraft was ascending or descending, even only slightly. The instrument includes a closed cylindrical box sealed at one end by an elastic membrane on which a needle is mounted by means of a special arrangement. At the other end is a tube connecting the interior of the box with the surrounding air. This opening to the outside is controlled by a timing mechanism so that it is closed 9 seconds out of 10. When the tube is open, the air pressure inside the box is the same as that on the outside. While it is closed off, the external air pressure might change because the apparatus was ascending or descending and there would no longer be an equal force on each side of the elastic membrane. A deformation in one direction or the other would ensue. It would be manifested by a displacement of the needle toward the right during an ascent and toward the left during a descent. The sensitivity is great enough that the needle's displacement would be easily visible for a gain or a loss of only 1 meter in altitude. Thanks to this apparatus, a pilot will know 9 seconds out of 10 whether he is rising or falling, and consequently if he is still in a propitious zone or is leaving it. He can even automatically prolong his flight by this means. These experiments, even though known to the public, did not interest the experts of the period. On the contrary, their remarks were rather sarcastic. They thought that to borrow from nature to build a machine was an unjustified extrapolation. This was based on the long-standing claim that beyond a certain size, birds are incapable of flight. It was argued that large birds are obviously inferior to the others in terms of flying ability because of the relative decrease in wing size as weight increases. This is a groundless assertion since, as I have proved, it is based on a mathematical contrivance. The example of the ostrich, who weighs 75 kg and does not fly, has been advanced to support it. The ostrich's inability to fly has nothing to do with weight, since small flightless birds like the kiwi or near-flightless ones like the wren are known to exist. For all of them, it is the consequence of an adaptation to a particular life-style that has little by little made flight unnecessary. Actually, it is easy to prove that size is no obstacle to airborne locomotion. /174

As I have already mentioned, the great pterodactyls and the pteranodons existed in America during the Cretaceous period. Their /175 wing-spread attained 9 meters and, as I indicated, their weight must have been about 300 kg. There thus used to be flying creatures as heavy as airplanes. Even heavier fliers than those we know about might have been living then. If there are no fliers as heavy today, that is not because a bird weighing more than 15 kg cannot fly, but is due to other causes. The experiments of Harth and myself did, however, prove to researchers the existence of significant rising currents on windward slopes. They were large enough that a powerless aircraft did not lose altitude. There was therefore no reason why soaring could not be accomplished in such winds. At this point the war intervened to put a stop to all research.

German Experimental Flights in 1920 and 1921

Immediately after the war, the Germans, who were deprived of motorized aircraft, got reinvolved in such experiments and successfully made some astonishing flights, even if they were of short duration. The first results were due to a judicious choice of terrain. To succeed, it was indispensable that no matter what the direction of the wind, strong enough rising currents existed in the area. The Germans chose the region around the Rhön Mountains, which suited them perfectly, as the future was to prove. The launching terrain was a plateau that dominated the neighboring region in every direction with gentle, treeless slopes and valleys wide enough to prolong the flights. In addition, facilities were planned for the personnel and equipment. Vehicles, for the most part constructed by students, were reassembled there. Some were gliders of the Lilienthal type. The best performance they achieved at first was a flight of 52 seconds covering 450 meters. Other devices included small, motorless gliders copying the design of motorized monoplanes, or occasionally of biplanes. By 1921 skids were used as landing gear. Launching the gliders was first accomplished by teams pulling on a rope while running against the wind. At takeoff, the rope was automatically detached.

The principal achievements were the following:

A 5 min 5 sec flight by Koller covering 4 km;
A 5 min 33 sec flight by Martens covering 3.8 km;
A 13 min 3 sec flight by Klemperer covering 2.8 km;
A 15 min 40 sec flight by Martens covering 7.5 km;
A 21 min 27 sec flight by Harth.

In this last flight, the difference in altitude between the highest and lowest points was 400 meters. Figures 259 and 260 depict some of the craft used.

The 1922 French Experimental Flights

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Here and there public opinion became interested in these performances. As early as 1922 the Association française aérienne [French Aviation Association] organized a soaring demonstration at Combegrasse.

This was at the moment when the German aviator Hentzen made a 3 hour flight above the slopes of the Rhön (figure 261).

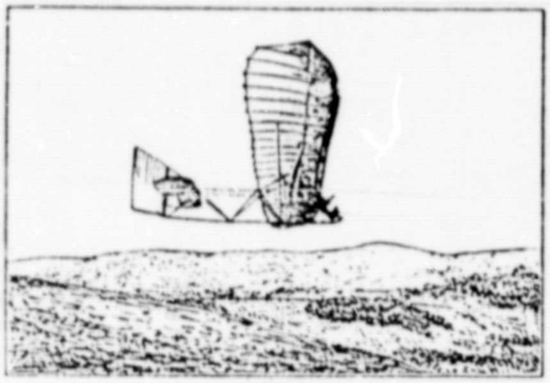


Figure 259
The Harth-Messerschmidt
Glider (1920)

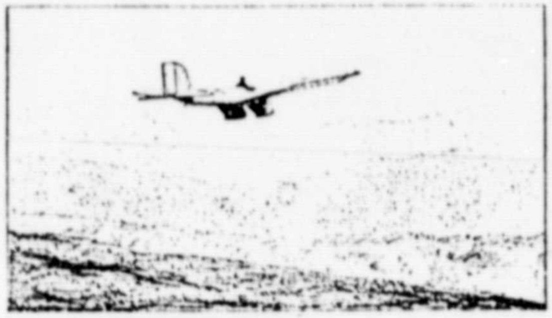


Figure 260
Klemperer's "Schwarze-
Teufler" Glider (1921)

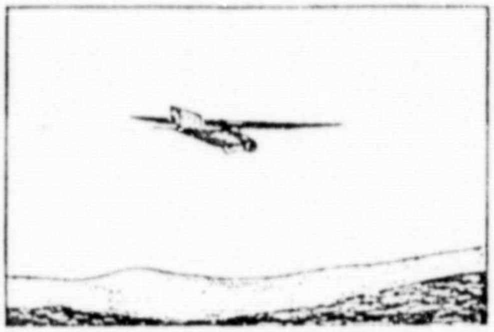


Figure 261
Hentzen's "Hanover" Glider
(1922)

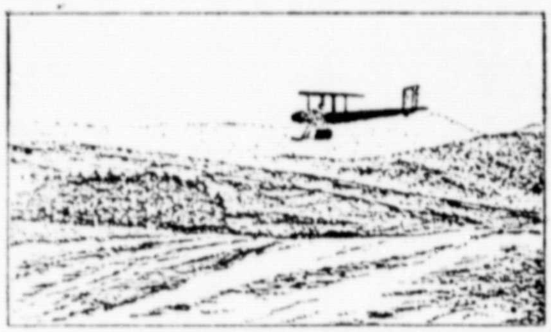
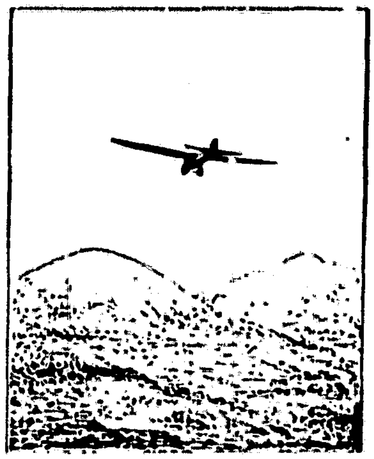


Figure 262
Bossoutrot's Glider
at Combegrasse (1922)

The majority of the apparatus located at Camp Mouillard was comprised merely of Farman's "Mosquito" piloted by Bossoutrot (figure 262), the Coupet monoplane, and the other biplanes, which were ordinary airplanes with their engines removed or had been built without any particular improvement over motorized airplanes. Only Dewoitine had come up with a flexible wing aircraft of new design (figure 263).

The gliding flights made by these vehicles were in reality no longer than any good aviator could accomplish with a machine of the period. Only Bossoutrot succeeded in staying in the air for 5 minutes, at the end of the conference.



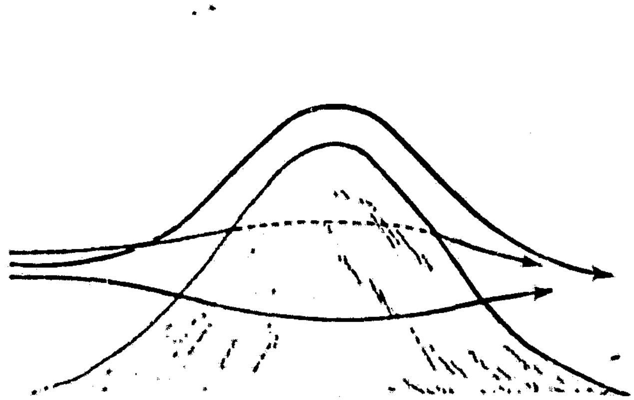


Figure 263
The Dewoitine Glider (1922)

Figure 264
Airflow around a
Mountain Peak

It is certain, however, that better performance could have been obtained at the conference in Clermont-Ferrand from several of the craft sent ot the region. The pilots who launched themselves from the summit of the Puy de Combegrasse should have been acquainted with the techniques of soaring, the structure of the wind they might encounter, and how to maneuver in air currents. As it was, the pilots taking part in the conference were flying gliders that for the most part they had not yet tried out. They thus did their apprenticeship at Clermont-Ferrand and it was for these reasons that they were mostly unable to carry out experiments other than exercises in gliding.

Airflow around a Peak /177

As we know, when layers of horizontal wind encounter a cliff or slope, turbulence arises in the lowest layers at the foot of the obstacle. Meanwhile, the other layers are deflected upward and over the edge of the cliff.

The part of the rising current having the highest intensity is located in front of the cliff's upper edge. The section which is the best for soarers is at least equal in width and in height above the cliff's edge to the height of the obstacle itself. Behind the cliff, and above the ground, an unfavorable zone exists which is the site of much turbulence.

If the cliff or slope is of considerable width, a rising sheet is encountered. I repeat, the sheet does not have a significant cross sectional area, but spreads along before the obstacle in the form of a slice of rising air.

In contrast, if the wind comes across an isolated peak, the airflow is not exactly the same as in the preceding case. (See figure 264.) If the windward slope is not too steep, the current follows its surface fairly closely and pretty much retains its normal speed. At the top of the hill this portion of the wind continues its upward climb, but is pushed back downward fairly rapidly by the upper layers of the air current. A complex phenomenon occurs: While the lower layers of the displaced air mass are deflected from the horizontal in the same proportions as the ground is, the layers a little further up undergo a much less significant deviation because they can more easily flow around the summit. The rising current is more limited here, as a result of the eddies formed on the sheltered side of the hill. It is furthermore never detectable high above the hill.

This is precisely the reason that the French aviators at Combegrasse found themselves in the presence of highly circumscribed rising currents of weak intensity.

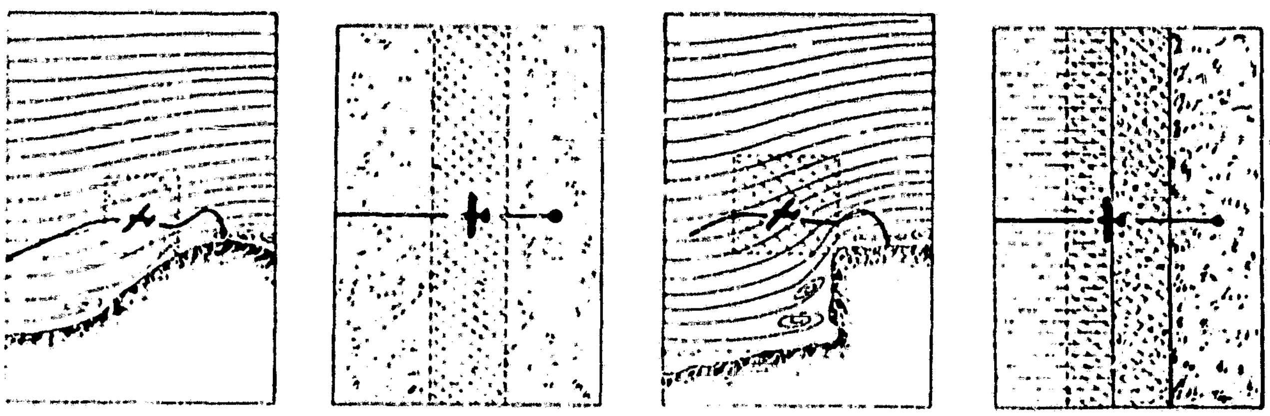


Figure 265
Incorrect Maneuvers for Soaring above a Slope or Peak

Drifting along Cliffs

At the time, we in France were also entirely ignorant of soaring practice. On taking off from a height and continuing along a straight trajectory perpendicular to the cliff's edge as soon as a suitable altitude and speed are attained with the help of a shock cord catapult, the narrow propitious zone is quickly entered and left without any benefit being obtained from the rising wind. (See figure 265.) This is another reason why the uninformed French pilots at Combegrasse could only perform gliding flights.

Since an elevated area is an unfavorable zone for soaring because of the eddies and turbulence existing there, shock cords should be used to acquire a certain initial speed and height for /178
entering the favorable zone. After the slight gain in height during

launching, the soaring aircraft is still in the unfavorable zone and descends to some extent as it advances toward the right.

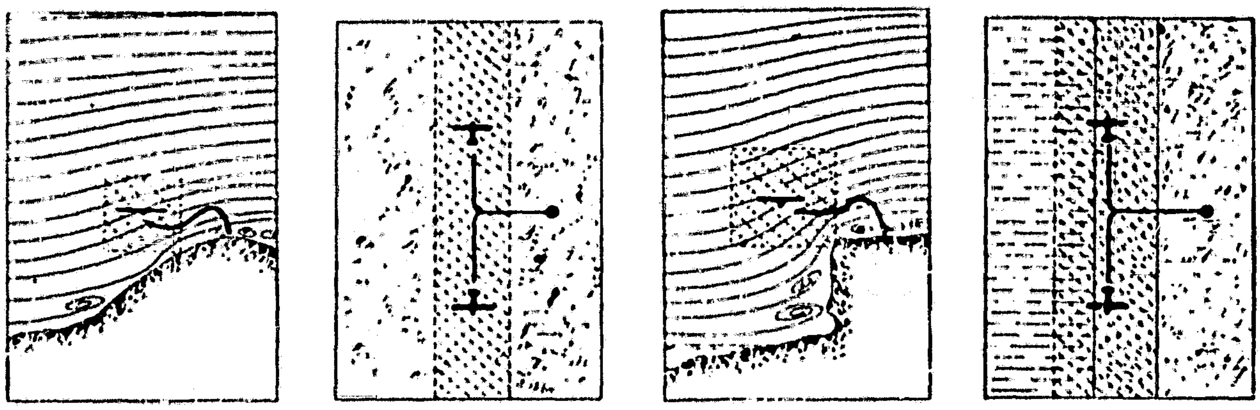


Figure 266
Necessary Maneuvers for Soaring above a Cliff or Slope

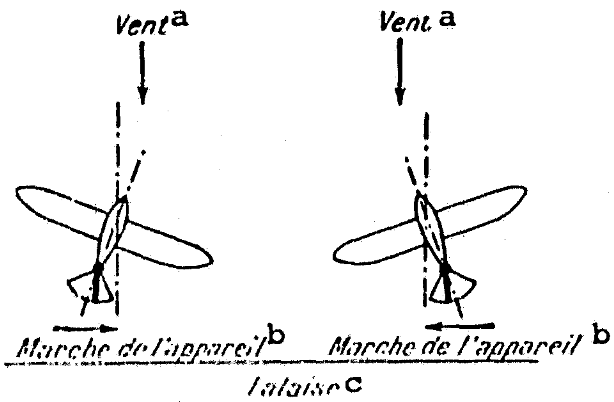


Figure 267
Position of a Drifting Glider

Key: a) Wind
b) Direction of motion
c) Cliff

At the moment when the aircraft penetrates the rising zone, it begins to gain height. It must therefore veer sharply to the right or left so as to fly along the ridge. (See figure 266.) The apparatus continues in these circumstances to rise above and before its point of departure. It can maneuver so as to remain hovering in the air in almost the same spot. It is also easy for it to move along a slope by copying the drifting of sea gulls described above. To do this, this pilot maneuvers the vertical rudders to keep his nose to the wind and the cliff at his back. He moves in one direction or the other, progressing sideways like the birds (figure 267).

Flight Duration Records

This was precisely the maneuver that Maneyrol performed when, in October, 1922, at Itford Hill, he broke Hentzen's record for time in the air by flying for 3 hours 30 min in a Peyret aircraft. This was done on the last day of the contest set up by the Daily Mail, which had established a 1000 L prize for the longest motorless flight.

At two o'clock in the afternoon, Maneyrol appeared with a biplane glider whose two airfoils were located one behind the other, in tandem, instead of being superposed (figure 268). He took off in a strong wind at 2:32 and attained a height of 50 meters. He then drifted along the cliff for 3 hours 30 min before he was forced to land because of darkness. He thus beat Hentzen's record by 10 minutes.

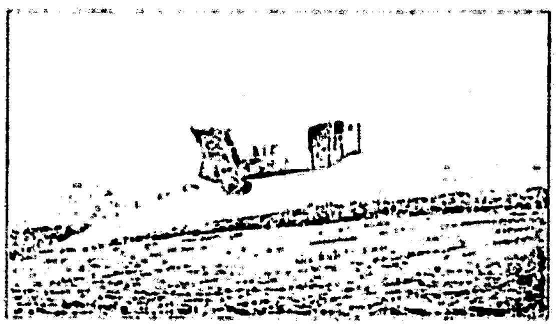


Figure 268
The Peyret Glider
Piloted by Maneyrol

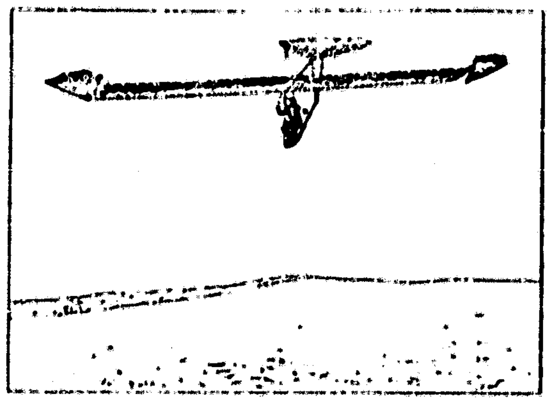


Figure 269
The Schultz Glider
during its Record
Flight

In January, 1923, at Biskra, Thoret soared for 7 hours 3 min in an ordinary airplane with its engine turned off.

Then, on January 29, 1923, Maneyrol remained above the cliff at Vauville for 8 hours 4 min 50 sec. On January 31 of the same year, Barbot unofficially pushed the limit to 8 hours 36 min at Biskra.

Only sixteen months later the German builder-pilot Schultz /179
performed a powerless flight along the slopes bordering the Baltic lasting 8 hours 12 min 9 sec (figure 269). Lieutenant Thoret bettered this record on August 29, 1924 in a stalled Hanriot H.D. 14. He successfully flew over the Alpines for 9 hours 4 minutes at a height of 500 meters above the ridges.

Since then, Commandant Massaux has increased the record to 10 h 20 min and Dinort made a night flight above the Rositten dunes lasting 14 h 43 min.

It should be pointed out that flight duration records no longer have much significance. If there is a continuous, suitable wind in a region of uneven terrain, a pilot can theoretically remain in the sky for days. His performance now depends only on his endurance.

Distance Records and the Influence of Gaps

In contrast, flights along cliffs and slopes can only be extended indefinitely with difficulty because of the very nature of coastal or mountainous terrain.

Gaps frequently exist in cliffs, for example. Although the wind rises before the cliff itself, it rushes into valleys almost horizontally. A veritable unevenness in the distribution of the neighboring air layers ensues. Those that have been deflected by the cliff in the vicinity of this funnel are abruptly pulled downward. The result is violent eddies that give rise to ascending currents on the edges of the gap and toward the center of the holes in the air. (See figure 270.) The influence of the rising currents can be felt up to a certain altitude. They make traversing valleys difficult for motorless aircraft.

Various attempts were made with this in mind. Thus, in 1923 Lieutenant Thoret set a record for linear distance with an 8 km 250 m flight above the Vauville cliff and the sea. /180

At the same time that they were striving to increase the duration of flight, the Germans were trying to establish long-distance records as well. On September 29, 1923, Botsch, in a vehicle with a wingspan of 18.7 m and an aspect ratio of 15.6, left Wasserkuppe and successfully followed ridges of hills from 4 to 500 meters high so as to make the best use of the terrain for a flight of 19 km.

Hirth, in 1925, made a flight of 29 km at Vauville. Since then, the Germans have done much better, but under other conditions.

Altitude Records

Lastly, other experimental flights were made to attain the highest possible altitude in rising obstruction currents. It seems that the greatest height above the point of departure attained so far was 250 meters in 1927.

Born in France in 1922, motorless flight has since then been the object of fewer and fewer tests in our country. In 1925, a demonstration again took place, this time at Vauville. There were some interesting apparatus to be seen there, including Abrial's "Vulture" (figure 271), which was piloted by Auger during its performance. Since that period, nothing was accomplished until 1930, when a society, Avia, affiliated with the Comité français de propagande aéronautique, tried to revive motorless aviation.

By contrast, in Germany, studies were pursued without interruption. Our neighbors have succeeded not only in perfecting the techniques of soaring above mountain slopes but have also created a new mode of powerless flight which will be described in the next lesson. (It should be pointed out that the pilot Thoret is also past master of soaring above mountains since he keeps flying over the peaks of Mont Blanc in his motorized airplane by using areas of rising currents to increase his ceiling.)

I stated in 1922 that to soar satisfactorily, particularly in rising currents, three conditions must be met:

1) An appropriate, efficient aircraft must be built;

2) The rising winds capable of increasing the craft's altitude must be studied;

3) Piloting techniques in such winds must be developed.

By fulfilling these conditons, the Germans were able to accomplish flights of a new order in 1929.

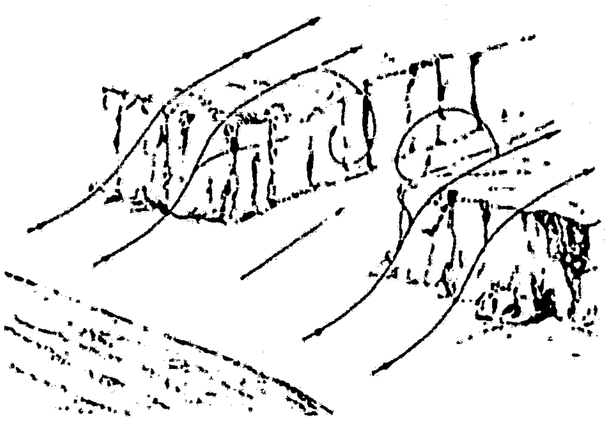


Figure 270
Air Flow in a Gap in a Cliff

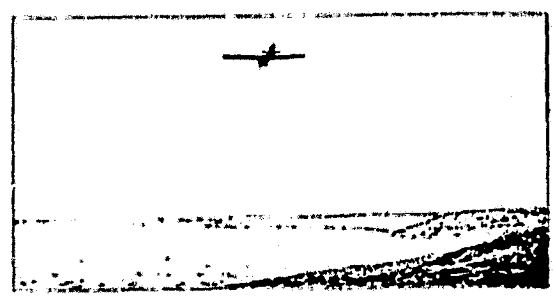


Figure 271
The Abriel Glider Piloted by Auger at Vauville

RECOMMENDED READING

Abrial, "Les efforts français pour le vol sans moteur" [French Work in Motorless Flight], Vort a. I Intern. Wissensch. Segelflugtagung in Darmstadt (1930).

Comité francais de propagande aéronautique, Le vol à voile [Soaring], (1930).

Kieffel, W., Der Segelflug, Berlin (1930).

Lilienthal, Der Vogelflug als grundlage des Fliegekunst (1889).

Magnan, Recherches expérimentales sur le vol à voile [Experimental Research on Soaring], Roche d'Estrez, Paris (1922).

Magnan, Pour voler à voile [In Order to Soar], Roche d'Estrez, Paris (1923).

Magnan, Le vol à voile [Soaring], Roche d'Estrez, Paris (1925)

Lesson Thirteen: Motorless Flight Below and Before Clouds /181

We have seen how motorless aviation was born and what had been accomplished through the use of horizontal winds forced upward by an obstacle: slope, cliff, or mountain.

I. The Study of Rising Winds in the Vicinity of Clouds

In another area, several scientists in France and elsewhere have shown that below cumulus clouds a rising air current, sometimes of considerable magnitude, always exists.

Personal Research

I myself, in the course of my studies on the structure of winds rising as a result of the heating of desert ground, have observed a predilection for such currents in certain locations. One can almost always see a white ball, a sort of cumulus cloud, above hillocks in Tunisia when the temperature and humidity are high enough. This is due to the existence of a rising humid air mass in these elevated regions. The air mass cools down at a certain height, thus causing the water vapor within it to condense. I have indicated that hillocks are points where thermal currents are easily created. They are frequently visible near cumulus clouds above the peaks of the Pont du Fahs region. They occur in midsummer, especially when the temperature exceeds 35°. Another area in which thermal currents can be seen is above the elevated points of the Kairouan and Medenine regions.

At certain moments, particularly when storm clouds are approaching at the same time as there is a horizontal wind, the formation of vertical swirls of sand in desert regions strongly heated by the sun is noticeable. They are tens of meters in height and resemble the whirlwinds that constitute the chimneys of rising thermal currents. Such whirlwinds are forced along by the horizontal wind, if there is one, and move at the wind's speed without being appreciably altered. We observed them several times in the desert between Graiba and Gabes.

We have seen several lined up one behind the other and moving with the wind over a course of several kilometers.

Since 1925 we have been able to study such currents with our hot wire apparatus, the anemometer and inclination indicator.

My observations, made in collaboration with Huguenard and Planiol, showed that air currents in the desert around Medenine display a marked ascendence above ground level ranging up to 15° and even 29° (figure 272). Near the ground they are practically /182
horizontal. In addition, they exhibit much less agitation near the ground than higher up. The vertical speed of such winds varies from .4 m/sec to 4 m/sec.

Although nobody paid much attention to these findings in France, some German professors, such as Georgii, sought to extend the existing body of knowledge about thermal currents.

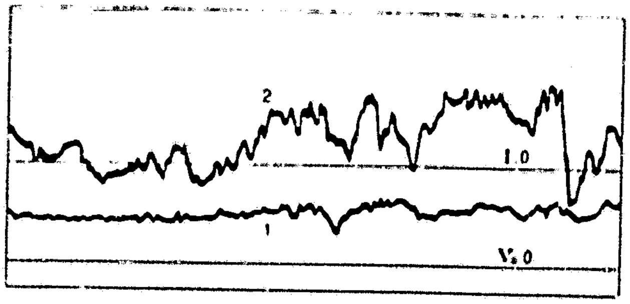


Figure 272
Speed (1) and Inclination (2) Recordings of a Rising Desert Wind at a Height of 10 m

Figure 273
Type of Cumulus Cloud Associated with Rising Winds

Georgii's Research

From the very beginning the Germans understood that the problem of soaring is a problem of aerology and could only be resolved by a scientific study of the atmosphere. This was the reason for the 1922 proposal to create a meteorological observatory on Wasserkuppe directed by a physicist. Its mission would be to study how winds ascend in the vicinity of the Rhön Mountains.

A research institute directed by Professor Georgii was thus founded on the summit of Wasserkuppe on April 1, 1925. The Institute was composed of four sections:

1) A section studying aeronautical technique;

2) A section studying aerodynamics;

3) A section studying meteorology;

4) A school of soaring.

The meteorological section had two subsections. One made test flights and ascents to report finding to the national weather service. The other had the mission of studying air currents on Wasserkuppe and at Rossitten.

Lastly, Georgii was also a professor at the engineering school in Darmstadt. This led to the creation of a specialized course of study not only for the students in Darmstadt, but also for other German students who came during their vacations for applied and scientific courses.

This organization enabled the Germans to pursue research on the nature of air currents, especially on the vertical movement of air under cumulus clouds (figure 273) and in the vicinity of storm clouds.

To study rising currents at high altitude, the Institute first used a light 20 hp airplane piloted by Nehring. As soon as he saw a cumulus cloud, the pilot ascended with the aid of the engine to an altitude of 2000 meters. He then stopped the propellor and tried to stay under the cloud without losing height. He was finally able to do this. Once, the pilot successfully supported himself under a cloud without using the propellor for ten minutes and even gained altitude. /183

Probing the Atmosphere by Meteorograph

The results encouraged the Germans, who then proceeded more scientifically. They used the well-known meteorograph which simultaneously records on the same paper atmospheric pressure, temperature, and relative humidity. Even though this instrument is not very precise, it provides some interesting information. Among other things, it indicates that the temperature curve, which theoretically decreases with altitude, has periods of leveling off and even of inversion in the vicinity of and inside of cumulus clouds. This is an important finding from the scientific point of view because it indicates that air density might have unsuspected variations.

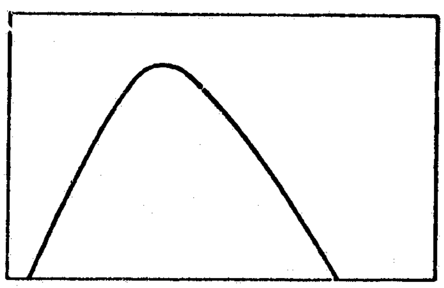


Figure 274
Meteorogram Made in Calm Air

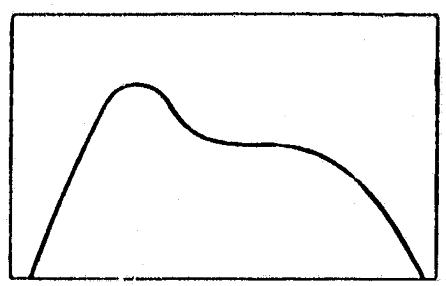


Figure 275
Meteorogram Made Under a Cumulus Cloud

The instrument furthermore revealed by examination of the pressure curve that the sinking speed of the airplane was frequently compensated for by the vertical speed of an air current. Thus, in 1928, Nehring observed ascending currents of 4 m/sec. The airplane which, with its propellor stopped, would have had a vertical falling speed of 2 m/sec, actually rose at a speed of 2 m/sec as a result.

Figure 274 represents a recording giving the variations in pressure during an airplane's normal descent or ascent. Notice that the airplane rose with its engine and then descended in a continuous fashion with its propellor off. In contrast, the following recording (figure 275) proves that during the powerless descent, the airplane remained at the same altitude under a cumulus cloud for 10 minutes with the aid of the rising current it encountered. Similar tests have shown that there are also rising currents in front of storm clouds.

The studies undertaken led one to believe that when a squall passes over, the soil cools down and a cold air current arises between the cloud and the ground. The current might flow toward the front of the cloud and force the warm air it finds there upward. What is certain is that there do indeed exist such rising currents. They sometimes have vertical speeds on the order of 6 to 7 m/sec, and are extremely turbulent.

The Determination of Airplane Trajectories in Germany

The study was carried still further. Each experimental flight was the object of measurements made from the ground by teams seeking to plot the airplane's trajectory as it maneuvered near the clouds.

Not only was wind speed measured, not only was the vehicle sighted at regular instruments by theodolites or telemeters, but cinemagraphic recordings were also taken by Dr. Raethyen. He /184
used an instrument he himself built along the lines of the one we described previously. At first it occurred to Raethyen to construct a coordinate grid made up of three panels. The movie camera was composed of a lens that received the rays coming from the airplane and projected them through a prism onto a sensitive film, The rays coming from the coordinate grid crossed a second lens and were projected onto the film by a second prism.

Later on, he set up a second apparatus that used a film sensitized on both sides. On one side the image of the airplane was recorded; on the other the image of a spherical network placed behind the camera was picked up.

Finally, Raethyen simultaneously obtained both images on the same film in a manner similar to our own method.

Thanks to these experiments, it is possible through photographic restoration to derive an airplane's trajectory and vertical speed (whether ascending or descending), as well as the vertical speed of the wind.

Figures 276 and 277 show that an airplane flying beneath cumulus clouds encounters rising winds whose vertical speed sometimes attains as much as 4 m/sec.

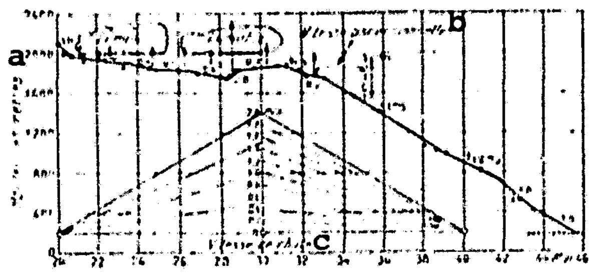


Figure 276
Trajectory of an Airplane with Propellor Stalled Passing under Cumulus Clouds

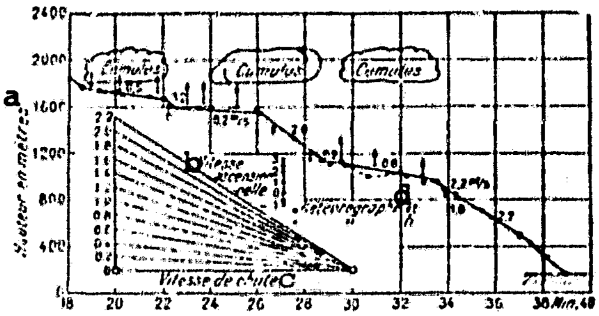


Figure 277
Another Trajectory of an Airplane with Propellor Stalled Passing under Cumulus Clouds

Key: a) Height in meters
b) Climbing speed
c) Sinking speed
d) Meteorograph

The studies undertaken documented the nature of air currents near clouds and showed how they were constituted. It was thus established that below cumulus clouds and in front of squall lines, there are always rising winds, which in the latter case can attain 7 m/sec. In addition, the universal existence of inversion phenomena was demonstrated. This means that on one side of a certain line the current ascends whereas on the other side the current is descending.

II. Motorless Flight in the Vicinity of Clouds

The Germans were not content with just scientific findings. They tried to make use of the rising currents below cumulus clouds and especially in front of squall lines to make long distance and high altitude flights. When soaring in rising obstruction currents, the heights attained are always small, 100 to 300 meters, depending on the obstacle's form and height. The flights do not last very long, either, because of usually insurpassable discontinuities in the elevated areas traversed.

Kegel had already made a flight in a storm during 1926. He climbed to 600 meters and covered a distance of 28 km. The tests demonstrated that to succeed it sufficed to take advantage of the clouds' currents. First, one climbs by means of rising winds dues /185
to slopes. Then either one reaches the ascending air layers on the lower surfaces of cumulus clouds or one remains hovering in the sky awaiting the arrival of the updrafts preceding storm clouds.

The possibility of powerless flight in these circumstances was demonstrated by Hirth, Groenhoff, and Kronfeld.

Hirth's Flight from Wasserkuppe to Schweinsberg (1928)

In 1926 Hirth climbed over the slopes of Wasserkuppe and drifted above the hill to a height of 400 meters.

The experimenters of the Rhön and their measuring team employed the same procedures to determine the trajectory of the powerless aircraft as were mentioned previously for motorized airplanes. They took all the required measurments along with the time the measurements were made. Whenever possible, they also sought to learn the vertical speed of the wind encountered.

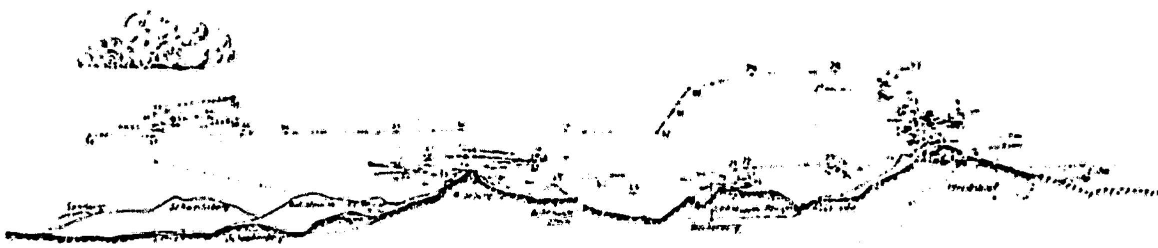


Figure 278
Trajectory of Hirth's Glider from Wasserkuppe
to Schweinsberg and Back

They were thus able to trace Hirth's path in the aircraft "Lore". This path is reproduced in figure 278. Notice that the pilot glided from the altitude at which he was located above Wasserkuppe in an attempt to reach a cumulus cloud above Schweinsberg. As soon as he was below the cloud, he found a propitious rising wind that enabled him to zigzag back up to a height of 300 meters. From there, he made a gliding descent and lost much altitude until he reached the slopes of Holstein and took advantage of the rising obstruction currents existing there. He regained altitude, maneuvered around Milseburg, descended slowly toward Weiherberg, climbed back up with the aid of the mountain slope wind, and made a final gliding fight to his point of departure on Wasserkuppe. The part of the flight made with the aide of mountain slope currents is traced with a solid line. The part performed using currents under clouds is represented by a dotted line. The numbers represent the elapsed time in minutes.

Kronfeld's Flight to Himmeldankberg (1928)

In 1928 Fronfeld elaborated the method to use for long distance flights involving rising cumulus winds during his voyage from Wasserkuppe to Himmeldankberg in his glider "Rhöngeist". After takeoff the German pilot first maneuvered through the ascending wind on

Wasserkuppe's west slope at an altitude a little higher than his point of departure. When a passing cumulus cloud helped him climb to 170 meters, Kronfeld followed the cloud in a SE direction. He then found himself in Wasserkuppe's descending wind, but since he was still under the cloud, Kronfeld was able to remain in the rising wind by maneuvering appropriately. He thus attained 430 meters above Wasserkuppe. As the cumulus cloud disintegrated, he tried to glide to Himmeldankberg. Once there, he remained for a fairly long time in its ascending slope currents. The passage of a new cumulus cloud enabled Kronfeld to abruptly ascend anew, and he returned to Wasserkuppe by taking advantage of rising currents he found on the way. /186

Kronfeld's 148 km Flight from Wasserkuppe to Gera before a Squall Line (1929)

In May, 1929, by applying all the information acquired through the research of the Rhön Institute, Kronfeld performed a flight of 100 km. Skirting Teutsbourg Forest, he made his trip, sometimes using rising slope currents, sometimes updrafts under cumulus clouds, in order to cross valleys.

On July 20, 1929, Kronfeld accomplished a new feat. The day was stormy with intermittent squalls. Storm clouds covered the entire Rhön range around 3 o'clock. Kronfeld launched his aircraft the "Wien," whose aspect ratio was 22, in a wind of 10 m/sec and reached the slopes of Pelzner, where he started to lose altitude. The pilot Hirth was already floating at 1000 meters in front of a strong squall line. Kronfeld directed himself toward Ehrenberg, his altimeter indicating a continuous ascent below a cloud and in the middle of lightning flashes. His vehicle, which was badly shaken and tossed about, kept rising and it tacked in circles up to 3,000 meters. Kronfeld flew with the storm, which was advancing rapidly northward, and arrived above Geisa. Below him small white clouds were forming, indicating the presence of rising currents.

The pilot flew around above Berkh and broke into the area in front of the storm. On turning around, he noticed that the cloud had split in two. He was then caught up in a descending wing and pushed lightly on the stick in an attempt to reach the storm on the east. The vehicle picked up speed and the indicator showed 70 km/h. Pulling on the stick did nothing to reduce its speed, which reached 120 km/hr. The glider was caught in the tempest and was cracking all over. It suddenly found itself under a cloud in front of the storm and above Gotha after having crossed the Thuringian mountains. Kronfeld gradually learned what distance he had to remain in front of the squall line so as not to lose height. After flying for an hour toward the east, he passed over Erfurt and Weimar. The night was falling, and he was still at an altitude of 2000 meters. He therefore decided to land and touched down near Gera, 148 km from Wasserkuppe.

Figure 279
Barogram of Kornfeld's Flight from Wasserkuppe to Gera (1929)

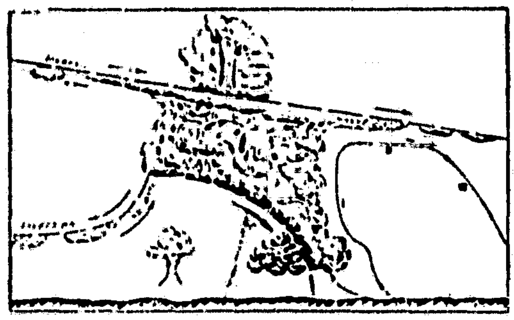


Figure 281
Flying in Air Current Inversions Near a Storm

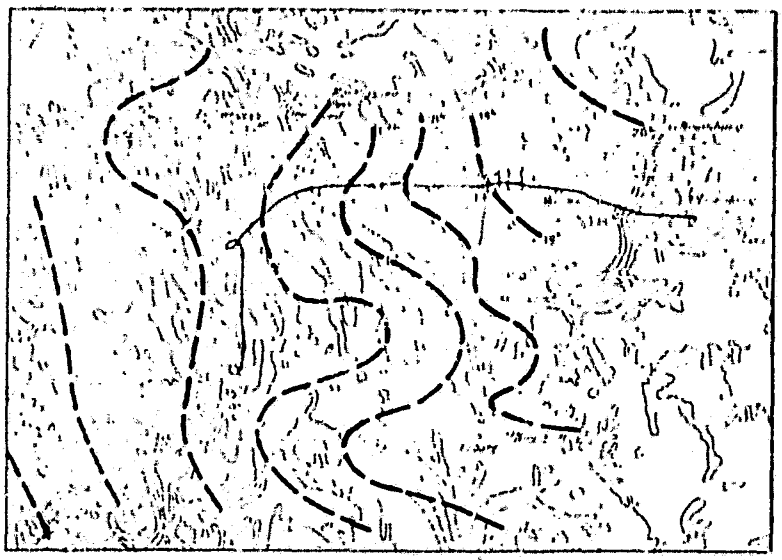


Figure 280
Successive Storm Fronts during Kornfeld's Voyage from Wasserkuppe to Gera (1929)

Figure 279 represents the barogram of Kronfeld's flight. Notice that after an ascent followed by a descent, the aircraft steadily gained height in the squall line's wind and reached an altitude of 3,000 meters. It was then above Eisenach, and the time was 4:20 P.M. The wind's greatest ascent took place between 1400 and 1800 meters. The pilot then flew horizontally at 3,000 meters for an hour. After that, he descended and flew between 2,100 and 2,400 meters for two hours before landing.

Figure 280 shows the various positions of the squall line from

hour to hour. The split in the line after 6 P.M. (18 hours) is visible. The solid line in the figure represents the trajectory /187
Kronfeld followed in front of the storm, with departure from Wasserkuppe and landing near Gera.

The Nature of Winds in a Squall Line

The diagram in figure 281 shows how to fly before a squall line. The flight is divided into three parts:

The pilot must approach the squall line after being launched above a slope and making maximum use of the rising currents due to the presence of cumulonimbus clouds. The arrows indicate the direction and inclination of the air current in the vicinity of the cloud. Note the lines of inversion. On one side the wind is ascending, on the other it is descending. The glider follows trajectory I and climbs with the aid of ascending wids until it reaches the cloud's upper edge. There is a slight rising current in front of storm clouds at this location. As is indicated in trajectory II, flying against this current will keep the glider at the same height and position relative to the cloud. Higher up, the aircraft would lose altitude. In order to descend, the glider moves away from the cloud and dives to reach the ground. It should be pointed out that in the case of such a storm cloud, three lines of inversion are encountered. The result is that below the cloud mass, there is a descending wind and that to the rear a descending current preceding an ascending current can be found.

Kronfeld's 150 km Flight from Wasserkuppe to Lienlas below Cumulus Clouds (1929)

Ten days after his first performance, Kronfeld made another voyage through the use of the updrafts observed under cumulus clouds. This flight took place on July 30th in a westerly wind of 12 m/sec. The cloud ceiling was about 500 meters above Wasserkuppe. The glider climbed rapidly immediately after departure and disappeared in the cumulus clouds (figure 282), which were several hundred meters thick. It ended up on the cloud's upper surface. The glider thus went from 950 to 3,100 meters in 22 minutes, which represents a rising speed of 2 m/sec. It then glided downward, either in a straight line or in circles above clouds, and reappeared below the cumulus clouds. It now flew horizontally with the aid of /188
the wind existing there. When night fell, it landed after a series of curves at Lienlas, near Bayreuth and not far from the Czech border. This was 150 km from its point of departure. (See figure 283.)

Figure 284 represents the barogram recorded during the flight. One can see that the glider surpassed an altitude of 3,100 meters, having therefore gained 2,160 meters, and then flew for a long time around 3,000 meters. Descending to around 1,200 meters, it traveled there for an hour. Another drop brought it to 800 meters, where it remained for two hours without appreciable loss of height.

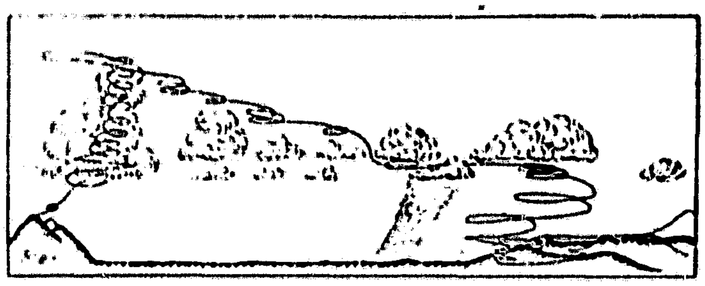


Figure 282
Kronfeld's Trajectory around Cumulus Clouds from Wasserkuppe to Lienlas (1929)

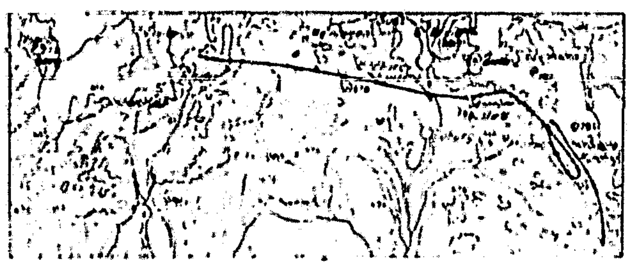


Figure 283
Tracing of Kronfeld's Voyage from Wasserkuppe to Lienlas (1929)

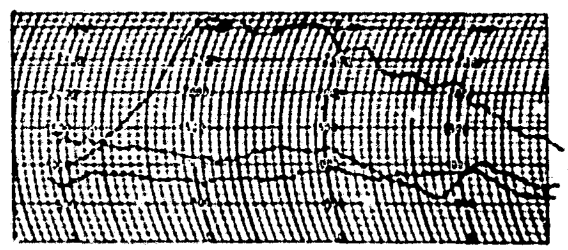


Figure 284
Barogram of Kronfeld's Flight from Wasserkuppe to Linelas (1929)

Figure 285 contains the ascent cruves of the glider "Wien" during the flights of July 20 and 30, 1929. These curves, drawn with solid lines, are marked with the climbing speed in meters per second.

As can be seen, the ascent of July 20th was made in stages with a maximum speed of 4 m/sec, between 1,400 and 1,800 meters.

In contrast, the ascent of July 30th was very rapid, as if the powerless craft had been sucked upward. The climbing speed was high almost the entire time. It reached 5 m/sec between 2,200 and 2,800 meters, when Kronfeld was crossing a cumulus cloud.

The dotted curve is that of temperature, which decreased regularly at first, but displayed oscillations within the cloud mass.

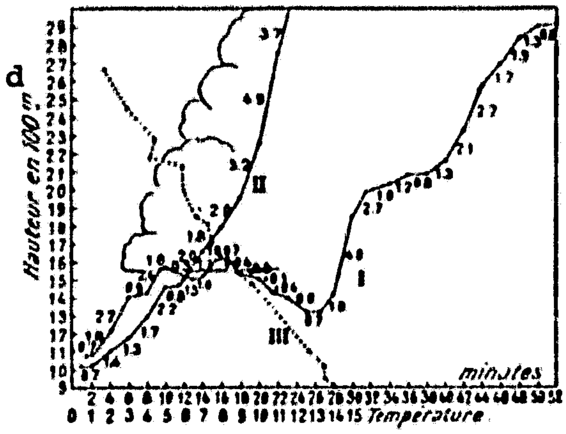


Figure 285
Ascent Curves of the "Wien"
I: July 20, 1929
II: July 30, 1929
III: Temperature Curve
on July 20, 1929

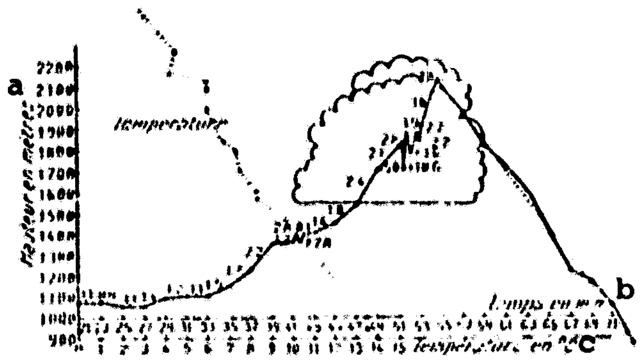


Figure 286
Ascent Curve of Groenhoff's
Glider and Temperature Curve
for July 30, 1929

Key: a) Height in meters
b) Time in minutes
c) Temperature in °C
d) Height in 100 m

Bedau's and Groenhoff's Flights in 1929

On the same day, July 30, 1929, the pilots Bedau and Groenhoff attempted flights in the vicinity of cumulus clouds in the soaring aircraft Luftikus and Rhönadler. Bedau's flight did not surpass 1,700 meters. Groenhoff's carried him to 2,100 meters, after crossing through the cumulus cloud. Examination of the temperature curve (figure 286) shows that there were the same oscillations as pointed out above. In contrast, the ascent curve does not indicate very great climbing speeds in general. The exception is inside the cumulus cloud, where extremely large variations cocurred between 1,700 and 1,900 meters. In this area the wind exhibited first ascending and then descending motion of -9 m/sec, +10 m/sec, -3.9 m/sec, +3.6 m/sec, -2.2 m/sec, and +7.7 m/sec in less than 2 minutes. /189

Remember that these flights inaugurated a new method of soaring. They make possible trips over any territory, even flat, and for potentially great distances on the conditon that the departure is made in rising obstruction currents. This enables the aircraft to reach either the bottoms of cumulus clouds or squall lines.

It is not without interest to point out that in 1925 the pilot Auger got into his glider the "Vautour" [Vulture] and rose above the slopes of Vauville. He was then blow in the direction of Cherbourg, far from the zone of rising current above the cliff, at the same time as he rose to an altitude of 720 meters. This performance, which was due to rising thermal winds, was not followed up because its cause was not understood.

RECOMMENDED READING

Francais de Propagande Aéronautique, Le vol à voile [Soaring], (1930).

Georgii, "Der 10 Rhön-Segelflug -- Wettbewerb auf der Wasserkuppe i. Rh. 1929", Z.F.M. (February 28, 1930).

Huguenard, Magnan, Planiol, Les appareils à fils chaud: leur application à l'étude des mouvements atmospheriques [Hot Wire Apparatus: Their Application to the Study of Atmospheric Motion], Bulletin du Service Technique de l'Aéronautique, 32 (1926).

Koch, "Anfwindmessungen unter cumuluswolken", Beitr. z. Physik d. Freien Atmosphäre, 14/4 (1928).

Lesson Fourteen: Gliders /190

After having studied the various factors enabling a motorless aircraft to remain airborne, we are now going to study how aircraft are designed to make the flights about which we have spoken.

Powerless aircraft, which are often called gliders, released in calm air can only descend in more or less rapid glides. If one wants to make them perform gliding flights, it is therefore necessary to launch them from an elevated point or to give them preliminary altitude with an elastic shock cord catapult.

Gliding in Still Air

We know how gliding takes place. I recently gave Painlevé's opinion on this question. He demonstrated very soundly that air resistance to a very oblique descent made by a glider is proportional to both its vertical sinking speed and its horizontal speed. Neither the slope of a downward glide nor its vertical speed can ever be less than a certain limit. The lower this limit is, the more remarkable is a glider's aerodynamic efficiency.

Consequently, a glider launched from a hill, for example, loses altitude as it glides in still air, i.e. when there is no wind, at the same time as it advances horizontally. The existence of the two simultaneous movements means that the glider falls toward the ground on a downwardly inclined trajectory.

It is easy to understand from previous discussion that the smaller the slope of the trajectory, the better the glider's flight characteristics. There are, meanwhile, two ways of looking at the glider's characteristics, depending on whether one is considering the slope of the glide or the sinking speed.

In the first case, the better a glider is, the less height it loses when covering a given horizontal distance. If it drops 10 meters in a horizontal distance of 200 meters, it is superior to another glider that covers only 100 meters while losing the same amount of height. The first glider descends at a 5% slope and has an aerodynamic efficiency of 200/10 = 20. The second glider descends at a slope of 10%, two times larger, and displays an aerodynamic efficiency of 100/10 = 10, which is two times smaller.

If we now compare gliders according to sinking speed, i.e. the amount of height lost per second while gliding, we must recognize that an apparatus that approaches the earth at 1 m/sec is better than one which approaches it at 2 m/sec.

The conclusion we can draw from this is that if two gliders are launched from the summit of a mountain dominating a large plain and fly in a straight line, the one that lands the furthest from the mountain is the better of the two. (See figure 250.) Similarly, the one with the smaller sinking speed or that took the longer time to touch down is more flightworthy than the other. This is true so long as both trajectories were straight and the pilots maneuvered in the same fashion, for by changing the wings' attack angle, pilots can also change the angle the trajectory makes with the ground. /191

Figure 287
Vertical Sinking Speed BA, Horizontal Speed AC and Trajectory BC of a Glider with an Efficiency of 10 in Calm Air

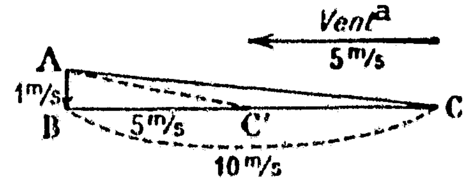


Figure 288
Trajectory AC' of the Same Glider Flying in a Head Wind of 5 m/sec

Key: a) Wind

Figure 287 makes it easy to find the slope of a glider in relation to the ground, no matter what the direction of the glide. In the right triangle ABC, BA is the sinking speed, 1 m/sec; AC is the horizontal speed, 10 m/sec; the slope is the ratio between AB and AC, or 1/10, which is the reciprocal of the aerodynamic efficiency, 10.

Gliding in a Regular Horizontal Wind

The situation is no longer the same if there is a wind. We are going to examine this point in detail for the case of a horizontal wind assumed to be uniform and regular.

As Col. Paul Renard stated so well, a fundamental notion that is often lost sight of because it runs counter to common sense must be kept in mind here. As long as a glider or any other aircraft remains on the ground, it responds to the wind like all things located on the surface of our planet. When it is released in the atmosphere, it no longer belongs to the earth, but to the air. In this new situation, the wind does not exist for it, and in its eyes everything happens as if the air were calm and the earth moved under it with a speed equal to the speed of the wind, but in the opposite direction.

Let us take the example of a glider in flight possessing an aerodynamic efficiency of 10, i.e. it descends 1 meter in still air for every 10 meters of horizontal distance it covers. If it is suddenly placed in a uniform horizontal head wind of 5 m/sec, the glider's horizontal speed in relation to the air will not change, but its speed in relation to the ground will now be 10 - 5 = 5 m/sec. Its sinking speed will not be changed either, although its forward

speed was divided by two. The net result is that the slope of its trajectory will be two times greater, as is shown in figure 288. The higher the wind speed is, the closer the glider's trajectory will approach a vertical line. When the speed of the head wind equals that of the glider in still air, its trajectory in relation to the ground will appear vertical. If the wind's speed is more than the glider's, the glider seems to go backwards in the air /192
while losing altitude at the same time (figure 289).

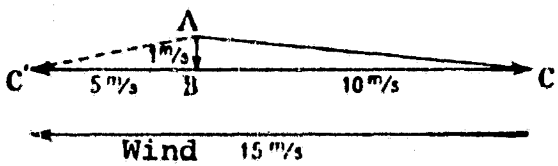


Figure 289
Trajectory AC' of the
Same Glider in a **Head**
Wind of 15 m/sec

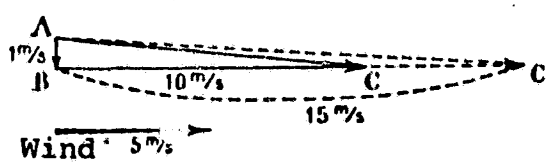


Figure 290
Trajectory AC' of the
Same Glider in a Tail
Wind of 5 m/sec

If the motorless aircraft is now placed in a tail wind of the same strength as the head wind was, the sinking speed is once again unaffected. The horizontal air speed also remains the same: 10 m/sec. However, relative to the ground its speed becomes 10 + 5 = 15 m/sec. because the horizontal speeds of the glider and the wind are additive in this case. The slope of the glider's trajectory will consequently be modified, as indicated in figure 290. The slope in relation to the earth will seem less inclined than in still air. It will appear to be 1/15 instead of 1/10.

To conclude this account, a glider's vertical speed relative to either the earth or the air is not influenced by the presence of a uniform horizontal wind. This is also true for its horizontal air speed. In contrast, the horizontal ground speed will be changed by such a wind. The slope of the trajectory will be altered to a considerable degree, without the gliders ever being engaged in anything other than gliding.

Gliding in a Regular Updraft

Let us now consider the case, no longer of a uniform horizontal wind, but of the horizontal wind after it has encountered a cliff, which has forced its layers upward even though they remain regular. The resulting inclined wind also displays two components of velocity. One is horizontal, and the other, called the rate of climb, is vertical. Consider the behavior of our glider with an aerodynamic efficiency of 10 in still air and a sinking speed equal to 1 m/sec. If the updraft encountered sometimes has a 1 m/sec rate of climb and sometimes a .5 m/sec rate, there is no change in the air speed of the glider. However, relative to the ground, the motorless aircraft descends at 1 m/sec while the first wind rises by the same amount and the second by half that amount, .5 m/sec. In the first case, the trajectory becomes horizontal (figure 292). In the second case, the slope is reduced by half, and the sinking speed is now .50 m/sec (figure 291). If we suppose an updraft with a vertical speed of 2 m/sec, the same aircraft, with an efficiency of 10, will rise relative to the ground with a speed equal to the difference between its sinking speed in calm air and the air current's rising speed: 2 - 1 = 1 m/sec.

The same reasoning applies to gliders maneuvering in rising thermal currents with or without horizontal wind (figure 293).

Obviously, this is exactly the opposite of what would happen if the wind were descending rather than rising.

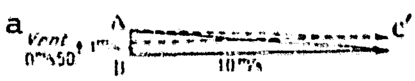


Figure 291
Trajectory A'C' of a Glider of Efficiency 10 in a .5 m/sec Rising Wind

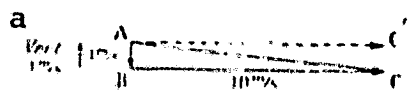


Figure 292
Trajectory AC' of the Same Glider in a 1 m/sec Rising Wind

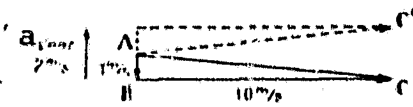


Figure 293
Trajectory AC' of the Same Glider in a 2 m/sec Rising Wind

Key: a) Wind

German Glider Types

The result of all this is that there is much interest in building highly efficient gliders for flying in updrafts. The advantage of an aircraft with an efficiency of 20 in comparison to an apparatus /193
with an aerodynamic efficiency of 10 when using such currents is easily understood. The first vehicle only needs a wind with a rate of climb of .55 m/sec to go upward, while the second requires that the rate of climb be greater than 1 meter. The first can therefore accomplish feats forbidden to the second. The Germans understand this very well in developing their gliders, which at present are of two types:

1) Training gliders;

2) High-performance gliders, or sailplanes.

The training gliders are themselves divided into two series:

a) Student gliders for teaching pilots how to fly motorless aircraft. They are very sturdy and easy to repair. Their wings have a low aspect ratio, about 6, and are attached to a triangular framework on which is mounted the pilot's seat and the landing skids. The engineer is not much concerned with aerodynamic efficiency when designing them. The emphasis is on safety and stability in flight.

This is why all these vehicles are provided with very effective controls and have relatively small loads per square meter. They are instruments for students (figure 294).

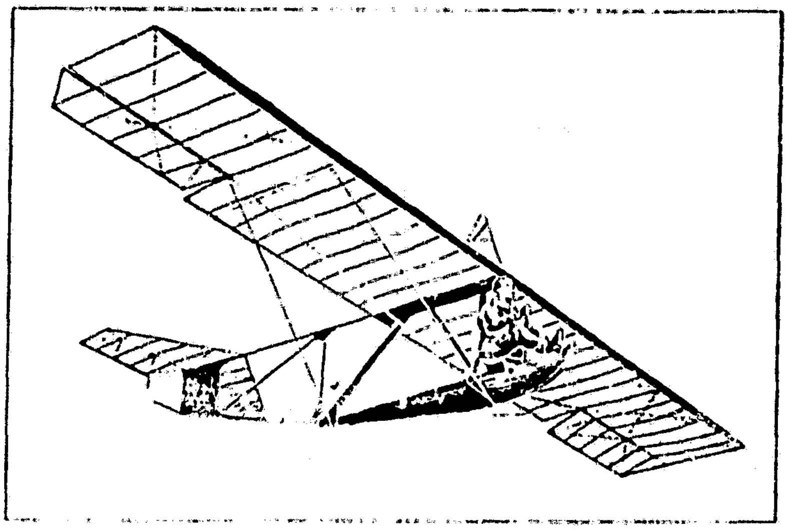


Figure 294
The Training Glider "Zögling" in Flight

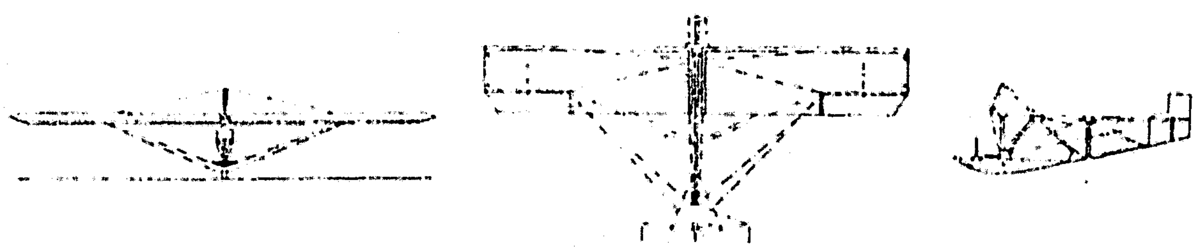


Figure 295
Plans of the Glider "Zögling" in Flight

b) Practice or training gliders which form a transition between the previous group and sailplanes.

In contrast, the so-called sailplanes, which are all very solid monoplanes that can nevertheless be easily taken apart, are always built very carefully. Their airfoil varies from 15 to 20 m^2, their aspect ratio ranges from 12 to 24, and their aerodynamic efficiency frequently attains 20.

The Rhön-Rossitten Gesellschaft itself constructs all three types of gliders, whose plans it sells. The models are: /194

1) The Zögling student glider (figure 295), conceived for teaching future pilots how to take off and land as well as to

perform their first glides along gentle slopes.

2) The Prüfling, a practice glider (figure 296), whose purpose is to improve the ability of pilots who have already been using the Zögling. Attempts at making flights of longer duration are made with it.

3) The Professor, a sailplane (figure 297), on which previously trained pilots attempt to set records.

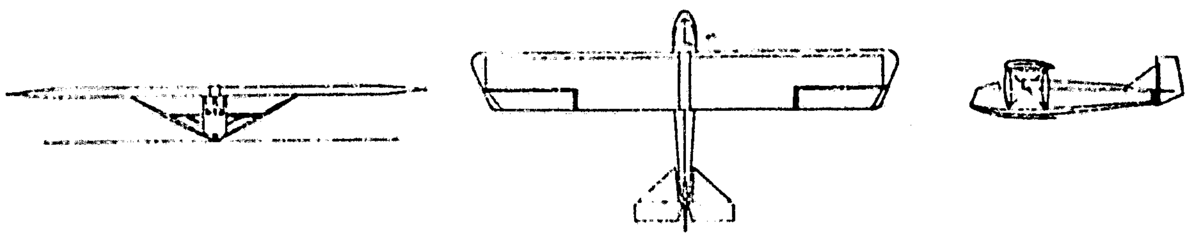


Figure 296
Plans of the Glider "Prüfling"

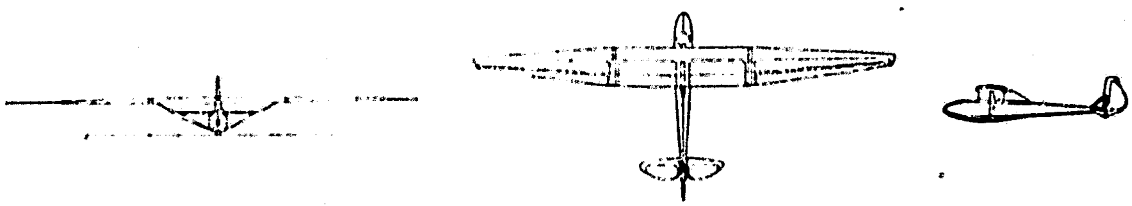


Figure 297
Drawings of the Glider "Professor"

Here are the principal specifications of the three gliders

	ZOGLING	PRUFLING	PROFESSOR
Total Weight	94 kg.	105 kg.	155 kg.
Length	5 m. 48	5 m. 48	7 m. 06
Area	15 m^2 85	15 m^2 25	18 m^2 6
Wingspan	10 m.	10 m. 58	16 m. 00
Maximum Wing Depth	1 m. 60	1 m. 50	1 m. 50
Aerodynamic Efficiency	11	14	21.5

Aspect Ratio	6,2	7,5	14
Sinking Speed	1,3 m./s.	0,90	0,67
Flight Speed	12,5 m./s.	13 m. s.	14-15 m. s.

All the German machines are derived from the above types. It should also be recognized that the sailplanes, in particular, display a certain high quality from the point of view of construction. It is the result of long study and merits attention.

German Glider Construction Method /195

Up to 1923, all long distance motorless aircraft were patterned on the motorized airplanes in service: monoplane, biplane, and even triplane. Sometimes they did have a special form, like Maneyrol's "Peyret" (figure 298) or the occasional glider whose function was already a little specialized. An example of the latter was the "Vampyr" which had almost rectangular and fairly deep wings and no landing gear, in the proper sense of the word (figure 299). By 1924, motorless aircraft with a larger aspect ratio were introduced in Germany. One such glider was the "Konsul" (figure 300), really the ancestor of the 1928 and 1929 gliders. It had a very large aspect ratio and very thin wing tips.

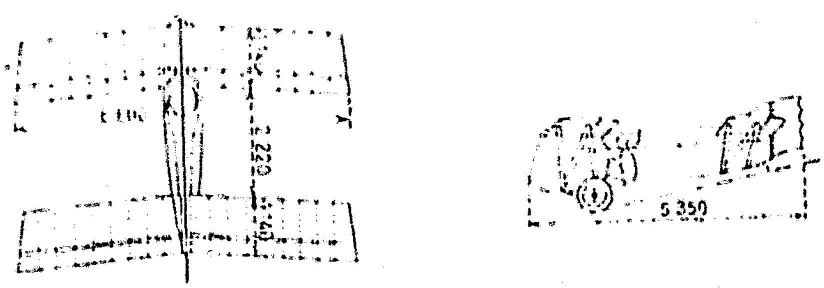


Figure 298
Design of the Glider "Peyret"

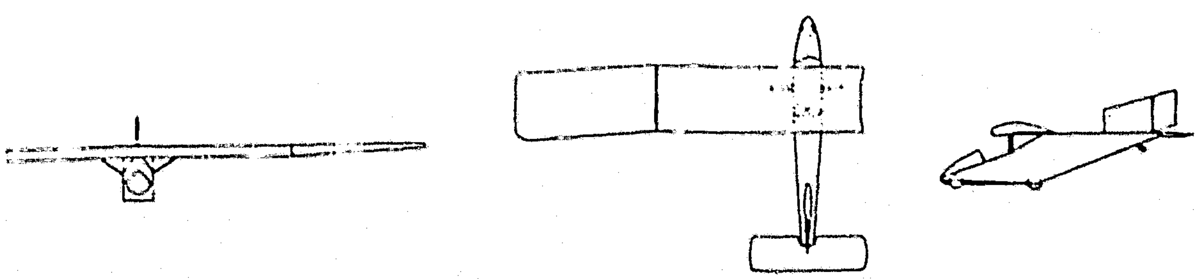


Figure 299
Design of the Glider "Vampyr"

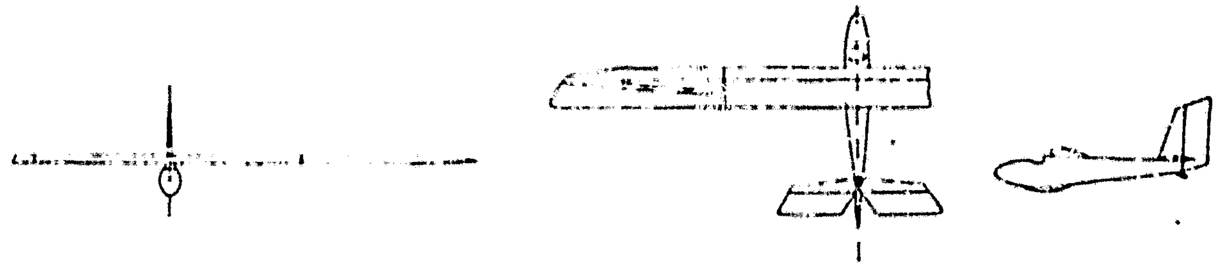


Figure 300
Design of the Glider "Konsul"

Currently, all the better German gliders have practically the same form. The latest models are monoplanes with overhanging wings, and their aspect ratio is generally 19. Sometimes their wings are still braced. The airfoil is most commonly made up of three parts. The rectangular central seciton is close to the fuselage while the two others are more or less triangular and form the wing tips. They also support the ailerons, which are almost as long.

A single box spar, most commonly accompanied by a dummy spar, supports the wing ribs, which are simple spruce or kieffer (a kind of pine) rods. The ribs are connected to each other by a lattice- /196
work made of the same wood (figure 301), and the whole assembly is glued together without nails.

Figure 301
Rib of a German
Soaring Glider

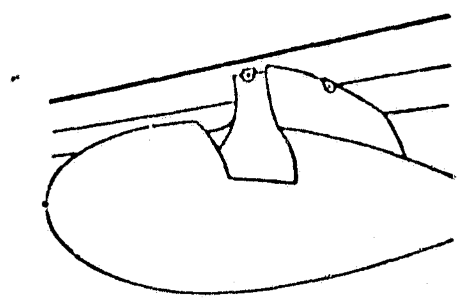


Figure 302
Wing Pylon and Method
of Attaching the Wing
of a German Engineless
Glider

The wings are partly covered by a wide, highly elastic sheet of alder and birch plywood, which constitutes the attack edge at the same time. The rest of the wing is covered with a fine fabric.

The fuselages of the Germans' sailplanes are very light. They are composed of frame members joined together by plywood sheets and have a very small cross sectional area, just sufficient to hold a man of average weight. In the front there is always a cockpit sealed by a piece of plywood that can be removed for inspecting the vehicle. In the middle is a streamlined pylon against which the wing is held flat by two fasteners on the wing spar and one on the leading edge (figure 302). In the rear is a sort of very elongated cone at the end of which a large tail unit is mounted.

The central landing skid is located below the fuselage. It is sort of an ashwood sole. Its form follows that of the keel, and it serves to brake the vehicle against the ground.

The fuselage of such gliders is generally 6 meters long, 1 meter high, and 50 cm wide.

The entire assembly is as well varnished as a piece of furniture from a good craftsman.

At present, the better German gliders weigh between 100 and 150 kg when empty. Their airfoils have an area of 16 to 20 m^2, and their aerodynamic efficiency often attains 20. An updraft of less than 1 m/sec is sufficient to cancel out the effect of gravity on them. In the research and development of their machines, the Germans have paid particular attention to reducing sinking speed, and they claim to have sometimes lowered it to below .80 m/sec.

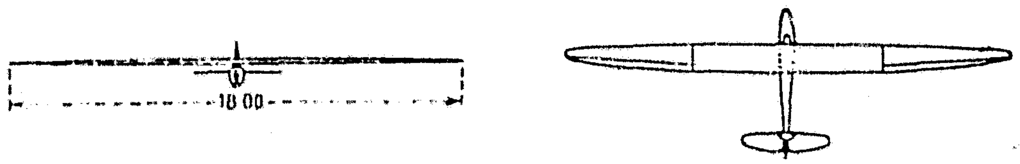


Figure 303
Design of the Glider "Darmstadt II"

Sailplanes

Here are a few supplementary comments on some of the German gliders that have accomplished exceptional flights. They are all more or less similar to the Professor type.

1) The "Darmstadt II", which is a version of the "Darmstadt I" designed by Wolker and was sent to America for public and private /197 demonstrations. However, it is inferior to its predecessor. Provided with a larger aspect ratio than the older one, a wingspan extended to 18 meters (figure 303), and a wing in three sections, it seems to be not as good because of its wing profile, which is said to be patterned after the flat Jonkowski type. Piloted by Nehring, it has nevertheless made some impressive flights.

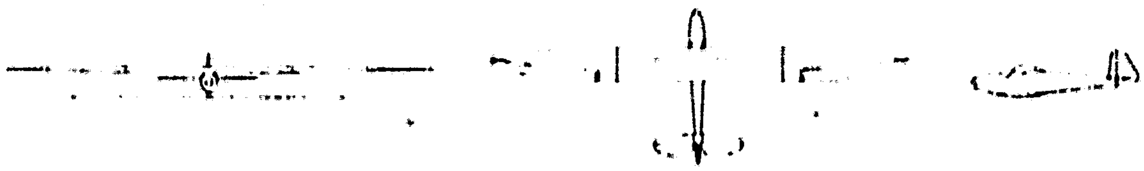


Figure 304
Design of the Glider "Westpreussen"

2) The "Westpreussen", the engineer Hoffmann's machine, which has a completely overhanging three-part wing and has been piloted successfully by the pilot Schulz (figure 304).

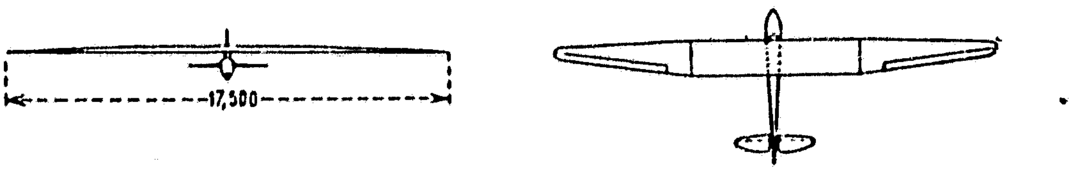


Figure 305
Design of the Glider "Kegel-Kassel"

3) The Kegel-Kassel, a parasol glider also with overhanging wings and a narrow, well streamlined and carefully constructed fuselage (figure 305).

4) The "Wien", a glider with strongly braced, two-part wings (figure 306), a fuselage having an elliptical cross section, an aerodynamic efficiency of at least 20, and a sinking speed of only 60 cm/sec. Like the Professor, it was developed by the engineer Lippisch, and is an improved version of it. It was the motorless /198
aircraft used by the pilot Kronfeld in his successful long distance flights in 1929, from Wasserkuppe to both Gera (148 km) and Lienlas (150 km). (See figures 306 and 307.)

5) The "Wurtemberg", an apparatus which participated in the 1928 Vauville and Rhön meets. It is equipped with overhanging wings (figure 308) with rounded ends, and its fuselage has an oval cross section.

6) The "Lore", an improved Wurtemberg type, possessing a narrower fuselage, which was successfully flown by Hirth from Mt. Wasserkuppe to Mt. Schweinsberg and back in 1928.

7) The "Kakadu", created by Aka flieg of Munich and built in 1928. Krebs has carried out some remarkable flights in it.

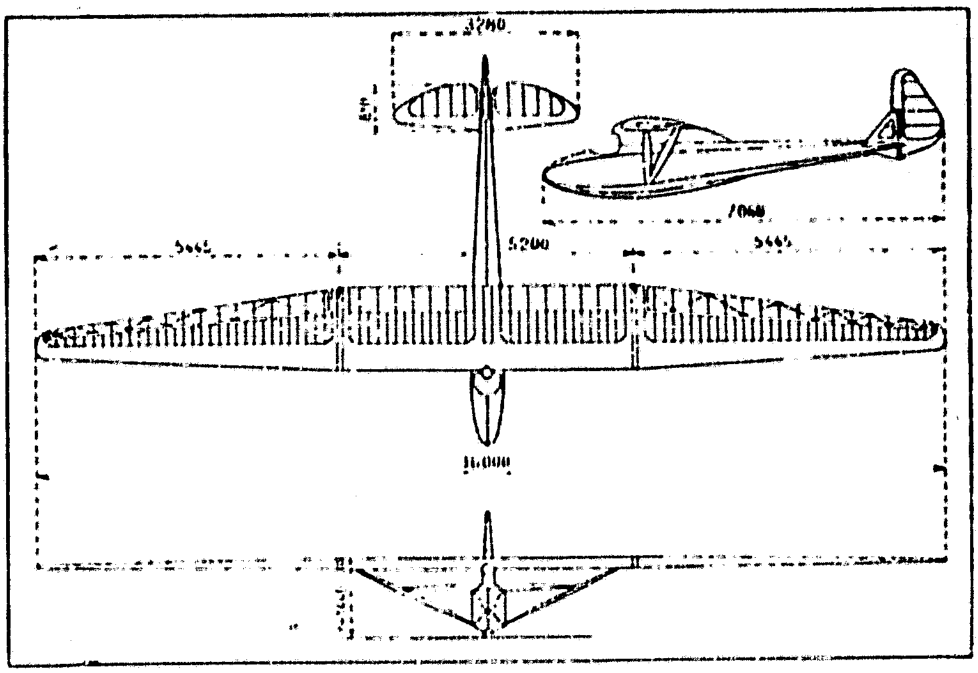


Figure 306
Drawing of the Glider "Wien"

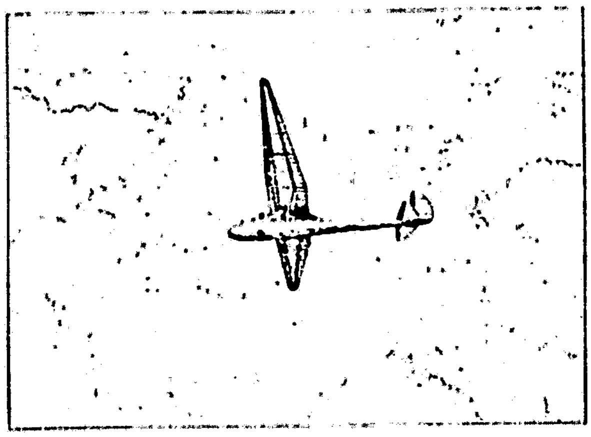


Figure 307
The Glider "Wien" in Flight

8) The "Munchen", which belongs to the same group as the preceding glider, and has high aspect ratio, overhanging wings attached to a round fuselage (figures 309 and 310).

9) The "Rhöngeist", a parasol glider of the Professor type. /199
Piloted by Kronfeld, it has produced some excellent performances, such as the round-trip flight between Wasserkuppe and Himmeldankberg in 1928. It has three-part wings with trapezoidal tips. They

are braced by slanted masts forming a v-shaped structure. The fuselage has a hexagonal cross section. (See figure 311.)

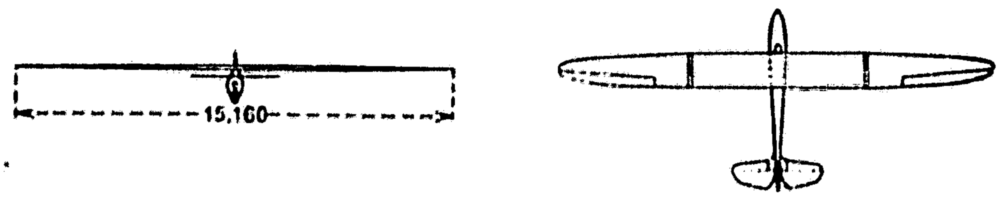


Figure 308
Design of the Glider "Wurtemberg"

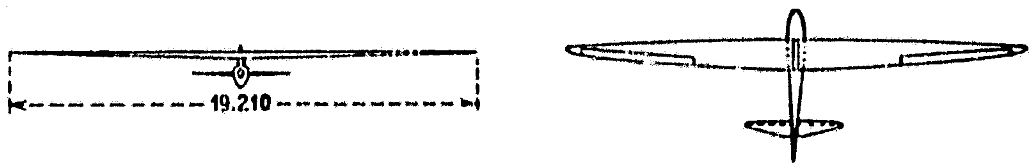


Figure 309
Design of the Glider "München"

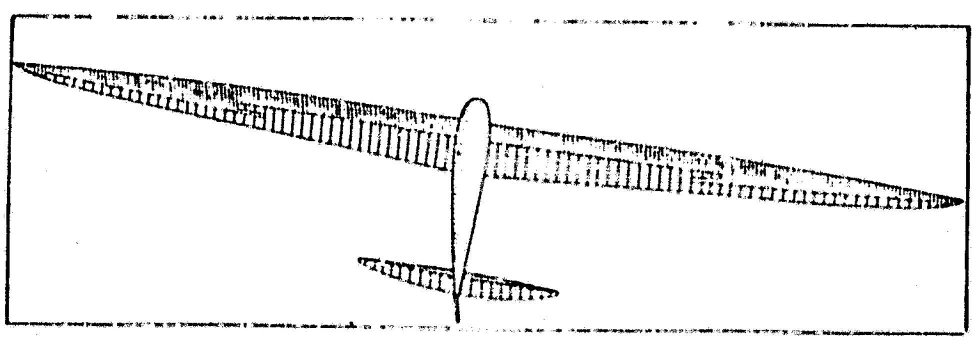


Figure 310
The Glider "München" in Flight

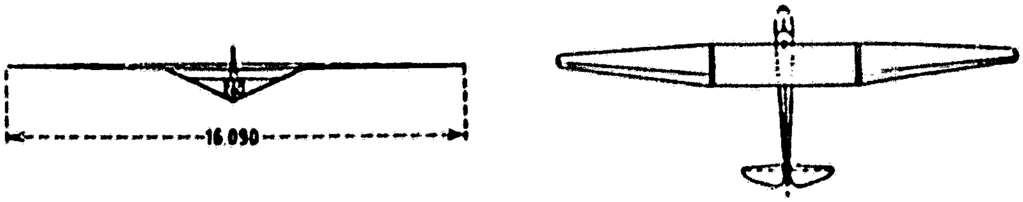


Figure 311
Drawings of the Glider "Rhöngeist"

Here are the specifications of these apparatus as well as of a few monoplane and biplane gliders currently used in Germany:

Vehicle	Wing-span	Wing Area	Empty Weight	P/S	Aspect Ratio
	m.	m²	kg.	kg. m²	
I. — One-seaters					
a) Student Gliders					
Zögling	10	15,85	85	9,8	6,3
b) Practice Gliders					
Prüfling	10,6	15,25	105	11,8	7,3
c) Sailplanes					
Professor	16,1	18,6	155	12,1	14
Darmstadt II	18	16,9	154	13,6	19,2
Westpreussen	16	»	»	»	»
Vieux-Kegel	16,1	16	150	13,1	16
Kegel-Kassel	17,5	19,8	110	9	»
Wien	19	18	154	12,4	20
Wurtemberg	15,1	15,8	160	15,6	14,6
Lore	15,6	15	141	14	13
Kakadu	19,5	17,6	170	15,6	21,6
München	19,2	17,6	135	11,3	21
Rhöngeist	16,1	18,6	156	11,2	13,9
Dresde 8	20	19	230	15,8	21
Luftikus	15	15,2	140	13,8	14,8
M. I.	11,5	16,9	118	11,2	12,5
II. — Two-seaters					
Herkules	15	27,8	190	11,9	»
Rhönadler	17,5	27	200	12,6	11,3

[Commas in tabulated material are equivalent to decimal points.]

German Tailless Gliders

The Rhön Institute has not limited its research to improving the form of traditional soaring gliders. It has also tried to investigate new forms and, in particular, to develop vehicles based on the shape of certain birds with very small tails. It has thus /200 introduced two types of tailless aircraft, the "Storch" (Stork) and the "Ente" (Duck), constructed in its workshops.

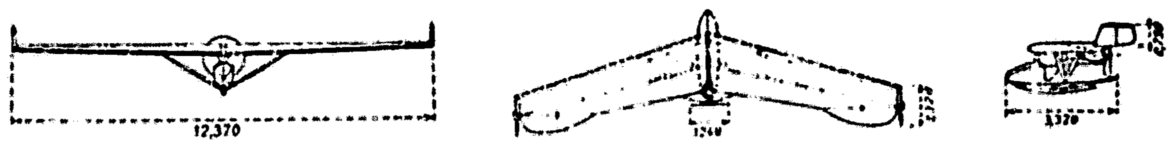


Figure 312
Design of the Glider "Storch"

The first is a kind of parasol monoplane with wings pointing rearward, as can be seen in certain birds during rapid gliding flight. The wings are maintained in position by two masts forming a V. Below the wingtips, two semicircular vertical planes accomplishing the tasks of directional rudders were fixed at first.

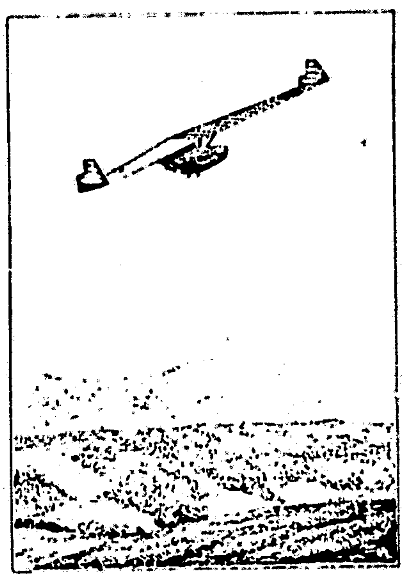


Figure 313
The Glider "Storch"
in Flight

Nehring was the first to try out this tailless aircraft. He noticed that the dihedral formed by the wings caused too great a directional stability and that the apparatus flew constantly in a straight line when the rudders were released.

The longitudinal stability was good, except when the pilot worked the ailerons excessively. In contrast, turning performance was mediocre.

To correct these problems, the wing dihedral was eliminated and the vertical rudders were placed above the wings (figure 312). The result was that turns were easier to execute if the vertical rudders were operated extensively and the ailerons only slightly. Furthermore, exiting from a turn was very easy thanks to the way the vertical rudders worked. In contrast, during inclement weather, the aircraft displayed a certain instability.

After many trials, the "Stork" was equipped with a 500 cm^3, 8 hp motorcycle engine, which was placed behind the short fuselage (figure 313) and directly drove a propellor.

The wingspan of the motorized vehicle was 12.1 meters and its wing area was 18 m^2. Its total flight weight was 250 kg. The "Stork" carried a load of 14 kg/m^2 and, despite its small motor, could fly at 127 km/h. Since it had neither wheels nor skids, it had to be launched with a shock cord catapult. The authors claimed that its aerodynamic efficiency was about 20.

Tests made on this tailless machine showed that it had a high level of stability that was not affected by even very turbulent air. Steep banking and sideslips were performed exactly as in a normal airplane. After the tests, the Germans stated that such a /201
vehicle exhibits no loss of speed or flat spin. A pilot had apparently been asked to pull forcefully on the joystick and to make the airplane rear up. The craft remained in this position without spinning. Similarly, if the pilot brought the stick all the way back towards him, the vehicle continued to respond to all movement of the rudders without any tendency to spin.

The second vehicle, the "Ente", is, as a whole, duck shaped. The central part of the body, which supports the wings, is preceded as in the animal by a sort of neck at the end of which is a small horizontal plane. (See figure 314.)

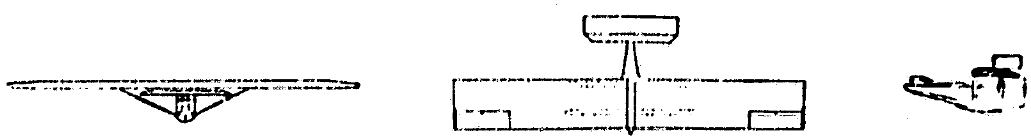


Figure 314
Drawings of the Glider "Ente"

Piloting such a tailless aircraft is very easy as a result of the fact that it is possible to let go of the controls both at take-off and in flight, thanks to the "Duck's" remarkable stability.

The vertical rudders are placed on the wing tips, as in the "Stork". They are very efficient since it is possible to go into a turn with a single rudder without using the ailerons. The aircraft exits from a turn just as easily through the use of the opposite rudder. In contrast, the "Ente" performs poorly in cross winds, especially when banking. In these circumstances, it sometimes even makes a sudden U-turn and ends up going in a direction opposite to the route desired by the pilot. It has another drawback when landing. It must be nosed up strongly because of its very long forward section.

C-4

RECOMMENDED READING

Abrial, Le concours de la Rhön [The Rhön Competition], (1929).

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Lippisch, "Das Nur-Flugel-Flugzeng", Vort. d. I. Intern. Wissensch. Segelflugtagung in Darmstadt (1930).

Painlevé, Le vol à voile et l'avenir de l'aviation [Soaring and the Future of Aviation], Paris (1922).

Renard, P., "Le vol plané et le vol à voile" [Gliding and Soaring Flight], Revue scientifique (October 27, 1923).

As we know, birds have three methods of soaring:

1) That practiced by such species as sea gulls and raptors like the buzzards above slopes thanks to upward obstruction or slope winds.

2) That used especially by vultures and marabous, who circle and climb in thermal updrafts.

3) That observed in the South Seas, for example. Here, albatrosses maneuver, ascend, and descend with their wings motionless through the use of horizontal winds of varying speed, inclination, and orientation.

We have seen that humans have succeeded in imitating the first two groups of birds. We now know how to remain suspended in the air above cliffs or slopes for 14 hours while covering distances of 150 km at more than 3,000 meters of altitude. To do this we use the updrafts occurring in front of squall lines and below cumulus clouds.

As far as the albatrosses' method of soaring goes, the achievements up to now have been very meager. This is probably because we know neither what to make use of in a horizontal wind nor how to maneuver to take advantage of the wind's internal energy.

Starting in 1906 and excepting the war years, I have been particularly preoccupied with this problem.

I. The Magnan Flexible Wing Aircraft

I based my work on the observations that I had already made of birds and especially on the experiments that had demonstrated for me the great advantage of flexible wings. In 1922, I built a soaring aircraft, as I had done in 1914 (figure 315), with the features of such palmipeds as the gannet. The aircraft was consequently a monoplane with thick, long, narrow wings whose profile, curvature, and angle of incidence varied like those of birds, and they responded elastically to forces deforming them in a singular manner.

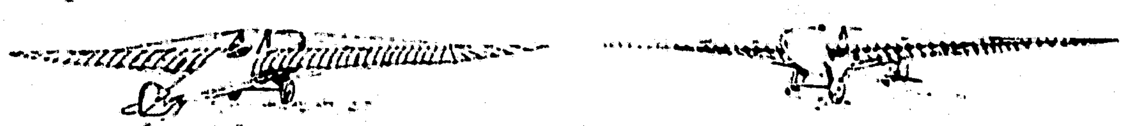


Figure 315
The Magnan Glider with Flexible, High Aspect Ratio Wings (1914)

The study I made of avian wing configuration during soaring /203 led me to consider two different wing designs. The first type had outstretched wings whose straight leading edges formed a continuous line. The other had flexed wings pointed rearward. As we have seen, the effects of gusts on wings increases as the wings are spread out. I therefore preferred not to use the second arrangement for the first tests. I also chose a moderate aspect ratio since the handling of high aspect ratio aircraft is more difficult in the beginning.

Lastly, I planned at the time that my aircraft would have an elevated weight. Until then, it was thought that soaring was possible only with a vehicle of low sinking speed and that the only way to achieve this was to reduce the load on the airfoils. This led to the construction of lightweight aircraft. For soaring in horizontal winds, however, heavy aircraft capable of supporting large stresses are needed. The large mass of heavyweight aircraft keeps them stable in gusts, just like marine palmipeds.

Wing Construction Methods

Each of the vehicle's wings contained a spar attached to the body of the aircraft at a point 60 cm from an elbow it possessed. The spars ended in two wood boards, one attached to the upper and one to the lower surface. The boards gave the wing tips a certain elasticity.

Furthermore, the spars diminished in thickness and width as they approached the wing tips. At the elbow, they were 214 mm wide by 144 mm high, whereas at the wing tip, they were only 120 mm wide by 50 mm thick.

The wing spars supported flexible ribs. Each rib was made of a sheet of ash going around the spar. The end of the upper sheet was attached to the lower sheet in the posterior third of the wing. It was fixed to the wing spar by two special fasteners. (See figure 316.)

The upper sheet of the rib supported two cross-braces linking it to a bearing housing by means of two interposed sleeves.

Ball bearings were lodged in the housing, which kept them in contact with a ball race on the wing spar.

As a result of this setup, the upper sheet could not become separated from the wing spar. It could, however, slide forward and backward without effort. It thus accommodated the deformation of the wing ribs by the wind and gravity.

Lastly, three sheets of ash formed the wing rib's lower surface. They were arranged like leaf springs so as to limit flexing and bring the supple plates back to their exact resting position in the absence of outside forces.

Numerous tests were carried out and twelve different rib patterns were built. This was done to assure that the ribs, and therefore the wings, had the capacity to automatically adjust their /204 attack angle, through their elastic response to the action of the load and the wind, without exceeding a certain maximum flexing. Each type of main rib was submitted to increasing loads. The sheets were mounted on a thick wood board forming a spar. The board was in turn attached to a rigid support in a static test position. This held the rib at the planned attack angle.

Loads distributed in a suitable fashion were placed on the flexible part, i.e. between the spar and the trailing edge. The doubly curved deformation that seemed the best was thus obtained. Then, the loads were increased until a deformation that would endanger the proper functioning of the aircraft resulted.

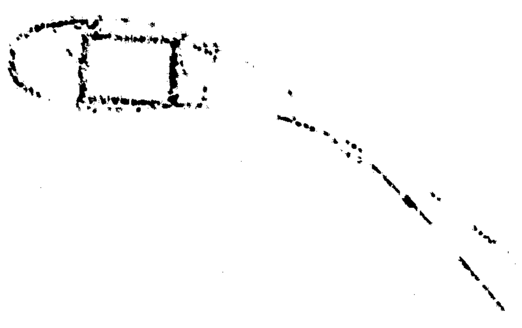


Figure 316
Rib with Ball Race in M2
Flexible Wing Glider

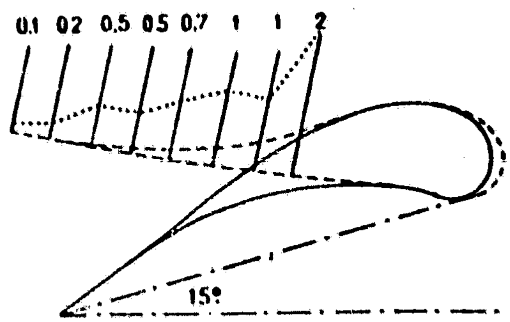


Figure 317
The Deformation of a Rib
Because of Unequally
Distributed Loads

The first type adopted as preferable possessed a ball race. The lower surface was made of three leaf springs, while the upper part was itself reinforced with another sheet. In these circumstances, the rib began to assume an undesirable form only after a 6 kg load was distributed decrementally from the vicinity of the wing spar to the end of the rib (figure 317). An ideal curvature was maintained up to 4 kg.

Lastly, I should point out that the part of the rib corresponding to the wing's forward edge moved forward 4 cm when deformed in the type of test considered here. The amount was smaller in ribs built for the aircraft.

The various elastic ribs were distributed on the wing in the following manner. There was first a series of 25 ribs in close proximity to one another. Their structure was similar to the standard rib, but they differed in thickness. The thickest were close to the body and had a vertical height of .195 meters whereas the thinnest ones were .080 meters high. The ribs were arranged so that the distance from the leading edge to the middle of the wing spar was everywhere equal to 24 cm.

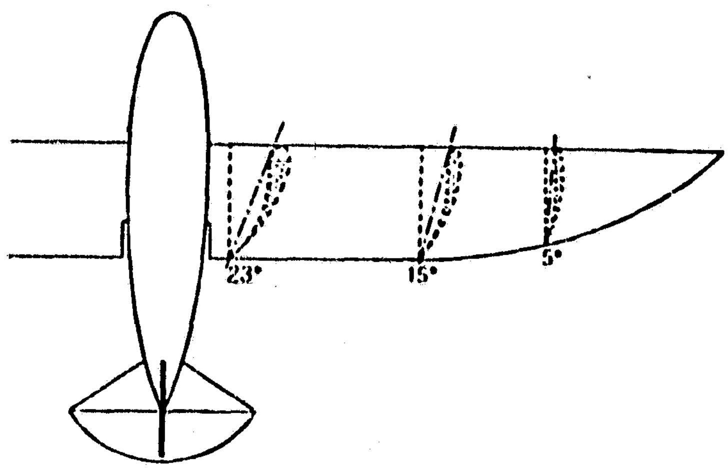


Figure 318
Thickness, Camber, and Incidence of
Some of the M2 Glider Wing Ribs

In addition, the radius of curvature increased uniformly from the aircraft's body to its wing tips. The wing ribs were also placed so as to differ in angle of incidence, with the largest angle closest to the fuselage (figure 318).

At the wing spar's elbow, the rib camber was 180 mm and the angle of incidence was 23°. The camber was 150 mm and the angle of incidence 15° at the middle of the wing.

The wing finally ended in a series of eleven ribs made up /205
simply of two wooden sheets attached to the upper and lower sides of the wing spar, with the upper one connected to the lower one along the posterior third of the wing. The ribs formed a fan-shaped structure. This gave a pointed form to the wing tip and exactly copied a sea bird's wing.

Lastly, a few ribs were fixed to one of the thin wooden plates terminating the wing spar.

The curvature as well as the angle of incidence in the end section were small. In fact, the camber was only 55 mm and the angle of incidence 5° in the outside third of the wing.

The wing's leading edge was composed of a series of thin, flexible layers of special, jointed plywood. They followed the anterior profile of the ribs and were connected to their flexible sheets.

The wings were covered with fabric attached to each rib and sealed in front to the leading edge in a manner that allowed the cloth to respond to the changes in wing shape without puckering up.

The method of constructing wings described above has numerous advantages. First the ribs easily change shape under the action of gravity and the wind. This movement is compensated for by the ball bearings.

Furthermore, the airflow makes the rear part of the ribs vibrate, which helps provide lift to the aircraft. I had thus obtained an easily deformable wing which changed shape and vibrated in response to gravity and the wind. It was consequently a wing of variable curvature and angle of incidence.

In addition, the wing tips were made very flexible by the thin wood plates, like the wings of birds, thanks to the upper rib sheets, which could slide freely over the wing spar.

The two wings thus constituted were linked by their spars at a point a little in front of the center of the aircraft's body. The angle between them was about 170°. The posterior part of each wing was completely detached from the fuselage and could bend freely. The two wings, which work under compression, were joined by a horizontal pylon laid flat against the fuselage and attached at the elbow of each wing.

Finally, the fact that the two wings were attached at approximately the middle of the aircraft's body allowed the center of gravity to be placed in a plane perpendicular to the longitudinal axis of the aircraft and intersecting the wing spars. In addition, the center of gravity is located below the wings as a result of their v-shaped configuration and their point of attachment with the fuselage. This is advantageous for balancing the craft and particularly in maneuvering while soaring.

In a static test, the wings supported a load of 5 without rupture or permanent deformation.

Fuselage and Controls

The aircraft's body was made of wooden frame members alternately inclined in one direction or the other relative to the vehicle's longitudinal axis. They were joined in pairs at their base and at their summit so as to form a series of juxtaposed V's. They also supported four longerons and longitudinal lathes constituting a base for applying the fuselage's fabric covering.

The two middle frame members were attached tothe wing pylon and held transverse members on which the wing spars were fixed. Their lower sections were linked to a part containing the landing wheel axle. The master midframe member was located here. It was 90 cm high and 80 cm wide.

The two middle frame members also leave an empty area where the aviator can be seated in a position where he can see the airfoils and the surrounding environment. /206

The aircraft's tail included a vertical fin and a directional rudder that turned about a vertical axis, a .5 m^2 horizontal plane and an .810 m^2 elevator rudder turning about a horizontal axis. This assembly was supported by a very light duraluminum beam attached to the body of the aircraft.

Banking the wings is, by all evidence, very useful in maintaining the lateral governability of a soaring aircraft. It should be allowed for when planning the aircraft, as an immediate reaction to sudden strong gusts. However, the problem of banking is difficult to resolve in the case of flexible wings. In spite of this, I was able to find a satisfactory solution after numerous tests.

Among the various aircraft controls, first of all, was the joystick, which controlled altitude and banking and was contained in its well-known socket. The stick was connected through a jointed shaft to the pilot's seat. The seat rested by means of four rollers on two rails mounted on the aircraft's body and parallel to its longitudinal axis.

There was a jointed connection between the joystick and a longitudinal tube parallel to the axis of the aircraft. The tube, which slid through several guides, supported a lever controlling wing banking. A control cable was attached to the lever. It passed through several guide pulleys and was attached to a king pin fixed to a flap extending from the ribs at the wing's end.

The longitudinal tube joined to the joystick was also connected to the horizontal rudder. The tube's rear end was square and fit into an opening in the rudder's strut assembly.

Directional control was established by means of a swing bar.

The landing gear included two wheels mounted on a duraluminum axle, which was streamlined at the section exposed to the wind. It extended only 15 cm over the sides of the fuselage.

The axle rested on the reinforced v-shaped connection formed by the two central frame members. It was attached by means of a set of elastic cords that dampened the shocks due to landing. /207

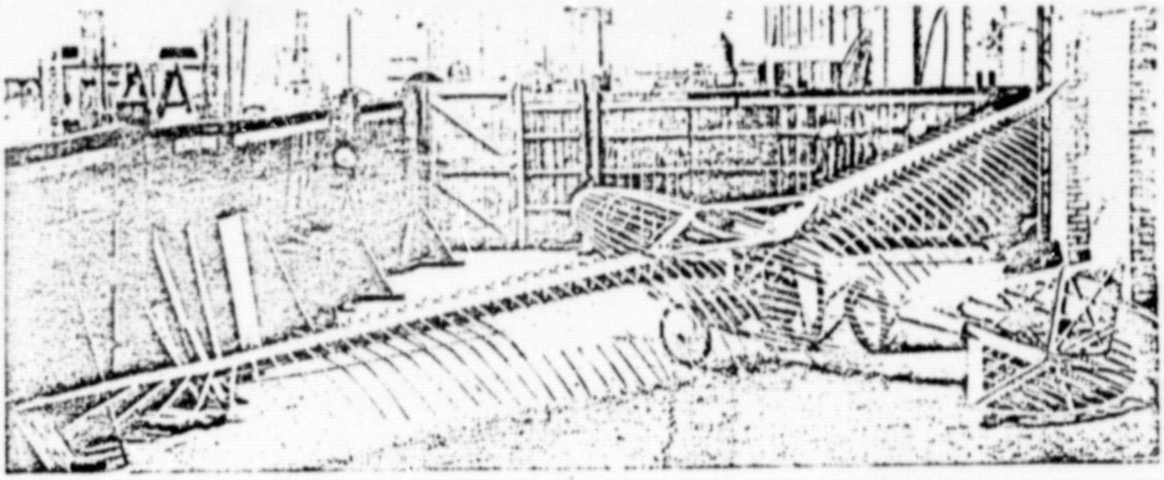


Figure 319
Magnan M2 Flexible Wing Aircraft, Uncovered

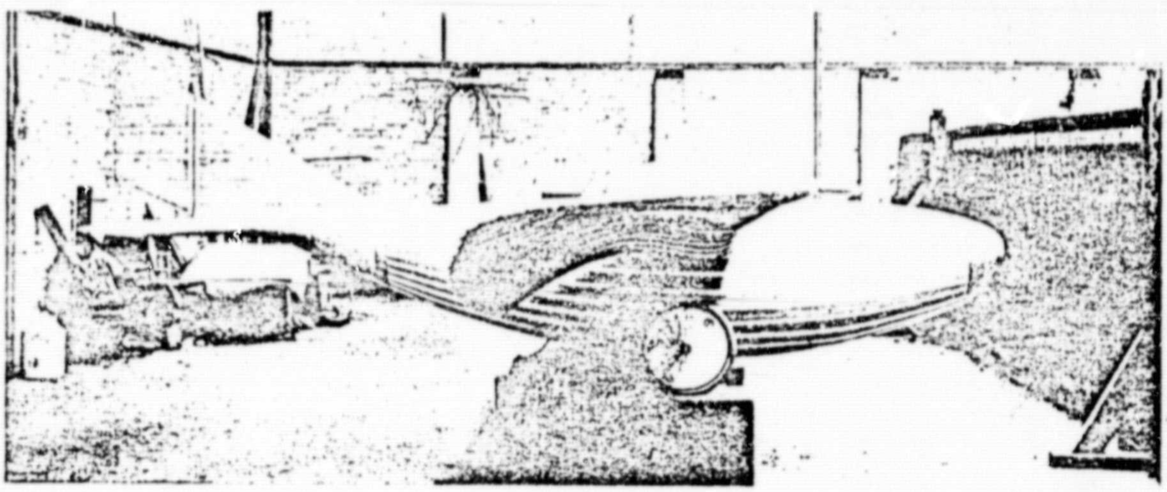


Figure 320
Magnan M2 Flexible Wing Aircraft, Viewed from the Side

Specifications of the M2 Aircraft

Here are some of the general specifications of the 1922 glider:

Flight Weight	200 kg
Empty Weight	130 kg
Total Wingspan	4.50 m
Midwing Depth	1.30 m

Total Length	4.95 m
Wing Area	10.5 m^2
Load per m^2	10 kg
Wing Weight	60 kg
Wing Weight per m^2	5.5 kg
Total Height	1.76 m
Height of Fuselage	1.10 m

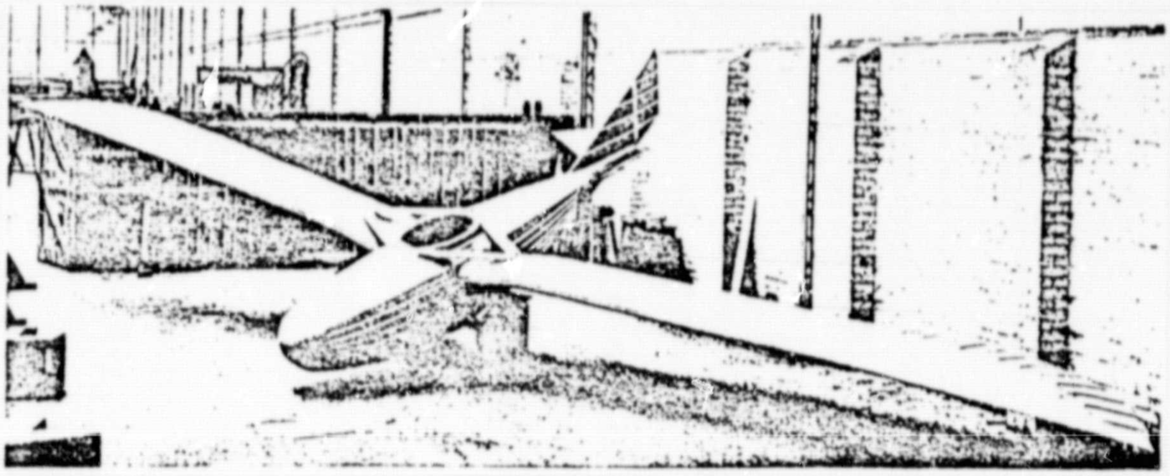


Figure 321
Magnan M2 Flexible Wing Aircraft Viewed from the Top

The photographs in figures 319 to 322 perfectly illustrate these specifications and the construction of the aircraft, both with and without its fabric covering.

The finished aircraft was suspended to determine its center of gravity and to find out if it was as well placed as planned. Its position was supposed to be a little in front of the anterior third of the wings. Experiments showed that it was indeed even with the wing spars. It was determined with precision, moreover. When empty, the aircraft's center of gravity was found to be 16 cm behind the middle of the wing spar, i.e., 40 cm from the leading edge and therefore at the 30/100 point on the wing. When ready to fly, i.e. with the pilot in his seat locked in its middle position, the center of gravity was located 7 cm behind the middle of the spar, or 31 cm from the leading edge. It was therefore at the 23/100 point on the wing. In these circumstances, the pilot, by moving his seat forward or backward, could cause the vehicle to tip immediately to the front or rear.

Tests of the M2

The first tests I performed before the war had already indicated that the effect of a gust was to make a gliding aircraft gain height. With the aid of the gantry crane arrangement about which I will talk in detail further on, it was possible to determine the maximum aerodynamic efficiency of my flexible wing aircraft. Based on the experiments that have been carried out, the efficiency appeared to be approximately 15.

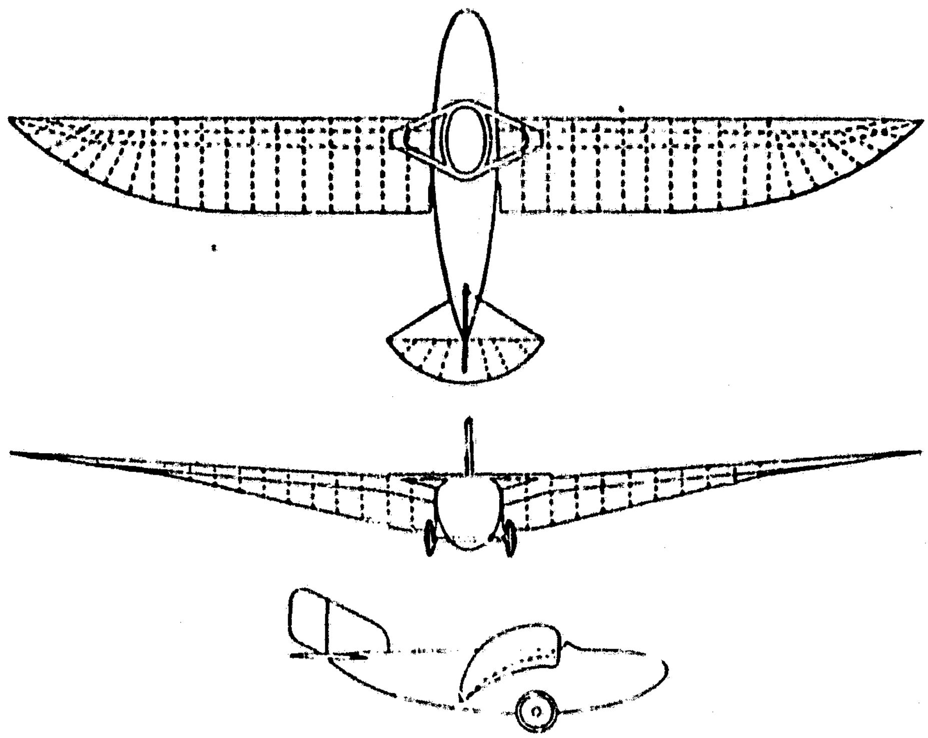


Figure 322
Plans for the M2 Flexible Wing Aircraft

The first experiments performed at Saint-Inglevert also allowed me to establish some of the principles of soaring by means of gusts. This was despite the difficulties that had to be surmounted during such tests. First of all, like the original aviators, I had to resolve the one basic problem impeding the start of experimentation. This is to insure that adequate lift was supplied in a given wind.

The vehicle was piloted in the test flights by Lt. Canivet, who had a considerable knack for applying the flight maneuvers of soaring birds. The following findings resulted:

1) The marine type of soaring aircraft, carrying a heavy load per square meter, never took off when facing the wind on level ground in the absence of any rising current, and pulled by an 18 mm shock cord stretched 100%. It rolled but it did not leave the ground when there was no wind.

2) When the average speed of the wind reached 6 m/sec, if the apparatus was placed in the same circumstances, i.e. on level ground and facing the wind, rolled along the ground for ten meters or so and then climbed into the air and glided. The flight was of variable length, depending on the circumstances. It was even possible for Lt. Canivet, by moving the horizontal rudder in an appropriate fashion, to gain height in midflight at the moment a gust passed over. /208

3) In a wind of 12 m/sec, the aircraft took off almost immediately, even when the shock cord was stretched only 50%.

A study of the question will allow these results to be understood.

To launch the aircraft and give it a propitious speed, I used a system of pulley blocks, releases, and shock cords. The last of these was composed of two strands 18 mm in diameter and 20 meters long.

I wanted first of all to find the pulling force exerted on the vehicle by the launch system. For this purpose, the shock cords were attached to a precalibrated stress ring dynamometer. We noted that the needle on the dial moved to the higher division for a load of 8 kg.

The figures contained in the following table were thus obtained:

Relative Strain $\frac{L - L_0}{L_0}$	Deformation of dynamometer ring ($\times 10^{-2}$ mm)	Load (kg)
0	0	0
1/4	13	104
1/2	17.5	140
3/4	29	232
7/8	40	320

Test flights were then attempted in calm weather. The shock cords were attached to the hook on the aircraft and were stretched by a factor of 7/8, so that the length of the strands increased from 20 meters to 37.5 meters. Each strand was pulled by a force of 160 kg, or a total of 320 kg. Every time it was released, the vehicle rolled over the ground for a distance of 20 to 30 meters, but it never took off under these conditions. /209

Study of Vehicle Takeoff

By using the data coming from the experiments, I sought to learn if the work furnished by releasing the shock cords was enough to launch the vehicle.

The amount of work is: $\frac{320}{2} \times 17.5 = 2{,}800$ kg-m.

The aircraft traveled 25 meters while the shock cords were being released. If one assumes that ground friction was only 20 kg, the work absorbed is then 25 x 20 = 500 kg-m.

Therefore, the amount available for launching was: 2,800 - 500 = 2,300 kg-m. This enabled the vehicle to reach a maximum velocity, neglecting air resistance, determined by the equation: $\frac{1}{2} \times \frac{200}{9.81} \times V^2 = 2{,}300$ kg-m, or V = 15 m/sec.

The study made with the crane of different aerodynamic efficiencies in the glider indicated that at departure the aircraft had a C_x of about 0.2 and a C_z of around 1.5, as had already been supposed. At a speed of 15 m/sec, the resistance is found to be 30 kg.

Since air resistance increases in proportion to the square of the speed, the work that it absorbs during a 25 meter long launching can be evaluated in an approximate manner. It is found to be 225 kg-m. Out of the 2,300 kg-m, there thus remains 2,075 kg-m available. These 2,075 kg-m give the aircraft a speed of less than 15 m/sec. The exact speed is determined by the equation $MV^2/2 = W$, and by replacing 2,300 with 2,075, one obtains V = 14.3 m/sec. At this speed C_x equals 27 kg and C_z equals 204 kg.

We have thus arrived at a figure that is just equal to the aircraft's weight, which is about 200 kg when in working order. The speed attained in these conditions is only enough to make the vehicle take off in calm air if the efficiency of the shock cords was equal to 1 and if there were no friction between the ground and the glider. Now, a test made with the apparatus I used to determine the speed and excess power capacity of birds in flight showed that the aircraft's rolling speed was obviously less than 15 m/sec and was in the neighborhood of 12 m/sec. That explained why the vehicle never took off in the absence of wind.

In contrast, a head wind of a few meters per second was enough to cause takeoff, since the supplementary work needed to overcome the increased resistance was small and the shock cords induced approximately the same ground speed. /210

For example, in a head wind of 3 m/sec, the calculated speed, 14.3 m/sec, increases to 17.3 m/sec. Resistance becomes 34 kg, while thrust goes up to 270 kg. One can see why, in the tests that took place, the aircraft was able to take off in a 6 m/sec wind after rolling on the ground for a few meters and that in a 12 m/sec wind it took off immediately, even though the shock cords were only stretched 50%.

The M3 and M4 Aircraft

In 1925, I built a third high aspect ratio, flexible wing aircraft, which was closer to the form of an albatross. This was the

M3 (figure 323). In addition, a built a fourth one, the M4 (figure 324), with m-shaped wings.

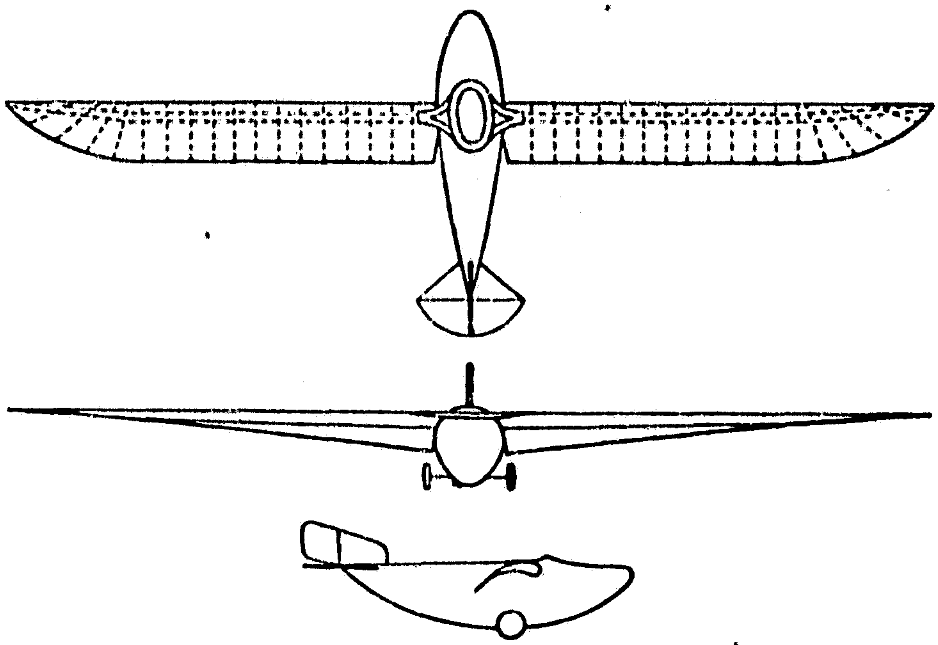


Figure 323
Design of the Flexible Wing M3 Glider

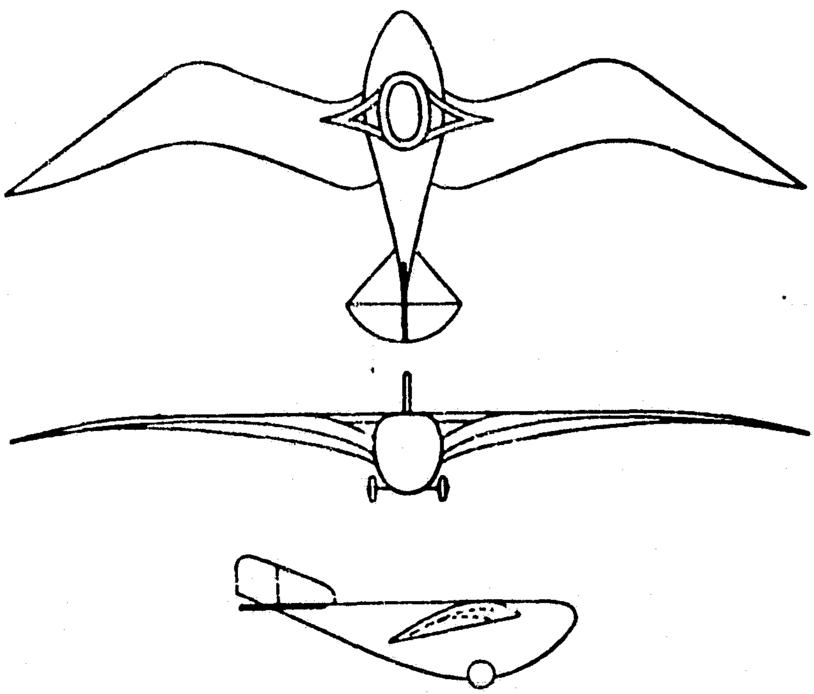


Figure 324
Design of the M-Wing M4 Glider

Here are the specifications of the two vehicles.

	M3	M4
Flight Weight	200 kg	200 kg
Empty Weight	130 kg	130 kg
Total Wingspan	17 m	10 m
Midwing Depth	1 m	1.30 m
Total Length	6 m	6 m
Wing Area	16 m^2	12 m^2
Load per m^2	12.5 kg	16.6 kg
Wing Weight	70 kg	76 kg
Net Fuselage Height	1.10 m	1.10 m
Aerodynamic Efficiency	20	20
Horizontal Speed	15 m/sec	15 m/sec
Sinking Speed	0.75 m/sec	0.75 m/sec
Aspect Ratio	17	17

It is interesting that by 1925 I had already created a high aspect ratio glider with fully overhanging wings. The German sailplanes closely resemble this vehicle. I should add that we lacked the means to test it out completely. /211

II. The Factors in Horizontal Winds Supporting Soaring

Indeed, for tests of the kind I pursue, the difficulty is not only to have the means, but also to know the exact features of horizontal winds enabling an aircraft to remain airborne and move forward without a motor.

Should one favor certain factors more than others? Should one maneuver in gusts using the variations in inclination or orientation, or rather employ the variations of speed with increasing altitude?

The Wind's Vertical Oscillations

In 1912, Betz, in a theory also supported by Knoller and based on Lilienthal's observations, had already stated the opinion that the cause of soaring resided only in the birds' use of the vertical oscillations of the wind. He then investigated the effect of an air current on an airplane wing.

He found that the arithmetic average of the various values of resistance could be negative, i.e. produce propulsion. In the model under examination, the apparent resistance was cancelled out by vertical wind oscillations ranging from +10° to - 10°. A negative apparent resistance, i.e. a propulsion, was obtained with oscillations to greater amplitude. According to the author, if a lift equal fo eight times resistance is assumed, supporting and propulsive forces become possible in winds whose oscillations deviate from the average direction by 16° in each direction.

Bertelli claimed in 1902 that in a small wind tunnel a surface could be sucked up by the air current striking it. In addition, Lilienthal found that a hollow wing suspended in a natural wind felt a slight pull forward.

a) The Katzmayr Effect

Inspired by the previous research, Katzmayr embarked on new wind tunnel experiments to support this theory, without trying to obtain supportive evidence from nature.

He placed wing mockups in a wind tunnel whose wind was made to oscillate by a system of slotted shutters capable of producing now a rising current and now a descending one. This experiment enabled Katzmayr to observe that the model wing no longer resisted moving forward, but actually was propelled and had a tendency to advance against the wind.

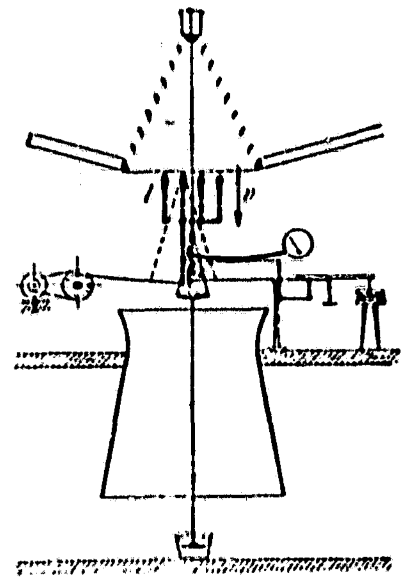


Figure 325
Katzmayr's Mechanical Shutters for Making a Wind Oscillate

The author made the following wind tunnel tests:

The wing under study was fixed in position. In contrast, by operating a system of plates arranged like slotted shutters installed at the exit of the wind tunnel exhaust, periodic variations in vertical direction were induced in the air current. (See figure 325.) /212

Katzmayr pointed out that by using four parallel plates to which he gave oscillatory amplitudes of 0, 9, 12, 15, 18, 21 and 24°, the direction of the air current underwent synchronous variations of 0, 4, 5, 7, 9, 10.5, and 12°. He noticed that the polar curve of the wigs being tested was clearly improved. He even observed negative resistances for two of the wings. The influence of the number of oscillations seemed secondary and the phenomenon was produced in an air current changing direction 30 times a minute.

All this means that in these conditions the wing is affected not by a resistance that impedes it, but by a horizontal force directed into the wind that makes it move forward in that direction.

Rateau formulated the equation describing the principal laws of what is called the Katzmayr effect in our country and the Betz effect in Germany. This equation clearly establishes the influence of an oscillating air current.

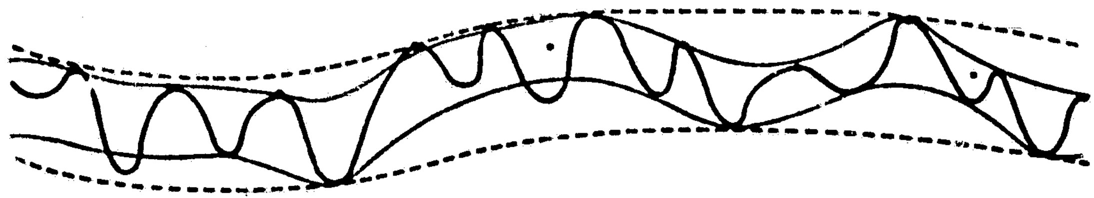


Figure 326
Schematic Drawing of the Vertical Oscillations
in a Wind Recorded at Marignane

b) The Influence of Vertical Oscillations on a Glider

Recordings of the instantaneous variations in wind inclination can help us gain a knowledge of the effect of these variations on the resistance to the forward motion of a bird, glider, or airplane.

Let us take the recording whose larger variations in inclination are roughly reproduced in figure 326. Three oscillatory systems are visible. One of them has a large undulation lasting around 6 seconds and whose amplitude is about 10°. The second system lasts an average of 2 seconds and displays an average amplitude of 13°. The third one lasts 0.6 seconds and has an average total amplitude of 15°.

Along with Huguenard and Planiol, I tried to calculate the Katzmayr effect resulting from the action of the oscillations on an airplane crossing through these disturbances without its own inclination relative to the ground being altered. We also had to take account of the fact that the smallest disturbances considered here have a length of 7 meters. We neglected the smaller oscillations appearing on the reel of film. Their length is on the order of a meter and they could consequently only have an effect on birds and insects.

We chose as a standard for study an airplane whose load per square meter was about 52 kg and whose speed was about 40 m/sec. It was equipped with Gottingen 430 wings, which have a C_z of 0.55 and a C_x of 0.026. Let us assume that the total drag is twice that of the wing, i.e. $C_x = 0.052$. The airplane's drag and lift, for an angle of incidence i of the wing to the wind, is represented by these equations:

$$C_x = 0.052 + 0.325\, i + 1.24\, i^2 \text{ in radians,}$$

$$C_z = 0.59 + 3.9\, i \text{ in radians.}$$

A. Rateau's calculation indicates that the Katzmayr effect produces a reduction in resistance equal to $(a_1 - b_2)j^2/2$, where j is the maximum inclination of the wind relative to a horizontal line, and a sinusoidal wind, which is similar to the wind studied /213 here, is assumed. This equation is independent of the oscillatory frequency.

The three systems of pulsations into which we have split the recorded wind have oscillatory amplitudes of respectively 10, 13, and 15°, which will be increased by the effect of the airplane. The inclination above the horizon is repectively 5, 6.5, and 7.5°. The average j^2 is therefore equal to: $(5^2 + 6.5^2 + 7.5^2)/57^2$ or 123/3,250 = 0.038.

The term $a_1 - b_2$ in Rateau's equation above has the value 3.9 - 1.24 = 2.66.

The reduction of C_x is therefore 1/2 x 2.66 x 0.039 = 0.051.

As you can see, in these circumstances, and with a wing inferior from the point of view of the Katzmayr effect to the one indicated by the author, the atmospheric disturbances under examination suffice to propel the aircraft.

This can be connected to the apparent increase in the lift of a wing near the ground. It can be taken for granted that a turbulent flow diminishes the apparent resistance to forward motion. The airplane can then fly at a larger angle without drag being greater than in calm air.

Now let us examine the situation of a narrow wing glider with an aerodynamic efficiency of 15, like the one we just considered. C_z can be taken to be 0.03 when the aircraft flies in these conditions, and certainly the glider is propelled all by itself in such a wind.

Take now an albatross weighing 10 kg and flying at a speed of 20 m/sec with a load of 13 kg/m^2. Let us suppose that the wings have an average contour equivalent to the preceding aircraft. However, it is obvious from our observations that the bird's total efficiency should be greater than 10 and that in place of the coefficient 0.052 that we used for the aircraft, one could use a coefficient smaller than 0.03. The efficiency in these circumstances would go up to about 20. The propulsive and lifting forces would thus be assured, even in weaker disturbances than those we have witnessed. Considering only the small, rapid oscillations in the wind, which extend over an air mass 7 meters long, C_x would be reduced by approximately half. This is enough to ensure the flight of a bird with an efficiency of 20.

Hitherto, we have assumed that the bird, like the airplane, does not maneuver. One would think, however, that opportune changes in the angle of incidence would improve the flight conditions even more. On the other hand, the regions of the world and the winds near the water through which albatrosses fly certainly are as agitated as the location where the film in figure 326 was recorded. /214
The variations of wind inclination could thus suffice in itself, like the variations evoked in other theories, to explain how this bird flies. Some solid experimentation would confirm that this is indeed the case.

However, it is proper to say at this time that by the time one reaches 10 meters above the sea, the variations in inclination rarely average greater than 3°, which would cause the reduction of C_x to be less than 0.004.

In these circumstances, the airplane mentioned above would have its resistance recuced by only 1/12, which is negligible, and the glider by 1/8.

In contrast, the albatross's resistance would be reduced by about 1/4.

Variations in the Wind's Orientation

It might also be possible to use variations in the wind's orientation.

Painlevé considered the question just as Sée did:

"Let us imagine a horizontal north-south wind that, however, alternately inclines a little to the east or west every ten seconds. A bird who starts out with a substantial south-north speed can fly indefinitely against the wind, i.e. from the south to the north, without making another wingbeat. This is the paradox in its most striking form.

"Let us represent the bird, who we are likening to a model glider, in a horizontal plane with its head northward and its tail southward. It constantly maintains the axis of its body in this direction, but when the wind blows a little to the west, the bird maneuvers about its axis to lean slightly to its right. When the wind blows from the east, it leans slightly to the left. Air resistance is always directed upward and perpendicular to the bird's plane, and therefore to its axis and the horizontal south-north direction. It alternately leans slightly to the left or the right, and it chooses its inclination so that the vertical component of resistance equals its weight. In these circumstances, the bird retains its horizontal south-north speed, but it festoons to the right and left in a barely perceptible fashion. It thus moves forward against the wind indefinitely by means of this simply rocking. What is more, if, at the same time that it leans slightly to the side, the bird tips very slightly forward, the air resistance, at the same time as it has a small lateral component constantly changing direction, will have a very small south-north component. This last component will always point in the same direction and pushes the bird forward, increasing its speed against the wind. The bird therefore flies against the wind with a growing speed, without flapping its wings, without any other effort than the small maneuver causing its body to lean alternately to the left and right."

This description is recognizably similar in every point to the explanation of how a boat tacks against a wind with the aid of its sail and its keel, which keeps it on course. The resulting trajectory caused by the series of tacks twists slightly around the average line it is following.

Variations in Wind Speed

We are now going to see that soaring in horizontal winds can very well be explained by the simple use of speed variations in the air current and, in particular, by gusts. We will find that the way in which birds maneuver in these gusts is easy to understand.

Let us take as an example a marine wind of 15 m/sec exhibiting speed variations of 5 m/sec in one direction or another, which occurs once in a while during storms in the Atlantic. Let us also go back to the case of the flexible wing aircraft weighing 200 kg in flying condition and whose horizontal speed is around 15 m/sec, with a sinking speed of 1 m/sec in still air. Let us launch it /215
against the wind while it is blowing at an average rate of 15 m/sec. As we have seen, the glider will sink vertically at 1 m/sec, its speed relative to the ground being zero.

a) The Influence of Speed Variations on a Glider

If a gust suddenly arrives that makes the wind speed go from 15 to 20 m/sec, the glider's horizontal speed, which was 15 m/sec relative to the air, will abruptly go up to 20 m/sec. Before the increase in speed, the lifting forces balanced the aircraft's weight, 200 kg. As we know, lift is proportional to the square of the air current's speed. It is therefore abruptly increased from 15 x 15 = 225 to 20 x 20 = 400, whereas the vehicle's weight remains unaltered. The glider thus finds itself with an excess of lift and rapidly gains altitude as it little by little loses its horizontal speed. It ends up by stopping at a certain point and then descending anew until it has reattained its normal sinking and horizontal speeds.

It is obvious that a reduction in wind speed will give the opposite results.

In a tail wind, an increase in air current speed will have the effect of augmenting the vehicle's horizontal speed and of making it lose altitude. On the other hand, a reduction in wind speed in theory will lead to an elevation of the aircraft.

Variations in speed are therefore capable, as we have just seen, of aiding a glider by increasing its lift. The same is true for an albatross.

For example, suppose that the arrival of a gust augments the wind speed by 40% and that the bird does not maneuver in response. The bird will then receive during a supposedly very short instant an upward impulsion representing approximately twice its weight P and an impulsion tending to impede its flight proportional to 2P/η, where η is its aerodynamic efficiency at the time.

If, on the contrary, the bird reduces the attack angle of its wings so as to maintain its lifting force almost exactly, it will produce a reduction in the resistance to its advance. Drag could become about four times smaller because the bird will have divided its wings' incidence by approximately two.

Finally, this maneuver, which increases its apparent efficiency, will have the effect of returning the animal's line of flight to the horizontal. If, besides, the wind takes on a slight ascendance at this moment, the line of flight could go up again above the horizontal.

Like the bird, the pilot also can gain height by maneuvering to make the best use of a gust's favorable effects and struggling as required against the unfavorable ones. It is true that the pilot has to display a very great adeptness and that the best thing for him is simply to try to copy the birds. He therefore has to glide downward when the wind weakens and to nose up slightly to rise back up when the wind increases in speed. In this way, he can move forward against the wind, although with a trajectory containing vertical undulations.

b) Sainte-Laguë's Calculations

Sainte-Laguë, taking my aircraft as a standard, was able through a special method of calculation to determine for every instant the vehicle's movement in a known wind. Here are some of the features of the trajectories he traced.

The trajectory in figure 327 corresponds to the case in which the wind encountered by the aircraft is sinusoidal with extreme values of 10 and 15 m/sec and has an oscillating acceleration ranging from -5 to +5 m/sec^2. The initial relative speed is 20 m/sec and the pilot engages in no maneuvers.

As you can see, the aircraft first rears and climbs close to 15 meters by borrowing the wind's energy. It then goes into a dive and loses more height than it gained. /216

Figure 328 depicts the trajectory followed by the aircraft when gliding in a calm atmosphere. The pilot performs a downward glide without oscillations. The abscissa represents the distance traveled in meters and the ordinate is the vehicle's altitude. The time in seconds is marked on the trajectory itself. Under these conditions, the vehicle descends regularly and at the end of 100 meters is located 14 meters lower than before, after having flown at 15 m/sec.

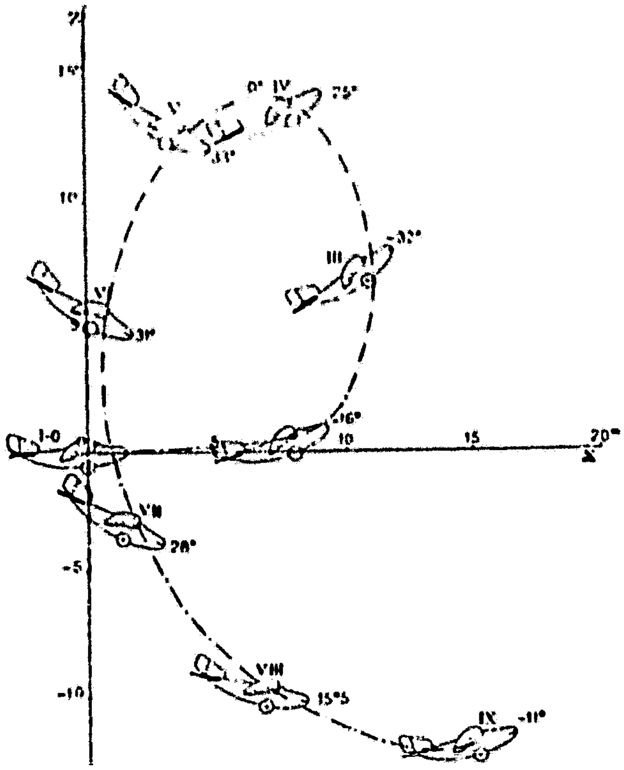


Figure 327
Trajectory of M2 Glider in a Gust whose Accelerations Range from -5 to +5 m/sec^2

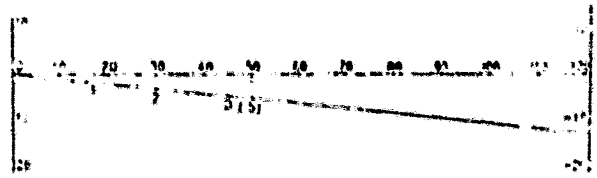


Figure 328
Trajectory of M2 in Still Air

Figure 329
Changes in the Preceding Trajectory Caused by a Six Second Gust, without Maneuvers by the Pilot

Figure 329 shows how the course changes under the influence of a gust lasting 6 seconds, during which the wind grows from 0 to 5 m/sec in 3 seconds and then goes back to zero in an equal period of time. The pilot executes no maneuvers during the flight. The vehicle, its controls locked, remains in its original state, under the conditions of the first trajectory. As you can see, at the end of 3 seconds and after traveling a little less than 40 meters, the aircraft is located approximately 5 meters higher than its point of departure.

The effect of the gust is to give the vehicle a speed of 18 m/sec at the end of its dive. The aircraft then performs a series of oscillations around its original gliding trajectory.

Figure 330 depicts the trajectory that results when, in the same gust, the pilot pushes on the joystick and reduces the wings' incidence by a few degrees after 1.5 seconds.

The aircraft, which had nosed up, goes into a dive. The pilot then pulls the joystick back so that at the end of the gust, the vehicle takes on a direction parallel to the simple gliding trajectory.

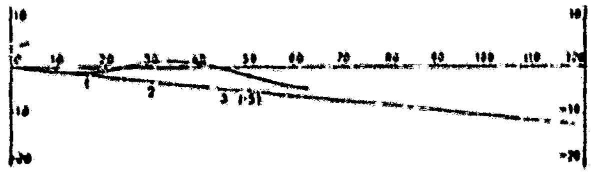


Figure 330
Changes in the Trajectory
when Maneuvering in the
Same Gust as Before

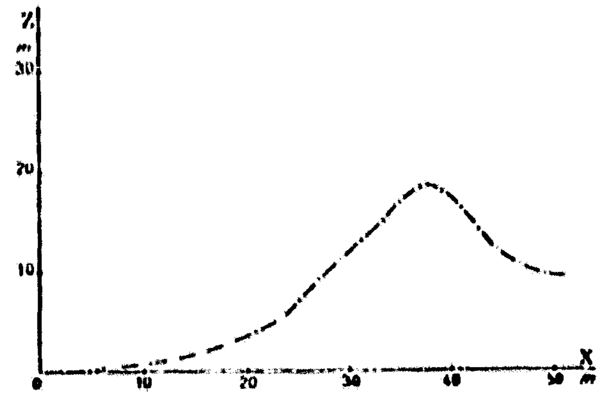


Figure 331
Trajectory of the M2 Glider
in a Gust of Long Duration

When this maneuver is executed, the aircraft is located approximately 2 meters above the latter trajectory. The gust has thus made it gain 2 meters in altitude. It appears that in shorter and stronger gusts, it would be possible at the end of the gust to again take up the downward glide at a point higher than the point of departure. A succession of such gusts would thus provide support indefinitely.

Figure 331 shows the aircraft located at point 0 in the lower part of a glide with a speed of 20 m/sec. At this moment it encounters a large, slow gust of constant acceleration equal to 2 m/sec^2. The pilot makes no maneuver in response and the vehicle rears up under the combined effect of its excess speed and the wind's acceleration. It then climbs approximately 20 meters while covering a horizontal distance of less than 40 meters, which takes it about 3 seconds. /217

At this moment it has been slowed down considerably, to the point that it stalls and abruptly goes into a dive.

When it again assumes a horizontal position, it has retained 10 meters of altitude and regained a speed of 3 m/sec relative to the ground and 19 m/sec relative to the wind. The aircraft will thus rear up anew in such a wind.

It should be pointed out that the gust under consideration is not entirely exceptional. In contrast, shorter gusts with higher accelerations are found in certain winds. This could be even more propitious for the aircraft.

Variations in Speed with Increasing Altitude

Finally, as Lord Raleigh, Baines, and then Idrac have indicated, soaring in horizontal winds can also arise from the variations in air current with increasing altitude.

Attempts with Flexible Wing Aircraft

I limited myself to attempts to fly by means of gusts during the tests carried out on my flexible wing aircraft. This is the situation in which control is easiest.

The tests carried out at Saint-Inglevert, in the absence of any updraft created by obstacles and even in slightly descending currents, confirmed the first findings yielded by experiments. First of all, the vehicles never took off in still air. In contrast, the passage of a gust made the vehicle gain height regularly. It is even possible to start ascending again in flight by maneuvering appropriately in the succeeding gusts and thus providing further lift.

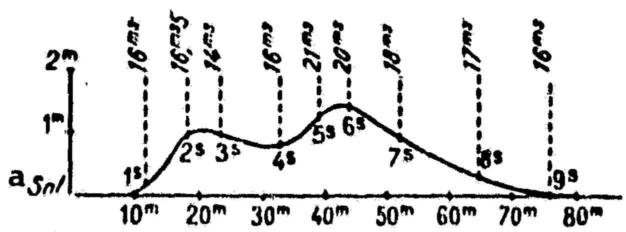


Figure 332
Trajectory Followed by an
M2 Glider in a Gusty Wind
Averaging 6 m/sec

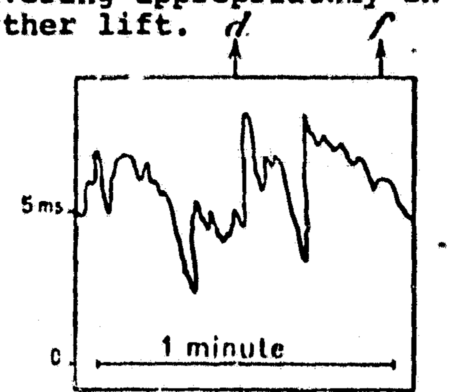


Figure 333
Recording of Speed
Variations of Wind
Blowing during Tests
d, Start of Flight
f, End of Flight

Key: a) Ground

Figure 332 depicts the reconstruction of the trajectory followed by my flexible wing aircraft in a wind blowing from the west, and therefore from the sea, at an average speed of 6 m/sec.

An anemometer placed 10 meters in front and a little to the side of the aircraft before launching recorded the wind speed at each instant during the experiments. In figure 333, the beginning and the end of the flight are marked off on the resulting graph.

The aircraft was launched into the wind by a shock cord catapult at a speed of 12 m/sec. It took off after rolling 9 meters and at this moment encountered the beginning of a gust whose speed went from 1.5 meters to 8.5 meters in 2 seconds. /218

The vehicle immediately climbed to about 1 meter from the ground in a time of 1 second. Then, as the gust died down, it began to glide donwward for ten meters or so. At this point a new gust intervened and the aircraft regained about 70 cm of height.

The wind speed then decreased regularly for 18 seconds, and the vehicle glided to the ground after traveling approximately 35 meters in the air and losing approximately 1.5 meters of altitude. The exceptionally small slope of this glide sould be emphasized. It implies an aerodynamic efficiency of 23 in still air.

Such a finding is obviously erroneous. It was the excess air speed at the peak of its trajectory that enabled the vehicle to support itself over such a long distance without losing very much height. The relative speed of the wind encountered by the aircraft at different points of its trajectory are marked on the figure. These numbers take account of the fact that the wind includes not only the air mass passing over the anemometer during the 9 second flight, but also the mass of air that was located to the right of the touchdown point at the same time as the aircraft.

As the wind's average speed was 6 m/sec, this latter mass had an approximate length of 54 meters. In its 9 second, 70 meter flight, the aircraft thus encountered 134 meters of wind. It therefore had an average relative speed of 16 m/sec, which represents what is necessary to provide lift. As you can see, such results are still pretty meager.

Conclusions

There is reason to think that the combined employment of flight experiments and calculations will one day bring about a solution to the problem of soaring by means of horizontal winds.

However, the possibility of testing craft that can soar without the use of upward currents depends above all on the success of research into the wind and its detection by the pilot. As long as the magnitude of the wind's oscillations remains unknown to the aviator, learning the proper maneuvers for making better use of the wind's energy will be long and painful.

In any case, what should be retained from all that has just been said about motorless flight is that such flight has enabled us to methodically study wing and fuselage characteristics under real conditions. Trying out gliders on propelled carts is too imprecise. In a wind tunnel, too, the results can be in error. This is because of the difficulty in copying an aircraft exactly when making a small model and also because it is hard to make adequate measurements when air turbulence is not recorded at the same time. /219

Tests of motorless flight have also resulted in increased knowledge of the atmosphere, whose effect on motorized airplanes is beginning to be plain to all. This enables me to state that in the last ten years, the scientific study of soaring has done more for aeronautical progress than research in any other field.

RECOMMENDED READING

Magnan, "L'aviation sans moteur" [Motorless Aviation], Bull. du Labor. de Morphol. et d'Avia. de l'Ec. des H. Etudes, 3 (1924).

Magnan, "L'aviation sans moteur" [Motorless Aviation], Rev. Gen. des Sciences (May 30, 1925).

Magnan, Etude sur le vol à voile dynamique [A Study of Dynamic Soaring], Bull. du Serv. Techn. de l'Aéronautique, 21 (1924).

Magnan, Pour voler à voile [In Order to Soar], Roche d'Estrez, Paris (1922).

Lesson Sixteen: Mechanical Flapping Flight /220

We have seen that man has learned how to imitate the soaring of birds. He has been able to closely copy sea gulls and vultures as they fly along without flapping their wings through the use of thermal and obstruction currents.

Mankind has also dreamed for a long time of flying like the majority of birds, by flapping wings. It must be acknowledged that until now the results have been much less significant than those obtained in motorless flight. However, it seemed to me a good idea to remind you of the efforts that have been made and to show you what could be achieved. The study of mechanical flapping flight should not be neglected. It seems to me that it has much to contribute to aeronautical progress. It is necessary to encourage unbiased researchers excited by long research that can often be disappointing. Do not forget that it was such researchers, in their constantly renewed individual experimentation, who created aviation.

Remember Marey's incisive experiments for analyzing birds' wingbeats. This great scientist was not content with his findings. He tried to recreate wingbeats artificially through mechanical imitations.

We are going to examine Marey's experiments in this area and see what results he arrived at.

Marey's Experiments in Imitating Wingbeats

In order to imitate birds' wingbeats in conditions easy to analyze, Marey thought that the actual wings had to be replaced by thin surfaces of well-determined geometrical form. They would then be abruptly lowered by releasing a spring of known force and the lifting force exerted by air resistance measured.

Marey's Mechanical Bird

For this purpose, Marey constructed an apparatus in the following manner. (See figure 334.) A Y-shaped framework was placed on a hollow m-shaped base in which lead shot could be inserted. This part of the apparatus represented a bird's body. Its weight could be changed at will.

A long shaft was joined by a hinge to each branch of the frame. The shafts were thinner at their tips and implanted in each of them were steel ribs supporting a thin fabric or paper sail representing a flexible wing. Angular motion around the shoulder joint could be /221 imparted to these wings. The wing surfaces had a visibly parabolic form. Their bases could be attached to a greatly stretched rubber band which curled around a pulley P further down on the machine. The rubber band represented the pectoral muscles. The pulley supporting it served to divide the tension equally between the two wings.

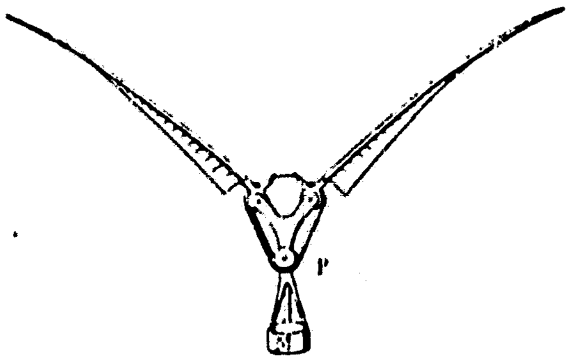


Figure 334
Marey's Apparatus for Imitating Wingbeats

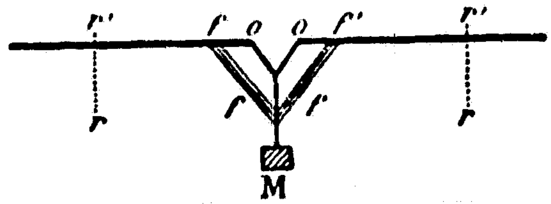


Figure 335
Theoretical Representation of Power and Resistance Moments in Marey's Apparatus

On the wings' dorsal side, close to their base, were two hooks that came together when the rubber band was stretched and the wings raised. A ring of thread thrown over the hooks held them together and kept the wings raised and the rubber band stretched. When the thread was burned, the wings were immediately forced downward by the release of the rubber band. They quickly attained a speed that remained constant even after they had passed the horizontal position. If the machine was not loaded too heavily with lead shot, it would make a leap and reach a certain height. This was because of the reaction of the air under the wings. The functioning of this little machine is well suited to clearing up the dynamic characteristics of a wingbeat.

We just saw that the apparatus imitating a bird's flapping wing jumped into the air at each wingbeat. If it were gradually loaded with lead shot there would come a moment when it would no longer leave the table. At this moment the air's reaction to the wing's downstroke can do no more than support the weight of the machine. Marey thought that he could thus produce the conditions surrounding a wingbeat during horizontal flight. In this case the descending wing gives rise to an air pressure equal to the weight of the body that it is supporting at a constant height. Marey stated that in such circumstances, the moment of air resistance is equal to the moment of the force of the rubber band. If, therefore, the point of application under the wing of the air's total reaction force were known, one could make the moment of the artificial muscle's force balance it out. This would entail applying a force equal to half the body's weight at this point on each wing. At the same time one would support the weight of the mechanical bird with its outstretched wings.

Marey added that the point to apply the force corresponding to the reaction of the air could be found by trial and error. It will be recognized by the fact that an upward pressure at that location will exactly balance the force of the rubber band and the weight of the machine.

Only one point underneath each wing satisfies these conditions. It is situated two-thirds of the way along the wing, starting at the shoulder.

The theoretical representation (figure 335) shows, according to Marey, the apparatus in equilibrium, with the wings extended and raised by two forces rr' applied two-thirds of the way from point 0 to the end of the wing. The rubber bands ff' are stretched and their force is in equilibrium with the body's weight M, which is thus exactly supported.

This apparatus permitted the author, after a few modifications, to measure the mechanical effects of a wingbeat in all sorts of situations.

The Mechanical Effects of a Wingbeat /222

In order to be able to determine rigorously the variations in the height of the jumps, Marey modified his apparatus to make it usable with a graphic recording device.

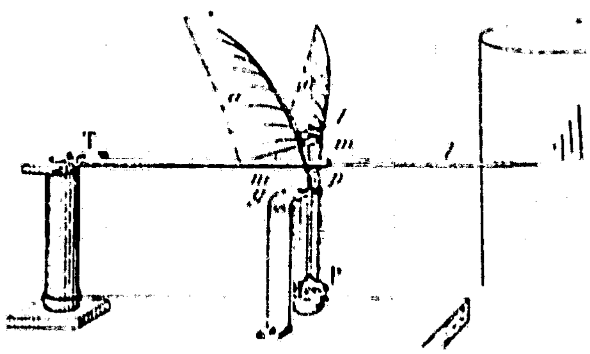


Figure 336
Marey's Equipment for Reproducing the Lifting of a Bird's Body duirng the Wing's Downstroke

Figure 337
Heights to which the Wingbeat Lifted the Apparatus with Loads from 95 to 175 Grams

Figure 336 shows the artificial bird mounted on a long light wood shaft Tl joined through a hinge to the top of a column. In this way, the machine leaped in an absolutely vertical plane. The shaft continued in front of the bird and ends in a pen for tracing the height attained on a smoked cylinder. A pin g resting on a metal arc supports the machine at a constant height. This height represents the minimum base point for the jumps, whose height depends on the force of the rubber band mm in relation to the weight lifted.

Lastly, the great physiologist made sure that the wings aa were always equally raised and the bands equally stretched in each experiment. This indispensable precaution consisted of using a wooden mandrel to fabricate a thread ring which linked the wings and held the apparatus taut until it was burned. A set of similar rings was thus obtained. The wings were always equally raised, and the rubber bands equally stretched.

Marey did several series of experiments with this apparatus. Various factors influencing the flapping wings were altered. First, Marey studied variations in the weight of the artificial bird.

The complete apparatus weighed 94 grams without any extra load. Through the use of additional weights, the author made the load vary from 95 to 175 grams and he obtained jumps of decreasing height.

Figure 337 depicts the resulting weight curve. The height lifted up is the ordinate and the weight lifted is the abscissa. The curve formed by the ends of the lines representing the height lifted does not correspond to a proportional relationship between the load and the amplitude of the movements. However, if the weight lifted is multiplied by the height of the jump, the product decreases regularly and its magnitude is inversely proportional to the weight lifted. Marey concluded that "given a constant quantity of motive work produced, the greater the mass of the machine, the smaller the quantity of work transmitted to this mass is."

Influence of Variations in Motive Force

Marey then conducted a second series of experiments to study variations in motive force. He changed the force of the rubber band motor in the following way. His technique was based on the fact that a homogeneous rubber tube always develops the same pulling /223 force when a given length is stretched by the same amount. He thus took three pieces of the same length and used first one, then two, then three at the same time to produce the mechanical wings' downstroke. Each of the rubber bands developed a static force of 900 grams. Marey thus worked with three motors pulling at a force of 900 grams, 1800 grams, and 2700 grams. He was able to document the progressive increases in the amount the machine was lifted corresponding to the progressive increase in motive force, as well as the lack of proportionality between the two. (See figure 338.)

Influences of Variations in Wing Area

Marey continued his work by investigating the effect of changing wing area. To study this he first compared the variation in height resulting from variations in load for wings of different surface areas. Figure 339 reproduces the heights machines with wings of 700 cm^2 and 1,092 cm^2 were lifted to. The first machine is represented by the solid lines and the second by the single dots. As you can tell, the influence of wing area is negligible after a certain weight.

It is interesting to note that the machine used weighed 900 grams. This weight is greater than that of many species and equal to that of such birds as the buzzard and the herring gull.

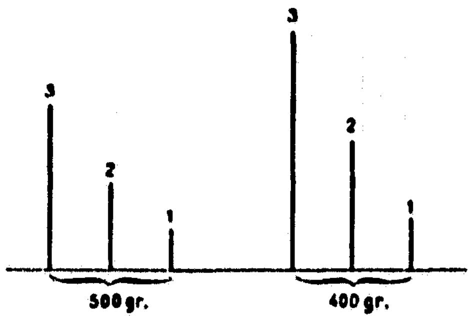


Figure 338
Differences in the Height to which the Mechanical Bird is Lifted Depending on its Weight and Motive Force

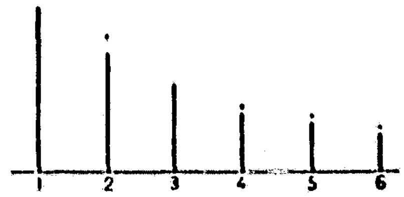


Figure 339
Effect of Changing Wing Area on Lift Height

Influence of Translational Movement

Marey also experimentally studied the influence of translational movement on the nature of wingbeats. He demonstrated that a wingbeat encounters more air resistance when the flying creature has a high enough horizontal speed.

Marey first of all mounted an artificial flier on his circular track for studying birds (figure 340). The machine's wings were put in motion by a pneumatic device. With the aid of manometric cells, he recorded the wingbeats (figure 341) and noticed that the oscillations diminished in amplitude as their length increased. This corresponds to what is observed in nature.

He then used two thin, rigid planes .5 meter long by .1 meter wide as wings. He locked them together and could lower them by releasing a rubber band. This crude flapping machine could move forward with the aid of a device for rolling on a horizontal metal wire f (figure 342). As part of this setup, two large pulleys RR' /224
were placed at the ends of a table. In their grooves was an endless cable c, one of whose strands was parallel to f and attached to the mechanical bird, which it pulled at varying speeds.

Marey tried first to measure the machine's speed and then the duration of the wings' downstroke. Since the artificial bird's speed was the same as the endless cord's, the wire was made to roll over a small pulley I, whose revolutions were marked on a cylinder turned by means of a system working like a Morse telegraph. To make the recording, the pulley I had a metal armature attached to half its perimeter. The armature controlled the current of a battery S by closing two contacts. An inscribing stylus put in motion by an electromagnet in the circuit traced a change in direction for every 0.20 meters the cable, and therefore the bird, had moved. Thus, the faster the bird moved, the greater the number of bumps inscribed on the cylinder in a given time. A second electrical signal S' served to determine the duration of the wings' downstroke. This was done with the aid of a device mounted on the bird which opened the circuit at the beginning of the wings' descent and closed it at the end. The length of the recording stylus's deviation, which was controlled by an electromagnet, thus indicated the duration of the wings' downstroke.

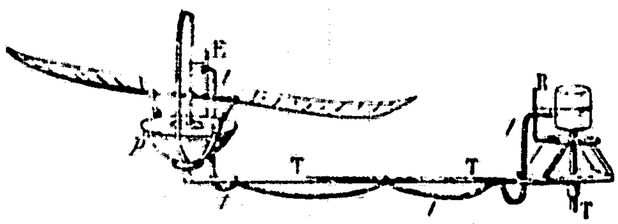


Figure 340
Marey's Mechanical Bird
Setup with Circular Motion

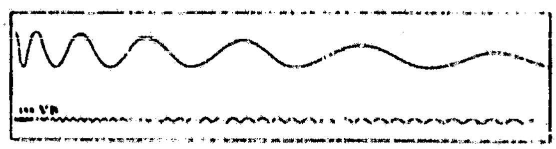


Figure 341
Decrease in Mechanical
Bird's Wingbeat Amplitude
During Circular Motion

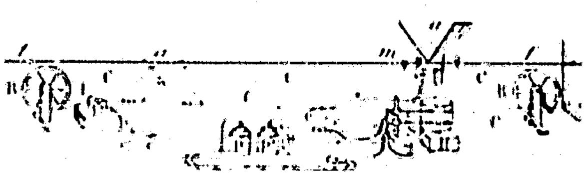


Figure 342
Marey's Experimental Setup
for Measuring Wingbeat
Duration during Linear
Motion

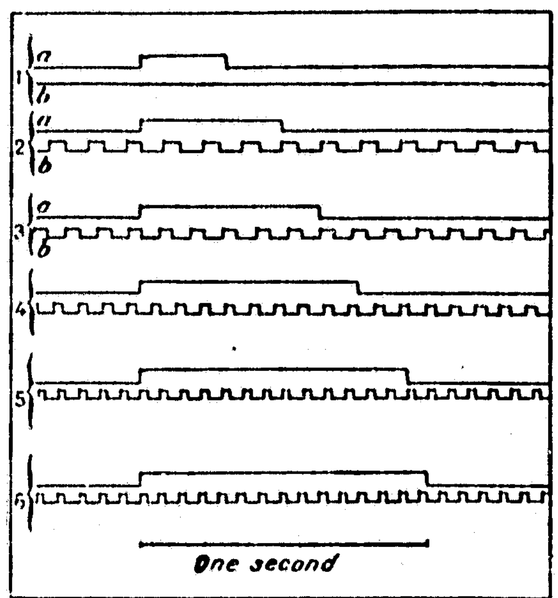


Figure 343
Variations in Wingbeat
Duration According to
Speed of Apparatus

Marey then made a series of experiments in which he obtained the simultaneous recording of the flapping apparatus's forward speed and the duration of its wings' downstroke (figure 343).

In the first experiment, there was no linear motion. Of the resulting traces, the upper one shows the downstroke duration, which is 1/3 second. This can be seen by comparing its length with the length of the time scale.

In a second experiment, the mechanical bird moved forward at a moderate speed. Its tracings indicate that a distance of 3 meters was covered in one second. They also document the increase in the duration of the downstroke caused by this forward speed. /225

Later experiments proved that downstroke duration always increases as translational speed grows. However, Marey was not able to find the exact relatonship between these two variables.

II. Prewar Ornithopter Tests

Instead of trying to carry out precise experiments as Marey did, several inventors have sought to create flapping wing apparatus that could be made to fly by copying the way birds flap their wings. Some of them were fully successful in tests of small scale models.

Among the attempts at reproducing the flapping flight of birds, those of Hureau de Villeneuve, Pénaud, and Tatin should be cited.

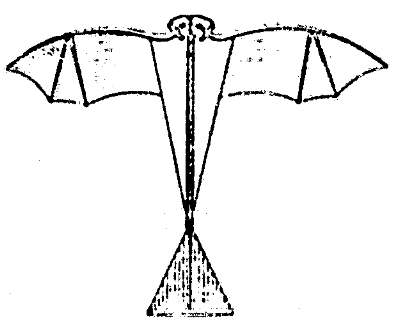


Figure 344
Hureau de Villeneuve's
Ornithopter

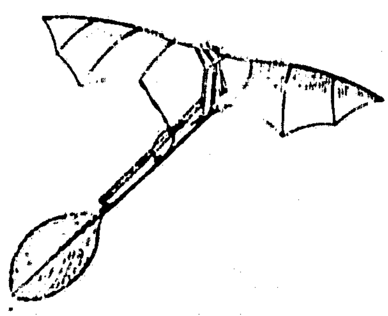


Figure 345
Pénaud's
Ornithopter

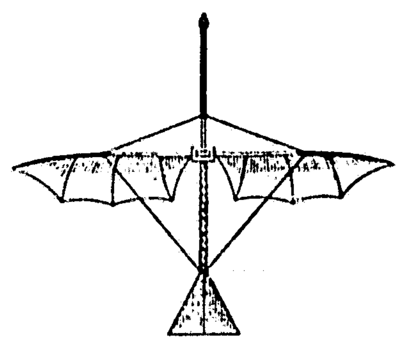


Figure 346
Tatin's
Ornithopter

Hureau de Villeneuve's Bird

In Hureau's 1872 bird (figure 344), the axes of rotation formed an oblique angle with each other and with the axis of the body. changes in the plane of the wings were caused by the direction of the joint. The bird had a remarkably powerful wingbeat. Each beat lifted it up forcefully, but there were not many of them. The vehicle first climbed to a height of 1 meter and then parachuted back to the ground.

A year later Hureau had a much larger model of his vehicle built with a 1.5 meter wingspread.

Pénaud's Bird

In Pénaud's vehicle, the axes were parallel to each other and to the axis of the body (figure 345).

Changes in wing plane were made by giving a certain mobility to the ribs around the wing spar and consequently to the fabric covering them. The ribs were then adjusted by means of a small rubber band. The effect of this device was that when the wings were thrust downward, their rear edge was partly raised up at the end of the storke. During the upstroke, on the other hand, the edge stayed down, which gave the airfoil an accentuated downward and rearward slant. The goal of this arrangement was to provide both lift and propulsion at the same time, and in the way it occurs in nature.

Pénaud's mechanical bird could not ascend vertically, it appears. /226
However it moved horizontally with rapidity and even climbed at a slope as high as 20%. During a public test it is said to have taken on speed by flapping vigorously and performed a rapid horizontal flight over a distance of 9 meters. It then curved and climbed 5 meters into the air while gradually losing speed. After hovering in the air, it descended and took on speed again. It gained height once more and finally landed in front of the spectators as its wings slowed down.

Tatin's Bird

Beginning his research in 1873, Tatin followed the same route. He built a small apparatus weighing only 5 grams out of microscopic parts. It worked very well. He also set up another apparatus which copied bats (figure 346) and obtained some very successful flights.

Tatin next wanted to expand, and he put together an apparatus the size of an eagle, but lighter. He equipped it first with a steam engine and then with a pneumatic motor. Despite all his efforts, he could not obtain any true flights, only some descents at various inclinations.

Ader's Bird

Ader first sought the solution of the problem of flight through imitating natural birds. He constructed a large bird with flapping wings designed to carry a man and to be propelled by his muscular force.

Tatin claims that Ader carefully copied nature as accurately as possible in building his machine. The vehicle represented a large bird with a 9 meter wingspan. All its sections were in the correct proportion and, probably to make it as close as possible to its model, it was entirely covered with artificial feathers. The feathers were composed of a central shaft of flexible wood on each side of which natural feathers were inserted to take the place of barbs. The large feathers were as numerous as on the model bird and arranged in the same way. Lastly, the articulations were the same as in the natural wing, up to that of the hand at the end of the limb. And it all worked. The motive force was obviously insufficient. What tests were made? It is unknown, says Tatin.

This was the first full-scale test.

Full-Scale Ornithopters

Others followed, with varying conceptions of what has been called an ornithopter.

Thus, in 1908, J.J. Bougart, of Colmar, created a flapping wing airplane weighing 50 kg. It included four wings which moved like those of a dragonfly and had a surface area of 16 m^2. Two men, one behind the other, were supposed to maneuver the wings so that their posterior ends were lowered at the same time. Flights of 200 meters at a height of 1.5 meters were successfully made with this apparatus.

Another ornithopter was built by J. Collomb. It included two wings that oscillated vertically about a hinge. They were made of wood strips jointed like the slats of a jalousie. During the downstroke, the strips overlapped so as to form a continuous surface. They separated from each other during the upstroke and were inclined at an angle of 15°. The rods controlling all this activity were set in motion by a 40 hp motor. They could produce three wingbeats a second without endangering the component parts. The vehicle's empty /227
weight was 250 kg. (See figure 347.) Its test flights do not seem to have yielded interesting results.

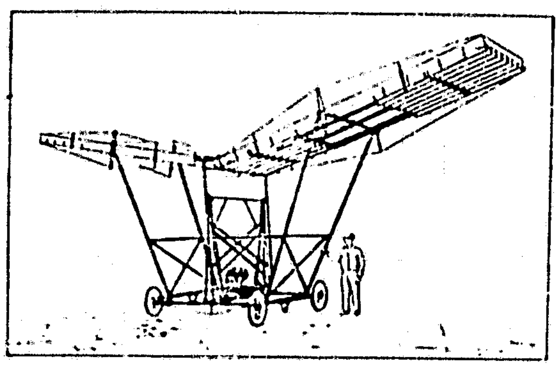


Figure 347
Collomb's Ornithopter

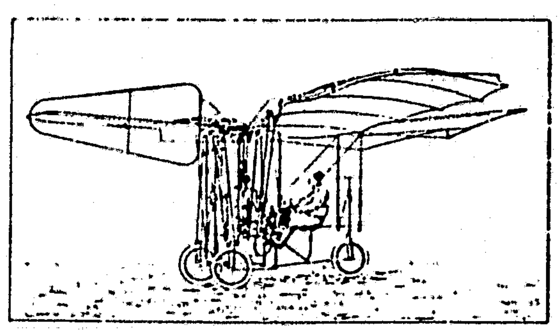


Figure 348
Soltau's Ornithopter

Gilbert Temploux designed a 60 kg vehicle with a 5.50 meter wingspread. Its two wings were flexible at their ends and trailing edges.

When thrust upward the wings attacked the air at a small positive angle. When going downward the wings struck the air from front to back at a negative angle.

Temploux's test model made several satisfactory flights. The best was one of 168 meters covered in 12 seconds. The machine rose to a height of 6 meters.

Let me also mention the Soltau ornithopter of Vienna (figure 348). It was a copy of birds of prey and had a wing spread of 14.6 meters with a wing width of 2.5 m. The vehicle rested on springs over a three-wheeled chassis. It had a liquid air motor and flapped 90 times a minute.

III. Modern Ornithopters

Since the war, attempts at flying by flapping have been taken up again throughout the world.

Particularly in France, certain inventors have recommenced the struggle, difficult as it is, to carry their ideas to a successful conclusion.

The Rouquette Apparatus

In the first place, let us recall Rouquette's attempts. He was already striving to build flapping wings before 1914.

He originally constructed wings with ribs made of steel plates. The wings were fixed to a harness worn by the pilot. (See figure 349.) The vehicle's flight weight was 88 kg, including the pilot. The author sought to accurately reproduce wingbeats and he succeeded in cancelling out his weight with each wingbeat. He verified this by being hooked to a dynamometer.

He later created a vehicle with two pairs of wings mounted on a bicycle frame. A piece of lead was placed on the pedal sprocket to act as a flywheel. The inventor was one of those who had noticed that at the end of the downstroke, the bird leans against its wings and, with the help of its pectorals, lifts its body. Through the use of the eccentric mass of lead, he was able to lift his body at the moment when the wings were thrust downward. His system was mounted on springs and he inscribed the displacement of the springs, and therefore of the body, on a cylinder. The recordings thus obtained revealed that in the end he was losing almost as much height as he gained.

Figure 349
The Rouquette Flapping
Wing Apparatus

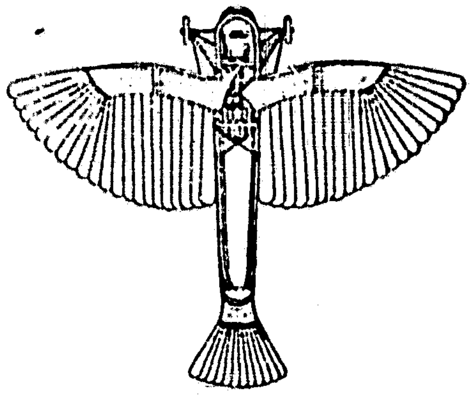


Figure 350
G. Roth's Flapping
Wing Aircraft

The Roth Apparatus /228

G. Roth came up with a highly ingenious flapping wing vehicle. The wings were endowed with flexible metal quills (figure 350), which were imbricated and connected by elastic joints. In this way, the wing surface during the upstroke was much smaller than during the downstroke.

The wings' alternating drive train was comprised of a gear box, a reduction gear, a set of transmission gears, and two rotating plates holding off-center pivot pins. Connected to the pins by a joint were the rods that directly drove the wings. In this way the wings were forced to flap at an average amplitude of 85°.

One of the motive plates included a slot for holding a threaded device capable of maintaining the wings in a horizontal position during gliding.

The L. Kahn Apparatus

L. Kahn's theory of flapping flight was summarized above.

Here is his mechanical application of this theory.

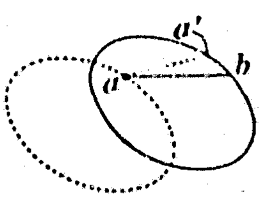


Figure 351

When the element ab (figure 351) describes an undulated surface in the fluid, the points b and a successively describe the same trajectory. They consequently have the same trajectory relative to their support structure. However, point a is constantly behind point b, and its trajectory, relative to the support structure, is behind that of b. Since a follows b and passes through the same points in space, a's motion is always out of phase with b's.

In this manner the law governing orientation is always synchronized with the law governing displacement, on the condition that the two generators of the airfoil describe identical, out of phase paths. One is thus confronted with a very large number of variables: On the one hand is the form of the orbital motion, which can be adapted to different flight conditions, while always following the law governing orientation. On the other hand is the phase difference, which controls the angle of incidence with the trajectory and, finally, the relation of the profiles to the source of propulsion.

A particularly simple case is given by the author in which the orbital movement is circular and uniform relative to the support structure. As far as following the law governing orientation is concerned, it is sufficient to give an out of phase circular and uniform motion to he two generators. Moreover, the mechanical solution can be simplified with the help of the following remarks: /229

Suppose that the hodograph of the orbital motion could be described. By simple displacement of the center of the hodograph, the hodograph of the motion relative to the fluid can be obtained. The radius vector of the new hodograph is, by definition, parallel to the tangent of the motion relative to the fluid. It therefore suffices to make the airfoils parallel to the tangent. Now, the hodograph of uniform circular motion is a circle. From this comes the especially simple solution of figure 352.

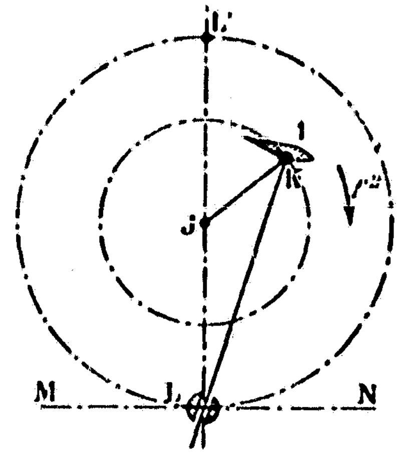


Figure 352
Hodograph of a Flapping Wing's Motion Relative to the Fluid

L. Kahn meanwhile pointed out that circular motion is not the most efficient sort. When hovering, wing motion should resemble a kind of horizontal, stationary sculling. A "complete" apparatus should therefore be capable of both movements, as well as all the intermediate ones between vertical or stationary flight and high speed flight.

This is the goal pursued by the author in the construction of a more complicated vehicle.

In order to establish the orbital motion spoken of above and also the orientation of the wing so that it had the desired inclination at every moment, L. Kahn adopted the following device:

The machinery was capable of creating a given orbital curve through the use of a system of three rods (crank, connecting rod, oscillating shaft), which is depicted very clearly in figure 353. The wings describe a figure 8 during vertical or stationary flight. The oval drawn with a dotted line is the curve corresponding to full speed flight. Between the two, all forms are possible. Any point B on the connecting rod could describe the orbital curve. In reality, however, this is done by a point O on the rod determined in such a way that there are five different ways to regulate the point's motion. Furthermore, the pilot has the ability to change the axis of oscillation so as to modify the orbital curve as the situation demands.

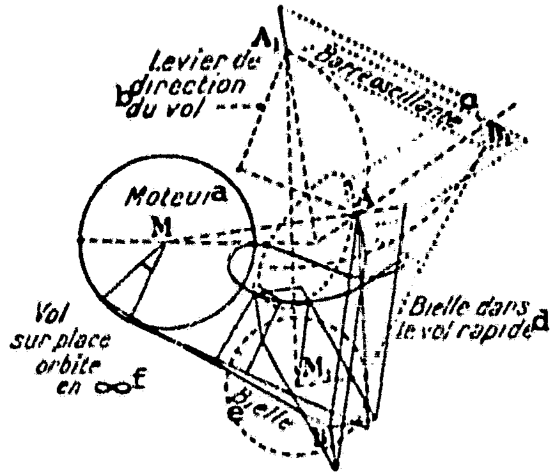


Figure 353
Three Rod System Used
in L. Kahn's Aircraft

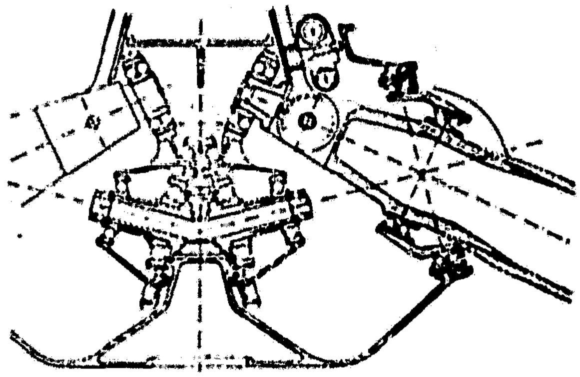


Figure 354
Wing Drive Train
in L. Kahn's Aircraft

Key: a) Engine
b) Flight direction lever
c) Oscillating shaft
d) Connecting rod in rapid flight
e) Connecting rod
f) Stationary flight, figure-eight orbit

The wing is constantly restricted to its trajectory, and its rear portion follows the same path as the front after a certain delay. It can therefore be guided by another three-rod system out /230 of phase with the first, but using the same axes M and A and the same drive shaft. The phase difference is instituted simply by setting the two crank shafts at a suitable angle to each other. There will then be two "lead" points driving the wings. The pilot can alter the way the system works by moving the oscillating shaft's axis with the directional lever. Moving the lever also can cause the transition from rapid flight (oval curve) to slow or stationary flight (figure-eight). The wing controls are illustrated in figure 354. To the left is the rotating shaft's ball bearing, in the middle are the connecting rods of the two three-rod systems, and at right are the oscillating shafts. The wing controls are contained in a housing that can turn around ball and socket joints connected to the wings. The wing rotation alone automatically alters the length of the base of the three-rod systems, and, as a result, the form of the curve described by the wing.

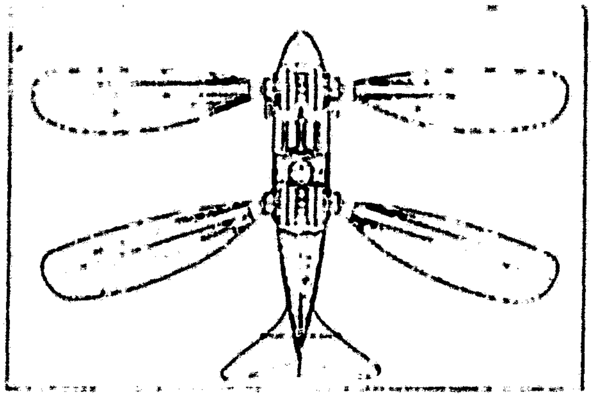


Figure 355
L. Kahn's Flapping Wing
Airplane, Viewed from Below

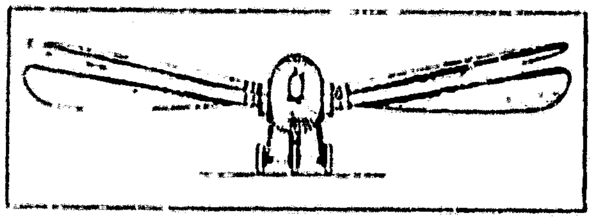


Figure 356
L. Kahn's Flapping Wing
Airplane, Viewed from in Front

The engine is in the middle of the airplane (figure 355), which has two wing planes. There is one shaft housing per wing. Between each pair, both front and rear, of housings, is a set of controls. Alongside the ordinary airplane controls are the ones for the wings. They are used during rapid flight, but are not effective at lower rates of speed, where equilibrium is maintained by differences in the motion of the four wings.

The structure of the wings is apparent here. They are made of glued strips coming together at the ball and socket joints.

In the frontal view (figure 356), the difference in phase of the wings is visible. This arrangement was instituted so as to regularize lifting force. When flying at moderate air speeds, the wings follow each other along the same undulated surface. Everything occurs as if they were part of a single flexible surface.

The aerodynamic coefficients used are the same as those for wings in uniform motion, such as they are found in collections of standard profiles. The vehicle is equipped with a 300 hp Hispano engine and weighs about 1,600 kg in flying condition, including an hour's worth of gasoline at maximum power. It appears capable of flying at all speeds between zero and full speed. This latter speed is fairly difficult to specify because it depends especially on the passive resistance to the actual vehicle built. It ranges hypothetically from 150 to 200 km/hr.

The wingbeat frequency varies between one and two per second. It is highest during stationary flight, when the frequency is limited by the flexing torque caused by inertia on the wing recesses. As horizontal speed is increased, the flapping has to slow down, exactly as is observed in birds.

As a whole, the vehicle reminds one of a dragonfly, even though this was not the author's intention.

The White Apparatus

/231

To wind up, let me cite the tests of White, who was killed in 1929. Figure 357 depicts his flapping wing machine.

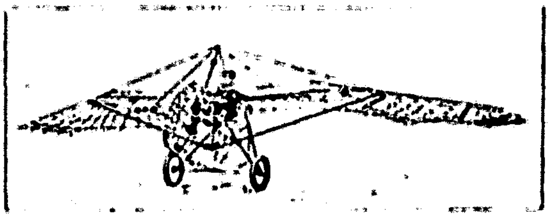


Figure 357
White's Flapping Wing Aircraft

Obviously, much remains to be done in the field of mechanical flapping flight. Many people claim that such studies have no contribution to make and that there is no reason to try to imitate birds. Man has supposedly done much better than nature by inventing the propellor.

Can it be reasonably claimed that flapping flight is inferior to flight with a propellor when there is no practical experience to support such a conclusion?

Did not Poincaré say that truth comes only out of experience?

RECOMMENDED READING

Bracke, Quelques machines à ailes battantes [Some Flapping Wing Machines], Vivien, Paris (1904).

Kahn, L., "La propulsion animale dans les fluides" [Animal Propulsion in Fluids], Ass. Techn., Mar. et Aéron., (June, 1929).

Marey, Le vol des oiseaux [Avian Flight], Masson, Paris (1890).

Tatin, Théorie et pratique de l'aviation [Theory and Practice of Aviation], Paris (1910).

An airplane is a machine that is heavier than air and that possesses special surfaces known as wings. It is capable of rising from the ground, supporting itself in the air, and moving forward thorugh the action of a propellor turned by an engine. The propellor gives it a certain horizontal speed and the resulting reaction of the air on the aircraft's fixed wings causes a rapid displacement through the atmosphere.

It is therefore because of the propulsive system, propellor and engine, that the airplane can find the necessary supporting forces in the air to give it lift. This is why an airplane starts to descend the moment its speed drops to the point that it is no longer sufficient to maintain horizontal motion. If the airplane is well designed, it will then glide back toward the ground, at least if it is not too close to the earth. Here, a sudden fall could result from stalling because the lifting forces turn out to be less than what is required.

I. Description of an Airplane

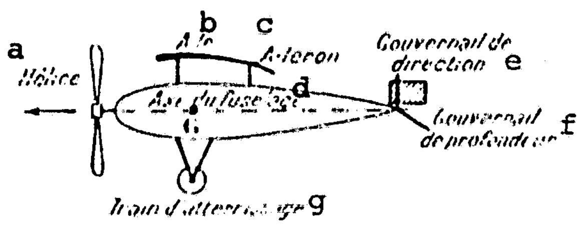


Figure 358
Schematic Drawing
of a Monoplane

Key: a) Propellor
b) Wing
c) Aileron
d) Axis of fuselage
e) Vertical Rudder
f) Horizontal Rudder
g) Landing Gear

An airplane is an apparatus that always possesses a longitudinal and vertical plane of symmetry. Its basic components are the following (figure 358):

1) A body with a system of propulsion.

2) A set of wings.

3) Controls and control surfaces.

4) Take off and landing equipment.

The Fuselage

The forward part of the body, also called the fuselage, generally contains an engine holding a propellor, an open or closed cockpit, and lastly a cabin for passengers or cargo. In the rear are two fixed planes. One is vertical and controls drift, while the other, the stabilizer, is horizontal and maintains longitudinal stability.

The Wings

Attached to the body are the wings, or airfoils, which include one or more wing spars supporting metal or wood ribs covered with plywood or thin fabric.

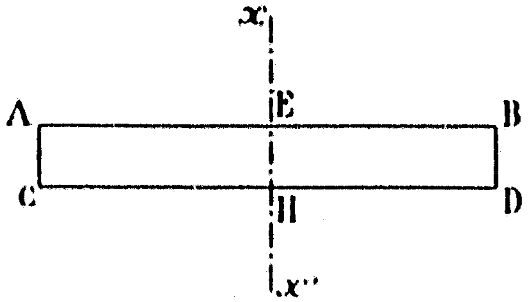


Figure 359
Schematic Airplane Wing
xx', Axis of Symmetry,
AB, Wingspan; EH, Depth

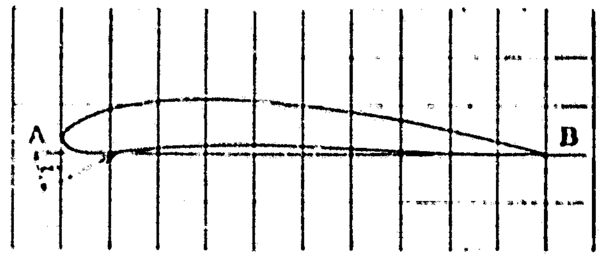


Figure 360
Transverse Cross Section
of an Airplane Wing
(STA Profile no. 206)
AB, Cord

The wings are always elongated in the transverse sense, perpendicular to the direction of the airplane. They have a plane of symmetry xx' (figure 359), and they all display a profile, i.e. a transverse cross section, EH possessing a special curvature. The exact curvature is chosen according to what wind tunnel tests on models show increases the favorable reactions of the air during flight. /233

In general, the upper wing surface is convex. It constitutes the extrados. The lower surface is concave and constitutes the intrados. Under these conditions, the line AB (figure 360) is called the wing cord.

If we look again at figure 359, the length AB is called the wingspan, and the length EH is the depth. The ratio of the wingspan to the depth is called the aspect ratio. The edge AB is the forward or leading edge, and the edge CD is the rear or trailing edge.

In the monoplane design that we are considering for the moment, the attachment of the wings is generally accomplished by means of rods forming the wing pylon, which join the wing spars to the fuselage. Very often, streamlined masts also unite the region near the middle of each half wing to the airplane's body to give a greater solidity to the frame and stop the surfaces from being lifted and broken by too large an atmospheric reaction.

The Control Surfaces

The control surfaces are planes that the pilot can maneuver and orient at will in relation to the average direction of the airplane. Thanks to their manipulation, he can direct the displacement of his vehicle. He can make it climb or descend, turn, bank, tip, or bring it back to its normal position if it should diverge from its route for some reason. The control surfaces include two rudders.

One is the elevator or horizontal rudder for controlling altitude. It is mounted on a hinge behind the stabilizer and can be raised or lowered. The other is the vertical rudder, which controls direction. It too is mounted on a hinge, and it can be displaced laterally. Finally there are the ailerons, which are small, moveable horizontal planes mounted on a hinge at the trailing edge and tip of the wing. They are lifted or lowered in opposite directions to change the inclination of the airplane from one side to the other.

The Controls

Every control surface can be activated by the pilot with the aid of various devices that he has in front of him. They are: the joystick, which allows him to raise or lower the elevator and ailerons, and the rudder bar, which permits him to move the vertical rudder to the right or left.

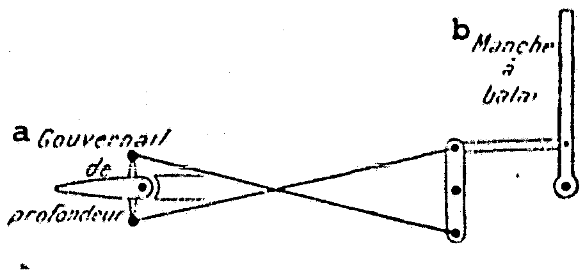


Figure 361
Schematic Drawing of Joystick and Elevator Control

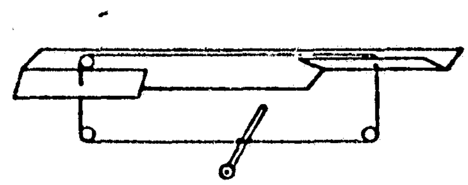


Figure 362
Schematic Drawing of Joystick and Aileron Control

Key: a) Elevator
b) Joystick

The joystick is a control lever (figure 361) that can be moved forward and backward in the airplane's plane of symmetry, as well as laterally, to the right and left of the plane, thanks to a universal joint. Longitudinal displacement is communicated by means /234 of cables and kingpins to the elvator, which is thus raised and lowered. The cables are crossed in such a way that pushing the joystick forward lowers the elevator and causes the airplane to dive, whereas pulling the stick toward the pilot raises it and makes the vehicle rear up.

Moving the stick to the right or left operates the ailerons. For example, if the stick is moved to the right, the right aileron is raised and the left one is lowered (figufe 362).

The rudder bar is placed horizontally and transversely relative to the major axis of the vehicle. It is worked by the pilot's feet and can pivot in a horizontal plane about a vertical axis attached to its middle. Each end of the bar is linked by a cable and king-pin to one of the sides of the vertical rudder.

II. Types of Airplanes

Present-day airplanes are designed for flying above either the land or the sea. Because of this, although they are built along the lines described above, they nevertheless possess characteristics that clearly distinguish them.

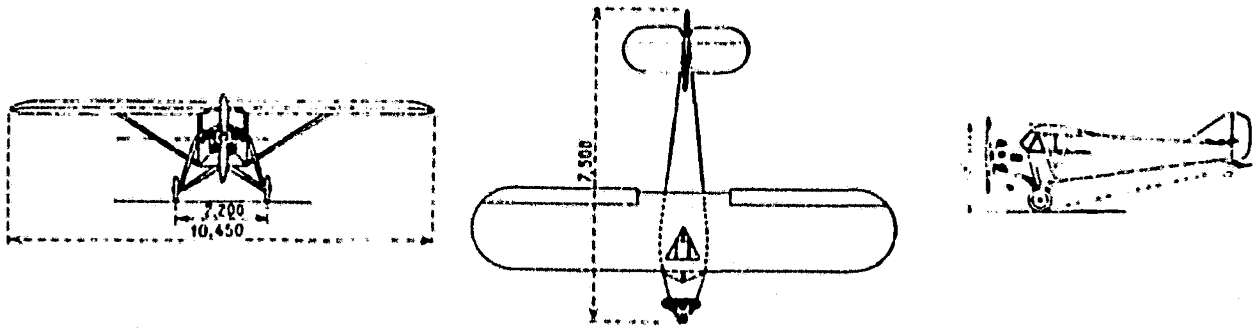


Figure 363
Design of the "Potez 36" Monoplane

Terrestrial Airplanes

Terrestrial airplanes (figure 363) have a special structure for arrival and departure known as the undercarriage. The latter includes a chassis attached to the forward part on the fuselage. The chassis supports the wheels and shock absorbers, which allow the airplane to roll on the ground during departure so as to acquire the speed necessary for takeoff and to absorb the speed and shock of /235
arrival: This is the landing gear. The undercarriage also includes a stand located at the rear end of the fuselage which diminishes rolling distance during landing by rubbing against the ground.

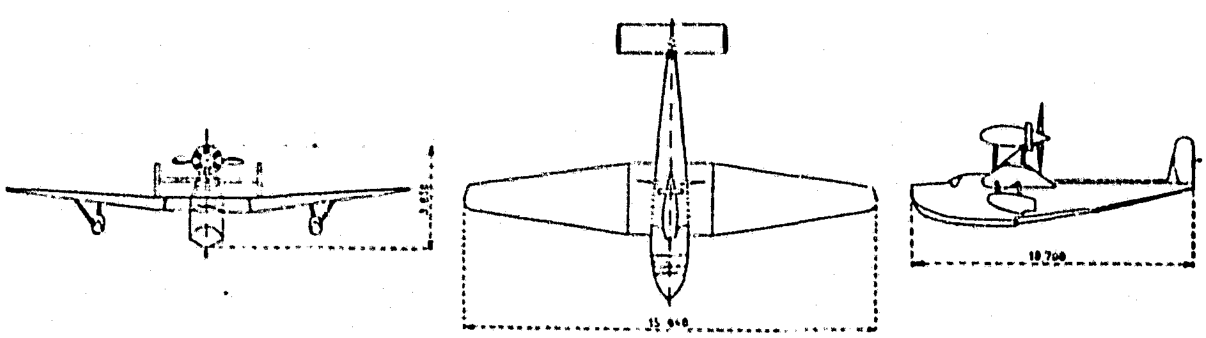


Figure 364
Design of the "Liore and Olivier 22" Seaplane

Seaplanes

The second group, the seaplanes, are built to land on the water. They are either equipped with floats attached to the chassis in the place of wheels or they have a hull that constitutes both the fuselage and the float. Either design supports the vehicle on the water when at rest and allows it to slide along during takeoff and landing. (See figure 364.)

Amphibians

Lastly, there exist amphibian airplanes which have both a hull and retractable landing gear and can land on the sea or the ground equally well.

Various Airplane Configurations

Finally, one should note that there are airplanes whose design differs from that of the classic monoplane described above.

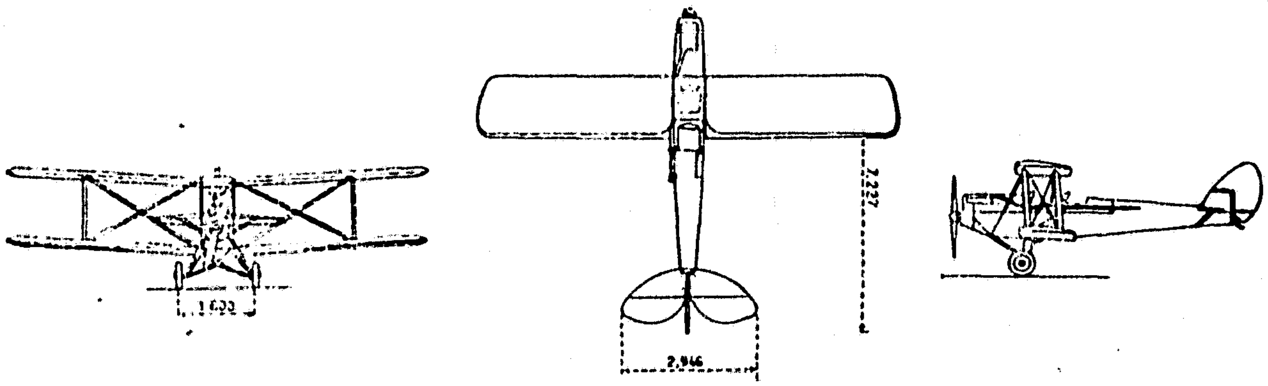


Figure 365
Design of the "Moth-Morane" Biplane

Some of them have superposed wings and are called biplanes (figure 365). Others, the triplanes, have three wings superposed. Airplanes have even been constructed with wings made up of a great number of planes arranged in such a way that they actually resembled Venetian blinds. In multiplane types, the superposed wings are braced to one another with poles and guy wires, so as to be almost inflexible.

Airplanes or seaplanes are not necessarily equipped with only a single engine. They can have two, three, four, or even more. In figure 366 there are two engines. They are attached at each end to the central fuselage in a fusiform housing located below or even above the wings. They can also be in front of each fuselage when /236 the airplane has two. Many multiengine airplanes have a flight weight of 20 (metric) tons and wingspans of 50 meters.

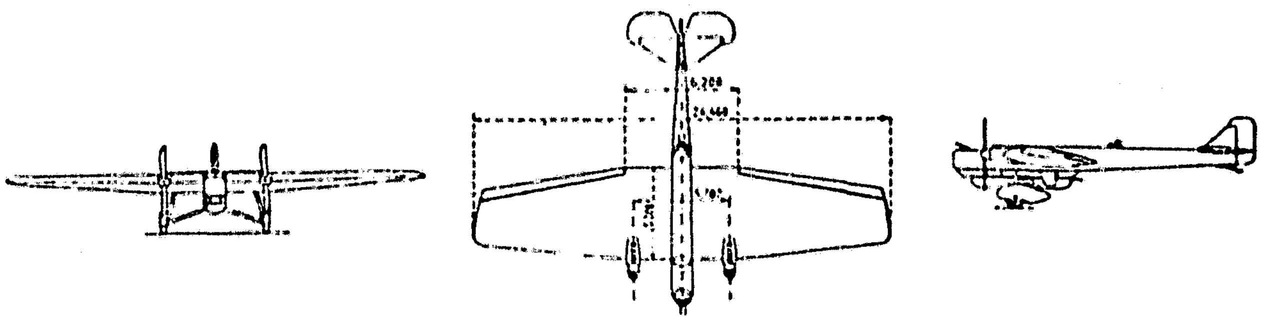


Figure 366
Design of "S.E.C.M. 140 M" Multiengine Monoplane

A joystick is not very practical for such large airplanes and maneuvering them in a high wind is very tiring for pilots. For this reason, the stick is modified. It still has a shaft that can be moved frontwards and backwards, but it can no longer move to the left or the right or, therefore, work the ailerons. Their operation is controlled by a steering wheel attached to the upper end of the tube and which pulls on a chain when turned. The chain in turn turns a pulley on which the aileron control cables are rolled up. The pilot can thus operate the ailerons with greater strength by holding the wheel with both hands. However, it sould be remembered that the steering wheel is inferior in terms of handling and efficiency to the ordinary stick. The stick is very sensitive and responds better to impulses. It can also be manipulated with one hand. For these reasons, it is more suitable for rapid aircraft of varying motion, such as fighter aircraft.

III. The Reaction Forces of the Air

In the beginning, research into the reaction of the air on airplane wings, i.e. of the laws of air resistance, was based on the principle of relativity. It was assumed that the reaction of a current blowing against the front of a stationary body was identical to that engendered in the air by a body moving within it, on the condition that the speed of the current and the body are equal.

Lift and Drag

Working under this assumption, wings of reduced size were placed in a wind tunnel containing a horizontal air current of known speed. The wings were in addition suspended from a balance so that the magnitude of the air's reaction could be measured.

It was then found that the air's reaction is manifested by a force R that passes through a certain point on the plane of symmetry called the center of pressure and is proportional to the square of the air current's speed.

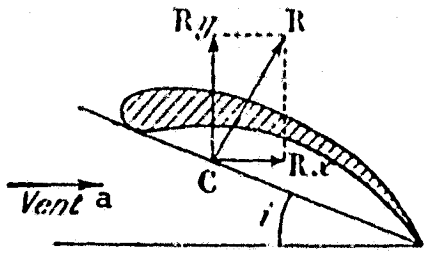


Figure 367
Resultant R of Aerodynamic Forces Exerted on a Wing and its Components R_y (Lift) and R_x (Drag)

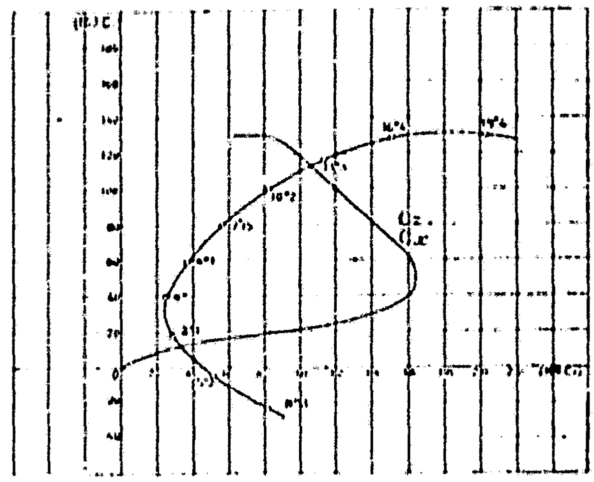


Figure 368
Polar Curve of STA Wing Profile no. 206

Key: a) Wind

The forces may be resolved into two others (figure 367), one vertical, R_z, which is the lifting force, and the other horizontal, R_x, which is the force resisting forward motion (drag), such that one has:

$$R_z = K_z S V^2 \text{ and } R_x = K_x S V^2,$$

where S is the wing area and K_z and K_x are the appropriate coefficients.

Angle of Attack and Polar Curve /237

If the wing is placed obliquely in a horizontal air current so that its cord makes an acute angle with the direction of the wind, this angle is called the angle of attack or incidence and is designated by the letter i.

The coefficients K_z and K_x are always constant for a given wing profile and angle of attack.

These coefficients are measured in a wind tunnel for all angles of attack. The polar curve (figure 368) for each wing is drawn based on them. For each polar point, representing a given incidence i, K_z or $C_z = 16K_z$ is the ordinate and K_x or $C_x = 16K_x$ is the abscissa. The ratio C_z/C_x is called the aerodynamic efficiency [lift to drag ratio] of the airplane. It varies with the angle of incidence and is at its minimum at the point where the tangent of the polar curve goes through the origin. In practice, as is shown on the figure, the abscissa represents $100C_x$ and the ordinate $100C_z$, with different units of length.

The same operations have been carried out on mockups of entire airplanes, as we will see further on.

IV. Different Modes of Flight

We are going to examine various features of airplane flight. Let us immediately take note of the fact that when studying mechanical flight, we will be especially preoccupied with the center of gravity. As you know, the center of gravity's motion is the same as if all the airplane's mass were concentrated in it and all the external forces were applied there. The speed of the center of gravity relative to the ambiant milieu is called the air speed.

Straight Horizontal Flight

First of all, let us take the case of a vehicle of weight P flying horizontally at a constant speed V and at a given altitude while keeping its plane of symmetry vertical.

The forces exerted on the center of gravity are:

P, the weight,

T, the propellor's traction or pulling force,

R_z, the lift, and

R_x, drag.

In order that there be horizontal flight at constant speed, it is necessary that all these forces be in equilibrium. Now, as we are going to see, some of these forces are variable. Thus, the pull of the propellor depends on the angle of attack. Look again at the polar curve in figure 368. For a point M_o corresponding to an incidence i_o in which there is no lift ($R_z = 0$), the pulling force of the propellor is very large (figure 369). The traction then decreases until it reaches a minimum at point M_m, which corresponds to the point where the tangent to the polar curve passes through point O. After this, the pull increases once again. /238

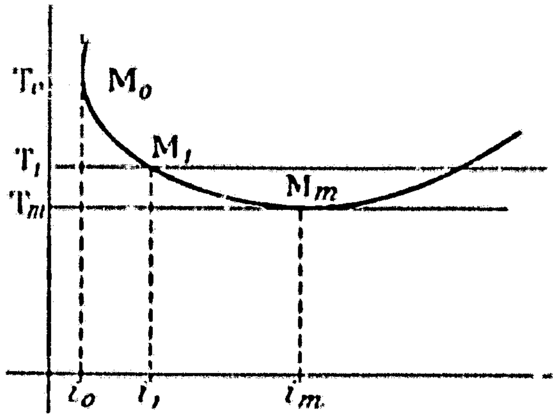


Figure 369
Propellor Traction vs.
Angle of Incidence

As you can see, for any pulling force other than that corresponding to the optimum angle of incidence i_m for which the pulling force is at its minimum, there exist two possible incidences and therefore two modes of flight. One has a small incidence and low lift and therefore a high rate of speed. The other has a large incidence and lift, and therefore a low rate of speed. Consequently, to have the largest area of action, one should fly at the optimum angle.

The power that is useful and necessary to horizontal flight at a given altitude reaches its minimum at an incidence i_2, a little larger than the optimum angle. There is therefore an indispensable level of power for providing lift. Because of this, at a level of power above the minimum, there are again two modes compatible with the given amount of power. One corresponds to flight at an incidence below i_2 and is at a high rate of speed. The other is at an incidence greater than i_2 and is at a low rate of speed. In practice, the first mode is the only one utilized. The second is too dangerous as a result of the ease with which it gives rise to stalling.

In this summary, we have considered an airplane flying at an unspecified altitude. Is it always true that altitude has no effect, given the variations in density that exist? Current thinking is that the air's reaction forces are proportional to its density. The preceding equations thus become:

$$R_z = K_y S V^2 d/d_o \text{ and } R_x = K_x S V^2 d/d_o,$$

where d_o is the air density at ground level and d the density at the altitude under consideration.

As for the power necessary to provide lift, it is inversely proportional to the square root of air density if the angle of incidence is held constant.

Gliding

As soon as the engine stops turning, the airplane is no longer able to fly horizontally. Gravity forces it to descend by gliding. The slope of the trajectory is always at a minimum at the optimum angle of incidence. This is the slope that allows the apparatus to land the furthest from its point of departure. However, and this must be stressed, it is impossible for it to descend at a smaller slope than this minimum.

Here again, there are two modes of descent, one rapid for small angles of attack, the other slow for large angles.

We have seen that for gliders two speeds could be considered. One is horizontal, and the other is the vertical sinking speed.

In gliding, the horizontal speed keeps growing as the angle of attack decreases. Beyond this, when the descent is very long, the horizontal speed varies and is inversely proportional to the square root of air density when altitude decreases. In contrast, when a glide is performed with little loss in altitude, there is no reason to take into account the variation in height. /239

Vertical speed is at a minimum when the angle of attack is larger than the optimum angle and is in the vicinity of the angle of minimum power.

Climbing

One says that an airplane is climbing when its trajectory points obliquely upward.

There are two cases to consider in a climb: either the pilot makes the climb by giving more power to his engine without changing the angle of attack, which he makes equal to the angle for flying at his ceiling, or he flies at full speed, but alters the angle of attack. In the first case, the pull of the propellor increases while the flight speed remains the same, and the vehicle follows an upward trajectory. In the second case, which is commonly employed in performance tests, the airplane climbs because traction increases with the reciprocal of aerodynamic efficiency, R_x/R_z, and therefore changes with the alteration of the angle of attack. This means that there is minimum traction at the optimum angle. During a climb, the speed of ascent decreases in a continuous fashion.

I should point out that in a complete study of ascending flight, it is also necessary to consider the propellor, whose rotation and efficiency are also linked to variations in altitude and angle of attack. However, this is outside the limits of the present account.

Ceiling

An airplane has to be capable of rising up to a certain height.

When its trajectory is pointed upward, the climbing speed is always smaller than the speed in horizontal flight, but the difference is close to zero when the angle of incidence is small.

An airplane close to the ground finds that its engine has a power that is always superior to the minimum power necessary for horizontal flight. The difference between these powers is called the excess power capacity.

An airplane climbs until the excess power that it possessed near the ground has disappeared. As a matter of fact, the power used in horizontal flight goes up with altitude and the power produced by the engine diminishes with altitude. There thus exists an altiutde which cannot be surpassed. This is precisely the height at which the power furnished by the engine is equal to the minimum power necessary to supply lift. Such an altitude is known as the airplane's ceiling, for which the angle of attack is always greater than the optimum angle. The slope required to reach the ceiling is always proportional to the excess power.

Let me add that it is possible to make an aircraft exceed its normal ceiling by stopping its power from decreasing with altitude. This has been done with such devices as Rateau's supercharger, which increases the pressure of the air entering the engine to that of ground level.

V. Airplane Stability

In the study that we have just made of airplane motion, we considered only the movement of the center of gravity. In reality, under the action of exterior forces or because of maneuvers it is performing, an airplane oscillates around its center of gravity during flight. /240

In order that an airplane progresses through the air properly, it is indispensable that its oscillations not take on exaggerated proportions capable of dangerously destabilizing it. The abnormal oscillations that might occur must be eliminated either automatically or through the action of the pilot.

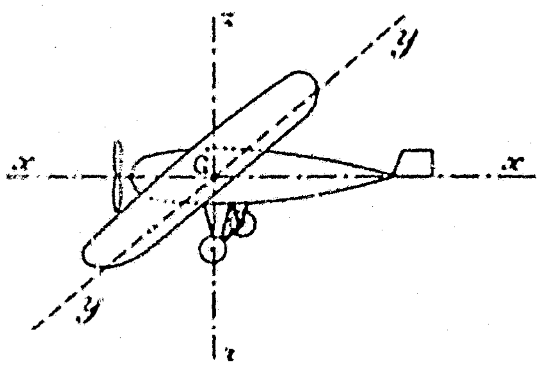


Figure 370
Axes of an Airplane

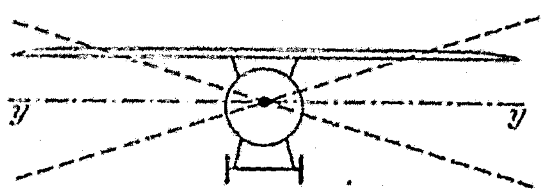


Figure 371
An Airplane's Angle of Roll

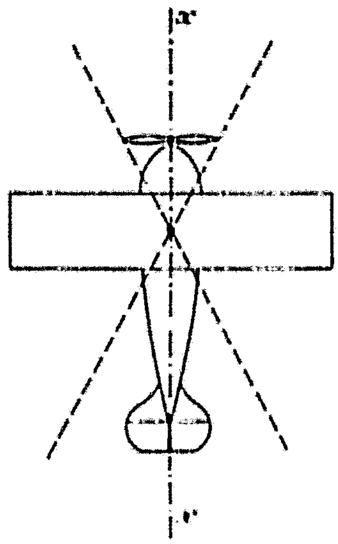


Figure 372
An Airplane's Angle of Yaw

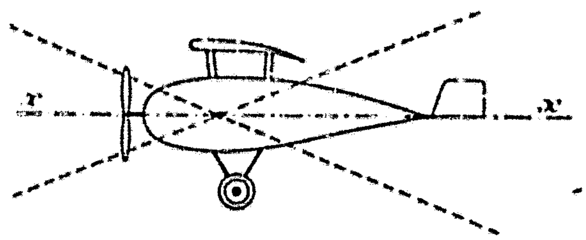


Figure 373
An Airplane's Angle of Pitch

The stability of an airplane is considered relative to three rectilinear axes passing through its center of gravity (figure 370).

1) The horizontal major axis Gx, which is the major axis of the plane of symmetry and about which the plane rolls (figure 371).

2) The axis Gz, the second axis of the median plane which is vertical in an airplane's usual position and around which it can oscillate in a horizontal plane or yaw (figure 372).

3) The axis Gy perpendicular to the plane of symmetry, or the transverse axis, around which an airplane can oscillate in a vertical plane, i.e. pitch (figure 373).

The motion of an airplane therefore takes place in three directions: vertical, longitudinal, and transversal. Its stability in flight must therefore be assured in these three directions.

The airplane's stability thus includes three distinct stabilities: one horizontal to oppose pitching, another lateral to oppose rolling, and the last, known as directional stability, to oppose yawing.

Longitudinal Stability

Longitudinal stability, about the transverse axis Gy, is obtained partly by means of certain planes located on an airplane, such as the fixed horizontal stabilizer of which I have already spoken. If an airplane starts to nose up, under the influence of a sudden wind, for example, the stabilizer's angle of attack increases in relation to the relative wind and the result is an augmentation of the air's reaction force. This creates a torque tending to level off the vehicle and return it to its normal flight position. The stabilizer plane also has a helpful influence during oscillations in the vertical plane. It dampens such oscillations by playing the role of a brake. /241

It should be added that experience has shown that the best reactions are obtained when the stabilizer is attacked from above. They are therefore mounted with a certain upward incidence, which make a sort of longitudinal V with the wings of the airplane.

Stabilization by the fixed horizontal plane is automatic. It is said to be intrinsic to the airplane.

Longitudinal stability can also be controlled by an appropriate maneuver with the joystick. The pilot can in fact make his vehicle oscillate as desired about the axis Gy. If he pulls on the stick, he raises the elevator, which is mounted on a hinge in back of the stabilizer. This makes the airplane rear up and consequently start to climb. If he pushes on the stick, he obtains the opposite result. He lowers the elevator, causing the airplane to go into a dive and therefore to descend.

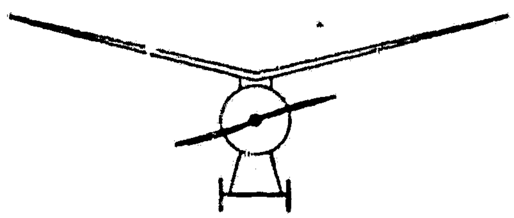


Figure 374
Wings Forming a Dihedral
or Vertical V

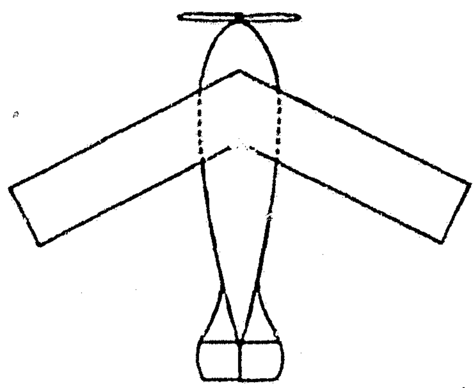


Figure 375
Flexed Wings

Lateral Stability

Automatic lateral stability, about the major axis Gx, is obtained through the use of the vertical tail fin located behind the fuselage. It acts in a similar manner to the stabilizer to straighten out the airplane and dampen oscillations, and its role is analogous to that of the keel in a boat. The airplane's intrinsic stability can be facilitated by giving the wings the form of a vertical V (figure 374). Under these conditions, the airplane constitutes a veritable anti-roll mechanism, with the restoring torque increasing along with the wingspan.

In addition, the pilot can manually control longitudinal stability.

By moving the joystick to the right, for example, he raises the right aileron and lowers the left one. This has the effect of making the airplane lean to the right and consequently of creating a restoring torque if the vehicle is leaning in the opposite direction due to outside forces.

Transverse Stability

Stability in a transverse direction is here too automatically acquired with the help of the fixed vertical tail fin. If the airplane turns toward the left for any reason, the vertical tail fin will make a certain angle with the relative direction of the wind. It will therefore be pushed more on the right side, which will force the tail back to the proper direction. The intrinsic stability can be supplemented by giving the wings a flexed configuration (figure 375), like that of certain rapidly flying birds. If the vehicle turns to the left, for example, the right wing will be moved forward and will be pushed on more than the left wing. The airplane thus will automatically return to its course.

Manual control of transverse stability is obtained by manipu- /242
lating the vertical rudder. If the pilot pushes the rudder bar to the left, he will also move the rudder and therefore the airplane to the left.

VI. Maneuvers and Acrobatics

As everyone has noticed, an airplane does not always fly horizontally in an absolutely straight trajectory. It does not always fly flat out, as they say in aeronautical circles. It can be made to perform certain popular maneuvers as the pilot desires, as is the case for fighter aircraft. The same maneuvers can also occur accidentally, outside of the will of the pilot. This can happen to any airplane, even a commercial one, under the effect of outside forces.

Among these maneuvers, called acrobatics when fighter aircraft are concerned, some are standard, such as the following:

Flat Turn	Loop
Vertical Bank	Renversement
Side Slip	Barrel Roll
Dive	Normal Spin
Pull-Out	Flat Spin

Turns and Side Slips

We have seen that by moving the rudder bar to the left, the pilot causes the vertical rudder to be pushed to the left. This causes the vehicle to turn about the Gz axis, or, more precisely, make a flat turn. In order that a turn be successfully completed by a vehicle traveling at a certain speed, whether it be locomotive, automobile, or airplane, the velocity must remain within the plane of symmetry. If not, the vehicle skids off course or, in the case of an airplane, side slips. This is remedied by tilting the machine.

For an airplane moving in a circle, one seeks to create an equilibrium among the forces acting on the center of gravity: the weight, the reaction of the air, the pull of the propellor, and centrifugal force. In particular, centrifugal force is balanced with the forces of lift, which have to be greater during a change in course than in straight horizontal flight, when weight alone plays a role. The increase in lift is provided by augmenting engine output and the angle of attack.

It follows from this that an airplane cannot veer properly unless it has a large excess power capacity relative to the minimum value necessary for horizontal flight. If not, it will stall.

Some turns are so tight that the airplane seems to have a vertical wingspan at a certain moment. This maneuver is commonly called vertical banking.

Dives and Pull-Outs

To make a dive, the pilot pushes strongly on his joystick. The elevator is abruptly lowered while the airplane is flying flat out. The airplane turns about its lateral axis Gy and begins to descend with its major axis more or less vertical. Its translational speed thus rapidly increases by as much as 50%. When the descent is made with the engine at full power, it is called a nose /243 dive. In these circumstances, very efficient aircraft can attain considerable speeds, which the Americans claim can range up to 800 km/h. Such descents are generally executed at the decision of the pilot and are possible in fighter aircraft. They can also be produced by such other causes as the pilot's sickness or a forward shift of the vehicle's load.

When the pilot judges that his dive has lasted long enough, he puts an end to it by pulling on his joystick, which makes the airplane rear and describe a curved trajectory ending with its nose pointing upward (figure 376). As we will see, this maneuver, which is called a pull-out, is among the most dangerous, even with elevator angles of only a few degrees. The airplane's frame undergoes considerable stress and the machine can break if the stick has been rapidly moved by a large amount.

Such a maneuver could be mandatory if the vehicle suddenly starts to dive for any reason. It is the only way to level off. Moreover, this often occurs automatically when the airplane's speed has reached a certain limit.

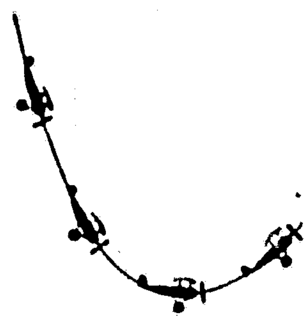


Figure 376
A Dive and Pull-Out

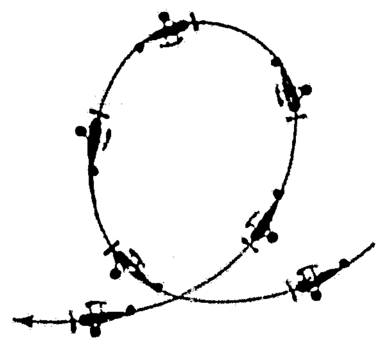


Figure 377
A Loop

Loops

Loops are a classic acrobatic maneuver thought up by Pégoud. It is easy enough if the pilot pulls the joystick towards him when the airplane is descending slightly at full speed. (See figure 377.) The aircraft then rears, levels off, and tips upward almost vertically while its speed diminishes at the same time. Little by little, it describes a loop in such a way that it flies upside down. At this moment, the airplane seems to be hanging in the sky as if its speed had suddenly been reduced to zero. It then completes the loop by diving toward the ground and descending faster and faster. In this way, it is lifted up again little by little and resumes horizontal flight, which the pilot obtains by pushing the joystick back a little.

Looping is sometimes done in the opposite way, by making the airplane first dive and then fly with its wheels upward. The airplane next noses up and climbs before reestablishing a level position.

Renversements

Renversements begin like loops. However, before arriving at the top of the loop and finding himself upside down, the pilot performs a sort of rotaton about the transverse axis which tips the propellor back downward and puts the airplane into a dive. The airplane next veers more or less tightly and returns to its line of flight.

Barrel Rolls /244

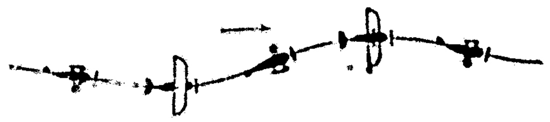


Figure 378
A Barrel Roll

Barrel rolls are a true rotation of the aircraft around its horizontally placed major axis, with one difference. This is that the vehicle does not actually turn about its longitudinal axis, but rather describes a helix about it as it advances horizontally. (See figure 378.)

Spin

Traditional spins are basically a sort of barrel roll performed with the airplane's longitudinal axis directed downwards and with a speed of descent that is sometimes fairly large. (See figure 379.) Characteristic of this maneuver is that the controls remain effective and the pilot is the absolute master of its duration, since he can exit from it whenever he pleases.

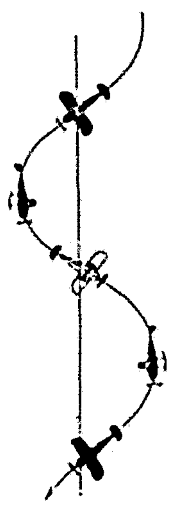


Figure 379
Normal Spin

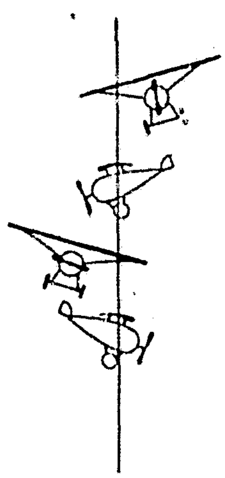


Figure 380
Flat Spin

Flat Spin

In contrast, during flatspin (figure 380), the airplane's fuselage is inclined very little. It no longer dives at a certain speed while spiraling around a vertical axis. On the contrary, it turns rapidly around a vertical axis passing through a point on the wing instead of through its center of gravity. The airplane is completely devoid of translational speed. It slides along the vertical axis and approaches the ground in the same way as a cardboard rectangle rotating around a long thin shaft stuck in to it near one of its corners would.

Unlike what occurs in a classic spin, the controls no longer have any effect and the influence of the horizontal and vertical rudders and the ailerons is absolutely zero.

It is a fact that an airplane in flat spin will remain in it until it crashes into the ground.

At the present time, there does not seem to be any effective remedy for this state of affairs. Neither increasing engine output to its maximum nor ejecting special loads placed outside the center of gravity, which supposedly would make the airplane go into a dive, appears to be capable of stopping flat spins. As the Germans in particular argue, only the appropriate construction methods seem to protect the pilot from this tragic eventuality.

VII. Flight Safety

The study of all these maneuvers, whether initiated consciously or not, is very important, as we will see.

Accidents in the air often appear to be the consequence of errors in handling the aircraft or material failure. Statistics /245
have proved that 51% of French aeronautical accidents, whether maritime, civilian, military, or colonial, can be blamed on pilot errors. This is the result either of faulty judgment or a lack of technical knowledge on the part of the pilot.

Out of 500 accidents resulting in an inquest, 350 were attributed to a mistake in piloting or imprudence, while 35 were considered to result from material defects and 10 from bad weather.

Do not forget that when maneuvering, additional reaction force against the wings can be created. This can make an insufficiently resistant airplane break up in flight. Similarly, high winds engender supplementary stresses than can also fatigue the wings.

The future of aviation is therefore linked to the safety that the pilot and passengers must be assured of having during their airborne travels. In line with this, a complete study and description of all the supplementary forces that arise in flight should be made, and the indicated changes in aircraft construction introduced.

The future of aviation is also linked to the average speed aiplanes can be endowed with. Airplanes must go faster than other types of transport: automobile, railroad, boat. Their speed must also be achieved with a minimum of fuel. The builder is thus forced to diminish or eliminate all sources of passive resistance and to obtain as high aerodynamic efficiency as possible.

This is why we will examine in the coming lessons how progress in airplane construction is in direct relation to the amount of success there is in determining exactly the speed of the vehicles, the acceleration caused by maneuvers and atmospheric disturbances, and, finally, the aerodynamic efficiency of airplanes. The data furnished from such experiments will allow the necessary improvements to be made in airplane design and construction.

RECOMMENDED READING

Alayrac, Mécanique de l'aviation [Aeronautical Mechanics], Gauthier-Villars, Paris (1926).

Blanc, Toute l'aviation [All about Aviation], Paris (1930).

Bouasse, La résistance des fluides [Fluid Resistance], Delagrave, Paris (1928).

Joukowski, Bases théoriques de l'Aéronautique: Aérodynamique [The Theoretical Bases of Aeronautics: Aerodynamics], Gauthier-Villars, Paris (1916).

Leroux, Cours d'Aéronautique [A Course in Aeronautics], Beranger, Paris (1927).

Lesson Eighteen: Methods for Studying Airplanes' Stresses, Trajectories and Speed in Flight /246

Without ignoring the difficulties of creating airplanes, both civilian and military, resulting from the multiple requirements made for each category, one cardinal fact dominates the whole question of aviation. As must be acknowledged, this is the problem of safety.

Safety is an obsession with aeronautical technicians, as well as for all those interested in flight. It merits particular attention in view of its humanitarian and utilitarian character.

Aircraft safety depends above all on an exact knowledge of the stresses imposed on aeronautical structures during flight.

Until recent years, people were more or less content to make hypotheses concerning the particular conditions to be found in each type of flight. They then mathematically deduced the added stress on the vehicle.

Thus, the safety formula applied at the end of the war by the Service Technique de l'Aéronautique was derived from the study of pull-outs, or vertical dives followed by sudden leveling off. The leveling off, whose curvature and duration were arbitrarily chosen, could be used to obtain mathematical results whose magnitudes depended on the more or less uncertain data serving as a point of departure. The added stress due to eddies and gusts of wind was also arbitrarily evaluated or even held to be negligible.

The study of the fatigue supported by airframes during flight is therefore of preponderant importance. This is what affects the resistance of fighter aircraft in the course of the various maneuvers they have to perform, as well as the transport capabilities of commercial aircraft.

Several government agencies have been preoccupied since the war with experimentally determining the stress supported by airplanes in flight.

Huguenard, Planiol, and I proposed to make such determinations ourselves with an airplane flying in air of varying turbulence.

We had several approaches available to us for that purpose.

I. Cinematographic Method for Determining Flight Stress

First of all, the cinematographic method using the camera gun with coordinate grid and double objective, of which we have already spoken, enabled us to measure the exact trajectory of an airplane in the course of its maneuvers.

Determination of Speed and Trajectory

We knew the position of the center of gravity in the full scale vehicle and therefore marked it with a dot on each film enlargement by superposing the appropriate template.

Next we traced on a sheet of square-ruled paper a grid equal to the sides of the coordinate network in the photographs. The successive positions of the center of gravity were transferred to each square with the aid of a divider. The points were joined together so as to form the trajectory described by the airplane.

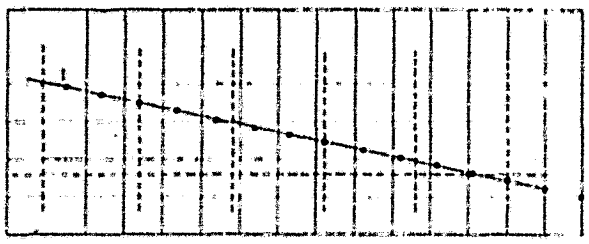


Figure 381a
Constant Velocity Straight Trajectory Followed by a Gourdou-Leseurre Airplane (Propellor Motionless)

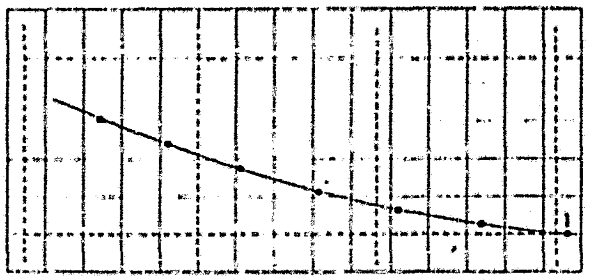


Figure 381b
Curved Trajectory Followed by a Gourdou-Leseurre. Airplane (Propellor Motionless)

If the points representing the positions of the center of gravity are approximately in a straight line and if the distance between them is approximately equal, they describe a straight trajectory at constant velocity (figure 381a).

The trajectory's slope angle β relative to the horizon is then determined with a protractor.

If the trajectory is a curve (figure 381b), and consequently of variable speed, it is easy to find the average radius of curvature and the inclination of the speed for each part of the trajectory, for example at the end of every second.

The distance of the airplane can also be determined. It is deduced from the length of its image on the film, its true length, and the focal distance of the objective, for example.

The path traveled by the center of gravity from one position to another divided by the number of intervals, and then multiplied by 16 (since the camera speed is 16 frams/sec) gives the apparent speed u on the enlargements, as we have seen.

The real speed in meters per second is then:

$$V = uL/l,$$

where L is the airplane's true length and l its apparent length on the photographs.

Calculation of the Acceleration Normal to the Wings

It is possible to use these data to calculate the value of the normal component of acceleration for every second.

As a given point on the trajectory let the radius of curvature be represented by R, the instantaneous speed by V, and let the angle α represent the angle made by the half-normal opposed to the center of curvature with a downward vertical line. The normal acceleration is obviously V^2/R. However, the projection of the acceleration due to gravity, $g \cos \alpha$, on the half-nromal must always be added to this centrifugal acceleration.

Under these conditions, the total acceleration directed along the normal is: /248

$$(V^2/R) + g \cos \alpha.$$

The ratio of the total acceleration to g is then:

$$\gamma = (V^2/Rg) + \cos \alpha.$$

II. Accelerometric Method for Determining Flight Stress

The acceleration caused by the resultant of the various forces to which an airplane is exposed can also be measured directly.

This is done with an accelerometer.

When a mass M is acted on by a single force F or by a group of forces having F as the resultant, knowledge of the acceleration Γ of M's center of gravity at every instant allows one to calculate the magnitude of F by the equation:

$$F = M\Gamma \quad (1)$$

Directly measuring the acceleration thus provides the means of measuring the resultant of the aerodynamic forces exerted on a projectile or airplane moving in the air.

An accelerometer includes an accelerometric mass m, small in relation to the mass M under consideration, and linked to this mass M by a dynamometer.

If the assembly is pulled by F and takes on an acceleration Γ, appreciably the same as before, the dynamometer is in equilibrium when M has taken on the same acceleration Γ. It then indicates a force f. One can write:

$$f = m\Gamma \quad (2)$$

The value of Γ can thus be found, and as a result the force F also. A comparison of equations (1) and (2) gives:

$$F = fM/m.$$

The force that imposes the motion under study on the system is therefore simply obtained by multiplying the dynamometer reading by the ratio M/m.

The indirect measurement of the force F is the major job of accelerometers. If the dynamometer is graduated in successive multiples of the weight of the accelerometric mass, the readings directly give the ratio of the acceleration Γ to the acceleration due to gravity, or, if you wish, the ratio of the force F to the mass M.

The H.M.P. Accelerograph

Huguenard, Planiol, and I created a recording accelerograph for the purpose of studying acceleration in flight. It includes (figure 382) a cylindrical column of mercury of density δ, Length L, and cross sectional area S. Its axis is parallel to the acceleration to be measured. The mercury is set against an aqueous liquid which transmits the pressures caused by the acceleration to a special manometer M.

In addition, a valve R, placed in the liquid column linking the mercury to the manometer allows the accelerograph to be adjusted. The accelerograph's intrinsic frequency is given by the equation: /249

$$T = 2\pi\sqrt{\delta L/KS},$$

where K is a coefficient measuring the volumetric elasticity of the manometer tube. For a tube swelling by 1 mm^3 for every 1 kg/cm^2, K has a value of 10^9 (CGS).

In order that the manometer readings remain constantly proportional to the acceleration, the following conditions have to be fulfilled. The manometer must not exhibit any solid friction. The intrinsic period of oscillation of either the system as a whole or its different parts has to be shorter than that of the phenomena to be measured, if they are periodic. If they are not, then it must be shorter than the duration of the shortest variations in the phenomena. Lastly, the dampening has to be adjustable by fluid friction, to the exclusion of all others.

A reservoir of compressed air A equipped with a bicycle valve V allows the air at the end of the column of mercury in opposition to the manometer to be compressed. Thanks to this device, it is possible to measure accelerations directed in both directions without having to fear that the column of liquid would break if large negative accelerations occurred. If the tube is placed horizontally, with the manometer to its right, the pressure indicated by the manometer goes up when the acceleration is pointed to the left. It goes down if the acceleration is pointed to the right. Obviously, the variations are proportional to the accleration imposed on the apparatus.

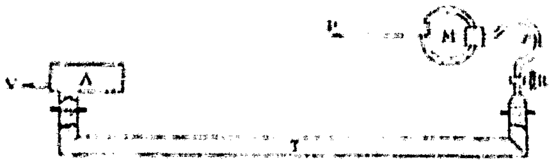


Figure 382a
Schematic Cross Section
of H.M.P. Accelerograph

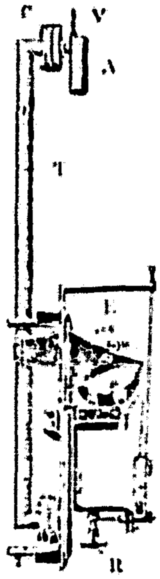


Figure 382b
H.M.P.
Accelerograph
No. 2

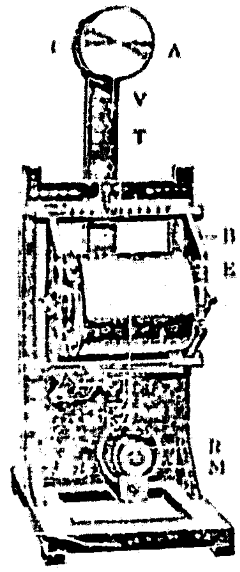


Figure 382c
H.M.P.
Accelerograph
No. 3

Key: T) Mercury tube
R) Dampening valve
M) Manometer
P) Manometer needle
r) Connecting tube
A) Air chamber
V) Valve
C) Rubber membrane seal
E) Recording cylinder

The manometers employed are composed of a metal Bourdon tube attached at its midpoint. The tube constitutes a sort of tuning fork with hollow branches connected by two flexible plates to a needle or mirror. Their short period ranges from 2×10^{-2} to 3×10^{-4} seconds.

Press for Calibrating Manometers

We created a press for studying these manometers. While it is easy to calibrate manometers accurately for measuring moderate pressures of 2 to 3 kg/cm^2, for example with a mercury manometer in free air, the calibration of high pressure manometers is a problem.

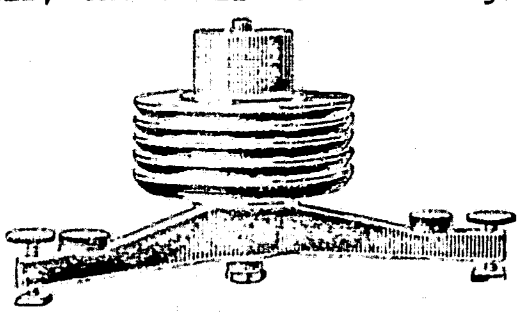


Figure 383
H.M.P. Press for
Calibrating Manometers

Our press is composed of a tripod base with threaded adjustable feet on which is screwed a hollow cylindrical body. Inside the cylinder there is a piston with a cross sectional area of 1/2 cm^2. (See figure 383.) /250

This hardened steel piston is very long and is extensively grooved. The purpose of this is to reduce both the area of contact, and thus the forces of viscosity, and also leaks.

The top of the piston ends in a socket which can hold a kind of cylindrical sleeve. Ring-shaped weights are places over the sleeve's spindle and their centers of gravity are thus over the head of the piston.

The same sleeve holds two guide fingers that force the piston to follow it when it is made to rotate. This motion has the effect of reducing to the absolute limit the axial friction between the surfaces in relative rotation.

The piston forms an excellent seal. In a pressure of 50 kg/cm^2, it takes it about 6 hours to complete its course when the cylinder is filled with castor oil at a temperature of 20° and a quarter of an hour when liquid parafin is used.

Even with liquid parafin, the time available is more than enough to completely calibrate a manometer for rising and falling pressure without having to refill the press.

When working under a load of 15 kg, or 30 kg/cm^2, the piston stops in about 2 minutes after starting with an initial rotation of 1 revolution per second. This makes it unnecessary to install a device for maintaining rotational speed.

The actual diameter of the piston is 7.977 mm. Its cross sectional area is 49.983 mm^2, or only 3/1000 less than the planned area of half a square centimeter.

Having put two presses, each loaded with 25 kg ($p = 50\ kg/cm^2$), in equilibrium and made both pistons turn at a good speed, two or three grams are added to one of the pistons to induce a very small downward motion. By transfering the extra load to the other side, the motion is reversed.

The exact limit is difficult to observe because of the extreme slowness of the motions produced.

Even though the precision thus obtained is very far from that of a good mercury manometer, it is nevertheless more than enough for practical purposes. The apparatus, which is much easier to handle than a mercury manometer several decameters high, has proved completely satisfactory in the many calibrations in which is has already been used.

For example, it has enabled us to trace the hysteresis cycle of a high precision diaphragm manometer from 0 to 10 kg/cm^2. In this way, we could see that the cycles' maximum width was less than 2/1000 of the maximum pressure. Manometers capable of measuring pressure with an accuracy of 1 in a thousand are thus foreseeable.

Accelerograph Calibration Method

The presence of an air reservoir in the accelerograph is very useful. The apparatus can be self-calibrated at any time, whether in the laboratory or in the field. If it is placed in a horizontal position, and the air reservoir is open to the outside atmosphere, the manometer reads zero. If the instrument is then stood up so as to be vertical, the point where the needle stops marks the acceleration g of gravity. If the accelerograph is put in a flat position again /251 and inflated with a bicycle pump, the needle is deflected. When the point g is reached, the pumping is stopped and the apparatus stood up anew.

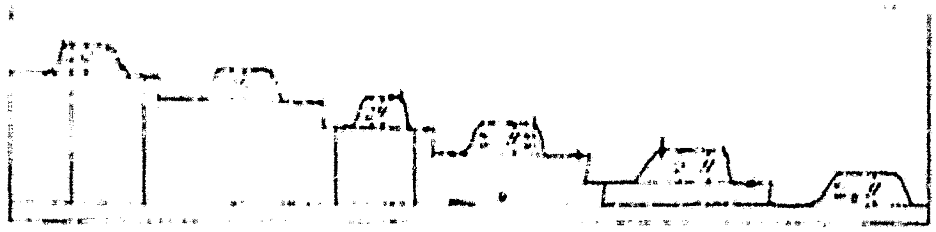


Figure 384
Calibration of the Complete H.M.P. Accelerograph No. 2, Equipped with a 5 kg/cm^2 Manometric Tube (Reduced by 1/2)

The needle will start at the initial value g and move up to a point that is obviously 2g. Recommencing the same series of operations, a graduation of the instrument in multiples of g is obtained (figure 384).

After several other types, we constructed an accelerograph, designated number 3, for aeronautical purposes whose period is 1/75 second and sensitivity is 1 to 3 cm at g with a 14 cm pen (figure 382c).

Study of the Apparatus's Accuracy

We used a dynamic procedure to study the precision of the readings furnished by our instrument in conditions close to those of actual use. The procedure was to make the accelerograph follow a simple motion that was as sinusoidal as possible and to isolate mechanical data from the movement necessary for the calculation of its maximum acceleration. The results of the calculation were then compared to the measurements of maximum acceleration made by the instrument.

The accelerograph was fixed to an elastic suspension whose coefficient of elasticity could be changed as desired. The suspension was arranged so as to allow rectilinear translational motion parallel to the axis of a mercury tube. In these circumstances, the accelerograph adopts a perfectly sinusoidal motion when displaced from its equilibrium position. This is because the restoring force is proportional to the elongation.

The apparatus was suspended vertically between two highly stretched coil springs. The springs were arranged in such a way that their line of action and also the axis of the mercury were vertical (figure 385). The first two conditions impart a vertical translational movement to the accelerograph. The third insures that the component measured equals the acceleration. An auxiliary device recorded the angular displacement on the accelerograph drum with a stylus controlled by the instrument's vertical oscillations. It was a very adequate resolution of the problem of measuring the oscillating motion's amplitude and period.

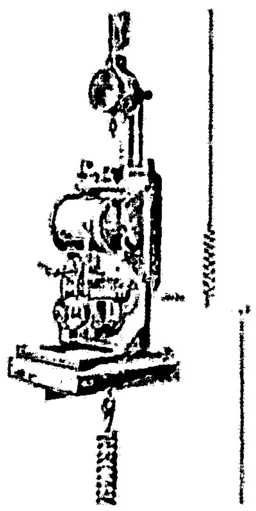
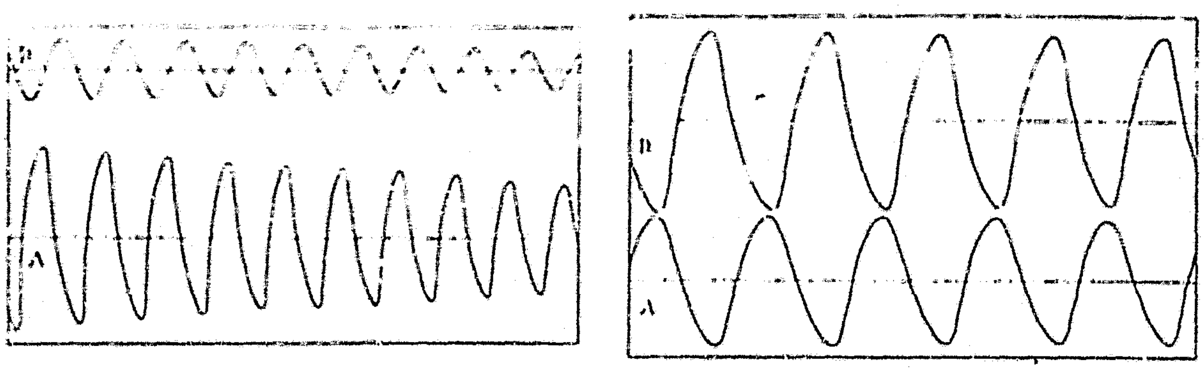


Figure 385
Accelerograph Setup for Studying Sinusoidal Motion

It is possible to calculate the maximum acceleration after the relation between the movements of the stylus as measured on the tracing and the real displacement of the accelerograph have been determined.

Comparing the value thus calculated with the value furnished by the tracing of the accelerograph itself reveals the amount of error in the instrument's measurements.

Tests have been run at three different frequencies of oscillation: 2.05, 4.4, and 8.4 per second. The tracings obtained allowed the amplitude to be measured to within 1/10 mm without any /252 difficulty. The measured acceleration varied from ±5 m/sec^2 to ±22 m/sec^2, with the actual displacement of the accelerograph ranging from ±3 to ±50 mm. (See figures 386 and 387.) Different tracings were made for each series of measurements of a given oscillation at different openings of the dampening valve. These tests showed that as the frequency of motion diminishes, the amount of dampening can be increased without increasing the amount of error. Also, it was always possible for the frequencies studied to obtain a margin or error less than 4%, and often of 1.5%, by making the appropriate adjustment.



Figures 386 & 387
Sinusoidal Tracings Obtained with the Setup in Figure 385
Left: 8.4 oscillations/sec; Right: 2.05 oscillations/sec
D, Displacement; A, Acceleration

Tests of the H.M.P. Apparatus

To become well acquainted with the operation of our accelerograph, we first used it to evaluate the acceleration found in various vehicles.

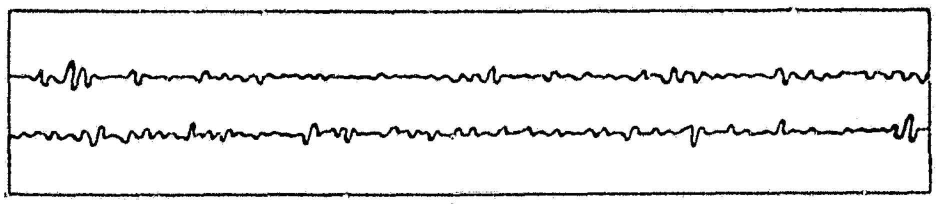


Figure 388
Recording of Acceleration in a 54-Ton Sleeping Car between Paris and Toulouse 1 sec = 3 mm; g = 2.2 cm

a) Measurement of Acceleration Imparted to a Railroad Car by the Tracks

Thus, we sought to measure the magnitude of the acceleration imparted to a railroad car by unevenness in the tracks.

The tracing in figure 388 was made in a sleeping car with the accelerograph vertical. As you can see, the acceleration was very small, on the whole less than 2 m/sec^2.

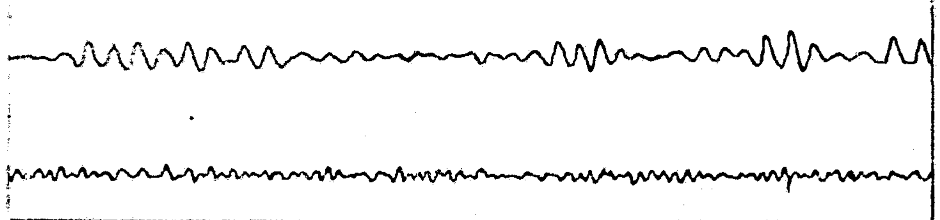


Figure 389
Recording of the Transverse Acceleration (Upper Tracing) and Vertical Acceleration (Lower Tracing) in a First Class Car on the Paris-Marseille Express, 1 sec = 3.8 mm; g = 1.5 cm

Other experiments took place on the Paris-Marseille express. Figure 389 shows at bottom the tracing produced by the accelerograph when placed in a vertical position in a first class car weighing 35 tons and having four axles. The upper tracing was obtained by placing the apparatus in a transverse position at a point when the speed was 88 km/h.

The variation in vertical acceleration was in general less than 1 m/sec^2. In the upper tracing, the variation is much larger. Its maximum was around 3.5 m/sec^2.

In addition, one can immediately see that the vertical agitation had a much shorter period than the lateral oscillations. It was approximately a half second in the former and a second in the latter.

Figure 390
Recording of the Transverse Acceleration in a First Class Car on the Paris-Marseille Express between Lyon and Valence
(1 sec = 3.8mm g = 0.75 cm

Figure 390 reproduces the tracing of the transverse oscillations /253
in the same car at the 464 kilometer point and at a speed of 102 km/h. Notice that the oscillations are much stronger here. The acceleration varies by 3 m/sec^2 on the average, but differences of 7 m/sec^2 or even 10 m/sec^2 between the two extremes are frequently attained. These extremes are, moreover, practically symmetric in relation to the median line.

The jolts recognizable by the spikes in the tracing occurred when the car's suspension bottomed out against the wheel assemblies. The P.L.M. car was in fact remarkable for its poor suspension, and the violent jolts made the trip unbearable. Meanwhile, the period of transverse oscillation remained the same as before, slightly superior to 1 second.

It sould be added that since the paper unrolled at a speed of 3.8 mm/sec and the period of the oscillograph was at least 1/30 second, the various oscillations visible on the tracings are not those of the intrinsic vibrations of the instrument.

b) Measurement of Acceleration Imparted to an Automobile by the Road

We also experimented with our accelerograph in a Ford automobile, which resulted in the recording in figure 391. For this tracing, the axis of the mercury tube was placed parallel to the direction the car was going in. Particularly in tracing 2, the oscillations caused by engaging the clutch and the fairly considerable acceleration (0.3 g) due to starting off in first gear can be seen.

The activity of the engine augmented the car's speed and the increase in the engine's rotation showed up as a widening of the tracing. On the other hand, . motive torque diminishes as the speed of rotation grows. The accelerationis reduced and falls from .15 to .05 g. The passage to direct drive is marked first by a fall in the acceleration towards 0, then by three jolts during engagement of the clutch, which lasted a little less than a second.

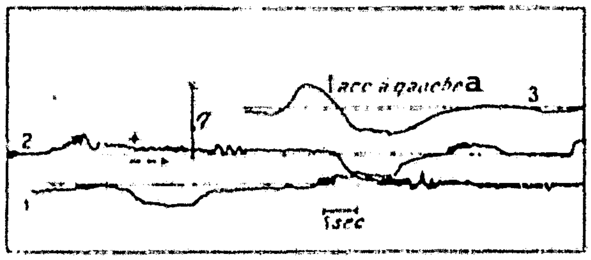


Figure 391
Recording of the Horizontal Acceleration Imparted to the Chassis of a Ford Automobile 1, 2 by Starting and Braking 3, by Veering

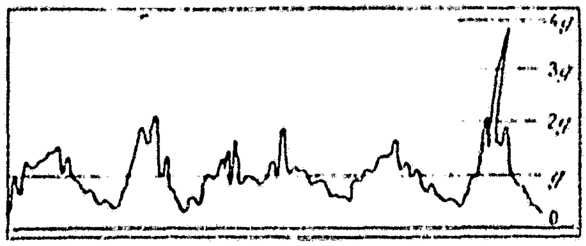


Figure 392
Recording of the Vertical Accleration Imparted to the Chassis of a Ford Automobile by Bumps in the Road

Key: a) Leftward acceleration

When in direct drive, the motive torque produced a basically constant acceleration of .1 g for 4 seconds. At this moment, an application of the brakes produced a negative acceleration ranging from .30 to .33 g for 2 seconds. The brakes were then released in 1 second and the car rolled, braked solely by the engine, which produced a negative acceleration of about 1/40 g. Next, the engine was speeded up and a series of positive accelerations resulted. Finally, the gas pedal was released and the acceleration fell to zero.

Tracing 3 of figure 391 was made by placing the axis of the mercury tube horizontally across the car while it was veering slightly to the left. Swerving to the right made the leftward centrifugal acceleration go up .33 g. This was immediately followed by a swerve to the left, producing a rightward acceleration ranging between .30 to .37 g. The swerves were sharp ones made on an asphalt surface. Afterwards, the automobile's course returned to a straight line. /254

The graph in figure 392 represents the recording of the acceleration imparted to the chassis of the same automobile by a bumpy road. The accelerograph was placed on the rear seat of the car. The road involved was the one leading from the main route between Bourg-la-Reine and Versailles to the entrance of the STA in the airfield at Villacoublay. This road is used by trucks carrying disassembled airplanes to the aerodrome.

One can see that the acceleration frequently attained 2g. At one point the chassis touched the rear axis, and the apparatus recorded an acceleration of close to 4 g, as shown on the right of figure 392. Near this acceleration, a series of oscillations relative to a period found throughout the tracing and occupying a length of 8 mm are clearly distinguishable. These oscillations represent the oscillation of the rear axle on the springs, while the accelerograph's intrinsic period, about 1/32 sec, does not appear on the tracing.

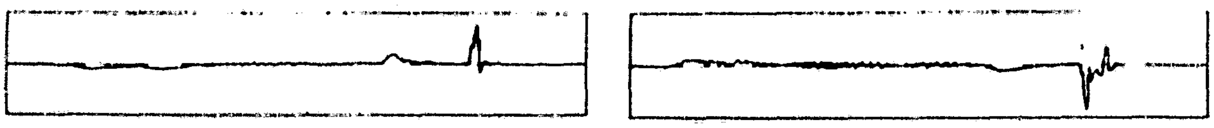


Figure 393
Recording of the Vertical Acceleration of a Subway Station Elevator (Place Saint-Michel) Left: Ascending; Right: Descending
g = 1.2 cm

c) Measurement of an Elevator's Acceleration

We also had the opportunity to use our accelerograph in the elevator of the Saint-Michel subway station. Figure 393 reproduces one of the recordings obtained in the course of an ascent followed by a descent.

The acceleration, directed downward like gravity, is inscribed below the zero line, which represents g. At the beginning of the ascent, an augmentation of the apparent weight by a factor of 1/15 is observable. The part of the tracing that follows corresponds to the agitation due to the winch, the motion being uniform at the time. At the end of this period, the current is reduced, and an acceleration opposite to gravity is produced until the moment when the elevator hits the bumper and stops abruptly. The result on the tracing is that there is a series of oscillations in the course of which an acceleration of approximately 4 m/sec^2 can be isolated.

During the descent, one witnessed first a relatively rapid fall causing a reduction in apparent weight by about 1/10. Then uniform motion sets in during which the agitation due to the winch is much greater than during the ascent.

A first slowing down produces an increase in weight comparable /255
to that occurring at the start of the ascent. Finally, the striking of the bumpers is indicated by a series of oscillations duirng which an acceleration on the order of 4 m/sec^2 is again exhibited.

d) Measurement of Acceleration Caused by a Man's Pace

It is possible to take up the study of acceleration in various movements, such as walking in humans and animals, with this same accelerograph.

The tracings in figure 394 show the displacement of a man holding the accelerograph in his hand, then going up and down a stairway.

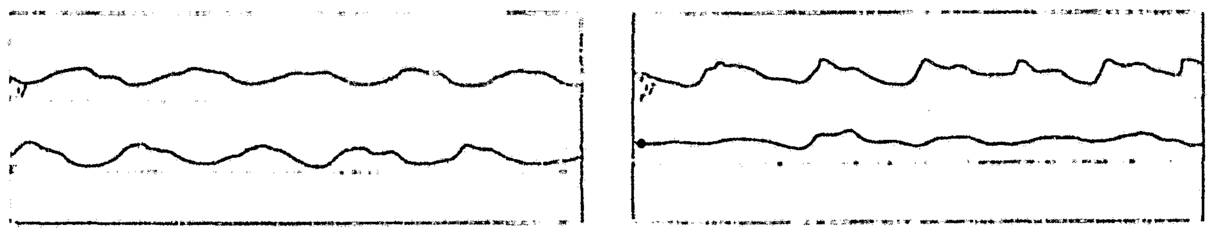


Figure 394
Recording of the Vertical Acceleration Caused by a Man's Pace
Left: Apparatus Carried in the Right Hand (Top) and Left Hand (Bottom)
Right: While Going Up (Top) and Down (Bottom) a Stairway
1 sec = 28 mm

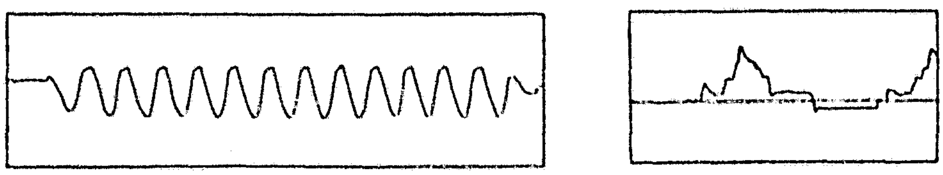


Figure 395
Left: Recording of a Rocking Horse; Right: Acceleration in a Whip

The next tracings (figure 395) were obtained by recording the acceleration on a rocking horse and a "whip", a carnival ride.

Figure 396
Acceleration Recorded during Launchings of "Robert Coton" Parachutes

Lastly, figure 396 presents the recording of the acceleration caused by opening a paracute supporting a 77.8 kg dummy. These tests, made by J. Mazer and J. Lemoine with our accelerograph, show that the magnitude of the acceleration sometimes reaches 5 g in these circumstances.

Simultaneous Measurement of Air Speed and Stress

To carry out a suitable study of stress in flight, it was indispensable to record not only acceleration, but also an airplane's instantaneous speed. We developed a recording instrument for this purpose.

In its present form, it is basically composed of a multiple Venturi tube, for example of the Badin type. This tube, which amplifies reductions in pressure, is linked to a metal manometer similar to those we used for our accelerographs, only much more sensitive.

It differs from them in that the pen, directed as before by two elastic plates constituting the amplifier, is in addition mounted on pivots. This arrangement, to which we were led by the desire to obtain a tracing free of vibration during motorized airplane flight, was imposed by the very great flexibility of the manometric tube itself and of the supple control plates. /256

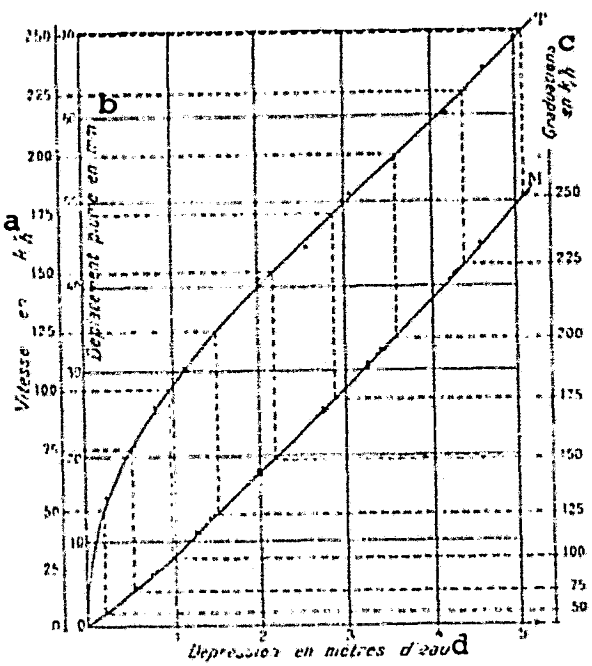


Figure 397
Calibration of Venturi Tube and Manometer for Speed Indicator

Key: a) Speed in km/h
b) Pen Displacement in mm
c) Graduations in km/h
d) Pressure reduction in meters of water

The manometer, equipped with a very light pen, has an intrinsic period of about 1/40 second. We mounted it on the accelerograph frame in such a way that it could trace the speed curve on the accelerograph's recording cylinder.

Calibration of the instrument was accomplished in the large wind tunnel at Issy-les-Moulineaux. The manometer was placed in the test chamber, i.e. in the space dominated by the static pressure of the relative wind, like in an airplane's fuselage. The Venturi tube is held in the tunnel's air current. A pipe transmits to the manometer the pressure reduction registered, which is simultaneously measured by a mercury manometer.

The calibration curves of the Venturi tube and manometer are reproduced in figure 397.

The calibration curve of the Venturi tube T was drawn with the pressure reduction in meters of water as the abscissas and the air current speed as the ordinates. The curve M of the manometer was drawn with the reduction in pressure to which it was exposed as the abscissas and the deflection in the tracing as the ordinates.

The speed scale in km/h marked on the left yielded, after following the dotted lines, the graduations of the instrument as shown on the right.

It is immediatley clear that since the two curves T and M have the same abscissas, all one has to do to find on M the deflection in millimeters corresponding to a certain speed is to cut the curves at the ordinate representing the reduction in pressure at this speed. The line consequently intersects the curve T at the ordinate equal to the speed under consideration, expressed in km/h, for example. The dotted lines were plotted for speeds equal to multiples of 25 km/h.

One can get an idea of the precision of the calibration under standard conditions (760 mm pressure, 0-15° C) with the aid of the eighteen points used to trace the curve T. The points' average deviation from the curve is 1.1 km/h, or 1 1/2% of the maximum speed.

Under these conditions, the average error in the measurements made by the manometer is known to be 3%. The total average error in measurement of speed based on the manometric tracing is therefore equal to about 1/2% of the maximum speed.

The pressure reducing Venturi tube is mounted on the airplane in the usual manner, taking care to place it at a point where the speed of the airflow is as close as possible to the airplane's air speed.

A pipe of suitable diameter links the Venturi tube to the manometer, which is placed with the accelerograph in the airplane's fuselage. The difference between the prevailing pressure in the fuselage and the pressure in the Venturi tube can thus be measured.

III. Comparison of Cinematographic and Accelerometric Methods /257

The two methods, cinematographic and direct measure, give similar results, as we are going to see.

Study of Flight Conditions in an Airplane

Figure 398 reproduces the curves, shifted back to time 0, of the flight parameters recorded during a level flight in a 180 hp Gourdou-Leseurre airplane at its maximum value.

On the bottom is the tracing produced by the air speed indicator, in the middle that of the accelerograph attached near the airplane's center of gravity in such a way as to record the acceleration perpendicular to the wings, and on top is the tracing made by a stylus activated by the joystick so as to inscribe the elevator's vertical movements.

The recording was made at an altitude of 110 meters, with the pilot flying horizontally at full speed over the airbase east of Villacoublay. Two passages over the base in opposite directions are shown. In the first passage, the speed was close to 210 km/h during the last ten seconds. The pilot then swerved sharply. The acceleration went up to 3 g, which corresponds to an inclination of 70° above the horizontal on the part of the airplane. This led to a rapid fall in the speed, from 205 to 100 km/h in 3 seconds. After finishing turning, the pilot returned to his line of flight and passed over the base again, this time at a rate of about 195 km/h. The difference in the air speeds going and coming stems from the fact that the airplane was in a slight dive during the first passage. This is revealed by the tracing of the elevator's movements.

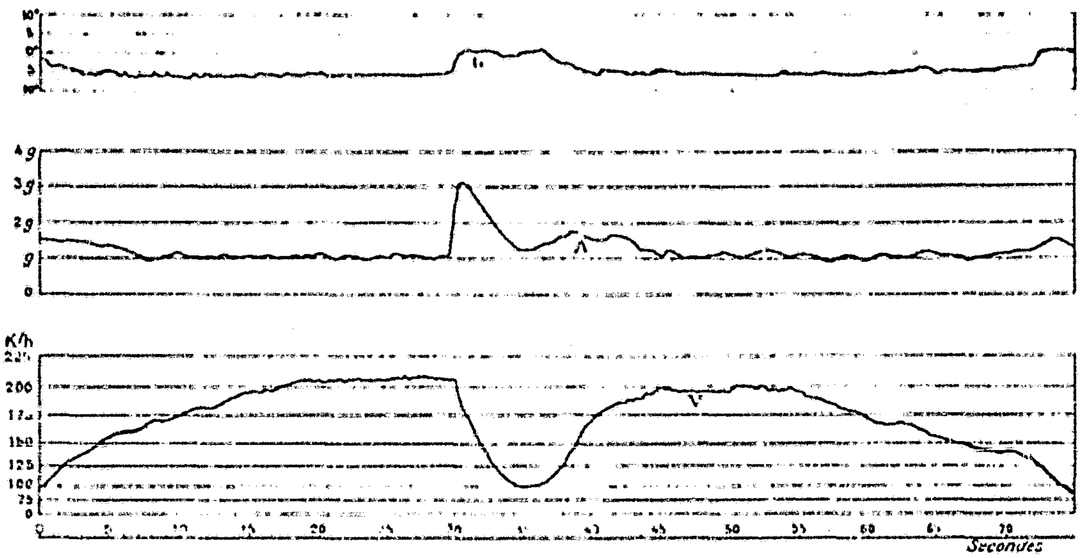


Figure 398
Simultaneous Tracing of the Movement of the Horizontal Rudder G, Vertical Acceleration A, and Air Speed V of a Gourdou-Lesseurre Airplane during Two Passages over a Base, Separated by a Vertical Banking Maneuver

At the same time as the recording was made, we used our equipment to film the airplane perpendicular to its trajectory.

Examination of the film first of all enabled us to confirm the existence of a slight dive during the first passage. The airplane descended with a slope of 4%. /258

Measurements made on the photographs established that the ground speed of the airplane, which was 410 meters from the objective, was 225 km/h when flying away and only 173 km/h when returning.

The first passage thus must have been made in a tail wind and the second in a head wind, and the air current's speed was therefore around 26 km/h. The accuracy of the measurements is revealed by the fact that the airplane's average ground speed was 199 km/h while its average air speed was 202.5 km/h.

Study of Looping

We then tried to record cinematographically the trajectory of the Gourdou-Leseurre airplane in the course of various maneuvers. Among other things, we succeeded in following the airplane across the coordinate grid with our camera gun during a series of three loops. These were performed by Lt. Joublin in a plane approximately parallel to that of our grid.

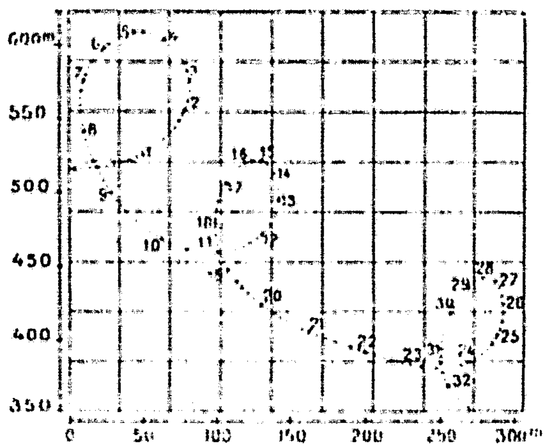


Figure 399a
Trajectory in the Vertical Plane of a Gourdou-Leseurre Airplane during Three Successive Loops

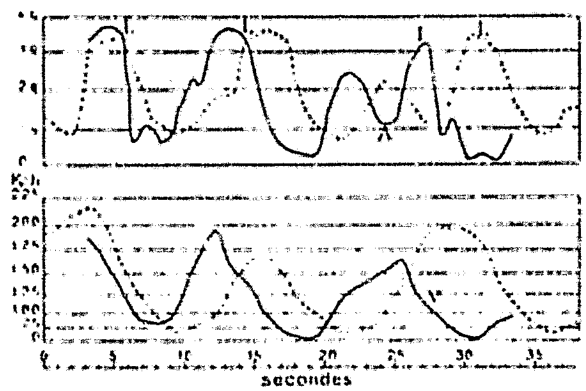


Figure 399b
Solid Lines: Vertical Acceleration (A) and Air Speed (V) Curves of a Gourdou-Leseurre Airplane, Derived from the Film of its Trajectory during Three Loops; Dotted Lines: Acceleration and Speed Curves Obtained Experimentally

Figure 399a represents the trajectory obtained by transfering the airplane's position as revealed in the film point by point onto a reproduction of the coordinate grid.

We employed the method described above to determine the airplane's distance from the camera gun (1,850 meters), height above the ground, horizontal displacement during the loops, and speed second by second.

Figure 399a shows that the first loop had larger dimensions than the two following it. Its height was 100 meters, as compared to 67 meters for the next two. The first two were also much tighter. Their width was only about 45 meters, while the first loop's attained 89 meters.

The numbers marked on the trajectory indicate the time elapsed since the start of the maneuver. The separations between the numbers

document the way the airplane's speed varied in the course of the maneuver. Through detailed examination of the film frames, we were able to determine the vehicle's ground speed. We thus established that the airplane's speed was 183 km/h during the first second, 82 km/h during the fifth, 194 km/h during the tenth, /259
46 km/h during the sixteenth, 165 km/h during the twenty-third, and only 32 km/h in the course of the twenty-eighth second.

We then sought to use the airplane's trajectory to determine the magnitude of the normal acceleration. We calculated V^2/R and then $\gamma = (V^2/gR) + \cos\alpha$. All the figures used are contained in the following table:

Av. Time	Av. Speed	Av. Radius	$\frac{V^2}{R}$	Inclination α of Velocity	$\frac{1}{g} \cdot \frac{V^2}{R} + \cos\alpha$ as a function of g
secondes	m/sec	mètres	m/sec²	degrés	
0,5	51	107	24	13	3,4
1,5	46	68	30	47	3,7
2,5	37	37	36	90	3,6
3,5	27	56	13	128	0,7
4,5	23	26	20	168	1,1
5,5	26	44	15	210	0,7
6,5	27	54	13	238	0,8
7,5	40	69	23	268	2,3
8,5	47	137	16	294	2,1
9,5	54	107	27	317	3,5
10,5	44	70	27	346	3,7
11,5	37	54	25	20	3,5
12,5	28	40	19	62	2,4
13,5	21	35	12	101	1
14,5	14	16	12	136	0,5
15,5	13	13	13	190	0,3
16,5	18	36	9	227	0,2
17,5	29	65	13	256	1,1
18,5	35	60	20	285	2,3
19,5	37	77	17	313	2,4
20,5	41	167	10	330	1,9
21,5	44	640	3	340	1,2
22,5	46	780	3	344	1,2
23,5	36	70	18	7	2,8
24,5	29	33	25	46	3,2
25,5	21	54	8	83	0,9
26,5	18	19	17	114	1,3
27,5	9	8	10	163	0,1
28,5	14	24	9	218	0,2
29,5	23	90	6	236	0,1
30,5	27	69	10	256	0,8

[Commas in tabulated material are equivalent to decimal points.]

We constructed the curves A and V in figure 399b from the figures corresponding to the airplane's acceleration γ and air speed. The instantaneous acceleration and air speed curves obtained with the accelerograph and speed indicator during the three successive loops are also plotted on the same figure.

The curves are basically equivalent in terms of speed, even though the airplane's speed was a little lower in the cinematographic recording than in the accelerograph's and the time elapsed during the /260
three loops was shorter in the first case than in the second. On the other hand, the magnitude of the acceleration is greater in the first case. It should be pointed out, however, that the loops performed by Lt. Joublin in this experiment were tight. In particular, the airplane's speed was very low and its acceleration practically zero at the top of the third loop.

In the next lesson, we will examine the differences between the magnitudes of the acceleration normal to the wings according to the maneuver performed as well as that resulting from atmospheric disturbances.

RECOMMENDED READING

Huguenard, Magnan, Planiol, "Sur la mesure des efforts aérodynamiques supportés par la voilure d'un avion" [The Measurement of the Aerodynamic Stresses Supported by an Airplane's Wings], C.R.A.S., (December 1, 1924).

Huguenard, Magnan, "La mesure en vol des efforts et des déformations dans la charpente des avions" (The Measurement in Flight of Stress and Deformation in Airplane Frames], L'Aérophile (1927).

Huguenard, Magnan, Planiol, L'accélérographe H.M.P.; son application à la mesure des accélérations en vol [The H.M.P. Accelerograph: Its Applicationto the Measurement of Acceleration in Flight], Bulletin du Service Technique de l'Aéronautique, 30 (1926).

Mazer and Lemoine, "Les parachutes d'avion" [Airplane Parachutes], Premier Congrès Int. de la Sécurité Aérienne [First International Congress on Aeronautical Safety], Reports Vol. 2 (1930).

Lesson Nineteen: Experimental Study of an Airplane's Acceleration Resulting from Maneuvers or Atmospheric Disturbance /261

In 1923, Huguenard, Planiol, and I began research on the measurement of acceleration in flight. Our goal was especially to record the component of acceleration normal to the wing plane, which seemed to us a priori to be the most interesting to know.

I. The Acceleration Due to Acrobatic Stunts

We first of all used a 180 hp Gourdou-Leseurre fighter monoplane for this purpose. Its specifications are the following:

Wingspan	9.20 m
Wing Area	18.50 m^2
Total Length	6.50 m
Control Surface Size	2 m^2
Weight	191 kg
Speed	205 km/h

The accelerograph was fastened directly to the fuselage just behind the engine without any soft substance for dampening vibrations in between. The intense vibrations of the engine did not interfere with the accelerograph's functioning.

Tests with the Pilots Christiany and Devillers

The airplane was piloted at first by two different aviators so that we could see the difference that might exist in the reactions arising from different methods of flying.

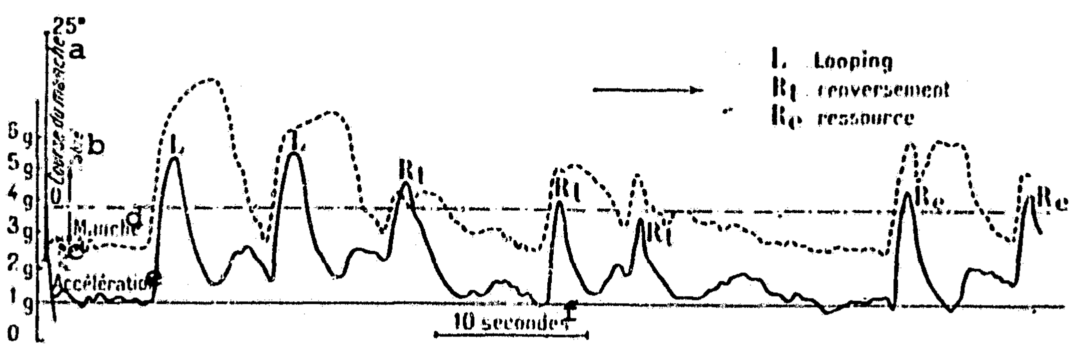


Figure 400
Simultaneous Recording of Acceleration Normal to the Wings and Movement of Horizontal Rudder (Pilot: Christiany)

Key:
- a) Path of joystick
- b) Nosing up
- c) Diving
- d) Joystick
- e) Acceleration
- f) 10 seconds
- L) Loop
- R_t) Renversement
- R_e) Pull-out

Figure 400 reproduces the tracing of the original recording of acceleration and elevator movement made during a series of maneuvers [illegible], renversements, and pull-outs, executed by Christian[illegible]ecause of the phase difference between the pen recording acceleration and that tracing the course of the joystick, we shifted the position of the two resulting curves in figure 400 relative to each other by a quantity equal to the phase difference. Figure 400 first of all reveals the way an airplane reacts to a shift in the elevator. Here, the airplane's reaction is very rapid and there is no appreciable time interval between the moment when the pilot starts to pull on the joystick and the moment when the airplane starts to nose up. On the left of the same figure we have marked off the scale of acceleration in multiples of g. A scale, whose zero point is on the chain dotted line level with the 4g acceleration ordinate, represents the movement of the joystick in proportion to the ordinates of the curve drawn with a broken line. Moving the joystick all the way to the rear shifted the stylus to the scale's top point, marked 25°. This corresponded to an elevator inclination of 25° relative to the fixed tail fin. /262

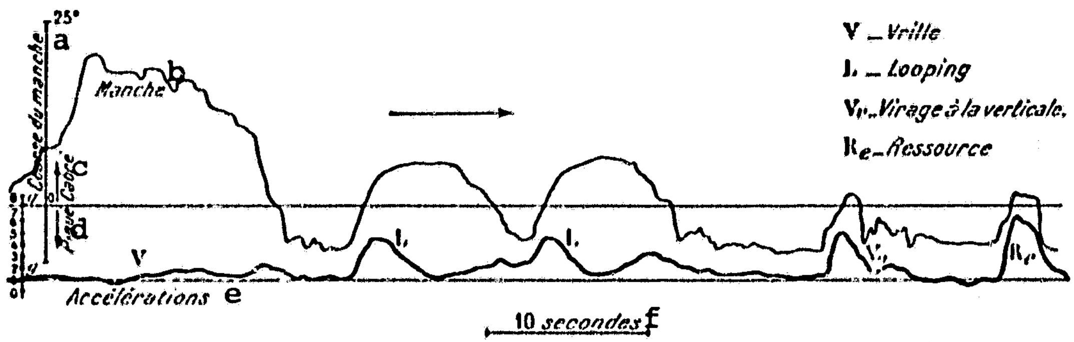


Figure 401
Simultaneous Recording of Acceleration Normal to the Wings and Horizontal Rudder Movement (Pilot: Devillers)

Key: a) Path of joystick
b) Joystick
c) Nosing up
d) Diving
e) Acceleration
f) Ten seconds
V) Spin
L) Loop
V_v) Vertical Bank
R_e) Pull-out

For purposes of clarification, we are showing a similar drawing in figure 401. It was made during maneuvers with the same airplane with the aid of accelerograph no. 2, equipped this time with a 15 kg/cm^2 manometric tube. In these two flights, the maneuvers, loops, and pull-outs, executed by Devillers produced similar accelerations. However, the joystick motion that gave rise to them is not at all the same. Devillers, who performed the maneuvers recorded in figure 401, attained a vertical acceleration of 5 g in one loop by moving the horizontal rudder 12°. Meanwhile, the pilot Christiany caused an acceleration of 5.5 g in figure 400 in a loop in which he displaced the elevator more than 22°.

Figure 402 depicts the tracing of vertical acceleration during barrel rolls and pull-outs performed by Devillers.

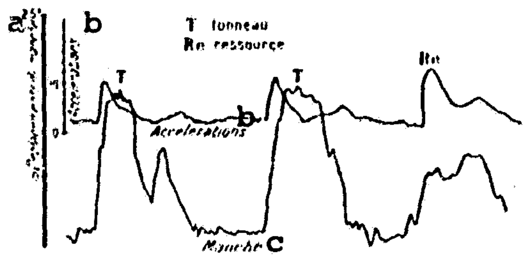


Figure 402
Simultaneous Recording of Vertical Acceleration and Horizontal Rudder Movement (Pilot: Devillers)

Key: a) Stick displacement
b) Acceleration
c) Stick
T) Barrel roll
R_e) Pull-out

We also were able to study the vertical acceleration resulting from the shock of a rough landing at the field in Vauville. The acceleration here attained 4.3 g, while in a very gentle landing with the same airplane, we obtained 3.1 g.

In addition, the pilot Devillers /263
intentionally made a rough landing on June 16, 1925, by letting his Gourdou airplane fall more than 1 meter to the ground. The accelerograph recorded a vertical acceleration of more than 5 g in this case.

After the landing, the undercarriage was found to have bent. This undercarriage had been designed to support five times its normal load.

Tests with Captain Joublin

We had thus pointed out the desirability in simultaneously recording acceleration, elevator movement, and air speed on the same tracing paper. This was an operation that had not yet been done. We successfully carried out such experiments in 1926-27 and we are going to relate them here.

For this purpose, we used our accelerograph mounted on the /264
stand to which we had attached a stylus driven by the joystick so as to record elevator movement, as well as the manometer of our air speed indicator.

Capt. (then Lt.) Joublin, who was a remarkable test pilot, then performed a series of acrobatic stunts with the instrument, whose stylus was linked by a thin cable to the joystick and whose manometer was connected with the Venturi tube by a suitable pipe. The Venturi tube itself was attached to the end of a pole below the wing and located far from the fuselage.

The first two experiments both included a loop and a pull-out. The tracings of the resulting curves are reproduced in figure 403. They are all shifted back to time zero.

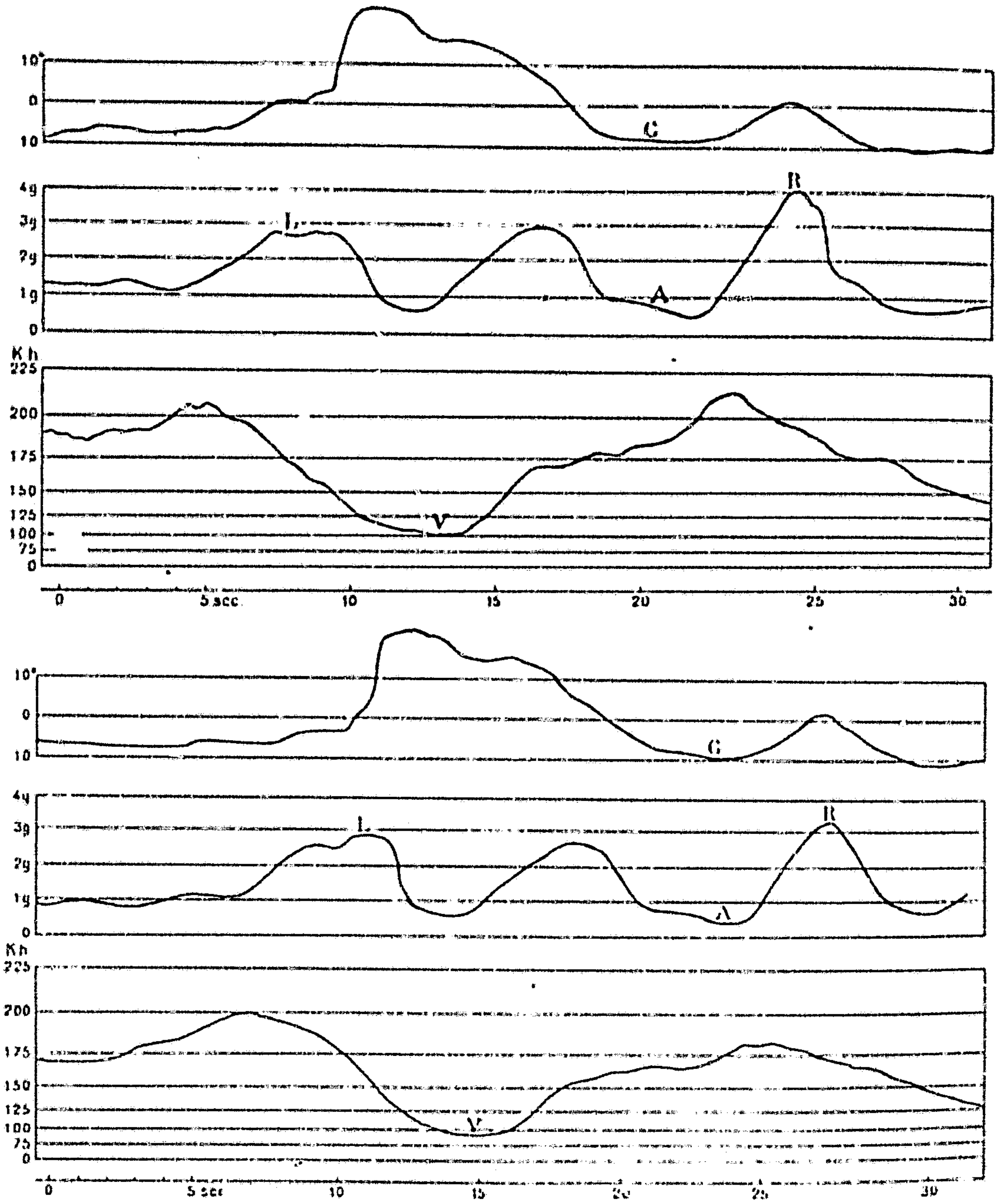


Figure 403
Simultaneous Recording of Horizontal Rudder Movement G, Acceleration Normal to the Wings A, and Air Speed V of a Gourdou-Leseurre Airplane in the Course of a Loop L followed by a Pull-Out R
Top: First Test; Bottom: Second Test (Pilot: Joublin)

Figure 403 shows that the maximum acceleration attained was a little over 3 g at the beginning and the end of the loop, which was intentionally very gentle. The variation in speed was simultaneously a good hundred kilometers per hour. During the pull-out, the acceleration was a little larger and attained close to 4 g. Furthermore, a high degree of similarity between the two recordings can be seen.

In these tests, as in the others, the movement of the elevator was very carefully ascertained beforehand. This enabled us to plot the corresponding graduations on the diagrams. The position chosen as zero is that in which the plane containing the rudder coincides with the fixed horizontal tail fin. Above zero are the angles corresponding to climbing. This is when the elevator is raised. Below zero are the angles corresponding to diving, when the elevator is lowered. Thanks to this scale, it is evident that the pilot is in a climbing position, i.e. nosing up, much more when looping than when pulling out.

The experiments were followed up by repeating the same maneuver three times on the same tracing.

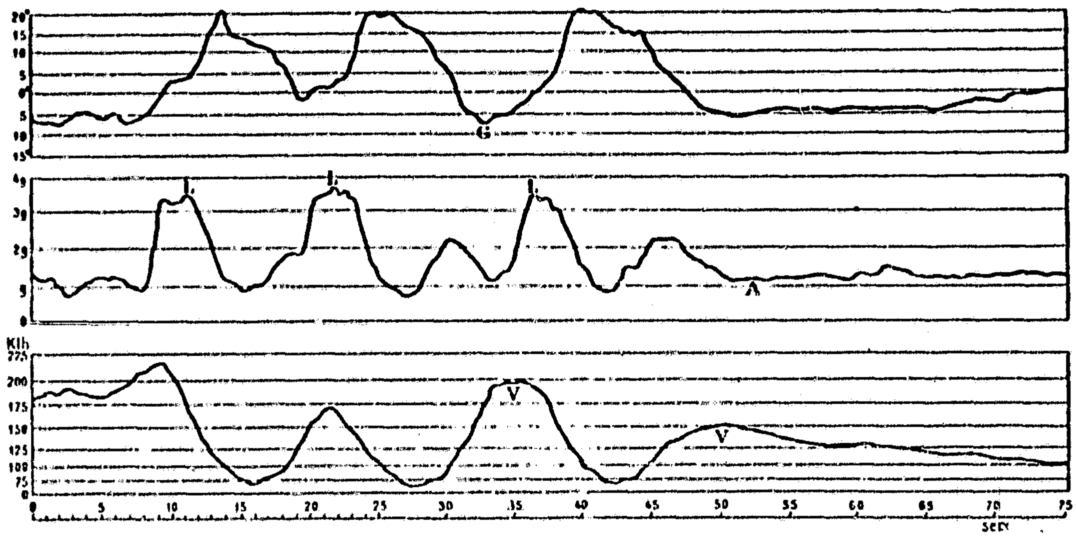


Figure 404
Simultaneous Recording of Horizontal Rudder Movement G, Acceleration Normal to the Wings A, and Air Speed V of a Gourdou-Leseurre Airplane during Three Successive Loops
(Pilot: Joublin)

a) Loops

Figure 404 reproduces the tracings resulting from recording a series of three successive loops, with the different tracings shifted so that their starting times coincide. The figure shows that the second and third loops are fairly similar in terms of acceleration and elevator movement. The second peak in the acceleration curve of each loop corresponds to the return to the line of flight of the air- /265
plane after it has fallen from the top of the loop that it has described. At the end of the first loop, this peak almost merges with the start of the second loop's curve, which indicates that the pilot went into the second loop upon leaving the preceding one.

This is confirmed by the tracing of elevator movement, which has a much less accentuated downward direction at this moment and shows that the pilot did not attempt to take up the horizontal line of flight again. The speed, which attained 215 km/h after a slight dive at the beginning of the first loop, did not exceed 170 km/h at the end of the first loop. It went up to about 200 km/h after the second loop and 150 km/h after the third. At the high point of the three loops, it fell to the neighborhood of 60 km/h.

The acceleration in the three cases reached 3.5 g, much lower than the magnitude obtained during our 1925 experiments involving flights by Christiany and Devillers. Capt. Joublin did not try to obtain elevated figures.

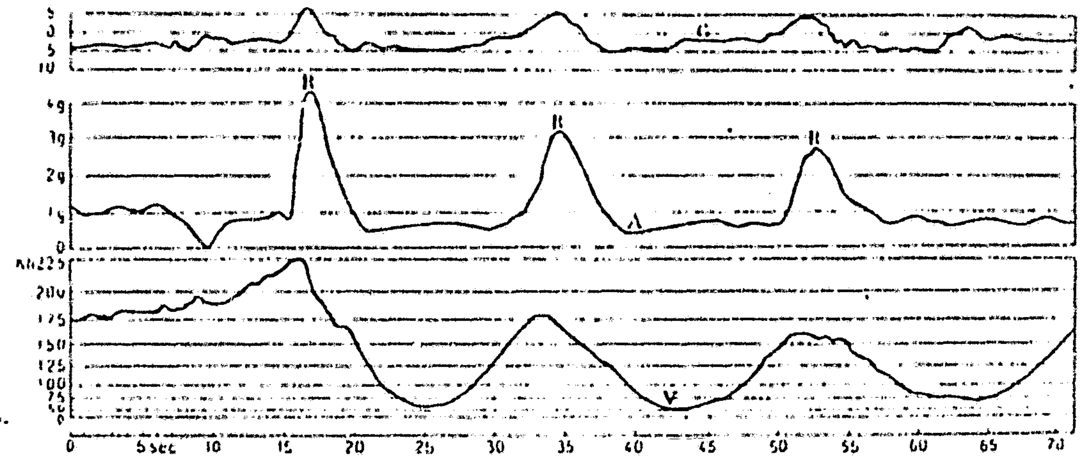


Figure 405
Simultaneous Recordings of Horizontal Rudder Movement G, Acceleration Normal to the Wings A, and Air Speed V of a Gourdou-Leseurre Airplane in the Course of Three Successive Pull-Outs (Pilot: Joublin)

b) Pull-Outs

Figure 405 reproduces the tracing of the recording made during three successive, fairly accentuated pull-outs.

In the beginning of the maneuver, the pilot made a sharp dive, and the speed reached 225 km/h. He then pulled abruptly on the joystick. The acceleration rose to 4.3 g. In comparison, at the entrance to the dive it had fallen to 0, with a speed of 190 km/h.

Note that the angular displacement of the horizontal rudder, which caused the considerable variation in acceleration, was very small. At the commencement of the dive, the displacement was 3 to 4° and at the moment of leveling off, it was about 7 or 8°.

Figure 405 indicates that the acceleration then went down to a level of about 0.5 g. Meanwhile, the speed diminished considerably and went from 225 km/h to 60 km/h in 9 seconds.

A new dive followed and brought the airplane's speed up to 205 km/h. The less rapid leveling off that the pilot performed, as documented by the elevator movement curve, was accompanied by an equally weaker acceleration, barely over 3.2 g.

During the following ascent, the speed fell a little more than before and was about 50 km/h. Moreover, the airplane gave the earthbound observer the distinct impression of extreme slowness. It seemed to almost hover at the peak of its trajectory before rushing toward the ground again for the third pull-out. The third maneuver was even less forceful than the one before, since the maximum acceleration did not exceed 2.7 g. /266

Let me add that the loops and pull-outs were performed at an average altidude of 500 meters.

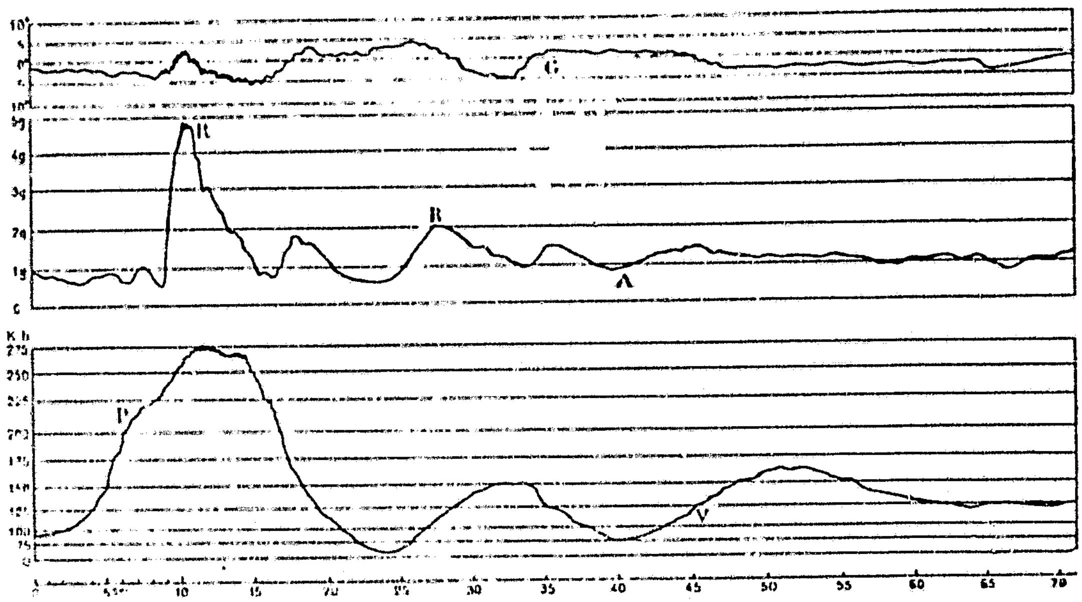


Figure 406
Simultaneous Recording of Horizontal Rudder Movement G, Acceleration Normal to the Wings A, and Air Speed V of a Gourdou-Leseurre Airplane in the Course of a Dive P Followed by a Pull-Out R (Pilot: Joublin)

c) Dives

In the beginning of figure 406, a very steep dive occurs. We had asked Capt. Joublin to dive sharply, as close as possible to vertically, and then to let the airplane go as long as he thought possible without endangering himself.

Figure 406 shows that after the pilot started the instrument running at the end of an ascent, the airplane's speed rapidly grew from 90 to 275 km/h. At 250 km/h, a slight trembling was exhibited which is highly visible in the figure. The trembling was due to wing tip and aileron vibration at the end of the dive. They started to vibrate, as the pilot noticed, with such an intensity that the joystick was knocking against his hand like drumbeats. This phenomenon led Lt. Joublin to level off so as to break his motion. The nosing up was performed very gently and resulted in an acceleration of 1.8 g. The elevator displacement was only 4 to 5°. The vehicle then started to climb, and its speed decreased to around 35 km/h. The pilot next took on speed until 150 km/h was reached. He then executed a renversement, which made the speed fall again to 75 km/h. After that, he gradually returned to his line of flight.

II. Acceleration Due to Atmospheric Disturbances

We next sought to get an idea of the magnitude of the inertial stress felt by an airplane as it passes through an air current rising after encountering a cliff. The area used for this purpose was the glider field at Vauville.

The Influence of a Sea Breeze /26

The airplane employed in the tests was the Caudron C.127 biplane.

At the time of the experiment, the wind at ground level had an average speed of 9.9 m/sec and was blowing from the WNW. At 100 meters up, the wind speed was appreciably the same, but was blowing from the W. The wind was of the sea breeze type already described. It was fairly regular and contained small gusts whose amplitude at an altitude of 100 meters rarely attained a third of the average speed. Above the ridge at Vauville, it had been deflected upward by its encounter with the cliff. In the meantime, it conserved its oscillations and slight agitation.

Experiments have proved that the inertial stresses engendered in an airplane by such a wind are small and do not exceed half the acceleration due to gravity, as figure 407 shows. This recording was obtained under the following circumstances.

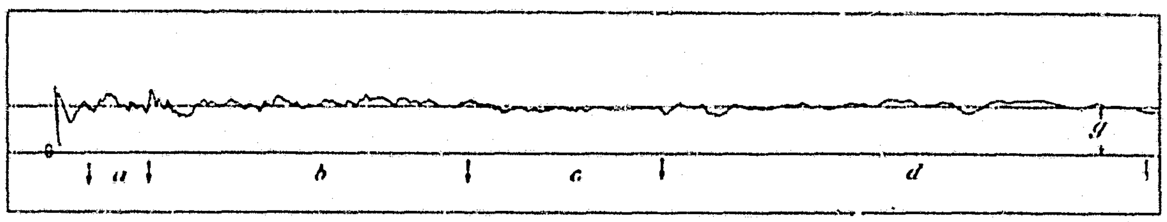


Figure 407
Recording of Acceleration Normal to the Wings of a Caudron C.127 Airplane while Passing through a Sea Breeze Deflected Upward by the Cliff at Vauville 10 sec = 23 mm (Pilot: Bécheler)

The airplane took off into the wind, i.e. perpendicular to the cliff and toward the sea. It then circled to attain a height of 50 meters. The engine was running at its normal operating speed and, having reached 50 meters, it was again pointed out to sea. Meanwhile, the pilot attempted to maintain a horizontal trajectory. Before arriving at the edge of the cliff, the controls were locked and the accelerograph's recording cylinder started up. The resulting record shows that at this moment (figure 407, part a) the airplane was located in the turbulence existing behind the ascending zone and underwent accelerations of 2 m/sec^2.

Upon arriving in the ascending zone, the acceleration reached 3 m/sec^2 (figure 407, part b). The airplane reared slightly and performed a series of oscillatons due to the irregularities in the wind. The average value of its oscillations remained positive and was equal of 1.25 m/sec^2. The vehicle rose by 50 meters under these conditions while continuing out to sea. Toward the end of the ascent, the acceleration weakened. At this point, the pilot opened the throttle a little more so as not to lose altitude, and made a horizontal U-turn. Then he cut off the gasoline and followed a straight trajectory parallel to the cliff in the zone of propitious updrafts.

The ariplane did not lose any height during this entire period.

During the part of the flight with the motor cut off, the airplane, whose controls were also locked, received a series of accelerations. They were sometimes positive, sometimes negative, and varied between 1 and 2 m/sec^2. They were caused by the airplane's encounter with gusts and eddies.

Lastly, the airplane's speed in this experiment was about 120 km/h during the horizontal powered part of the flight. It fell to about 50 km/h after the motor was shut off.

The Influence of a Terrestrial Wind

We tried to complete the findings we obtained at Vauville while investigating the inertial forces acting on an airplane flying through atmospheric disturbances by recording the forces on a flight from Barcelona to Toulouse. This route was chosen from /268
among those of commerical lines because it seemed that the greatest atmospheric disturbances were encountered there.

Our accelerograph was placed in a Latécoère Airlines four-seater Farman Limousine airplane powered by a 12-cylinder 300 hp Renault engine. The instrument was positioned so as to detect the acceleration normal to the wing plane.

Tracings 1 and 2 in figure 408 represent the start of the flight, before and after passing over Barcelona. The weather was calm, and the acceleration almost zero.

Tracing 3 was started near the mountainous zone. It first shows jolts of increasing intensity due to a wind blowing from the NW. This is followed by a less agitated section.

Tracing 4 corresponds to the entrance of the mountainous zone at an altitude of 2,300 meters. The jolts were fairly strong, with the wind rising.

Tracing 5 records the flight through the Pertus Pass, whose altitude is about 400 meters. As it entered the pass, the airplane descended from 1,200 meters to about 600 under the effect of atmospheric disturbances and downdrafts. This was done without any voluntary maneuver by the pilot.

The pass was entered at a height of 200 meters above the ground.

The most violent shaking occurred at this time. Positive accelerations as high as 10 m/sec^2, in addition to gravity are found in tracing 5, though it is true that these are exceptional. In the opposite direction, the acceleration barely exceeded 5 m/sec^2.

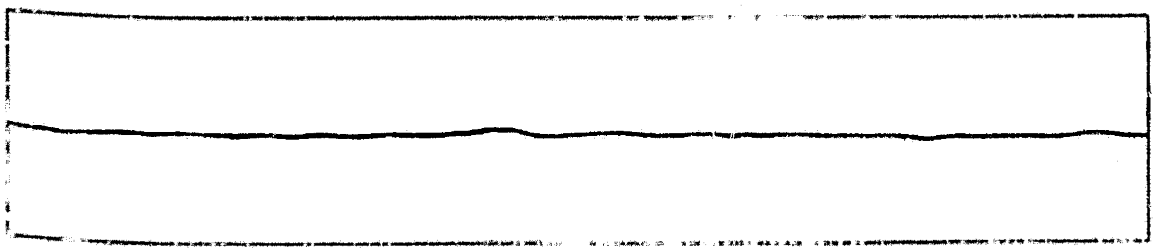
The airplane's wings therefore underwent a stress ranging from .5 to 2 times its weight. In addition, the jolts followed each other at intervals of 4 to 5 seconds. It must be pointed out that the average duration of the atmospheric disturbances causing the jolts would be much longer for an observer on the ground. It would be multiplied by the ratio of the airplane's speed to that of the wind, which in this case is a number close to three. The airplane's air speed at an engine speed of 1,350 to 1,400 rpm, at which the voyage was made, was in the vicinity of 40 m/sec. The wind's speed was on the order of 15 m/sec. The gusts therefore lasted 10 or 15 seconds. This corresponds to what we have found in other situations with our anemometers.

The magnitude of the strongest accelerations imparted by the atmospheric disturbances during the flight, in addition to gravity, ranged from -6 to +10 m/sec^2.

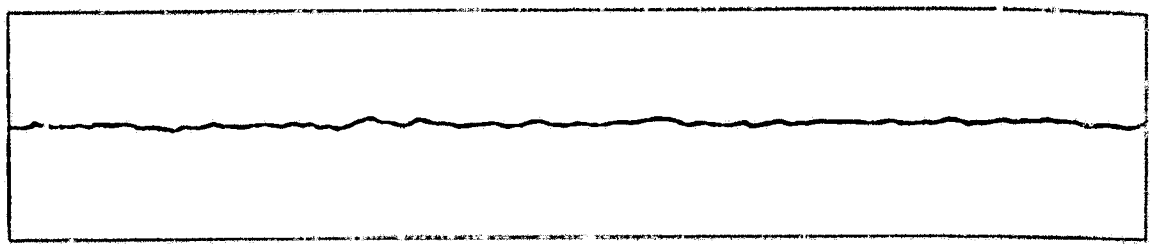
We should note here that, in the pilot's opinion, the air was relatively calm for the season. The pilot claims that the shaking is twice as great during heavy winter weather. This indicates the possibility that the acceleration can impose loads on the airplane equal to three times its weight.

III. Comparison of Magnitude of Acceleration According to Flight Characteristics

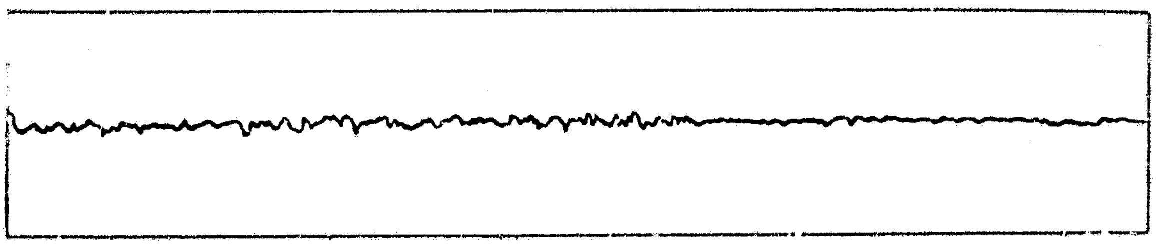
An examination of all the acceleration curves we obtained during our test flights have given us the values on pages 373-4 for acceleration during various maneuvers, as well as the corresponding joystick movements.



1. Before Barcelona (6:30) in Almost Still Air
g = 9.5 mm; 1 sec - 3.8 mm

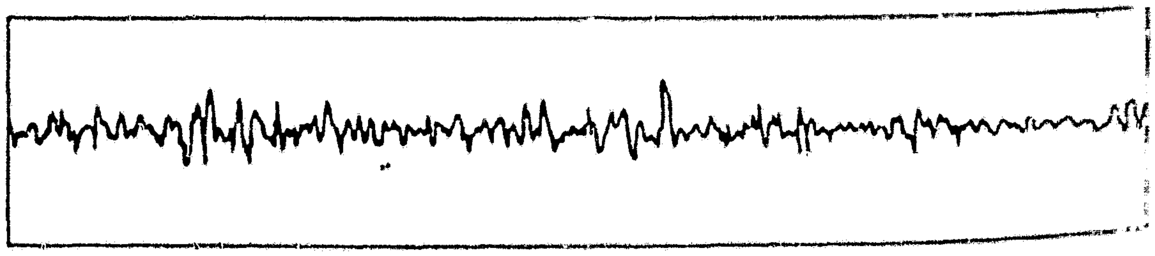


2. Between Barcelona and Gerona (6:50) in Almost Still Air
g = 9.5 mm; 1 sec = 3.8 mm



3. Approaching the Pyrenees (7:19) with the Wind Rising
g = 9.5 mm; 1 sec = 0.6 mm

4. Entering the mountains (7:21) in a Steady Wind
g = 9.5 mm; 1 sec = 0.6 mm



5. Flying through the Pertus Pass (7:32) in a Stiff Wind
g = 9.5 mm; 1 sec = 0.6 mm

Figure 408
Recording of Vertical Accelerations Imparted to a Farman Airplane by Atmospheric Disturbance between Barcelona and Perpignan

These values are fairly accurate even though the accelerograph was never constantly positioned along the normal to the trajectory. For one thing, an airplane's angle of attack is usually small and varies from -0.3 to +12.9°. In addition, the accelerograph is attached so as either to be vertical during horizontal flight or have an incidence on the order of 3°. The instrument's axis therefore deviates from the normal by ten degrees at most. The result of this is that the projection of the normal acceleration onto the accelerograph's axis differs from its value by at most 1 1/2%. They consequently differ by a quantity that is in general less than the probably uncertainty in the measurements. /270

Maneuver	Airplane	Pilot	Total Acceleration g	Max. Inclination of Joystick deg
Loop	Gourdon 180 ch	Christiany	5,5	+ 18
"			5,7	+ 13,5
"		Devillers	4,85	+ 5,8
"		—	4,82	+ 6,8
"		Lt Jourlin	3,5	+ 20
Barrel Roll		Devillers	4,91	+ 14
"		—	5,27	+ 15,5
Renversement		Christiany	3,9	+ 6,5
"		—	4,4	+ 2,3
Vertical Bank		Devillers	5,01	+ 1,6
"		Lt Jourlin	3,1	+ 5
Pull-Out		Christiany	4,2	+ 2,1
"			4,3	+ 9,5
"		Devillers	5,59	+ 3
"		—	6,46	+ 1,8
"		Lt Jourlin	4,8	+ 2
Spin		Devillers	0,6 —1,3	+ 20,5

Maneuver	Airplane	Pilot	Total Accel-eration	Max. Inclin-ation of Joystick
Exit from Spin			2,3	"
Rough Landing		—	5,2	"
Moderate Landing	Caudron 127	[illegible]	4,3	"
Gentle Landing			3,1	"
Flight in Rising 9 m/s Sea Breeze Motor Cutoff			1,43	"
Flight in Atmospheric Disturbances behind Zone of Updrafts	Farman limousine	Hamm	2,1	"

[Commas in tabulated material are equivalent to decimal points.]

This table demonstrates the benefits there are to recording the movement of the elevator so as to know its position at every moment and to get an account of the stress resulting from its manipulation.

In any case, our tests have already shown that the maximum value of the component of acceleration normal to the wing plane can attain 6.5 g. This means that at that moment the airplane supports 6 1/2 times its own weight. This figure is not in disagreement with the maximum value of 7.8 g obtained by the Americans with another model airplane and other pilots. In addition, let it be pointed out that the figures we found in the course of acrobatic maneuvers should not be considered as absolute maxima. First of all, the atmospheric disturbances occurring during a maneuver certainly augment them, as we have seen. Next, do not forget that the airplane's frame also undergoes vibrations originating in the engine. They can give rise to considerable supplementary stresses. During our experiments, the accelerograph was dampened so as to eliminate the vibrations it was not intended to study. It recorded only the resultant of accelerations due to aerodynamic forces. It would be interesting to know something about these vibratory stresses, which are very fatiguing for the metal. /271

IV. Measurement of Frame Deformation in an Airplane in Flight

All the stresses that we detected in the course of maneuvers or in the middle of strong gusts have an incontrovertible effect on airplane frames. There is thus an interest in discovering the deformations that can result from such supplementary forces.

Furthermore, measurement of deformation is another way of determining the aerodynamic stresses undergone by an airplane's wings during flight.

Description of the H.M.P. Wing Stress Indicator

Along with Huguenard and Planiol, I created a wing stress indicator for this purpose. The device includes a sort of light-weight antenna fixed to an airfoil or in the interior of the thick part of the wing. This is done in such a manner that it is possible to consider it as fixed and indeformable under flight conditions. The antenna constitutes a reference line for measuring deformations of the wing spar.

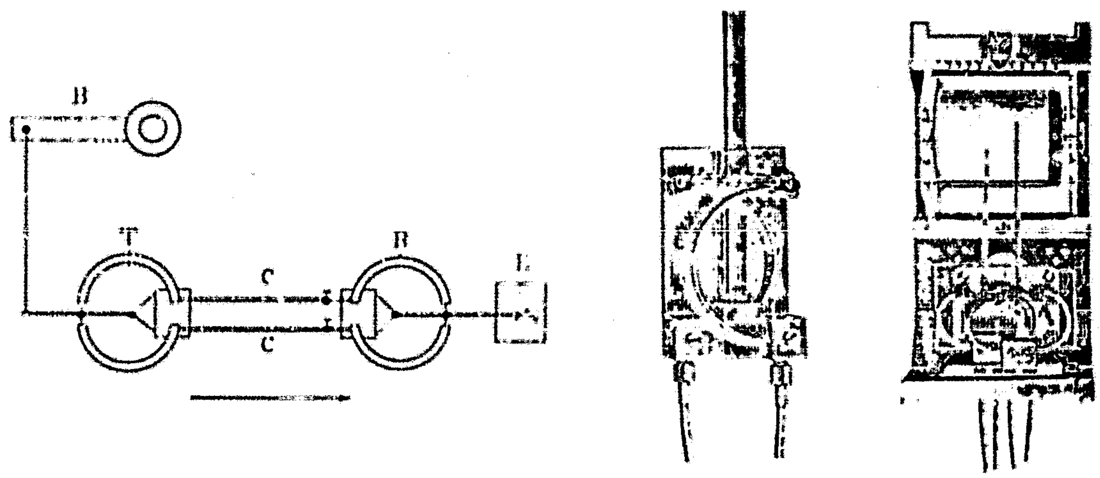


Figure 409
Wing Stress Indicator with Liquid Transmission
Right: Schematic Diagram; Middle: Transmitter; Left: Receiver

Key: B) Push rod
T) Transmitter
C) Tubing
R) Receiver
E) Recording cylinder

The measuring unit is a liquid comparator composed of a transmitter T, a receiver R, and tubing C (figure 409).

The transmitter includes a base attached, for example, to the wing spar. One end of a lever is connected to the base by a joint and the other is fastened to a fixed frame member, brace, or exterior pole. A deformation of the wing results in an angular movement by the lever. The lever's movement affects two variable reservoirs. The reservoirs are mounted in opposition to one another such that the volume of one increases as the other decreases. /272

A deformation of the wing therefore has the effect of forcing the liquid into one tube and sucking it from the other. A deformation in the opposite direction produces the reverse movement of liquid in the tubes.

The receiver is made of a base on which are mounted two reservoirs similar to those of the transmitter. Each of them is connected to one of the above-mentioned tubes. However, the preceding control lever is replaced by a pen which can either inscribe a curve on a recording cylinder or move in front of a dial.

The movements of the liquid engendered by the wing's deformations have the result of displacing the pen by an amount proportional to the deformation undergone by the wing.

The variable reservoirs in the transmitter and the receiver are made up of manometric tubes of approximately elliptical cross section. Each is rolled into a semi-circle. The transmitter is depicted in the middle section of figure 409. It includes two tubes arranged in opposite directions. They are welded to two different blocks which also hold the fittings on the ends of the transmission tubing. At their free end, the two tubes are connected by a flexible steel sheet to the middle of which the control lever is jointed. The lever is also jointed by another flexible sheet to the common base.

The receiver, arranged for recording with pen and ink or lamp black, includes two manometric tubes similar to the transmitter's. As indicated on the right of figure 409, they are arranged about a common block connecting to the two lines feeding them.

Huguenard-Magnan Electrical Indicator

Huguenard and I designed another type of wing stress indicator having electrical transmission instead of liquid.

The apparatus includes a transmitter and a receiver which can be similar, lines linking the two units, a capacitor, and the alternator for supplying current to the device.

The transmitter and receiver are each made up of a stator having at least two poles and a rotor wound like the armature of a direct current motor. Both rotors have two contacts 180° apart located on laminated iron cores, as do the stators, moreover.

The schematic diagram in figure 410 indicates how the units are set up. AA and AA' represent the transmitter and receiver stator windings through which a current creating an alternating flux passes.

The transmitter rotor B is connected by two contacts to the contacts on receiver rotor B'. A capacitor D of suitable strength shunts the wiring. An alternator of moderate frequency simultaneously feeds both stators.

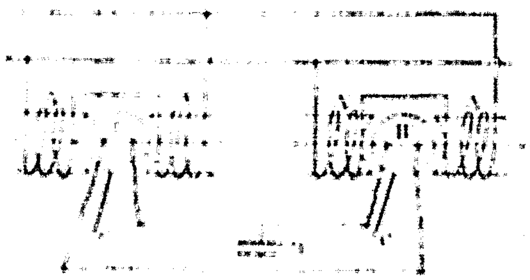


Figure 410
Schematic Diagram of Huguenard-Magnan Elecgrical Remote Motion Transmitter

Key: B, B': Rotors
AA, AA': Stator Windings
D: Capacitor

Rotor B is connected to a fixed post C, whereas the stator is held by the wing spar whose deformation in relation to the fixed post is supposed to be measured.

Rotor B' supports either an indicating needle C', a recording needle, or a mirror for photographic reccrding.

The circuit constants are chosen so that the circuit including the two rotors and the capacitor is synchronized with the current produced by the alternator when it is turning at its normal rate. In these circumstances, for each rotor position B, rotor B' has only one equilibrium position. This is the one for which /273 the current is zero in the rotor and capacitor circuit. If rotor B' is moved from its equilibrium position, it returns to it immediately.

If, on the other hand, a deformation of the wing spar alters transmitter rotor B's position, a current arises in the rotor circuit and displaces B' up to the point that the current is cancelled out by the displacement.

The instrument presents the following advantages:

1) The apparatus does not contain any spring. Its zero point is absolutely invariable whatever the electromotive force produced by the alternator, the current's frequency, and the resistance of the wiring.

2) Its scale is also independent of these variables, and also of atmospheric conditons.

3) It is easy to drive several receivers with the same transmitter, if desired.

4) It is possible to establish in advance an amplification or reduction factor between the angles through which the transmitter and receiver rotors turn.

5) The power consumption of such an indicator is very small. A radio or lighting alternator can drive several without affecting its normal role.

Such an instrument is also attractive because it provides a way to make long distance reproduction of rotational motion, whether or not it has a constant direction or angular speed. The receiver unit exactly repeats the movements of the transmitter unit or even amplifies or reduces them by a factor chosen at will during construction. The amplitude could be either a certain number of revolutions or merely a fraction of one revolution. Because of this, the instrument could have a great number of applications in numerous fields, even outside of aviation.

Airborne Tests

We sought to make direct measurements of the deformation undergone by an airplane wing in flight. However, the only airplane available to us was the Gourdou, which was not built with such a purpose in mind. It was impossible to lodge the entire device inside the wing. We had to place a carefully streamlined 1.20 m long pole below the wing. Very rigid steel fittings held the pole 110 mm from the lower side of the wing plane and near the leading edge. The comparator used was fastened to the forward wing spar. It was wired to a receiver whose pen inscribed on the accelerograph's cylinder. A tie rod connected the comparator to the streamlined pole in relation to which the wing spar deformations occurring in flight were supposed to be measured.

The pole's flexibility was first of all investigated by suspending weights from the point where the indicator control rod was to be attached. The pole-transmitter system was thus deformed and the amount of deformation measured by the displacement of the receiver needle, the amplification factor having been determined before hand.

A graph of deformation as a function of load could thus be traced.

We have carried out some experiments at Villacoublay by ... using the first device described. We attached a transmitter to the left forward wing spar of a 180 hp Gourdou-Leseurre airplane and connected it to a receiver that inscribed its displacements, with an amplification factor of about 30, on the same cylinder as the accelerograph and air speed indicator were using.

Figure 411 shows the tracings of deformation, acceleration, and speed shifted so that their median parts concur. Since the ordinates are not linear, the concurrence has not been verified outside the level for which the phase difference has been suppressed. /274
The close resemblance between the accelerograph and wing stress indicator tracings can be seen immediately. This is completely natural. It is obvious that if the acceleration normal to the wings grows, the stress on the wing spars normal to the wing plane grows by the same proportion because this acceleration is due to the increase in lift supplied by the airfoils.

Do not search too far for apparent coincidences between the two wing tracings. There are, in fact, several phenomena that intro-

C ~ 5

duce fairly appreciable differences in the results. First of all, the acceleration is recorded close to the center of gravity and the deformations are those of a single longeron in its section furthest from the center of gravity. It follows that each time an acrobatic stunt is not performed in a vertical plane containing the airplane's plane of symmetry, the work imposed on the two wings is not the same. Thus, when the airplane rotates about an axis parallel to its translational velocity, only measurement of the deformation of both wings can indicate the acceleration undergone by the center of gravity.

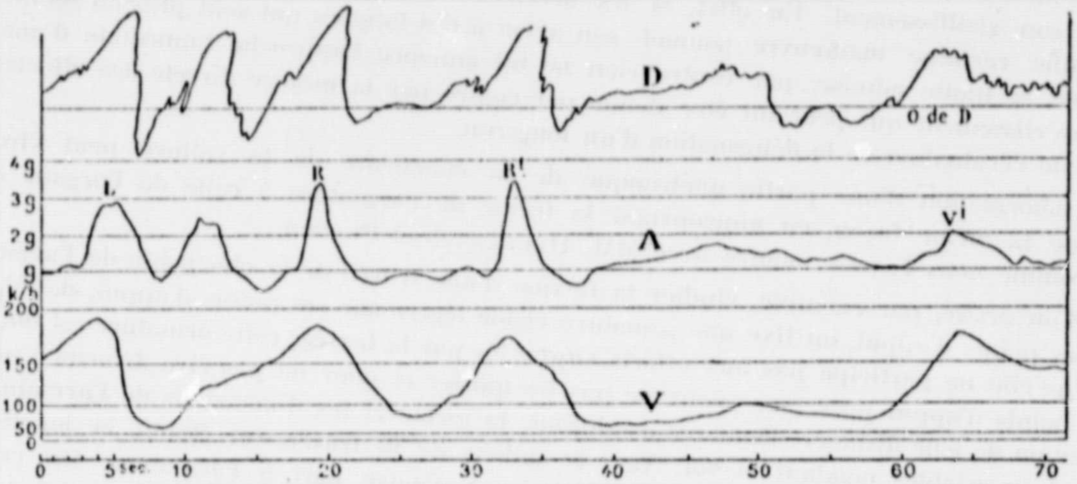


Figure 411
Simultaneous Recordings of Wing Spar Deformation D, Acceleration Normal to the Wings A, and Air Speed V of a Gourdou-Leseurre Airplane in the Course of Various Maneuvers
L, Loop; R, Pull-Out; R^t, Renversement; V^1, Vertical Bank
(Pilot: Joublin)

Lastly, the necessity of mounting an exterior pole close to the wing introduces another cause of deformation in the tracing of the wing stress indicator. During flight, the proximity of the pole and wing gives rise to an interaction between these two bodies. The result is that as the speed varies, the bending of the pole also varies, all other conditions remaining the same. We were able to discover the effect of the pole's aerodynamic deformation by using the tracing of speed. Our idea was that the quantity to be considered was not speed, but the air current's kinetic pressure. Now, the Venturi tube's amplification factor varies little, and the manometer readings are basically proportional to the reduction in pressure. Thanks to this, it can be assumed that the ordinates in millimeters of the speed curve provide a sufficiently accurate measure of the kinetic pressure reduction. It therefore suffices to consider the points where the accelerograph's tracing indicates a lift equal to weight and to measure point by point the corresponding ordinates of the speed and wing deformation curves. A relationship between the variations of speed and deformation can then be derived from this body of measurements.

We have done this work, but will not give any more details on it here.

It has enabled us to see, for example, that in the region of the tracing corresponding to a loop followed by a dive, the measurements reveal a real wing spar deformation of 1.1 mm, showing that this deformation corresponds to an acceleration of 2.7 g. Now, when measuring the acceleration at the corresponding points on the accelerograph tracing, we found a difference of 2.6 g, proving that the extent to which the results agreed should be considered satisfactory. /275

Our method, contrary to those of accelerometers, makes possible a constant surveillance of wing behavior. It also allows wing fatigue and aging to be detected. While the accelerometer can tell a pilot that a certain maneuver exposes his airplane to fatigues more or less close to the acceptable limit, nothing announces to him the immediate approach of a rupture. In contrast, such a warning can be obtained from the direct measurement of stress by means of evaluating wing spar deformation.

The deformation of any part of the wing frame can be measured in the same way by adapting the shape of the armature to the component to be studied. This was demonstrared to us by Huguenard and Planiol.

If, for example, one desires to study the bending of a frame rib between two support points, one attaches a light, rigid brace to the two support points in such a way that it does not contribute to the stress supported by the rib. The brace is therefore fastened to the support points just enough so as not to fall off or be deformed by a variation in their distance. In these circumstances, the brace's shape and dimensions remain constant during flight. Towards the middle of the rib, the deformable measurement junction is established. It is connected on one side to the rib and on the other to the brace. It is thus possible to measure the displacement of the middle or any other point of the rib, or even or a neighboring rib, relative to the straight line joining the points of support.

The same setup also can be applied without alteration to the measurement and surveillance of strain in a particular aircraft part, such as a stay.

For this purpose, a light brace acting as a dummy stay is installed parallel to the real stay. It is attached at one of its ends to the corresponding end of the stay under study. The rest of its length is left free except that its other end is linked to the free end of the main stay by the deformable junction.

Any difference in strain in the stay and dummy stay is transformed into a relative displacement of their free ends and, consequently, into a deformation of the measurement junction. The deformation can be left as a function of the load on the stay and the temperature or made a function of the load only. In the latter case all that has to be done is to build the dummy stay out of a substance with the same coefficient of expansion as the stay and to make the two components the same length. The deformation of the elastic junction can then be used to measure the stay's mechanical deformation.

The unit designated as the elastic or deformable measurement junction can also be adapted to a system enabling the pilot to have a knowledge of the deformation of his airplane's frame by reading it off a graduated scale. Alternatively, it could be used to set off a luminous or acoustic alarm to warn him when the deformation has reached a level endangering the safety of the airplane.

It is obvious that such devices are particularly adept at watching for permanent deformation or aging of airplane frames. They can also be used with similar mountings adapted to each particular case to check on the bending, strain, compression, twisting, or, in general, all the elastic or permanent deformations of an assembly during its work.

Of course, pilots of transports do not perform acrobatic stunts and in theory execute only normal, straight flights in which acceleration does not exceed 1 g and the frame deformation is small. However, it can happen that damage to the engine or rudder or shifting of their load forces them to dive and then abruptly level off. /276
As a result of this, and also often because of strong gusts of wind, their vehicles can undergo stresses close to those arising from acrobatic stunts. There is thus a need to gain a knowledge of such stresses for the construction of transports. It is of course universally understood that for such airplanes, as for fighters, the measurements made on one vehicle are not applicable to another of different shape, power or guidance system.

V. Measurement of Vertical, Tangential, and Transverse Acceleration in an Airplane

In all the preceding studies, only investigation of vertical acceleration was considered. There is also reason to determine the value of horizontal and transverse acceleration during certain maneuvers, e.g., flat spin. With this in mind, we built a three-dimensional accelerograph which will soon be tested out. Our instrument is comprised of four accelerometric tubes:

1) Two horizontal placed perpendicular to the axis of the fuselage, one at the tip of each wing.

2) One vertical situated near the center of gravity.

3) One horizontal and parallel to the axis of the fuselage, positioned in the tail section, for example.

The readings of the four accelerographs are inscribed simultaneously on the same recording cylinder at the same time as those of an air speed indicator, densigraph, and revolution counter.

Each accelerograph includes a mercury reservoir like the present type. However, the reservoir has a 1 cm^2 cross section and is 1 meter long in the wings and 1.50 meters long in the tail. Only the vertical apparatus retains the specifications already described.

The transmission of pressure due to acceleration is accomplished by small diameter steel tubes completely filled with a glycerine solution. Each tube is accompanied by a compensator tube which is parallel to it and whose other end opens onto a mercury-filled vessel. In this way, the columns of water are more or less in equilibrium and the manometers record only the pressures due to the acceleration acting on the mercury in the various tubes.

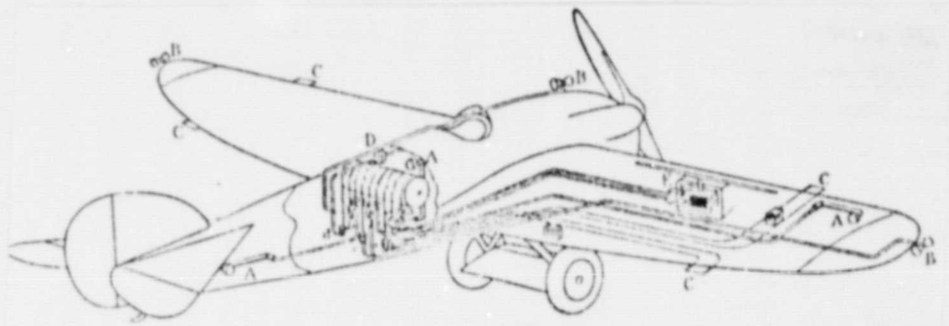


Figure 412
Arrangement of Instruments for Studying Airplane Stress
A, Accelerometric Tubes; B, Venturi Tube for Speed; C, Hot Wire; D, Densigraph; E, Wing Stress Indicator, with Single Recording Cylinder

The intrinsic period of the various instruments is about 1/5 second.

The four manometers are fixed along a recording cylinder along with such systems as those for recording speed, horizontal rudder movement, direction, and banking. (See figure 412).

The recording cylinder that was installed has a length of 30 cm and a diameter of 15 cm.

VI. Measurement of an Airplane's Air Speed at All Altitudes /277

All the experiments that we carried out have been done in the vicinity of the ground, at less than 1,000 meters up. It might be necessary to know the exact speed of an airplane at any given height.

The pressure reduction spplied by the Venturi at a speed V is of the form $p = \delta \cdot f(v)$, where δ is the air density at the point under consideration. This density can only be found by measuring the conditions on the ground: H_o and θ_o, and by applying to them the standard laws of decrease in H and θ as a function of altitude Z, which is recorded at the moment of measurement by a barograph. In these circumstances, serious errors might occur at high altitude.

To convince oneself of this, remember that an error of 100 meters in altitude corresponds to an error of a little more than 1% in atmospheric density. We know, from experiments we have done, that the amount of altitude lost when making a loop is on the order of 100 meters, whereas an airplane will lose more than 500 meters in 10 seconds during a very steep dive.

The desirability of a speed recording device whose readings are independent of atmospheric density is thus plain to all. This is why we sought to develop a compensating apparatus.

Our compensating anemometric speed indicator is based on the new principle described in the course of the second lesson, and used in the construction of Sylphon capsules, barographs, and densigraphs, whose designs are reproduced above.

The Huguenard, Magnan, Planiol Compensating Air Speed Indicator

This instrument is based on the use of a Venturi tube amplifying the kinetic pressure reduction created by the airplane's relative speed.

In the absence of any experimental data on the functioning of Venturi tubes in conditions of changing temperature and pressure, we assumed that the tube's amplification factor, the ratio of the pressure reduction produced by the tube to the difference between the air current's dynamic and static pressures, depended only on the speed.

This hypothesis, which basically consists of supposiong that density and the distribution of speeds inside the tube are independent, is not at all illogical despite its simplicity. It constitutes a first approximation that is probably close enough to reality.

Under these conditions, the pressure reduction has the form $h = Pf(v)/T$, where v is the speed, P and T the absolute pressure and temperature of the ambiant air, and $h_o = P_o f(v)/T_o$, the equation for the Venturi tube calibration curve at ground level. To have a compensating apparatus, the angle α by which the instrument's indicating needle is deflected has to be independent of variations in P and T.

If one puts together an apparatus in such a way that the angle α is proportional to the pressure reduction h at constant temperature and pressure, the relationship $\alpha = KTh/P$, in which K is a constant characteristic of the apparatus, is a necessary and sufficient condition for obtaining the desired result. /278

Since $h = Pf(v)/T$, one then has $\alpha = Kf(v)$.

In these circumstances, the apparatus's readings, defined by the angle α, now depend only on the speed v to be measured and the function f(v) can be determined through calibration in a wind tunnel. The compensation is obtained in the following fashion.

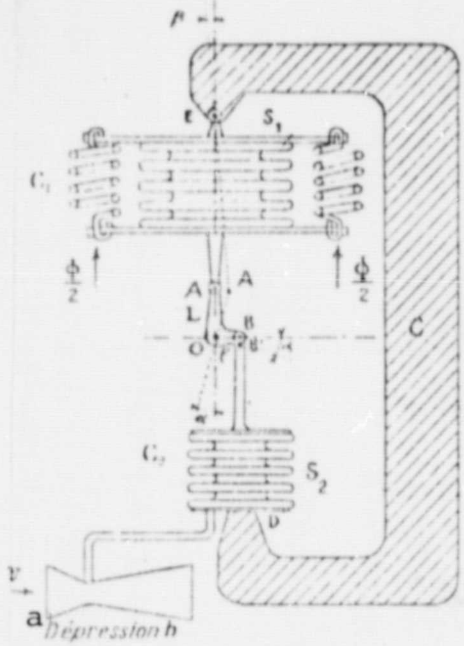


Figure 413
Schematic Diagram of Compensating Speed Indicator

Key: a) Pressure reduction h

A closed housing contains all the mechanical parts for the apparatus. It is maintained at the ambiant temperature and static pressure by a suitably arranged circulation of air.

The pressure reduction produced by the Venturi tube is exerted inside the housing by a very elastic and flexible cell C_2. (See figure 413.) The cell is attached at end D to the housing C. It moves a right angle lever fixed at point O by means of a push rod pivoting at end B of the lever. The other lever arm, A, is acted on by another cell C_1 pivoting about axis E.

The dimensions of the apparatus are such that at rest E, A, and O are lined up, and angle AOB is straight.

The angular displacements α of the lever O from its original position are small enough that the approximations $\sin \alpha = \alpha$ and $\cos \alpha = 1$ are sufficiently accurate. An appropriate secondary amplification gives the instrument's needle a total deflection of 5 to 6 cm without exerting any reaction force on the right angle AOB.

Let us temporarily suppose that the cell C_1 has been evacuated and let S_1 be its functional cross sectional area. The restoring force exerted on L, $F = S_1P$, will be proportional to the ambiant pressure, and the deflection for a given pressure reduction H will be $\alpha = Kh/P$. The apparatus will thus compensate for pressure changes.

Let us now refill cell C_1 with air at the ambient pressure P. This eliminates the force C_1 exerts, but let us add two springs, r and r', to it. The springs are symmetrically placed and exert on C_1

the same force $F = S_1P$ as before. Let us seal this cell and then make the ambient temperature vary from T_o to T in absolute degrees. The pressure inside C_1 will vary proportionally to the absolute temperature and the total restoring force will be:

$$F' = F + S_1P(1 - \frac{T}{T_o}).$$

The ratio T/T_o is always close enough to 1 so that one has, by making $\varepsilon = 1-T/T_o$ and by replacing F:

$$F' = S_1P(1 + \varepsilon) = \frac{S_1P}{1-\varepsilon} - S_1P\varepsilon^2.$$

However, since ε is small, a first approximation can be made by eliminating ε^2 and the equation becomes: /279

$$F' = S_1P/(1 - \varepsilon) = S_1PT_o/T$$

and the deflection for the pressure reduction H under consideration will be $\alpha = KhT/P$.

Experimental Study of the Apparatus

Figure 414
Theoretical Error Curves of a Speed Indicator Usable to 3500 m and Adjusted to be Exact at Ground Level
· A, in Standard Atmospheric Conditions
+ B, with a Temperature 20° Higher than Standard
- C, with a Temperature 20° Lower than Standard

Key: a) Error e in per cent
b) Altitude in Km

We studied a very large number of analyses of a compensating speed indicator, first theoretically and then for several versions of the apparatus. The error curves C = f(z) have been constructed from 0 to 10,000 meters in altitude.

As an example, we give the error curve A (figure 414) of one of these instruments usable up to 3,500 meters under standard atmospheric conditions. The curves B and C show the magnitude of errors of the same recorders in an atmosphere 20° above or 20° below a standard atmosphere's. The error does not exceed 2% for this apparatus.

We then experimentally studied the first speed indicator that we set up. We first calibrated the instrument with the aid of a mercury manometer permitting precise measurements. The calibration was done under the following conditions:

Ambient Pressure: 755.5 mm of Hg

Total Tension of the Springs: $\phi = 10.22$ kg

Pressure reduction in the restoring cell: 147 mm Hg

Absolute pressure H_1 in the restoring cell: 755.5 - 147 = 608.5 mm or 0.826 kg of Hg

Needle deflection: 51.7 mm for 1/2 kg/cm^2

Lever deflection: $\alpha = 0.098$ radian

These conditions provide an apparatus adjusted for use between 0 and about 3500 meters.

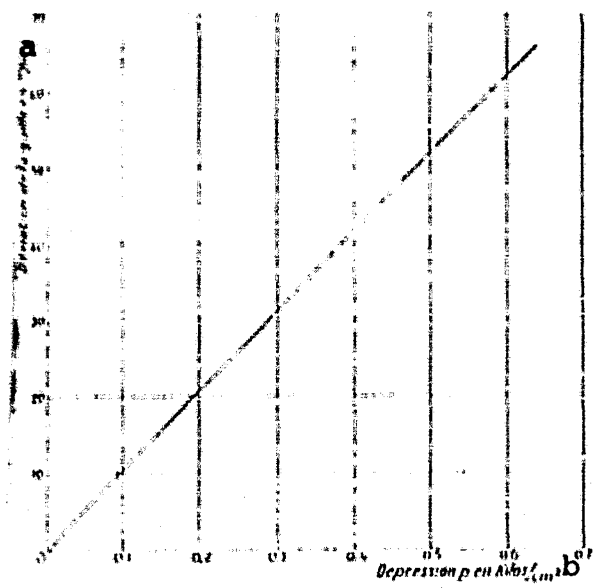


Figure 415
Calibration Curve for Compensating Speed Indicator

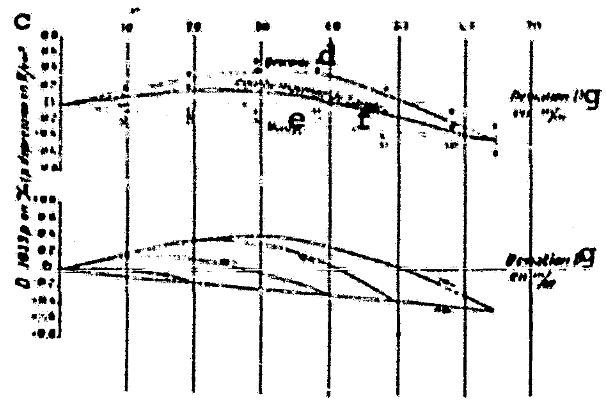


Figure 416
Calibration of Compensating Speed Indicator
Top: Maximum Deviation from the Average Curve, 0.3 mm or .5% of the Maximum Deflection
Bottom: Hysteresis Cycles Corresponding to Various Maximum Deflections

Key: a) Needle deflection in mm
b) Pressure reduction in kg/cm^2
c) D. 103.9p in mm (p pressure reduction in K/cm^2)
d) Descent
e) Ascent
f) Average calibration curve
g) Deflection D in mm

Figure 415 is a reproduction of the curve plotted with the pressure reduction in kg/cm^2 prevailing in the measurement cell as the abscissa and the deflection of the apparatus's needle in millimeters as the ordinates.

One can see that it is difficult to study the error in measurement at different experimental points.

To make the study of accuracy and hysteresis clearer, we traced figure 415 using a scale that considerably exaggerated the separation between the points, curves, and straight line. (See figure 416.)

According to figure 416, the deflection is basically proportional to the pressure, and the deviation from exact proportionality is of the same order as the half-amplitude of the hysteresis cycle.

Also, the form of the hysteresis cycle remains basically independent of its amplitude. The relative error due to this cause is therefore independent of the range of measurements. /280

It can be concluded from these findings that the amount of error intrinsic to the apparatus as far as imperfections in its functioning go is of the order of 1/2%. This error corresponds not to the measurement of air speed, but to the pressure reduction produced by the Venturi tube. Errors in compensation naturally are added on to this.

Experimental Study of the Influence of Temperature on Elastic Properties

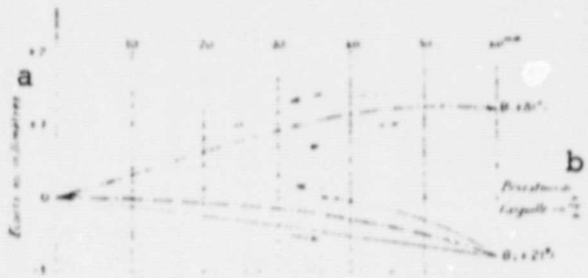
The apparatus was tried out with a restoring force made up solely of the elastic tension due to the springs. At an ambient temperature of 21°, this was equal to 10.8 kg and gave the instrument its normal sensitivity corresponding to an angular deflection of the lever by about .095 radians for a pressure reduction in the measuring bellows equal to .5 kg/cm^2.

The elimination of corrections due to the air contained in the restoring bellows is obtained immediately by letting it be open to the surrounding atmosphere.

Experiments were performed at temperatures of 21° and 81°. They included ten series of measurements made equally during ascent and descent. We were thus able to establish the hysteresis cycles at these two temperatures.

It can be seen in figure 417 that the hysteresis cycles exhibit appreciably the same thickness, about 1/2 mm. This is similar to that obtained at other adjustments and corresponds to a relative error of 1% since the total deflection is about 60 mm.

Examination of the cycles' median curves, which are the calibration curves for the apparatus at the temperature indicated, will reveal that for any deflection of the needle, the separation between the two curves is basically proportional to the deflection under consideration and is very close to three hundredths of it.



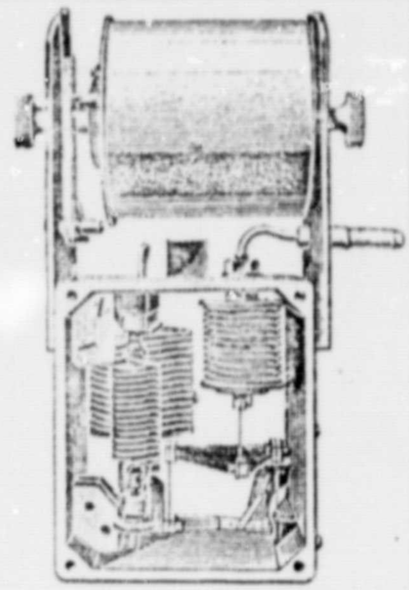


Figure 417
Determination of the Influence of Temperature on the Compensating Speed Indicator

Key: a) Deviation in millimeters
b) Deflection of needle in mm

Figure 418
H.M.P. Compensating Speed Indicator

Thus, when the temperature rises by 60°, the measurement furnished by the apparatus increases by 3% of its value. /281

One can see that for variations of ±20°, which were considered above as the practical limits of the deviation of real temperature from standard, the error would amount to 1%.

It is therefore clearly inferior to that arising from imperfect compensation by means of air filling the restoring cell for an apparatus adjusted for 5,000 meters. This latter error is about ±2%.

On the contrary, when the instrument is adjusted for 3,000 meters, the two errors are of the same order.

However, it is essential to point out that beyond the random variations of ±20°, the apparatus is also exposed to the standard decrease in temperature with altitude, which is approximately 40° at an altitude of 6,000 meters.

The experiments made with the apparatus were completed by a modification designed to make it insensitive to vibrations and variations in the magnitude and direction of the average acceleration to which it is exposed.

The tests have shown that a suitable balancing makes it possible to keep changes in needle below 0.2 mm for six different positions of the apparatus.

The error due to a variation of ±g in the acceleration is therefore only ±0.1 mm, or less than 0.2% of the total reading.

Furthermore, it was found desirable to considerably lengthen the apparatus's intrinsic period of vibration. Under current conditions it is about 1/30 second and threatens to result in a resonance with the engine vibrations, whose period is similar.

Balancing and slowing of the intrinsic motion can be obtained without any difficulty by attaching to the needle axis a part with a high moment of inertia and possessing an off-center piece adjustable in terms of both radius and azimuth. Such a part can be easily fitted inside the housing of the apparatus.

Construction of the Actual Indicator

As can be seen in figure 418, the apparatus is made of a cast aluminum housing closed by two plates of the same material.

The housing contains the supports for the knife-edges attached by strong screws to special exterior tabs. The supports are made of treated forged steel, as are the knife-edges.

Contrary to the schematic diagram in figure 413, upon which the theory of the apparatus is based, the measurement bellows C_2 does not act directly on the mobile lever restored by the bellows C_1 and the springs. /282

The arrangement actually constructed, which gives the same results, reduces the instrument's bulk and gives the mobile lever a much more convenient form. It consists of making the bellows C_2 act through an intermediate lever that amplifies the deformation three times. This allows a very great reduction in total size and therefore in weight.

Note that the entire system formed by the two bellows, the right-angle lever, and the intermediate lever includes no friction-producing joint. It contains solely knife-edges and very weak springs.

On the contrary, the needle and its amplifying system, which are not exposed to any stress, are mounted on pivots.

The amplification realized can be adjusted at will by moving the push-rod linking the extension of the right-angle lever to the lever directing the needle.

RECOMMENDED READING

Huguenard, Magnan, Planiol, L'accélérographe H.M.P.: son application à la mesure des accélérations en vol [The H.M.P. Accelerograph: Its Application to the Measurement of Acceleration in Flight], Bulletin du Service Technique de l'Aéronautique, 30 (1926).

Huguenard, Magnan, Planiol, Nouvelles expériences sur les conditions mécaniques du vol des avions [New Experiments on the Mechanical Aspects of Airplane Flight], Bulletin du Service Technique de l'Aéronautique, 38 (1926).

Huguenard, Magnan, Planiol, Sur un appareil mesurant les déformations des ailes en vue de la fatigue et du vieillissement des avions [An Apparatus for Measuring Wing Deformation for the Purpose of Detecting Airplane Fatigue and Aging], Bulletin du Service Technique de l'Aéronautique, 24 (1925).

Huguenard, Magnan, Planiol, "Sur un principe permettant la realisation d'appareils mesurant les conditions aérodynamiques du vol des avions" [An Approach to Building Apparatus to Measure the Aerodynamic Parameters of Airplane Flight], C.R.A.S. (November 14, 1927).

Huguenard, Magnan, Planiol, "Sur une methode d'étude des efforts d'inertie resultant des manoeuvres de pilotage des avions" [A Method for Studying Inertial Stress Resulting from Intentional Airplane Maneuvers], C.R.A.S. (June 22, 1925).

The study of the reaction exerted by the air on a body moving through it is one of the most difficult problems to resolve. Much theoretical work has been carried out on this subject and it can be said that as a whole the authors have not arrived at satisfactory solutions to the problem.

For these reasons, experimental studies have moved ahead of theoretical ones during the last several years. However, while they have yielded some interesting findings, they have rapidly proved how difficult such research is to perform. This is why, even at the present time, it cannot be claimed that the experimental findings surpass the theoretical results by a great deal.

We have already seen that the projection of the general resultant R of aerodynamic forces on the direction of relative velocity is called drag, R_x, and that the projection of R perpendicular to the relative velocity is called lift, R_z.

The force R is well defined if in addition to the strength of the two components, its moment M relative to a certain point on the plain of symmetry is known.

What is more, the orientation of a moving body in relation to its relative velocity is given by the angle formed by the velocity and a lubber line contained in the solid's plane of symmetry. This is the angle of incidence or attack, i.

In order to determine experimentally the components R_x and R_z, one can directly measure the forces resulting from the body's or, in the present case, the airplane's displacement in the air.

I. Methods for Studying Airplanes on the Ground

Numerous methods were conceived for this purpose at the beginning of aviation.

First there were the experiments performed with circular courses, like those of Marey, Lilienthal, and Hiram-Maxim. They set up large turning devices from which they suspended a large sized airplane, like that of Deutsch de la Meurthe at Saint-Cyr. Much work was carried out with these devices, but the least that one can say is that the circular track method gives rise to very complex turbulent phenomena in the air. This makes it impossible to consider the movement of an airplane fixed to the end of an arm as identical to rectilinear displacement.

The Saint-Cyr trolley allowed tests of full-scale assemblies to be carried out. Six meters long and 2 meters wide, the trolley moved freely over a straight electrified track close to 1,400 meters long.

The speed attained during the tests was recorded with the aid of a Richard tachometer which measured the rotational speed of an axis placed between the axles of the machines supplying motive power. A wing was mounted on the trolley (figure 419) and the effect of the air on it was measured by a hydraulic dynamometer whose pressure was transmitted to instruments of the Bourdon type. Unfortunately, the effect of the air on the surfaces under study was influenced by the presence of the trolley and the interactions between the wing, the trolley, and the ground could not be calculated. The results obtained were thus held to be fairly random. /284

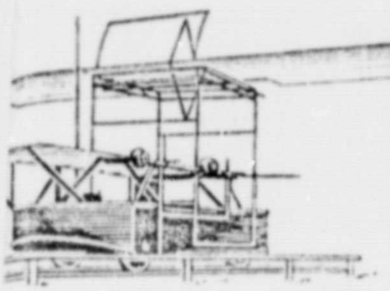


Figure 419
The Saint-Cyr Trolley

II. Studies of Small-Scale Models

For these reasons, tests of full-scale assemblies were abandoned before the war. Researchers turned to wind tunnels, which, although they were only capable of indirect experiments, possessed some indisputable conveniences for running tests. However, the results were probably not any more accurate, as we are going to see.

The first advantage the experimenters enjoyed by using wind tunnels was that they could substitute small-scale models for life-size aircraft. Such models could be placed right before one's eyes, in a regular enough air current.

Wind Tunnels

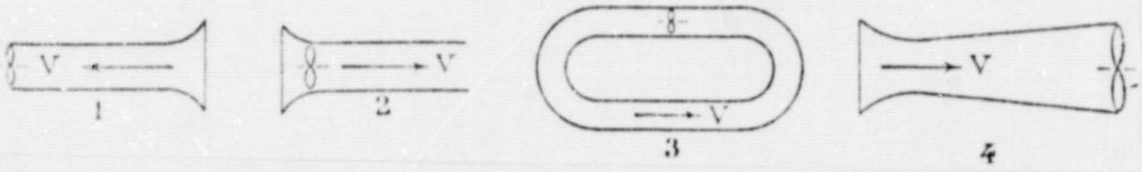


Figure 420
Wind Tunnel Types
1, Aspiration without Recovery; 2, Exhaust without Recovery
3, Closed Circuit; 4, Eiffel Type

The first constructors of wind tunnels created installations made up of only intake and exhaust fans (figures 420-1 and 420-2). Those who followed, desirous of having more rapid air currents of fairly large cross sectional area at their disposal, quickly thought of returning the air leaving the tunnel to the fan and of circulating this air in a closed circuit. This would reduce the required energy to that needed to overcome passive resistance. The wind tunnel designed by Prandlt at Göttingen represents one type of closed circuit wind tunnel (figure 420-3). However, it has a serious inconvenience. The air in the tunnel heats up in such a way that it is indispensable to add a device for keeping the adjustment of the instruments stable.

Another wind tunnel system was invented by Eiffel. It consists of sending the air stream leaving the test chamber through a divergent diffuser. Since Eiffel's wind tunnel has served as the model for the majority of modern laboratories, this is the one that we are going to examine in detail.

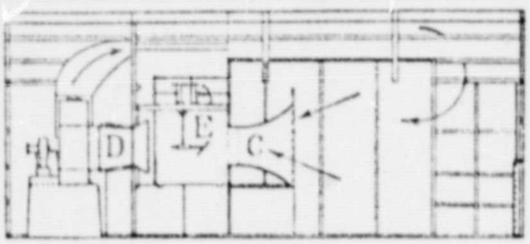


Figure 421
Longitudinal Cross Section of Eiffel Wind Tunnel

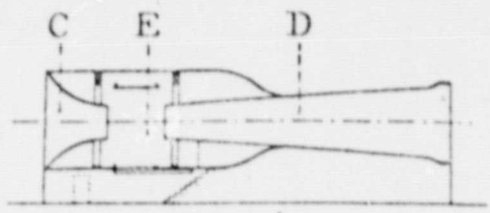


Figure 422
Longitudinal Cross Section of the Large Wind Tunnel at Issy-les-Moulineaux

Key: C) Collector
E) Test Chamber
D) Diffuser

A fan, i.e. a special propellor, sucks the air located in a large, closed room and pushes it into a collector shaped like a truncated cone (figure 421). The air current at this point takes on a greater speed, while its pressure diminishes.

The air next arrives in a perfectly air-tight room entered by double doors. This is where the measurements are made and where the current's static pressure prevails. The air current then passes through a truncated cone-shaped diffuser, which is the inverse of the collector, but longer. There, it is compressed at the same time as it slows down. This reduces the work of the compressor. Finally, the air goes back to the large room and returns to the collector. /285

The diameter of the air current in the Eiffel wind tunnel is 2 meters and its speed is 30 m/sec. The power necessary to achieve this is 50 hp.

Since then, other wind tunnels similar to Eiffel's have been built in France. One of them is at the Institut Aérotechnique de Saint-Cyr [Saint Cyr Aerotechnical Institute]. It has a diameter of 2 meters and an air speed of 38 m/sec. The other is at Issy-les-Moulineaux. This one's diameter is 3 meters and its air speed is 80 m/sec (figure 422).

The power required by the three tunnels, if the air was continuously renewed would be 70 hp, 270 hp, and 3,000 hp. In fact, however, the same mass of air is indefinitely recirculated and the energy necessary to compensate for the various losses and the imperfection of the fans is only 50 hp, 66 hp, and 1,000 hp respectively.

The Measurements

The models used in the wind tunnels are theoretical reductions of the full-scale airplanes whose lift and drag are being investigated. The models are generally made of polished and varnished wood and are held stationary in the fluid by aerodynamic balances serving to measure the forces resulting from the action of the air.

Some of the balances, like Eiffel's, are rigid. The horizontal shaft, on which the mock-up is fixed in such a way that its major axis can assume various inclinations, is linked to a rigid vertical support ending in two knife-edges mounted in opposite directions. The horizontal shaft can oscillate about them successively thanks to the action of a cam.

The forces due to the two components of R are balanced by weights giving the forces' average value. The values of R_z and R_x are determined for various angles of attack. While one operator is doing the weighing, another checks the average value of the air current with an inclined water manometer connected to a Pitot tube placed in the path of the air current. The magnitude of the pressure is thus supplied and the speed can be calculated from it.

At Göttingen and Issy, wire balances are employed. They hold the model in the stream by means of less voluminous bodies than the arms the Eiffel wind tunnel uses. At Issy, the components are measured by hydrostatic dynamometers attached to the wires and linked to metal diaphragm manometers whose readings can be inscribed on a cylinder. The values of C_z and C_x can be derived from the values of R_z and R_x as a function of i obtained in this way. First, however, the corrections necessitated by the supplementary resistance due to the supports themselves, which has to be separated from that felt by the stationary model, must be made.

The mock-up's polar curve is then traced. It is similar to the curve reproduced in figure 423, which was obtained with a small-scale model of a Gourdou-Leseurre fighter airplane. Like the original, the model had fabric-covered wings and fuselage, and stays. These were set up to allow comparisons with the full-scale vehicle. /286

Several criticisms of an experimental order can be made of such measurement procedures.

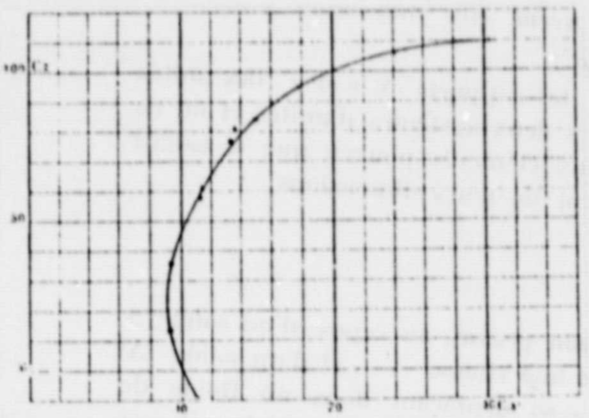


Figure 423
Polar Curve of a Model 180 hp Gourdou-Leseurre Airplane Obtained at the Issy-les-Moulineaux Wind Tunnel

First of all, the mock-ups generally are not complete reproductions of full-scale airplanes. Rather than having wings covered with fabric or corrugated steel and fuselages provided with their accessory equipment, they are made of wood. In addition, all the poles and stays are usually eliminated. The least that one can say is that they are only very rough copies of the original.

Secondly, the small-scale model is not isolated within the air stream. The supports or supporting wires not only have their own reaction, but they introduce perturbations and phenomena arising from their interaction with the mock-up. Such phenomena are very difficult to study and, most often, to calculate.

Finally, the air current can be turbulent to a greater or lesser degree, depending on various factors: the form of the tunnel, and the interaction between the model and its support. Eddy currents are produced that sometimes have the effect of changing the minimum values of C_x for a single model by a factor of 2, as Karman demonstrated.

Furthermore, air speed is most often read with a water manometer. It would be better to substitute for this somewhat arbitrary estimate direct measurement of speed using a manometric recording apparatus like the one we used to determine the air speed of airplanes.

Such a procedure would be particularly attractive in wind tunnels in which measurement of aerodynamic forces can be done by recording their instantaneous value. In addition, the variations in inclination or orientation, which always exist to a certain extent in air currents, are never investigated, even though their effect is important.

A simple, double hot wire instrument would give one a recording of directional variations next to a simultaneous recording of the instantaneous values of R_x, R_z, and speed.

It is true that attempts are made to diminish the amount of air turbulence by employing special partitions known as filters placed in front of the testing chamber. However, since the magnitude of the remaining oscillations is unknown, the improvements brought about by such devices are insufficient.

III. The Utilization of Wind Tunnel Measurements. The Laws of Mechanical Similitude

The findings thus obtained are not directly applicable to airplanes and the curves representing C_z, C_x, and C_m as a function of i are only characteristic of the solids geometrically similar to the model being studied under certain conditions.

We are now going to see how it is theoretically possible to derive from the values of the reaction force exerted by the air on one body the corresponding ones for another, similar body. We will also see how small-scale models are used to obtain figures for the analogous full-scale vehicles. /287

The basis for doing this is the application of the principle of mechanical similitude concerning fluid resistance, as enunciated by Newton.

According to the principle of mechanical similitude, it is possible to have two systems of values such that any element in a material system S_1 measured with one group of units, can be compared to a similar element on a second system, S_2, measured with a second group. The two are then said to be completely similar if their elements are in a one to one correspondence.

What is more, it is possible to arbitrarily choose the ratios λ, τ, and μ of the fundamental units of length, time, and mass in the two systems of units. From this, it is correct to think that there exists a similitude between the two elements, provided that the calculations of λ, τ, and μ are in accord with the conditions resulting from their dimensions.

The Case of a Perfect Fluid

Let us take the case of a perfect, incompressible, weightless fluid at rest. A solid A moves through a fluid of density ρ and velocity V. Another solid, A', similar to A such that their lengths differ by a factor λ, moves through a fluid of specific mass ρ' with a speed V'. Mechanical similitude exists if the speeds created are similar and if the solids in the neighborhood of A and A' are also similar and similarly placed according to the ratio λ.

One can go from the first system to the second in the following fahion, without, moreover, getting involved in a question which is far from being cleared up, for the laws of similitude might not have the value customarily accorded to them.

It is customarily assumed that the model and the body are, for example, of the same material, as two birds or two fish of different size would be. This implies that their weights are proportional to their volumes, and therefore that the acceleration due to gravity, LT^{-2}, has the same dimension in both cases.

If the ratio of lengths is designated by λ and that of time by τ, and since acceleration, LT^{-2}, is constant, $\lambda = \tau^2$, or $\tau = \sqrt{\lambda}$. The speeds, of magnitude LT^{-1}, then differ by the factor $\lambda\tau^{-1} = \sqrt{\lambda}$, and the masses, weights, or volumes by the factor λ^3. This is because mass is transformed to weight by the acceleration, which has a ratio of 1, and volume is derived from mass by way of density, which was assumed to be constant in the original hypothesis.

The fluid resistance R opposing the body then depends only on the fluid's density ρ, and the speed and linear dimensions of the solid.

Lastly, the work performed (dimensions $LMT^{-2}L$) differs by a factor of λ^4, and the power, i.e. the work divided by time (L^2MT^{-3}) differs by a factor of $\lambda^4\tau^{-1} = \lambda^3\sqrt{\lambda}$.

This is why it is customarily assumed that, because of these laws, a 1/100 scale model airplane should be exposed during wind tunnel tests to an air current whose speed is ten times smaller than that encountered by a real airplane if the air is of the same density.

Similarly, if one wants to fly the small model at a speed of V/10, with the airplane having a weight P and the model a weight $P/100^2$, the ratio of power required will be $\sqrt{100}$ or 10. The model's engine will then have to be ten times weaker per kilogram of material than the airplane to be in accordance with the laws of mechanical similitude.

Note that if the two ratios λ and τ are considered to be independent, no comparison can be made between quantities of different dimensions.

Since speed has the dimensions LT^{-1} and weight the dimensions MLT^{-2}, like a force, if one wants to compare weight and flying speed of an airplane and a model, is it necessary to consider the ratio weight/speed, which is dimensionless in relation to length, and of dimension 1 in relation to mass and -1 in relation to time? Alternatively, should one deal with the ratio weight/speed^2 which eliminates the time dimension, but is of dimension 1 in relation to mass and dimension -1 in relation to length? /288

The Case of a Real Fluid

Despite these reservations, we shall assume the principle of mechanical similitude to hold, even though it is only valid for a perfect fluid. Air, however, has a weight, a viscosity, and a compressibility. New conditions are needed for similitude to continue to exist.

Since the fluid has a weight, the ratio V^2/Lg must have the saem value for the two bodies, one full-scale, the other reduced. The ratios V^2/Lg and $V'^2/L'g$ must therefore be equal. This is Froude's law.

Since air has a viscosity, defined by the coefficient ν, the ratio VL/ν, called the Reynolds number, must have the same value for experiments in a wind tunnel as in the atmosphere, i.e. $VL/\nu = V'L'/\nu'$.

Lastly, since the air also has a compressibility, the ratio V/C, where C is the speed of sound in the fluid under consideration, must remain constant. Therefore, $V/C = V'/C'$. This is Bairstow's and Booth's law.

The ratio VL/ν, the Reynolds number, plays an especially great role in aerodynamic studies because several different modes of flow around certain solids are established or disappear according to its magnitude.

In order that the principle of mechanical similitude be applicable to a mock-up of an airplane, the same stable mode of flow must exist for the two.

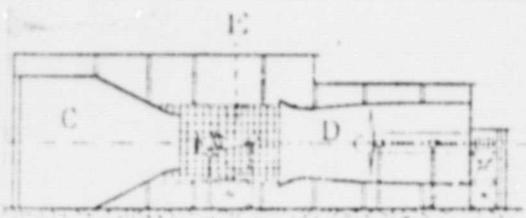


Figure 424
Longitudinal Cross Section of the American NACA Wind Tunnel for Testing Full-Scale Airplanes

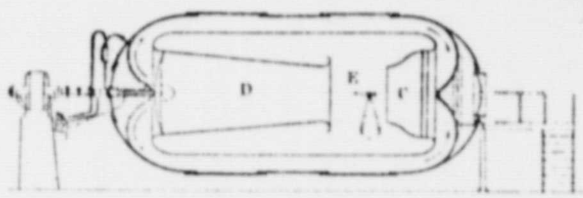


Figure 425
Longitudinal Cross Section of the Variable Density Wind Tunnel of the American NACA

Key: C) Collector
E) Test chamber
D) Diffuser

The difficulty encountered in wind tunnels is precisely that of not being able to achieve values of VL/ν close to reality except by increasing the speed or dimensions of the model, and therefore of the tunnel itself, or by decreasing V and increasing the air density in the experiment. This leads to creating wind tunnels either with a high air current speed, like the one at MacCook Field /289
in Dayton for testing full-scale airplanes (figure 424), or of variable density, as at Langley Field (figure 425).

Going from the Polar Curve of a Model to a Real Polar Curve

The present manner of determining polar curves applicable to real airplanes often has unsatisfactory results.

As a matter of fact, some people are content to derive airplane polar curves from wind tunnel tests on model wings. They are working under the hypothesis that only the wings provide lift and that the other parts of an airplane only contribute to drag. Under these conditions, it obviously suffices to alter the values of C_z and C_x by taking account of the real surface area of the wing and of the supplementary drag that is added onto the wings', which is estimated at best.

Others prefer to perform wind tunnel tests of an airplane with a fuselage. However, the Reynolds number is too small in experimental conditions, around the stays, for example, in relation to the Reynolds number at other parts of the plane. The stays therefore are purely and simply eliminated from the models, which no longer resemble a real airplane.

The interaction between the wing and the other parts of the airplane thus is ignored, although it is probably one of the most important sources of drag.

It meanwhile can be assumed as a first approximation that if a model airplane is better than another, its superiority will be retained when full-sized. A qualitative, but not quantitative, classification can thus be obtained.

There is therefore much to be said for trying to determine a full-scale airplane's polar curve in the atmosphere.

I am going to show that at the present time the difficulties of such a method do not surpass the means of modern experimenters, as has been claimed.

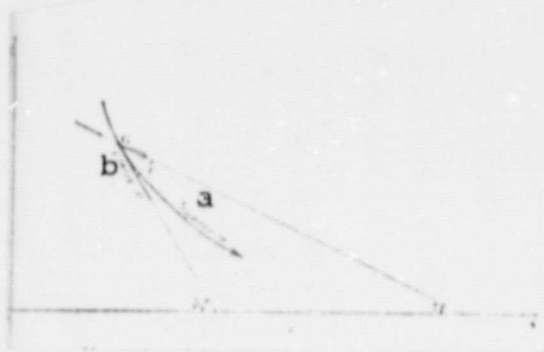
IV. Determining the Polar Curve of an Airplane in Flight

Huguenard, Sainte-Lague and I have shown how it is possible to determine an airplane's aerodynamic characteristics by a chronophotographic procedure. The procedure has the advantage of measuring lift and drag during flight for birds just as well as for airplanes.

Cinematographic Method

This procedure consists of following the maneuvers of an airplane or other object in a known plane by sighting it through a Cartesian coordinate grid with a double objective camera-gun. The camera-gun, of the type designed by Huguenard, Planiol, and myself, simultaneously furnishes clear images of the coordinate grid and of the flying target on the same film. It thus accurately records the latter's geographic trajectory.

Knowledge of such trajectories allows a problem similar to that of the "inverse ballistic" to be solved in certain cases. It also enables one to derive the laws of air resistance in a moving body, and consequently the polar curve of a glider or airplane deprived of the action of its propellor.



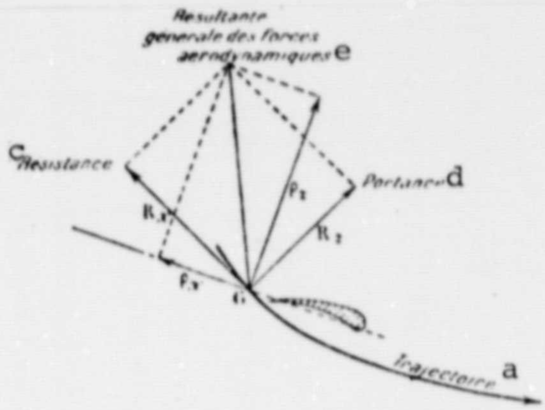


Figure 426
Definition of the Angles β, τ, i of an Airplane Describing a Trajectory in Still Air

Figure 427
Aerodynamic Forces Exerted on an Airplane in Flight

Key:
a) Trajectory
b) Velocity v
c) Drag
d) Lift
e) General resultant of aerodynamic forces

Theory of Airplane Motion /290

Let us take up again the theory describing airplane motion through the air. We shall limit ourselves to the essential points and suppose zero wind.

We shall consider a glider. Its center of gravity G describes a trajectory whose tangent makes an angle β with the horizontal line OX. The same horizontal line also makes an angle with the aircraft's fuselage. (See figure 426.)

We shall call angle $i = \beta - \tau$ the glider's incidence for reasons of simplification. This is the same angle that is considered as a measurement of incidence in wind tunnel tests, moreover.

In the case of figure 426, the three angles β, i, τ are positive. There is no wind, and the only vector involved, v, follows the tangent of the trajectory.

There are two forces to consider: the airplane's weight P and the general resultant of aerodynamic forces, which we will suppose passes through G.

From the point of view that concerns us, it is convenient to decompose the resultant into two components at right angles to each other. The decomposition can be approached in two different ways, according to what type of study is being done. One way is to decompose the force into one component, R_x, pointed in a direction opposite to the airplane's velocity and known as drag, and a second component, R_z, which is normal to the trajectory and is the customary lift. Another way is to break down the aerodynamic resultant into the component ρ_x following the axis of the airplane and the component ρ_z normal to the same axis. (See figure 427.)

If the lift were zero, the drag alone would constitute what is often called, for example in ballistics, "head resistance."

Construction of Polar Curves

Consideration of ρ_x and ρ_z can be useful for the builder, for these components directly give the stress an airplane has to support. However, only the first pair of components, R_x and R_z, will be retained here. When an aerodynamic balance whose supporting arm is constantly parallel to the air current in the wind tunnel, as in Eiffel's, is used, only the components along the air current's axis and normal to it are obtained by the weighings made, regardless of the model's angle of incidence.

Let us recall here the conventional equations defining the coefficients C_x and C_z, which are used to construct the ordinary polar curves:

$$R_x = \frac{C_x}{16} SV^2 \qquad R_z = \frac{C_z}{16} SV^2$$

In these equations S designates airfoil area and V the airplane's or air current's speed. /291

The experiments performed in wind tunnels have shown that the values of R_z and R_x, and consequently of C_z and C_x, are closely dependent on the incidence given to the model's wings in relation to the air current's direction.

Remember that by making the abscissas the values of C_x multiplied by 10, so that each curve is not too flat, and the ordinates the values of C_z listed in order of increasing incidence, a curve known as the airplane's polar curve is obtained. For each angle, the ratio R_z/R_x yields the aerodynamic efficiency. The maximum efficiency is the largest ratio found. It can also be obtained by drawing the tangent to the curve that passes through the origin O and finding the ratio R_z/R_x corresponding to the point of contact. Determining the polar curve in this way can also be done for full-size airplanes.

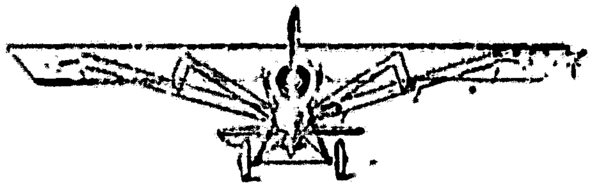


Figure 428
Position of Venturi Tubes T and t Linked to Differential Manometers on a Gourdou-Leseurre Test Airplane

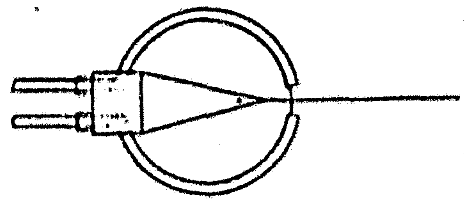


Figure 429
Schematic Diagram of Differential Manometer for Recording the Speed Difference behind and beyond the Propellor

Study of a Motorized Airplane

We reduced the case of a motorized airplane to that of a glider thanks to the following device. Two multiple Venturi tubes are placed one behind the propellor and the other a little outside the wings (figure 428). They are connected to a differential monometer, which the pilot keeps at zero by controlling the engine, and to another, recording, differential manometer. These manometers are of the same type as those used in the wing stress indicators (figure 429).

Under these conditions, the relative wind is the same before and after the propellor, whose effect on a glider is zero. The differential manometer is useful for studying the variations in speed existing between different points on the airplane. All that has to be done is to place the first manometer outside the wing and to attach the second at various spots, either in front of or to the rear of the wing, or near the fuselage or tail unit.

Take the case of zero wind, which is not very common in the atmosphere but sometimes exists. Consider the decomposition of the general resultant of aerodynamic forces into drag R_x and lift R_z. One can immediately derive the following two equations of motion by projecting these forces, weight, and the force of inertia, on the tangent and the normal to the trajectory of the center of gravity.

$$R_x = P \sin\beta - (P/g)\ (dV/dt)$$

$$R_z = P \cos\beta + (P/g)\ (V^2/r),$$

where t indicates time, r the trajectory's radius of curvature, β the angle of the tangent to the trajectory with the horizontal, P the airplane's weight, and V its speed.

As the radius of curvature is not immediately obtainable, it /292
is preferable to note that it is related to variations in the angle β

by the following equation, in which ds is the differential of the arc described.

$$1/r = (\pi/180)\ (d\beta/ds) = -(\pi/180)\ (d\beta/dt)\ (1/V)$$

The "-" sign comes from the sign conventions adopted here. Thus, in the case of figure 426, the correctness of this sign is assured by noting that the angle β, which is positive, is decreasing and as a result $d\beta/dt$ is negative.

As to the term $\pi/180$, it occurs because we have supposed that all the angles are measured in degrees, and the derivation consequently introduces this coefficient.

By replacing the radius of curvature by its value, the following formulas are obtained:

$$\text{Drag } R_x = P \sin\beta - (P/g)\ (dV/dt)$$

$$\text{Lift } R_z = P \cos\beta - (P/g)\ (\pi V/180)\ (d\beta/dt)$$

In the case where the airplane follows a trajectory of constant slope and velocity in still air, the equations to apply become:

$$R_z = P \cos\beta \qquad R_x = P \sin\beta$$

All that needs to be known then is the flight weight of the airplane and the angle β. β can be obtained with the help of the images on film. The coordinate grid is transferred onto graph paper along with the various positions of the airplane's center of gravity. The angle between the straight line joining the centers and the horizontal is β. One can verify on the graph that the angle is constant and that the distance separating the different centers of gravity, which is proportional to the airplane's speed, is also constant.

The airplane's speed is determined by the formula $V = uL/l$, where u is its apparent speed on the film, L its true length, and l its apparent length.

This done, the value of the angle τ is found by measuring on each frame the angle a lubber line, e.g., the airplane's major axis, makes with the horizontal.

The vehicle's incidence i to its trajectory is then the difference between the angles β and τ.

The Polar Curve of a Full-Size Airplane in Flight /293

We have used this method to successfully record numerous trajectories of variable slope (figures 430 and 431) followed by a 180 hp Gourdou-Leseurre airplane in zero wind with its propellor still.

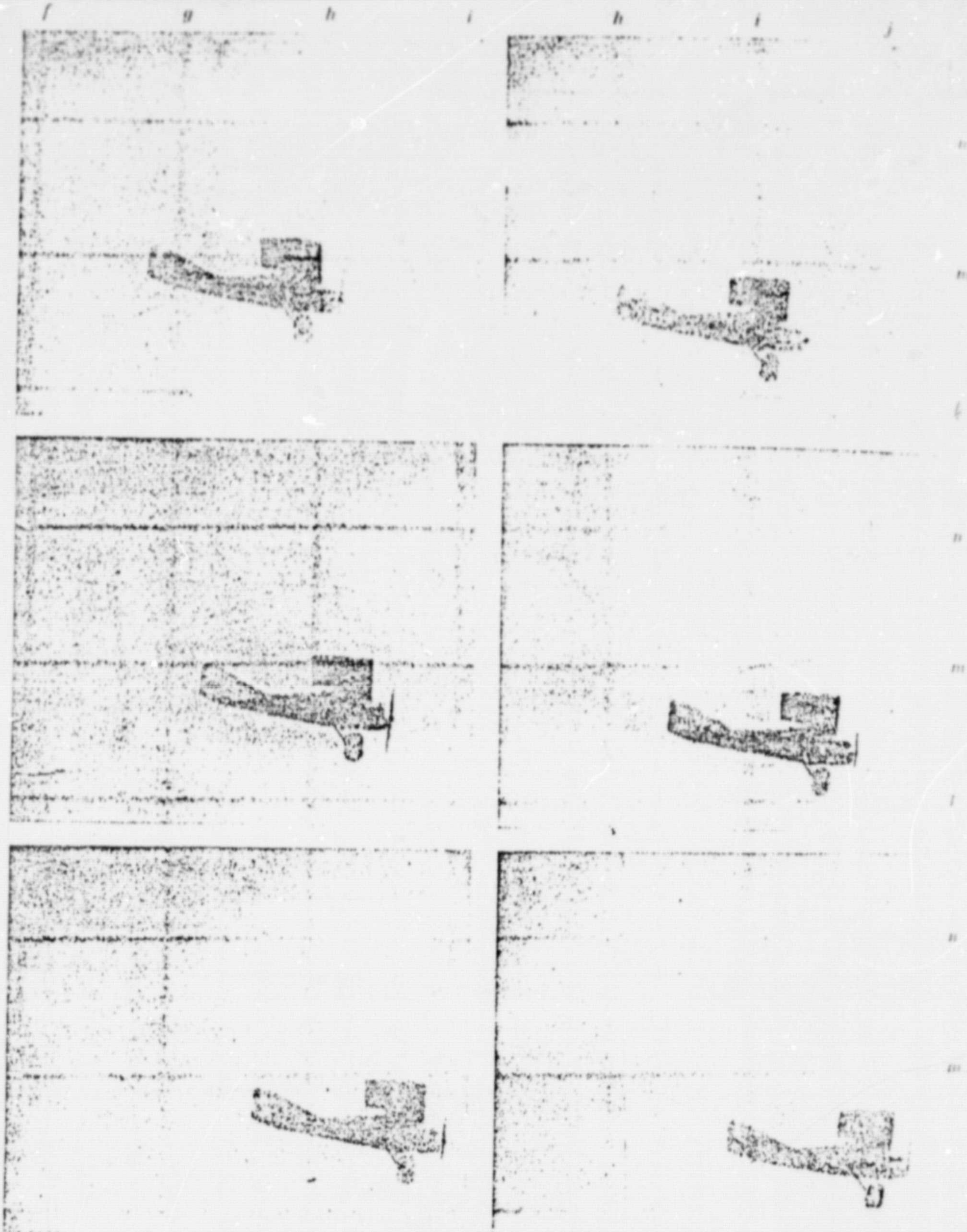


Figure 430
Film of Coordinate Grid and Motion of a Gourdou-Leseurre Airplane Following a Rectilinear Trajectory at Constant Speed with Propellor Still in Zero Wind
(16 frames/sec) (Read from Top to Bottom and Left to Right)

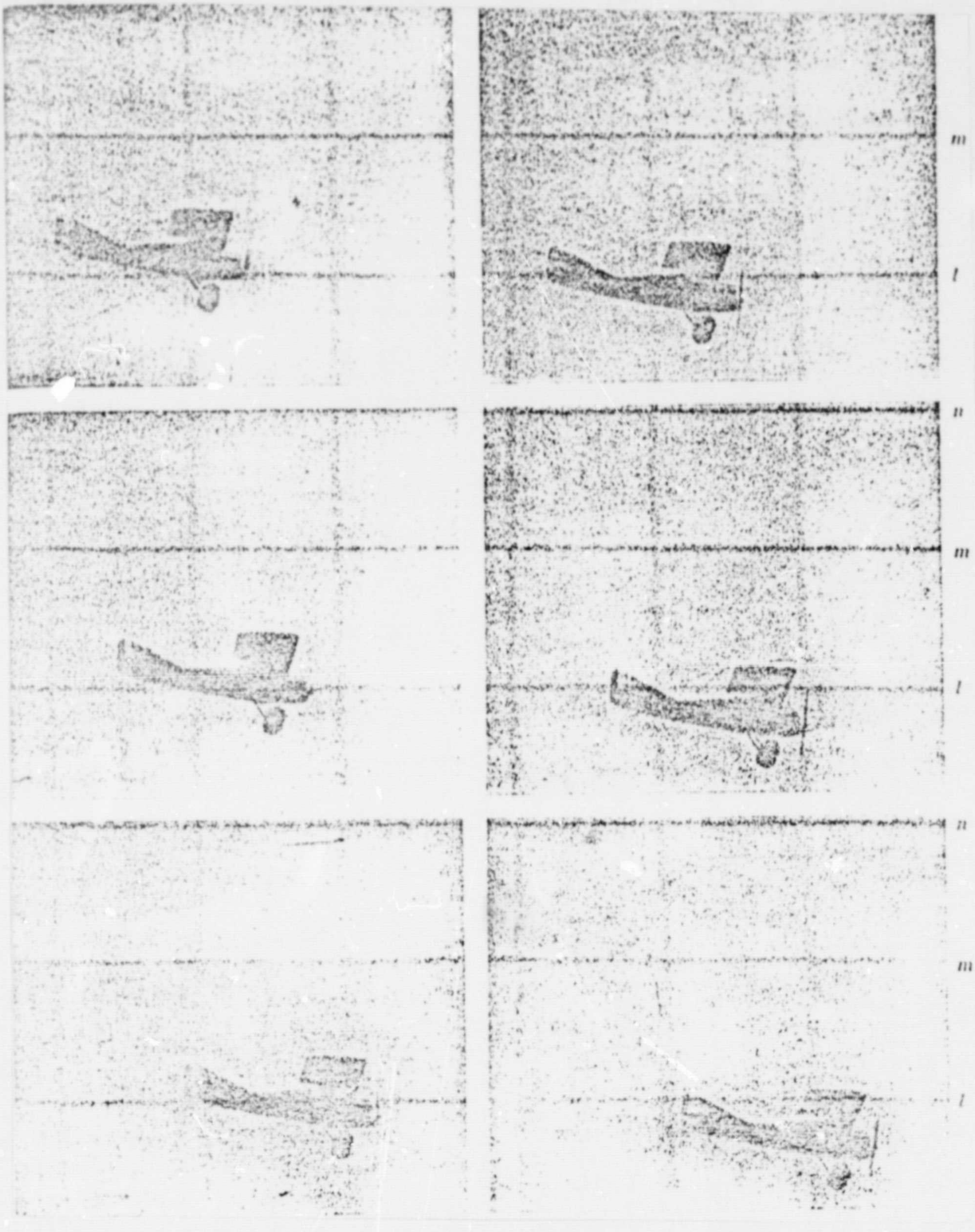


Figure 431
Film of Coordinate Grid and Motion of a Gourdou-Leseurre Airplane Following a Rectilinear Trajectory at Constant Speed with Propellor Still in Zero Wind
(16 frams/sec) (Read from Top to Bottom and Left to Right)

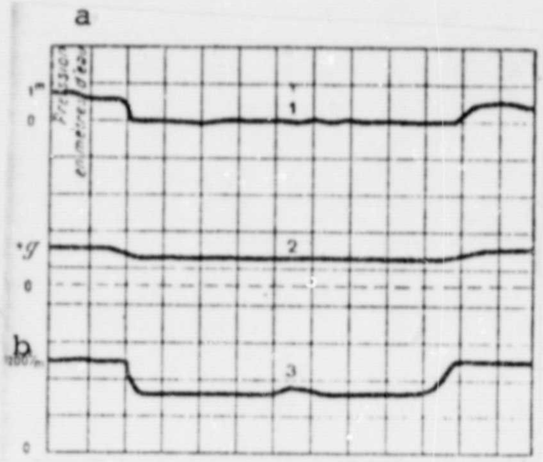


Figure 432
Simultaneous Recordings Furnished by a Differential Manometer (1), an Accelerograph (2), and a Tachometer (3) Located on a Gourdou-Leseurre Airplane in Flight Time Scale: 1 square = 0.1 second

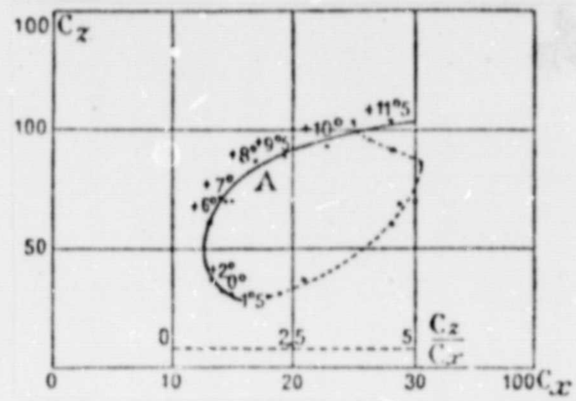


Figure 433
Solid Line: Polar Curve of a 180 hp Gourdou-Leseurre Airplane in Flight
Dotted Line: The Curve of Aerodynamic Efficiency, C_z/C_x

Key: a) Pressure in meters of water b) 1200 rpm

At the same time, we recorded the acceleration and the readings of a differential manometer and of a tachometer in the airplane. One of the recordings is displayed in figure 432. Notice in curve 3 that the engine has maintained a constant rate of a few revolutions in the part corresponding to the descent. The differential manometer tracing, which remained near zero the entire time, demonstrates this. Furthermore, the accelerograph tracing proves that the descent really was done at constant speed.

We used the recordings to determine several values of R_z and R_x and we derived from them the corresponding C_z's and C_x's, which we transfered in the usual manner to a graph as the ordinates and abscissas of the airplane's polar curve (figure 433).

We observed that the vehicle's aerodynamic efficiency, represented by the ratio C_z/C_x and traced with a dotted line on the figure, had a maximum of less than 6. It should be added, moreover, that, according to our already long-standing experiments, there is not one polar curve per airplane, but as many curves as the engine has operating rates. The polar curve also varies as the wings are deformed in flight under the effect of maneuvers or atmospheric disturbance.

V. Determining a Bird's Polar Curve

Wind Tunnel Studies

As soon as wind tunnels were invented, it came naturally to several researchers' minds to find out the aerodynamic efficiency of birds. Tests were carried out by Lafay and Arnau before the war on stuffed specimens placed in wind tunnels like mock-ups. They yielded results revealing that under these conditions the birds were somewhat less efficient than the airplanes of the period, since the ratio C_z/C_x did not exceed 4 for vultures or seamews.

Such results are hardly surprising for the reasons given above concerning the poorly understood interactions between the support and the object being tested. Also, the stuffed animals may no longer have a form comparable to that of living animals. Lastly and especially, the wings of the former are not at all comparable with those of the latter.

As we have seen, an outstretched bird's wing not supporting its body's weight resembles a deep gutter. Placed in a wind tunnel, it therefore opposes a significant resistance to the action of an appreciably regular air current. In reality, in flight a bird wing exhibits a characteristic double curvature that exhibits very little resistance. In addition, avian wings are flexible and deformable. In a wind tunnel, it is not possible to study a mock-up of a flexible wing any more than a flexible wing. That would suppose that the distribution of aerodynamic forces over the entire surface were known.

The Gantry Crane Method

In contrast, the study of flexible wings in a natural variable wind is much more interesting, even though it furnishes only incomplete data.

If one marks on a rigid wing airplane's polar curve the incidences corresponding to each point, one has all the elements necessary for determining its aerodynamic characteristics. On the contrary, /294
with a flexible wing airplane or bird, the same tracing as a function of incidence must be constructed for each flight speed. Since the wing becomes less arched as the flight speed increases, the efficiency of such flying machines, which is practically constant for ordinary airplanes, is altered at the same time as the speed. The wing in general flattens out at high speeds, and its aerodynamic efficiency tends to increase. The variation in efficiency could therefore be represented by a sort of polar curve that would describe a flexible wing by using wind speed as a variable for fixed incidences chosen beforehand. In other words, the usual polar curve, for rigid wings, represents a curve whose coordinates, C_z and C_x, are expressed as a function of incidence. In contrast, the coefficients C_z and C_x have to be expressed as a function of two parameters, the incidence i and the speed V, for flexible wings.

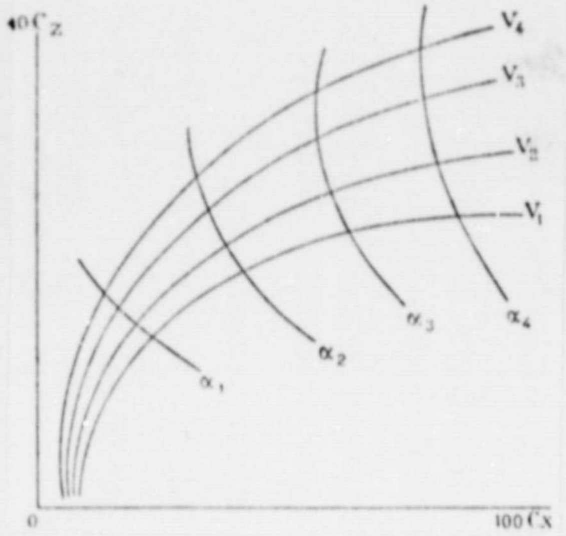


Figure 434
Family of Polar and Characteristic Curves of a Flexible Wing Airplane
V_1, V_2... Various Speeds
α_1, α_2... Various Incidences

Two families of curves can then be constructed (figure 434). For every value of V there corresponds a polar curve obtained by making wing incidence vary within the aircraft's limits of utilization. The polar curve group constitutes a first family whose members are associated with the various forms a wing can take under the influence of winds of different speed. If on the contrary α is given a series of constant values, a new curve, which corresponds to each value and characterizes the wing's flexibility, is obtained by making the speed V of the wind striking the wings under flying conditions vary. These characteristic curves constitute a second family whose members are associated with the various forms a wing can take as its incidence changes. The variations in speed deform the wing profile and produce a variation in the wing coefficients C_x and C_z. This engenders the curves of characteristics. The two families of curves obviously are derived from each other.

a) Case of a Flexible Wing Glider

Along with Huguenard and Planiol, we took up the problem of studying flexible wings and performed our first experiments with the flexible wing aircraft that I designed and of which we have already spoken.

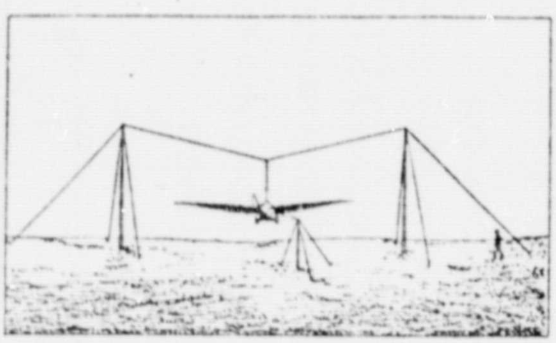


Figure 435
Crane Setup for the Aerodynamic Study of the Magnan M2 Aircraft

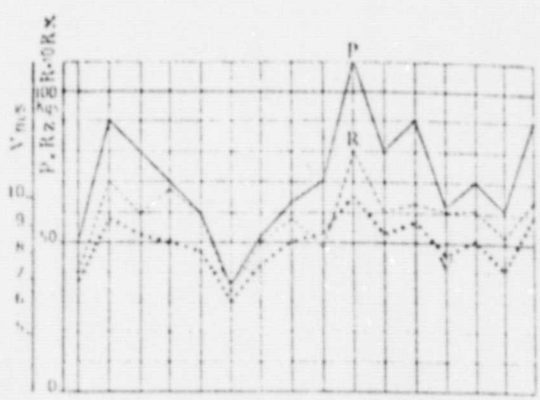


Figure 436
Variation of Wind Speed V, Lift P and Drag R in an M2 Aircraft Suspended from a Crane

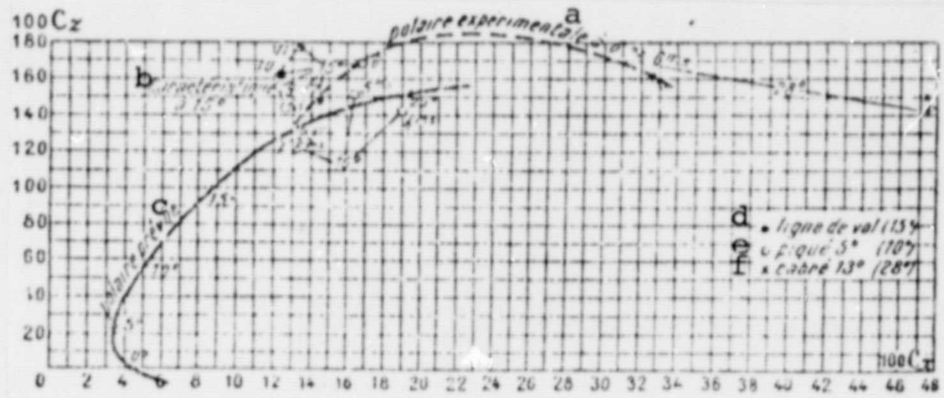


Figure 437
Comparison of Predicted Average Polar Curve and Polar and Characteristic Points Obtained in Gantry Crane Tests of an M2 Aircraft in a 6 m/sec Wind

Key: a) Experimental polar curve at 6 m/sec
b) Characteristic at 15°
c) Predicted polar curve
d) Line of flight (15°)
e) 5° Dive (10°)
f) 13° Climb (28°)

The aircraft was suspended a certain distance from the ground by suitable supports equipped with dynamometers for measuring the horizontal and vertical components of the resultant of the forces exerted by the natural wind (figure 435). For these experiments, we first of all used spring dynamometers. Their needle position was read every time a set period of time had passed. The speed and the direction of the wind was noted at the same instant. As soon as this empirical method showed us the value of the results obtained, we photographed simultaneously both recording dynamometers every second with two synchronized movie cameras. The time of the photograph was also marked on the anemometer's record. Once the difficulties resulting from making such tests in the open air were resolved, we employed another procedure to discover in a continuous manner the variation in the lift of flexible wing aircraft. It consisted of using high pressure hydrostatic dynamometers with remote recorders and a stabilization time of 1/20 second.

The body of measurements was found to be consistent. It allowed us to isolate a certain number of the flexible wing aircraft's polar and characteristic points. With the help of the data from two hundred measurements, we were able to see that, as shown in figure 436, for all incidences the ratio of R_z to R_x increases with speed because the wing flattens out under the force it is supporting. For a wind speed of 6 m/sec, the ratio R_z/R_x has a value of 10 to 11 at an incidence of 10°, a value of about 10 at 15°, and only /295

5 to 6 at 28°. Other experiments have show that an aircraft displays an efficiency reaching as much as 13 for a wind speed equal to 11 m/sec and even 15 for a speed of more than 11 m/sec.

We also calculated the coefficients C_z and C_x in the usual manner. We then transferred the average figures that we found onto the average polar curve predicted on the basis of the types of aircraft known through wind tunnel experiments on mock-ups. One can see that for an incidence of 15° (figure 437), the group of points associated with high speeds is located above the points associated with low speeds. This implies that the greater the wind speed is, the more efficient the airplane is, at least between the limits within which we operated. The three points associated with a speed of 6 m/sec belong to the polar curve corresponding to that speed. The points associated with an incidence of 15° belong to the characteristic curve corresponding to that incidence.

It could be argued that the elevated efficiency found for the flexible wing aircraft is due to the fact that part of the drag was eliminated by the Katzmayr effect. The experiments we have done on this subject have shown that this reduction is not significant.

b) Case of a Stuffed Bird /296

I carried out experiments of the same type with stuffed birds. I constructed a special gantry crane, a sort of metal bridge 5 meters long and 50 cm high and held 5 meters from the ground by two posts suitably braced up. The bird, an albatross, was supported by wires attached to the forearm of each wing and fixed by their lower part to the shaft of a recording spring dynamometer and by their upper part to plates giving them the desired tension.

Two small pylons maintained the wires supporting the drag that the air exerted on the bird in a forward position. These wires were also connected to inscribing spring dynamometers. A third pylon placed on the opposite side held a stay held taut by a coil spring which kept the assembly rigid.

Changes in the bird's incidence were obtained with a device able to pivot the bird's axis in the vertical plane.

At the same time as variations in lift and drag for each wing were recorded, instruments measured the instantaneous speed, inclination, and orientation of the wind.

The experiments show first of all that the posterior part of an albatross's wing changes shape considerably in response to the action of the wind and follows all the wind's fluctuations. Furthermore, the measurements made by the apparatus revealed a maximum aerodynamic efficiency of 17. This could be in part the consequence of the Katzmayr effect, given the amplitude of some of the oscillations.

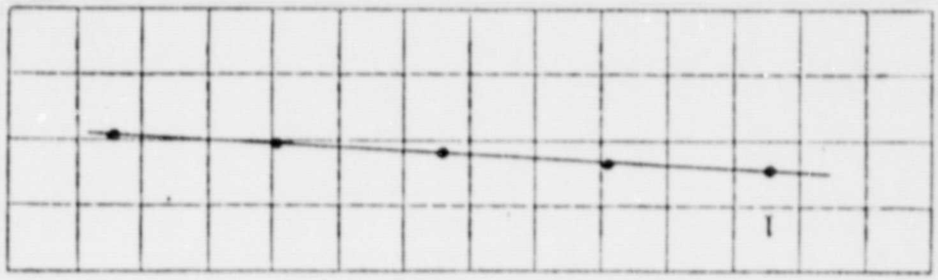


Figure 438
Rectilinear Trajectory Described by a Martin at Constant Speed, without Beating its Wings

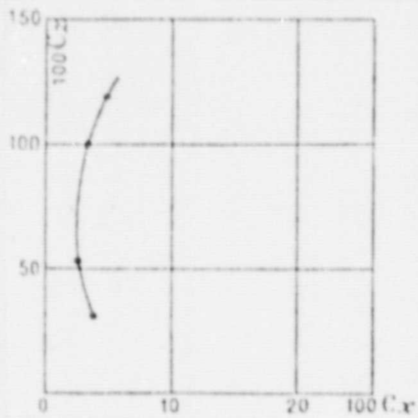


Figure 439
Polar Points of a Martin in Flight

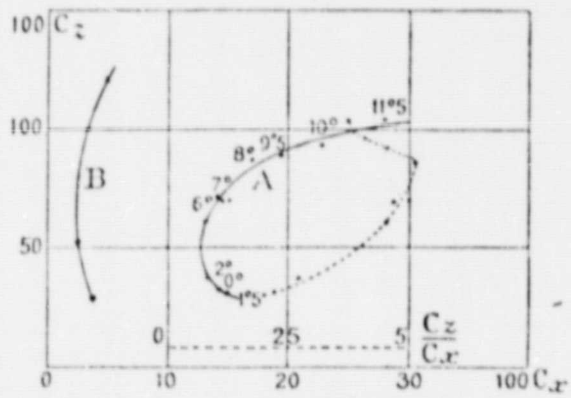


Figure 440
Comparison of Average Polar Curve of a Martin (B) and the Polar Curve of a Gourdou-Leseurre Airplane in Flight (A)

Cinematographic Method

The possible existence of such an effect on the one hand and, on the other, the manner of attaching the bird, which created a situation where the wings neither supported the animal's weight as in flight nor retained the natural flight form, should naturally /297 lead to applying the chronophotographic method to birds gliding in a calm atmosphere. At this moment, it is certain that the animals exhibit the form of least resistance, the most favorable for gliding, and at certain moments the greatest efficiency.

However, since birds fly where and how they wish, much patience is needed to film a flight in the vicinity of the coordinate grid, given that the flight has to be basically parallel to the grid. It must also be a glide, i.e. the bird must follow a rectilineal descending trajectory without beating its wings once. Finally, the wind has to be completely absent.

We were able meanwhile to obtain some satisfactory trajectories (figure 438) with a house martin (chelidon urbica L.). We were able to find four polar points which formed a curve different from that of a motorized airplane (figures 439 and 440). This curve shows that as the angle of incidence grows, lift rapidly increases, while drag undergoes much smaller changes. In addition, the bird's aerodynamic efficiency attained a maximum of 30, which is five times greater than that of the fighter we studied.

We assumed in tracing the curve that the bird's wing had kept an appreciably similar form throughout its gliding. This is probably inaccurate.

Conclusions

In the course of the lessons which I have had the honor of presenting to you, I strove to show you all the interest aviation has in the study of avian flight. I indicated the research that had been carried out on flying creatures as well as the experimental methods employed. You have been able to see that these new methods were all applicable to studying aircraft flight and have yielded interesting, useful data just as much for science as present-day aeronautics.

Nature reveals to us examples of different modes of flight each day. They take on a truly impressive multiplicity of forms whose study can only prove to be very fertile in the future.

Is this to say that we must get our inspiration only from the example of birds and other flying creatures? Not necessarily, but the repeated observation of living things gliding through the air is very educational. It can make us hope that human science will one day discover flying apparatus of a design completely different from contemporary airplanes, which will seem primitive and childish to our descendents.

In any case, it must be affirmed very forcefully that progress in current airborne locomotion or the birth of a new type of locomotion can only come out of experimental research. In aeronautical science, as in the others, progress is based on experimentation, and on experimentation alone.

I do not want to finish this course without taking advantage of the opportunity offered me to note that the scientific findings related in these lessons and which are due to my collaborators and myself could only be obtained thanks to the considerable support of the Caisse des Recherches Scientifiques de l'Aéronautique [Fund for Scientific Research in Aeronautics] and of J.-L. Breton, Director of the Office des Inventions [Office of Inventions].

RECOMMENDED READING

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