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BIOLOGICAL AND AERODYNAMIC PROBLEMS WITH THE FLIGHT OF ANIMALS

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16. Abstract: This article discusses the biological and aerodynamic considerations related to birds and insects. It is noted a wide field is open for comparative biological, physiological and aerodynamic investigations. Considerable mathematics related to the flight of animals is presented, including ~ 20 equations. The 15 figures included depict the design of bird and insect wings, diagrams of propulsion efficiency, thrust, lift and angles of attack and photographs of flapping wing free flying "wing only" models which were built and flown. The authors hope this dissertation will soon lead to the formation of a new fruitful branch of German science, Flight Biophysics (this to include close cooperation between biological, physiological, physical-thechnological and aerodynamic methods and viewpoints).

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Biological and Aerodynamic Problems of the Flight of Animals /348

by Erich V. Holst and Dietrich Kuechemann, Goettingen

I.

Among the boundary areas of biology which touch upon human technology, the flight of animals takes on a special position, not only with respect to its meaning, but also with respect to its theoretical and practical experimental difficulties. Naturally the biologist and the engineer look at it from different angles: the biologist is interested in the production history of flying animals, explanations of the manifold adaptions of structure and functions which, naturally, affect not only the wing and its mode of movement, but also their muscle structure, their nerve system and senses, circulation and breathing, or to be exact their entire organism, for flying is a high-efficiency performance which requires an optimum of technical design, properties of the construction materials, and of operating economy. The physicist, on the other hand, is interested in the motion itself and explanations from an aerodynamic, and, above all, an energy standpoint.

The problems of the biologist, especially with regard to questions of anatomy, have been solved only in large generalities; much remains to be done with individual problems. Here the physiologist faces a complete wasteland where initial efforts have been expended in only a few areas. Whoever tackles the anatomical-physiological problems of flying animals must soon realize that he cannot continue without more exact knowledge of the physical side, that his conclusions become unreliable or even impossible because such a large part of the organism is directed toward solving these purely technical problems. One should take advantage of this problem situation; for one does not often get an opportunity in living nature to subject a process or functional complex to a purely technical and thus unambiguous judgment. Thus, to look at only one aspect, the much contested, often scorned but yet unavoidable point of view of "functionality or usefulness" of animal development then takes a certain immediate importance where the biological functionality becomes a technical one. In order to give an actual example for today's genetics we can, assuming we know the aerodynamic laws, state immediately, for mutation stages which affect the wing, its size, shape, elasticity, bristles, etc., and for which a great number are known in the insect world (see figure 1), under which external conditions (flight conditions) the new shape will be different ("better" resp. "worse", everything else being equal) than the initial shape; such a statement is of decisive importance in evaluating such a change.

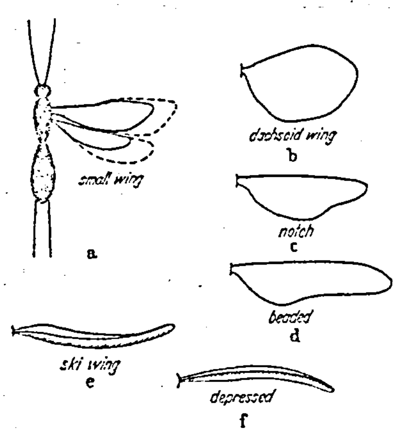

Figure 1: Some examples of extensive wing changes from mutations in insects; a) slip wasp Habrobracon, reduction of area to about one half (the normal wing contour is shown by the dashed line); the mutant cannot fly; b-d. changes in the shape of the wing; e-f (looking from in front) changes in wing curvature of the dew fly Drosophila.

The technical point of view takes on special interest for the biologist in two different connections for comparative investigations of the many-sidedness of animal flight organs: first where it competes with the historical concept in that starting material and development potentials for adaption to obvious "desired" technical goals face limitations; here it is always astonishing to what degree nature has extended these limits and how little the "ballast", depending on genetic history, has obstructed the technological perfection. We shall learn of many such examples. In the second place, all those cases are of interest where the wing, at the same time, is an object for adaptation to other, not flight-technological functions, where it must serve further life requirements or, at least, shall not prevent them.

As is well known the function of mechanical protection, for instance, plays an important role among insects where either a close mutual correlation of body- and wing shape (e.g. for many bed-bugs) or a more one-sided adaptation of a pair of wings so that it no longer serves as a flight organ but as a protective organ (e.g., for many beetles). In addition to mechanical protection optical protection often is required whereby the wings are also utilized through various development stages. The thus arising changes in shape necessarily affect the flight capability and often force it to give up its flight potential - a concession which is understandable in all those cases where flying is not needed for the search for food or for reproduction, but primarily for escape; this is a case where, by means of camouflage it is /349
replaced by an incomparably more economical medium and thus becomes expendable. Figure 2 presents some examples of these statements for the category of grasshoppers. The comparative study of such transformation shapes with retrogressing flight capability becomes especially intriguing because here, as often in other places, the functional changes precede the change of shape, i.e., shapes which become physiologically incapable of flight while flying, considered from a technological-anatomical standpoint, is still very much needed; in addition it is of interest because rudimentary flight organs can still find application (e.g., as a "scare medium" by means of sudden expanding of the wings). Here a wide field is open for comparative biological, physiological, and aerodynamic investigations.

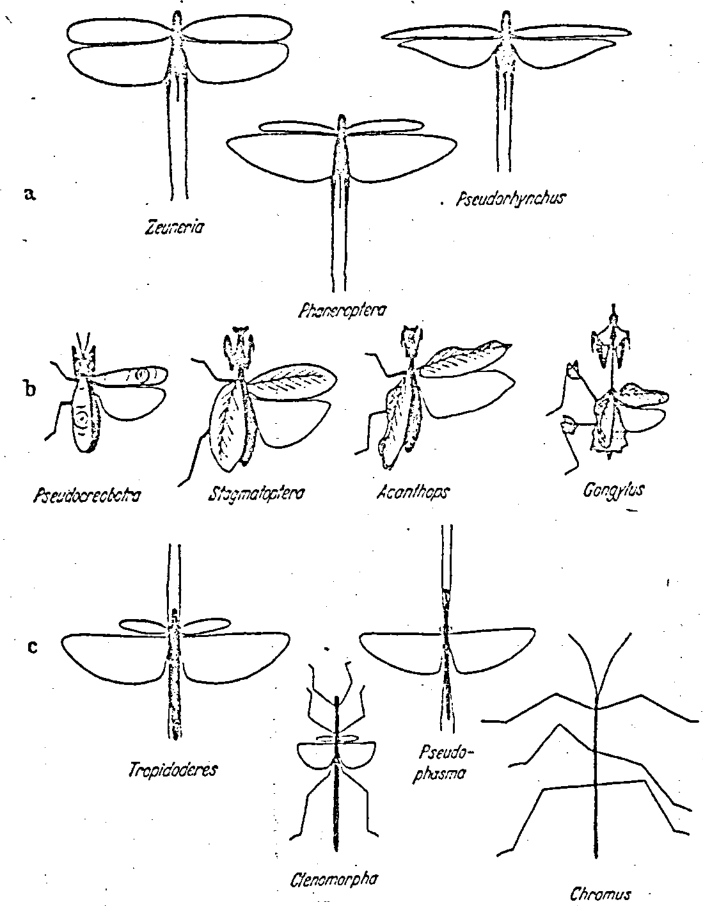

Figure 2. Examples of several wing transformation ways in grasshoppers. The types in row a differ from each other, for about equal size and area loading, mainly in the shape of the surface and thus primarily from a flight-technological aspect. In rows b and c the optical adaptation influences the make-up of the wing; b) simulating the appearance of a leaf; the shape on the left still carries (while maintaining the usual wing contour) the look of a blossom; in the second one the front wing imitates a yellow, freshly fallen leaf, and the third one a brown, somewhat rotting leaf; the fourth, as a bundle, looks like the very much destroyed remains of a leaf, only the hind wing, not visible in the rest position, does not change (except for a decrease in size; c) increasing adaptation to the appearance of a twig with backward formation of the wings.

For all these problems mentioned here the biologist cannot get along without an experimentally or theoretically confirmed concept of what occurs physically during flight; beyond that the aerodynamicist can teach him to observe certain relationships and to gather data in such a way that they can also be evaluated physically. Much is still lacking in this connection; the subject presentation shall give some pointers in this regard.

On the other hand, the physicist interested in animal flight is dependent on the assistance of the zoologist; for, except for purely practical standpoints, every subjective physical consideration can also lead easily to false conclusions of which a large number are known in history since, as already mentioned and in contrast to the flying machine, various necessary living functions, in addition to flying, must be brought into balance with the flight prerequisites; this must be accomplished with the shapes dictated by its genetic history.

We can pose the question here as to just what benefit aircraft technology can still derive today from its interest in the flight of animals. The time where birds generally set the ideal example and where imitation of their flight was the goal of human flight technology, has long since passed; one can say that it ended with LILIENTHAL'S fatal crash in 1896. All previous and later attempts to build flapping airplanes failed and only taught us to better recognize the difficulties; this, however, did not prevent that even today and probably in the future many will praise flapping flight as the only ideal flying mode and will always "invent" flapping-mode airplanes, although only on paper. However, the number of serious proponents of the flapping-mode airplane concept is small among today's designers.*

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*In the first place we should here mention A. Lippisch (Flugzeugsport 17, 246(1925); Luftwelt 2, 106 (1935); Der Segelflieger 1936, No's 9-12) who attempted to clarify the status in various presentations and who also build flight-worthy models which, in addition to a pair of rigid wings, include two small elastic flaps which replace the propeller-a partial solution which can be realized in practice considerably more easily than the "100% flapping" concept of animals.

However, since the animal flapping-mode flight is always considered in the light of a potential imitation of this mode of movement - /350 the introduction of the curved, thick, front rounded-off bird profile into flight technology by LILIENTHAL is the only important innovation which is practical today and which owes its concept to the example of the birds - the interest of technology in the flight of animals has decreased considerably as can easily be understood. According to our ideas the continuous discussions of human flapping-mode flight (possibly even with muscle power) have done more harm than good because they diverted attention from other ideas which are of importance even for today's aircraft technology and from special problems which flying animals and flight aircraft, despite the differing propulsion modes, must be able to solve in similar ways and which have actually been solved in part independently of each other.

Let us illustrate the meaning of this with an example: the requirement existing for faster, larger flight animals (larger birds) as well as for the faster aircraft, namely to reduce their speed, as needed, by means of special auxiliary devices without corresponding loss of lift. In airplanes there is a large number of such "high-lift devices" of which the most important are shown in figure 3. Their common principle rests in the capability to produce a larger angle of attack or a higher curvature of the wing and thus a higher lift without allowing the flow at the wing upper surface to "detach" with the formation of energy-consuming turbulence. The endangered zones lie behind the wing nose in front and at the trailing edge of the wing because at both places the velocity along the surface decreases rapidly; here also they are increased artificially by means of jet-like slots (because of pressure differences between the upper and lower wing surfaces) through which air is forced to flow and thus to supply anew kinetic energy to the upper surface. Therefore, such slots, often only formed when needed, are attached in front (slats) or behind (slotted flaps, Fowler wings). In principle this effect can be increased still more by numerous

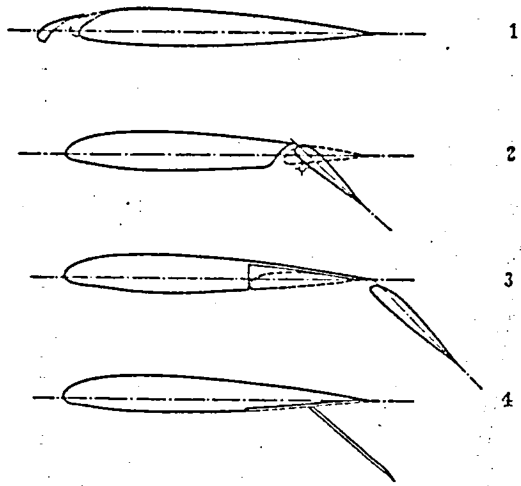

Figure 3: Various versions of landing aids (means for generating high lift) in airplanes:
1. slat 2. slotted flap,
3. Fowler wing, 4. split flap (Zap flap);
dashed lines: position of the auxiliary surfaces during non-use (fast cruise),
solid lines: position during slow flights

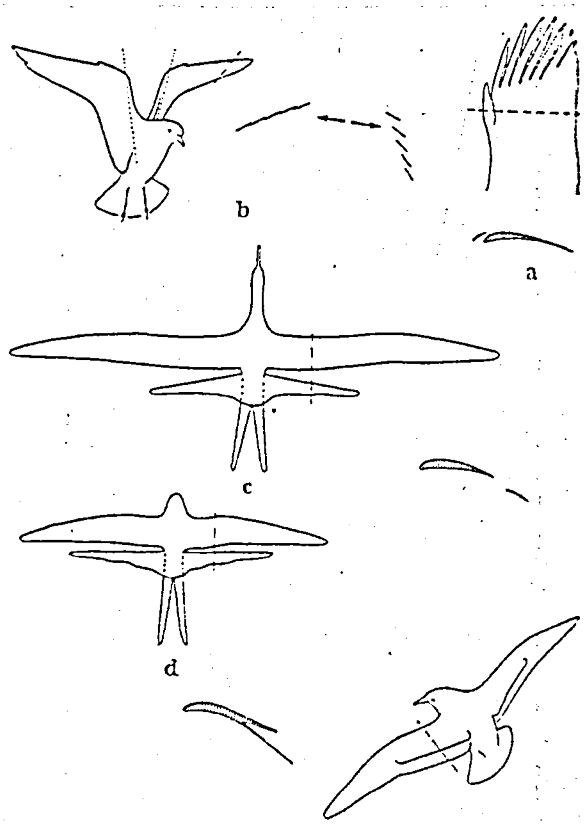

Figure 4: High-lift means for birds: a) wing of an acceleration shaker (pheasant) with slots between the hand swings and spread thumb wing; below, section through the center of the wing length.
b) sea gull in shaking position; the wings swing approximately around the turn-axes indicated by dotted lines; next to it a section through the wing tip when pulled away (= front flap) and when returned (= back flap); the arrow denotes the incident flow direction.
c) frigate bird (Fregata) and
d) forked tail falcon (Elanoides furcatus) with closed and with widely spread tail; next to it a cross-sectional view. e) sea-gull on landing while pulling away arm swings and cover feathers from each other as two surfaces; next to it a cross-sectional view (b and e from fast-action photographs).

such slots, although with considerable increase in resistance. An analogous function is performed by a split flap which produces a suction under the trailing wing edge and thus better attachment of the flow over it.

The above-mentioned high-lift devices are also found on many birds. Already well known is the function of the thumb wing (figure 4a) corresponding to that of the airplane slat whose lifting-off from the wing during landing (and at the start) has been proven by fast-action photographs.* The method to install several slots in succession has been implemented in various ways in birds. Thus, for example, in many shapes which for straight-line flight exhibit a closed surface, slots appear between the hand flaps during flapping at the moment when the wings touch (figure 4b). For "acceleration flaps" the hand flaps at the spread wings are always separated by slits so that an analogous effect is produced here as the wings come together and separate. Even much larger birds, especially upwind sailors, often have wide slots between the hand flaps (cf. figure 5a). Because of the lack of more exact information we shall not discuss in detail the presumably, in individual cases, differing aerodynamic effects of such slot wings. /351

The protruding movement of a part of the wing toward the rear, such as in the Fowler wing, where increases in area, increases in curvature, and slot effects together increase the lift, do not occur in birds for anatomical reasons; instead many birds apparently make use of the possibility to press against

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* compare E. Stresemann, Aves (in Handbuch d. Zool.) 1931, 572; nice pictures, especially of the stork, are also found in K. Lorenz (J.f. Ornithol., 81, 107, 1933). To judge from his description, the first hand flap can also take on this function (alpine jackdaw). Special mention should also be made of the work of Lorenz, rich in content and based on un-preconceived observations. It is probably the best that has been written since LILIENTHAL with respect to the problem of animal flight although some of the explanations contained therein can no longer be upheld.

the wing a long and strongly-forked tail consisting of two wings simultaneously folded toward the rear. A tendency toward this type of development direction can be found in many bird types; extreme cases are the frigate bird (Fregata) and still more noticeable an American falcon (Elanoides furcatus) for which the longest tail feather largely corresponds to the longest of the very long hand flaps with respect to strength, curvature, and length (see figures 4c, d). The mode of operation of the forked tail presented here was first investigated by us theoretically and then was observed for swallows and gliders; later we discovered a flight mode of the frigate bird described by A. Magnan* with a certain amount of wonderment and without attempt to explain it which agreed exactly with our assumption.** By observation and fast-action photographs of landing sea gulls we have convinced ourselves of the existence in birds of a device analogous to the split flap. Here, at times, the angle of the arm flaps is lowered to such an extent that they separate from the cover feathers and that a wedge-shaped opening develops between the two, as explained in figure 4e.

The parallels between birds and airplanes, demonstrated by the example of the high lift devices, suggest that, by a study of animal flight, new and important forms could be found for the technology for application to aerodynamics; our own experiences which we cannot discuss in greater detail in this place, confirm these suppositions.

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* According to A. Magnan (Le vol des oiseaux et le vol des avions, Paris 1931, p. 133) this bird has the capability to rise suddenly without any visible, wing flap where only, the tail is parted extremely ("tres etaleé et grandement echancrée").

**Obviously many, and e.g., all soft and loosely constructed forked tails of the birds do not have aerodynamic, but rather other biological functions.

Even for analyses with respect to theoretical aerodynamics animal flight poses a plethora of interesting problems. The very astounding wide range of the absolute values for flying animals - from a 9 m span width of the extinct flying lizard Pteranodon to 2 mm and less for insects - and the just-as-wide range of flying speeds - from about 200 km per hour for the peregrine falcon (Falco peregrinus) and more than 100 km per hour for a number of other birds to a maximum speed of 4-5 km/hour and below for certain insects - suggests that one estimate the range of Reynold's numbers which apply for flying animals. The Reynold's number $Re = \rho vl/\mu$ where v is the velocity, l a characteristic length (wing depth), ρ the density of the medium and μ its viscosity (μ/ρ for air at room temperature is about $15 \cdot 10^{-6}$ m^2/sec), denotes the ratio of the inertia to the viscosity forces. Its importance lies in the fact that the laws of motion of fluids are appreciably different, depending on whether inertia forces (large Re) or viscosity forces (small Re) predominate. For many birds in horizontal flight the Reynold's number lies considerably above 100,000 (buzzard about 250,000, dove and frigate bird about 300,000, peregrine falcon up to 550,000). These values are not too far below those of our airplane types (several 1,000,000); this shows that the wing of birds is also comparable to the lift surfaces of airplanes with respect to shape, profile, and surface make-up (compare figure 5a).

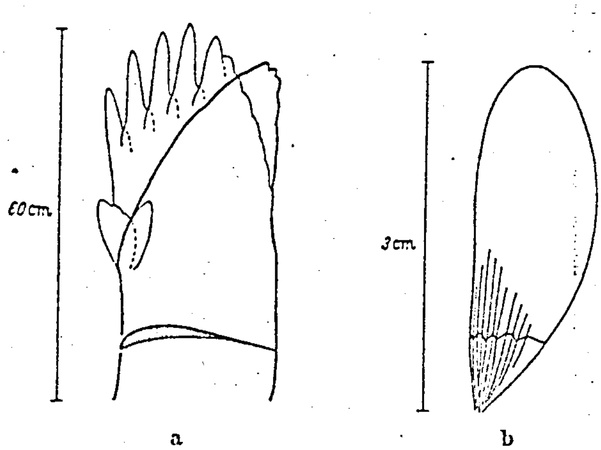

Figure 5: a) wing contour for bent and extended hand and profile of a fresh buzzard wing;
b) contour and "profile" of a dragonfly (Calopteryx).

For insects, however, the conditions are entirely different. A certain problem arises here because of the high flapping frequency since, for this reason, flow velocities over the various positions of the wing span differ greatly. As average Reynold's numbers one can estimate: butterfly 500, bumble-bee 4000, dragonfly 6000. For these small Reynolds numbers it is now very questionable whether there's any circulation at all about the wing as prescribed in airfoil wing theory. It is known that for Reynolds numbers of the order of magnitude conventional in flight technology this ideal flow can be used as an approximate of the real flow because the flow is attached almost to the tail section of the wing on account of the turbulent friction layers.* However, for lower Reynolds numbers the flow is preferably laminar. For laminar friction layers reverse flow easily occurs because of energy losses caused by internal friction which can result in flow separation from the wing and thus a decrease in lift. This phenomenon, however, can be suppressed by the installation of some devices which generate turbulence in the friction layer (such as a thin wire ahead of or above the leading wing edge) because the thus produced particle exchange transverse to the flow direction feeds energy of motion to the layers near the wall which counteracts a reverse flow. From this standpoint one might also suspect that insects have devices which convert a potential laminar flow to a turbulent one. Indeed, upon microscopic observation, one finds on many insect wings and especially at the leading edge, bristles, teeth or similar formations which could actually serve this purpose (cf. figure 6). The especially frequent bristle coverage is not surprising in such cases where it extends over the whole body and thus could have a protective /352

*The term friction layer was introduced by L. Prandtl and is based on the idea that viscosity effects play a role only in the immediate vicinity of the wall while in the free stream an ideal, frictionless flow can be assumed.

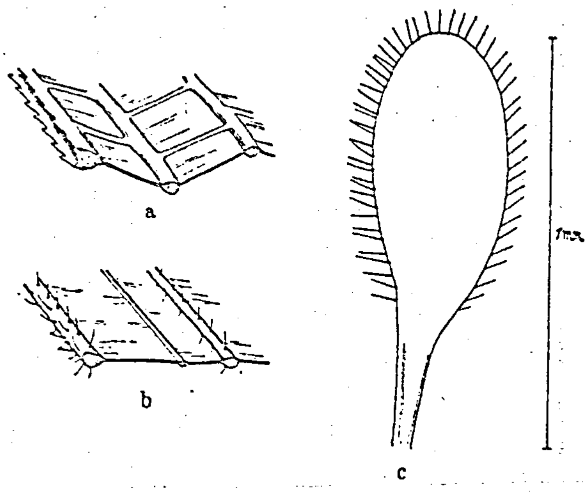

Figure 6: Turbulence-generating devices on insect wings
a) section through front edge of a dragonfly wing (Calopteryx) with two rows of teeth,
b) through the corresponding zone of a mosquito wing (Tipula) with bristles all over the front edge,
c) wing of a gall bug (Oligarces) with hairy edge. (The enlargement scale is about equal in all 3 cases.)

function, even for the wing; in other cases, however, such as oligarces) the bristles are limited to the edge of the wing, and only as far as the wing is effective as an airfoil; here only the presumed aerodynamic function of the bristles could come into consideration. Even the fact that the insect wing is a thin plate, often kinked at the base for strength purposes (figure 5b) could have a favorable effect on flow at low Reynolds numbers.

A second group of aerodynamic problems is concerned with the swinging motion of the wing and thus with the fact that the flow around the surface is not stationary. The non-stationary air foil theory which we had to consult for a theoretical overview*, has shown that here the physical processes are characterized by a new parameter γ, the reduced frequency. $\gamma = n\, s/v$ is formed by the frequency n of the wing flapping, the half-span width s and the incident flow velocity v.** For processes at the wing cross section the frequency formed and reduced by the half wing depth 1/2 is the deciding factor. For $\gamma = o$ the motion is stationary;

*cf. H.G. Kuessner (Luftfahrtforschung 13, 410 (1936); 17, 370 (1940)

** $I/\gamma = \lambda/s$ denotes the wave length λ referenced to the half-span width s.

as γ increases, first the effect of the turbules which are dropping off periodically as the result of changes in circulation and then the effect of mass accelerations of the air become noticeable. If γ is small (order of magnitude of about 0.1 - 0.2), one can neglect the non-stationary effects and can assume that at every point in time those flow conditions would prevail, as an approximation, which govern the stationary case. /353

The reduced frequencies of the mid-sized to large birds in horizontal flight, according to various existing data, move at about 0.1 (e.g. peregrine falcon at 0.06, dove at 0.08, crow at 0.11, partridge at 0.12*). One could thus try to get along with a quasi-stationary theory. Such a theory for the case of simple motion (where the wing swings up and down as a whole) shall be discussed later. - However, for many insects and some small birds, also for larger ones during start and landing, the reduced frequency could be considerably higher. For the extreme case of flying in place where the wings are to be moved primarily in an approximately horizontal path (hummingbird, many insects) one could try a theory based on the concepts developed for helicopters; however, we will not discuss this further in this presentation.

III.

The ideas presented so far served to explain more closely our opinion that a theoretical-experimental explanation of the flight of animals could produce fruitful results not only for biology, but also for technology and aerodynamics. What means are available today for researching this area?

On the purely biological side the methods, especially the physiological ones (muscle-, nerve-, and sensing physiology) have generally been developed sufficiently far to give promise to

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* Although numerous data as to velocities and flapping frequencies are available, there are no associated ones from the standpoint of reduced frequency; for that reason the numbers quoted are somewhat uncertain.

the involvement with the problems of animal flight motions. From a kinematic-technological aspect good slow-motion photographs, taken under completely natural as well as under various experimental conditions, are indispensable. However, the experimental investigations of animal flight mechanics are limited by the fact that we deal here with creatures which react to every forced action with disturbed or changed functionality which by themselves, rule out many necessary measurements, such as in a wind tunnel, as well as tests concerning the power requirements during flight, etc. This fact inspired one of us (v.H.), based on extensive tests with animals over many years and with various (in part newly-constructed) drives as well as with wings moved in different ways, to construct swinging-flight models which in all their essential characteristics imitate the various animal flying modes. With them it becomes easier, as will be shown below, to conduct more accurate measurements since here one has control of all effective causal measures. - The term "model tests" has different shadings in biology and in technology. Biological models (such as protoplasma motions, nerve conductors, nerve coordination) only afford, as is generally admitted today, only formal analogies and thus have primarily only heuristic and didactic value. Model tests in technology (such as wind tunnel tests or tests with free-flying models such as have been employed successfully in the study of spins) are already conducted with the object itself, although under predetermined simplifying conditions. This possibility to simplify, to vary only one of many effective factors at a time and thus to be able to recognize its role within the entire framework, is afforded by the tests of free-flying swing models. Thus it becomes indispensable as a connecting link between theory and the flight processes in nature.

IV.

In order to get a more exact view of the underlying conditions in wing flaps we developed in the following, as a basis for discussion, a quasi-stationary theory which starts with a simplified motion of the wing. We assumed here that the wing moves up and down as a whole, that is, it produces the same movement at each position of the cross section.

In a fixed-volume coordinate system (x - axis horizontal, positive toward the front; z - axis vertical, positive upward; unit of length: half-span width s; $x/s = \xi$; $z/s = \zeta$) the motion of a point in the mid cross section of the wing would be in the path

$$\zeta(\xi) = a \cos 2\pi\nu\xi$$

where a is the amplitude of the flapping motion (measured in half-span width and $\nu = ns/v$ [with n = flap frequency, v = (constant) path velocity] is the reduced frequency which we shall consider, as explained above, to be of a small magnitude. Furthermore the wing should periodically change its angle of attack α, with respect to the given incident flow direction, by an average value α_o with changes in amplitude α_1:

$$\alpha(\xi) = \alpha_0 + \alpha_1 \cos(2\pi\nu\xi - \varphi).$$

Thus first a phase difference φ between the flapping motion and angle of attack movements is introduced whose optimum value we shall determine later. We can now determine the forces arising from these motions. As a unit for these forces we choose, as usual $\frac{\rho}{2} v^2 F$ where ρ is the density of the medium and F is /354
the wing area. For the flight forces normal to a given incident flow direction (lift, c_a) we obtain, based on Prandtl's airfoil theory and with the assumption of elliptical lift distribution across the span width (which produces no significant limitations) a linear relation with the angle of attack:

$$c_a(\xi) = c_a' \cdot \alpha(\xi)$$
$$c_a' = dc_a/d\alpha = \frac{2\pi}{1 + 2/\Lambda} = \text{const},$$

where Λ is the aspect ratio $4 s^2/F$ of the wing. The force of the air in the direction of the given onflow (drag c_w) is made up of the induced drag c_{wi} which is a square function of c_a, and the profile drag c_{wp} which is assumed to be independent of the angle of attack: $c_w(\xi) = \frac{c_a^2(\xi)}{\pi \Lambda} + c_{wp}.$

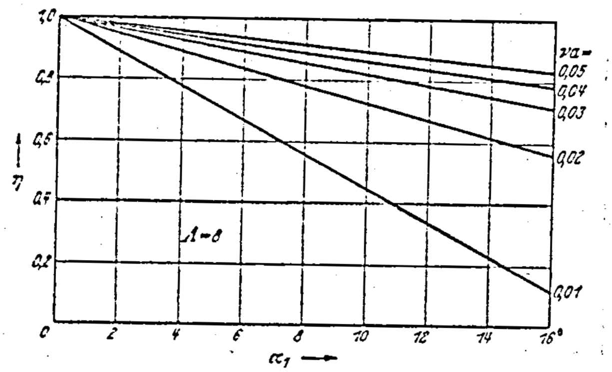

Figure 7: Propulsion efficiency of wing flapping as a unit.

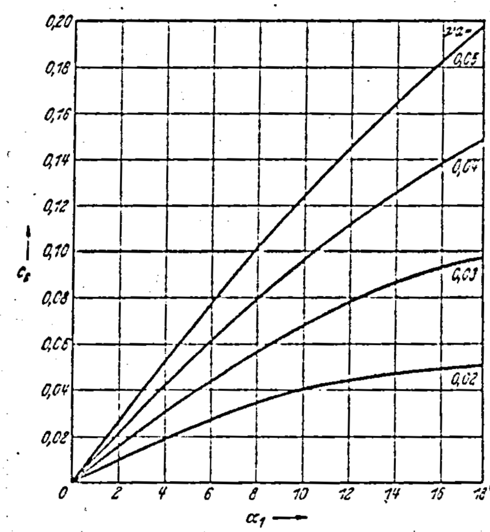

Figure 8: Thrust values $\bar{c}_s$ attained by the wing while swinging as a unit.

Of particular interest to us are the components of the air forces c_z in a vertical and c_x in a horizontal direction. We denote with

$$\gamma(\xi) = -\frac{d\zeta}{d\xi} = 2\pi\nu a \sin 2\pi\nu\xi$$

the angle between the path (incident flow direction) and the horizontal at every location ξ which, according to our assumptions, can be considered to be small so that sine $\gamma \approx \gamma$, cos $\gamma \approx 1$; then between c_x, c_z, and c_a, c_w the following relations* hold

$$c_z = c_a + c_w \cdot \gamma \approx c_a$$

$$c_x = -c_a \cdot \gamma + c_w$$

In this way we have the means to determine horizontal and vertical

* Vertical forces have a positive sign in an upward direction and horizontal have a positive sign toward the back. Thus the forward thrust has a negative sign.

forces at every point in the path. We calculate their average values over one wave length of the swing as:

$$\bar{c}_z = \nu \int_0^{1/\nu} c_z(\xi)\, d\xi = \frac{2\pi}{1 + 2/\Lambda}\, \alpha_0 = c_a' \cdot \alpha_0 = c_{a0}$$

and accordingly

$$\bar{c}_x = -\pi c_a' \cdot \sin\varphi \cdot \nu a \cdot \alpha_1 + \frac{c_{a_0}^2}{\pi \Lambda}\left(1 + \frac{\alpha_1^2}{2\alpha_0^2}\right) + c_{w_p},$$

where $c_{wio} = c_{a_0}^2 / \pi \Lambda$ is the induced drag which the wing would have if the onflow were stationary with an angle α_0. This equation shows that the average vertical force $\bar{c}_x$ is not changed by the swinging motion and that we have obtained indeed, beside an additional induced drag (swinging drag)

$$\frac{c_{a_0}^2}{\pi \Lambda} \cdot \frac{\alpha_1^2}{2\alpha_0^2} = \frac{c_a'^2}{2\pi \Lambda} \cdot \alpha_1^2$$

(which, incidentally, is exactly half the value as that associated with a stationary onflow at an angle α_1) also a force effective in the forward direction, the swinging forward thrust

$$-\pi c_a' \sin\varphi \cdot \nu a \cdot \alpha_1$$

In order to make this as large as possible, we must first set $\varphi = \pi/2$: the incident swing must lag the stroke swing by $\pi/2$ which is immediately clear. One further recognizes the need for a change in the incident angle because for $\alpha_1 = 0$ one obtains no forward thrust on the average. The forward thrust increases with increasing stroke amplitude ν a* and with increasing angle of attack amplitude α_1. However, both are limited in their upper values: ν by the assumptions of the quasi-stationary theory, a in practical cases for constructive reasons and α_1 by the requirement that the maximum angle of attack $\alpha_0 \pm \alpha_1$ must not lead to a detachment of the flow from the airfoil.

Since the drag resulting from the swinging motions at the same time increases as the square of α_1, it would be practical

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* $\nu a = as/\lambda$ is the stroke amplitude referenced to the wave length λ

to consider for which stroke - and for which angle of attack amplitude the examined swinging thrust produces the most favorable results. Therefore we define a propulsion efficiency* /355

$$\eta = 1 - \frac{\text{swinging drag}}{\text{swinging thrust}} = 1 - \frac{1}{\pi(\Lambda + 2)} \cdot \frac{\alpha_1}{\nu a}$$

Thus the propulsion efficiency increases with increasing stroke amplitude νa and with decreasing angle of attack amplitude α_1 (see figure 7). A greater aspect ratio of the wing also increases η. Except for very small stroke amplitudes $\nu a = 0.01$ we find efficiencies which equal those attained in propeller-driven airplanes. Whether one can utilize in practice the extraordinarily high efficiencies for small angle of attack amplitudes α_1 depends on whether the thrust $\bar{c}_s$ thus generated (= swinging thrust + swinging drag)

$$\bar{c}_s = -\pi c_a' \sin\varphi\, \nu a\, \alpha_1 + \frac{c_a'^2}{2\pi\Lambda}\alpha_1^2$$

is sufficient to overcome the stationary drag. For a quicker look at this question the thrust $\bar{c}_s$ has been plotted against α_1 in figure 8 for various values of νa. (For an airplane including fuselage and drive the drag $\bar{c}_w$ which must be overcome is of the order of 0.05 for horizontal flight).

In order to clear up the situation immediately for subsequent applications, let us consider several examples. For a given wing we have three mutually independent free parameters: the average angle of attack α_0 (or correspondingly c_{a_0}), the angle of attack amplitude α_1 and the stroke amplitude νa. A simple motion would be one where the angle of attack does not change

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*This is (for $\bar{c}_x = 0$) simultaneously the ratio of the power which we must input in order to overcome the stationary portion $c_{wi_0} + c_{wp}$ of the drag to the power which we must actually expend and which is greater than the first by the amount (swing drag x flight velocity).

($\alpha = \alpha_o$ = constant; $\alpha_1 = o$); the determining factor for the air forces that arise is the angle of attack with respect to a given incident flow direction, and not with respect to the horizontal. Thus at each point in the path we obtain the same lift c_{a_o}. While the forward thrust arising from the away-stroke of the wing is cancelled by a corresponding backward thrust as the wing returns (figure 9a). - A different limiting case is obtained if we set $\alpha_o = o$ and thus assume α_1 to be different from zero. In this case the lift generated by the away-stroke is compensated for by a corresponding negative lift for the return stroke. In this way we obtain for both motion phases a coinciding (but fluctuating periodically in its magnitude) forward thrust (figure 9b, solid curves). - Between these extremes different intermediate shapes are conceivable. Starting with figure 9b we obtain, for small average angles of attack, a corresponding small, but different from zero, average lift (figure 9c). Figure 9d represents a special case, to be mentioned later, where reverse thrust never occurs, but where forward thrust and lift temporarily become equal to zero during the return stroke. In figure 9e we approach the case for 9a; although we have a lower fluctuation in lift corresponding to low fluctuations in angle of attack, we only obtain a low forward thrust. The dashed curves plotted here show how the situation reverses if the swing of the angle of attack, instead of lagging, leads the stroke swing by $\pi/2$, a case to which we shall also return.

Until now we made the assumption that stroke- as well as angle of attack oscillations are sine-shaped. Let us quickly show that this fact does not affect the general validity of what has been presented here. This can already be seen from the fact that one can resolve any arbitrary curve into harmonic oscillations. For a non-sinusoidal path curve $\zeta(\xi)$ we can easily show in another way the truth of our statement that without changes in the angle of attack no forward thrust can be generated on the average. We only assume that $\zeta(\xi)$ is a periodic function (with the period $\lambda/s = 1/\nu$):

$$\zeta(\xi_0) = \zeta(\xi_0 + 1/\nu)$$

If $\alpha = \alpha_o$ = constant, then also $c_a = c_{a_o}$ = constant and c_{w_o} = constant.

The average forward thrust:

$$\bar{c}_x = \nu \int_{\xi_0}^{\xi_0 + 1/\nu} c_x(\xi)\, d\xi$$

is then because $c_x(\xi) = -c_{a_0} \cdot \gamma(\xi) + c_{w_0}$ and $\gamma(\xi) = -d\zeta/d\xi$ equal

$$\bar{c}_x = c_{a_0} \nu [\zeta(\xi_0 + 1/\nu) - \zeta(\xi_0)] + c_{w_0} = c_{w_0}.$$

An example of such a motion is shown in figure 9f.

Even for the case of non-sinusoidal angle of attack oscillations one can use the above treatment. Figure 9b presents an example in the dashed curves.

Constant incident flow velocity was another assumption. If this fluctuates about an average value v_o according to

$$v(\xi) = v_0 + \Delta v(\xi) = v_0 \left(1 + \frac{\Delta v(\xi)}{v_0}\right)$$

by the small contribution Δv, then one can easily show from Prandtl's airfoil theory that this change in velocity Δv corresponds to a change in angle of attack

$$\Delta\alpha = \alpha \frac{\Delta v}{v_0}$$

which furnishes a link to our earlier statements. In this way we could also, for example, obtain a forward thrust which does /356 not vanish, on the average, for the case of constant angle of attack $\alpha = \alpha_o$.

Until now we have not considered the third parameter, the stroke amplitude γa. The motion of the animal wing differs, as is well known, from that just treated by the fact that the wing is connected to the body so that the stroke amplitude increases toward the end of the wing. Thus the theory should be expanded such that "a" is inserted as being dependent on the coordinate y in the direction of the span width. Compared to the theoretical treatment this motion, aside from some insignificant disadvantages, has some primarily practical advantages. The main disadvantage

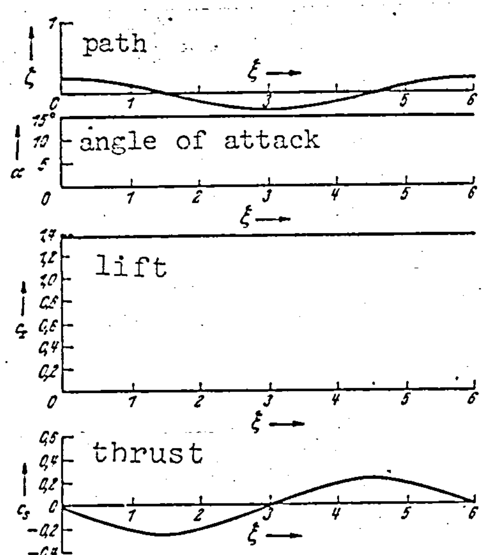

Fig 9a. $a = 0{,}2$; $\nu a = 0{,}033$; $\alpha_0 = 15°$; $\alpha_1 = 0$; $\bar{c}_z = 1{,}37$; $c_s = 0$.

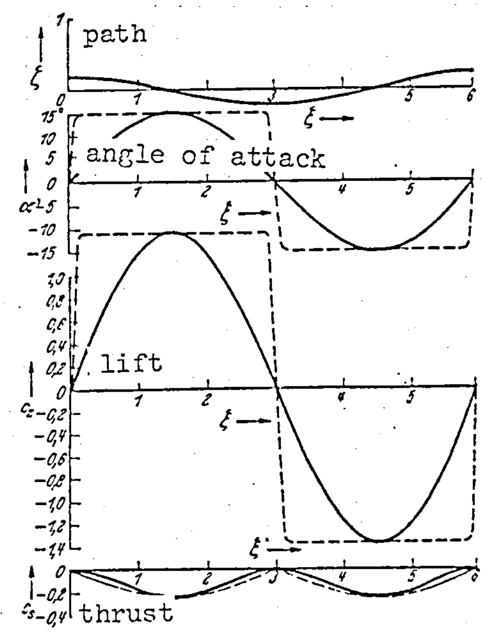

Fig. 9b. —— $a = 0{,}2$; νa $0{,}033$; $\alpha_0 = 0$; $\alpha_1 = 15°$; $\bar{c}_z = 0$; $c_s = -0{,}11$; $\eta = 0{,}79$.

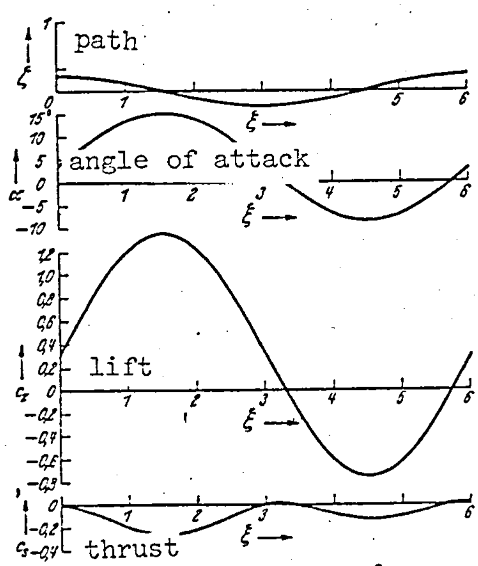

Fig. 9c. $a = 0{,}2$; $\nu a = 0{,}033$; $\alpha_0 = 3{,}75°$; $\alpha_1 = 11{,}25°$; $\bar{c}_z = 0{,}34$; $\bar{c}_s = -0{,}09$; $\eta = 0{,}84$.

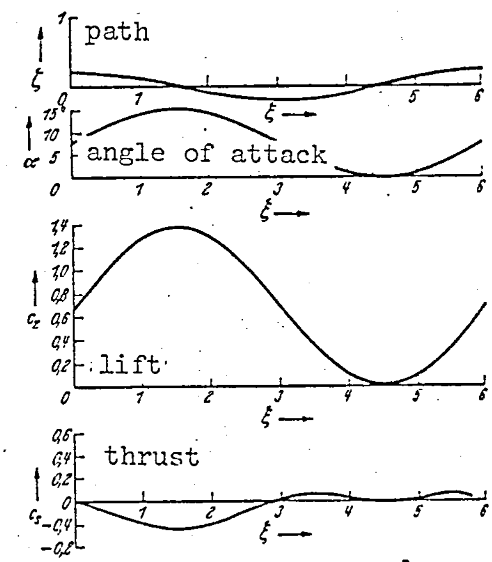

Fig. 9d. $a = 0{,}2$; $\nu a = 0{,}033$; $\alpha_0 = 7{,}5°$; $\alpha_1 = 7{,}5°$; $\bar{c}_z = 0{,}68$; $\bar{c}_s = -0{,}064$; $\eta = 0{,}90$.

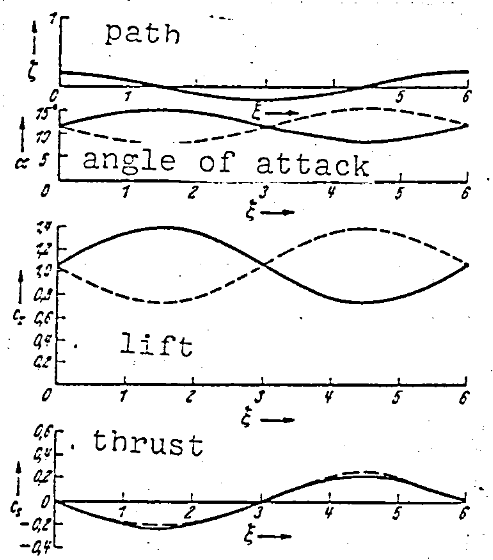

Fig. 9e. — $\varphi = \pi/2$; $a = 0{,}2$; $\nu a = 0{,}033$; $\alpha_0 = 11{,}25°$; $\alpha_1 = 3{,}75°$; $c_z = 1{,}03$; $c_s = -0{,}034$; $\eta = 0{,}95$.
— $\varphi = -\pi/2$; $a = 0{,}2$; $\nu a = 0{,}033$; $\alpha_0 = 11{,}25°$; $\alpha_1 = 3{,}75°$; $c_z = 1{,}03$; $c_s = 0{,}034$; $\eta = 0{,}95$.

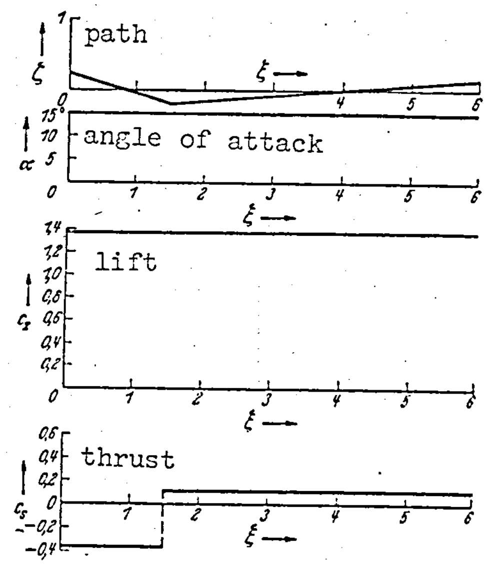

Fig. 9f. $a = 0{,}2$; $\nu a = 0{,}033$; $\alpha_0 = 15°$; $\alpha_1 = 0$; $\bar{c}_z = 1{,}37$; $c_s = 0$.

Figure 9: Various forms of motion and their associated air forces during a swing for the entire swinging wing.

could be in the fact that the lift distribution is no longer elliptical which would result in an increase of induced drag. However, one could conceive a motion for which the increasing stroke amplitude is accompanied by such a decrease of the angle of attack that the elliptical lift distribution would be retained. However, this type of motion would share a decisive disadvantage with the plate swinging up and down as a unit: the large fluctuation of the vertical force during one oscillation. However, this fluctuation must lead to an increasingly strong up-and-down movement of the center of gravity with decreasing stroke frequency, /357
everything else being equal. If we now consider large, slowly beating birds, we cannot observe a significant vertical pendulum movement of the body (in horizontal flight); only those shapes with very long wings and lightly loaded wing areas (such as sea swallows) exhibit this motion to a noticeable, but still lower degree. The compensation of this vertical motion, however, is made possible for an angular movement, as performed by animal wings, by the fact that individual wing zones have different stroke amplitudes and that they can thus assume different functions. How this is possible will be explained in the following by means of flight models.

V.

In this place we shall not go further into the history of the swinging-flight model construction ("full swinging" model) - a long chapter if we consider the number of people who have investigated this area and a very short one if we consider the results. - As far as we know nobody has surpassed the results of Pénaud which go back a long way and who in 1870 succeeded in lifting off the ground a small model with elastic wings by means of a rubber motor and simple crank drive (in a type of motion which one could designate as "shaking"). The main difficulties of a true-to-nature simulation of the motion lie first in the proper combination of stroke and turning motion of the wing and secondly in the not less important, but always ignored proper force

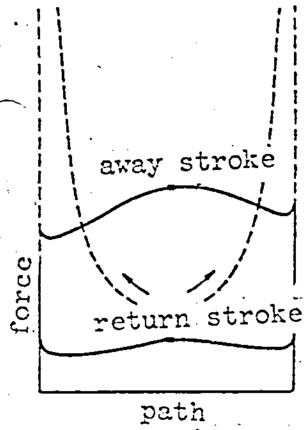

Figure 10: Force expended by the engine on the wing versus path during a swing of the flight model (cf. figure 13) used as example. For a comparison the force distribution for crank-mode thrust/drive (dashed curve) -

distribution (the almost always employed thrust-crank drive is not suited for this purpose, compare also figure 10), and finally in the production of a stable flight position. A more detailed description of how these 3 problems are solved by the flight model constructed by us, is beyond the scope of this paper. The following general statements should suffice.

As far as the motion of the wing itself is concerned, stroke amplitude, changes of angle of attack, and twist of the surface along the span width, are variable and can be adjusted as desired. The distribution of forces during a stroke phase can also be varied within wide limits, as well as the force ratios between the lifting and return stroke of the wing which can vary a great deal among the individual animal flight modes. A compensating drive takes care that the tension of the rubber motor which is decreasing as the wings continue to flap, do not affect the flight movement; /358 the flaps of the wing can be produced, as desired, with equal or gradually or suddenly increasing resp. decreasing force. The flight model can easily start from the ground and can rise at an angle of above 45°; some can also shake temporarily in place. For the models built to date with 0.3 to 2.2 m span width flight durations of 20 to 60 sec were attained; a powered flight is followed by a glide. The general stability, even for "only-wing" models, is good beyond expectation, even in strongly agitated air. Some typical flight pictures are shown in figures 11 and 12.

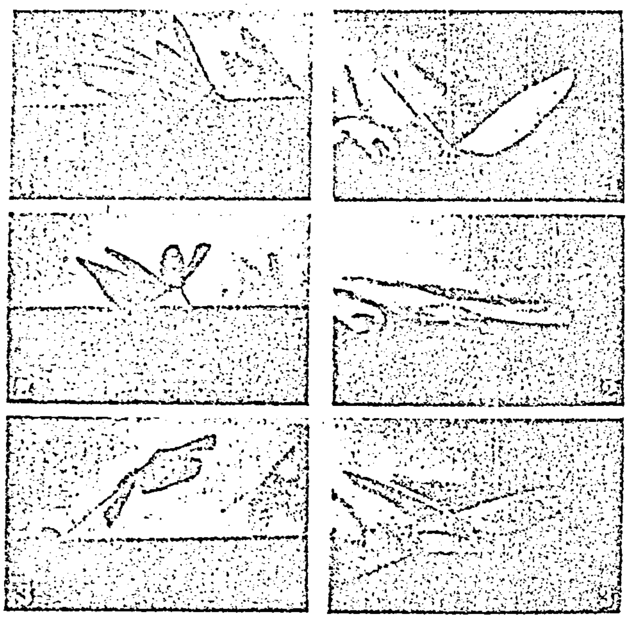

Figure 11: Pictures from slow-motion photographs of two swinging-flight models; left: model with simple slot wing, at an ascension angle of about 40°, "greatly shaking", right: another model during ground start (cf. also curve from fig. 13 taken with same model). Sequency of pictures: 1) upper reversal point 2) "away" stroke 3) return stroke. The rubber motor is located in the wing (below the wing leading edge) in the left model and in the lower cross tube of the drive frame for the right-hand model.

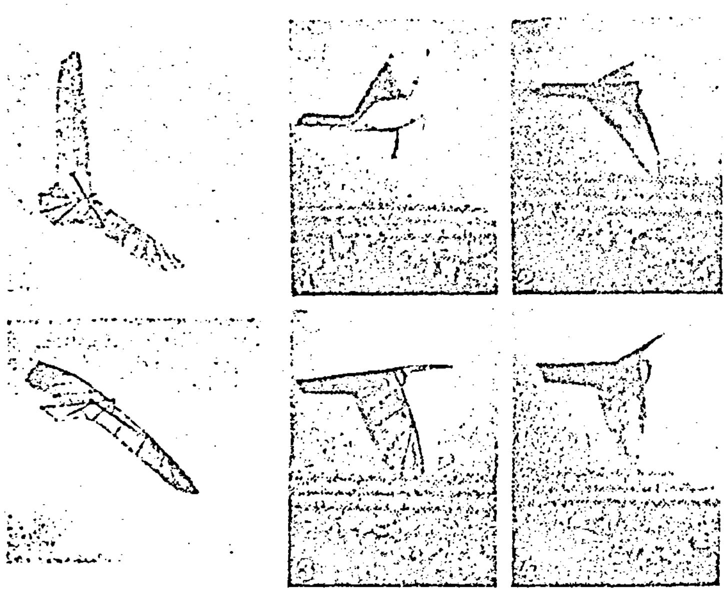

Figure 12: High-speed photographs of a free flying "wing-only" model with views from below and from the side.

Let us still mention here that we were primarily concerned with proving, above all, the possibility of simulating animal flight modes - primarily we were occupied to date with the flight modes of the medium-sized to large birds, the bats, the flying lizards*, the dragonflies, and the larger butterflies -; a detailed simulation of the mode of movement of an individual flying animal has not been attempted to date but should be attainable** without too much difficulty on this basis. For the objective pursued by us here, namely to furnish "proof of existence" for the new method, it should be sufficient to present more accurate data for a single example and, with their aid, to examine more closely several remarkable points.

Figure 13 shows the curve-shaped evaluation of a flight path taken with time-exposure photography; the model starts without assignment of initial velocity in a "jump start" from the ground. /359
The middle zone of the curve shows the picture typical of this flying mode. The center of gravity first exhibits a certain weak periodic motion normal to the mid-path direction. (It should be mentioned that for horizontal flight this pendulum movement

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*The flight technology of the pterosaurs and their particular, interesting problems shall be reported in another place based on extensive model tests; it shall only be mentioned here that the flying mode can also be simulated in the model by means of an elastic flying membrane attached only at the front edge such as is typical for such animals (the enormously elongated fourth finger represents a stirrup-like device).

**Various models have often been demonstrated to the public, such as during the model contests of the NS Flying Corps in Breslau where they were awarded prizes; also in a presentation made by the author (v.H.) to the session of the Lilienthal Society for Aeronautic Research on 29. I. 1941. Description of the flight performance in Breslau are found in W. Haas (Luftfahrt u. Schule 6, 22, 1940; in the same volume one can find a presentation by v. Holst about the same subject) and also by H. Winkler (Modellflug 6, 2, 1940) who also presents the kinematics of the Breslau models.

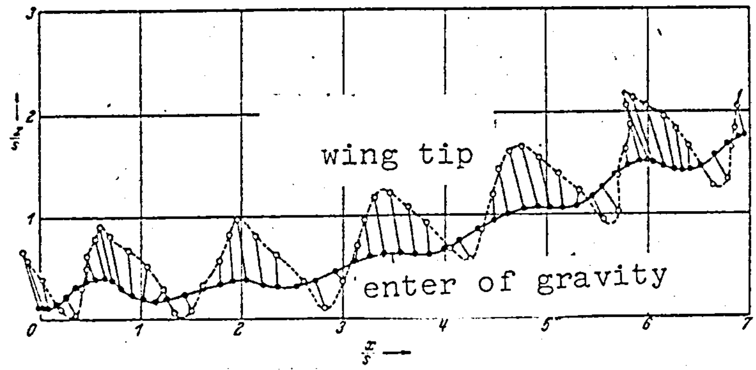

Figure 13: Motion of the center of gravity and the wing tip in space (x - axis toward front, z - axis upward; S = half span width) at the start of the model used as example. Time interval between two data points: 3/80 sec. (Evaluation of a film strip with 80 frames per second).

disappears almost completely, just as in birds). In the second place there are periodic velocity fluctuations whose magnitude can be readily seen by the data points separated by equal time intervals: an increasingly steeper path is accompanied by an increase in velocity. An attempt to draw conclusions as to the effective air forces from the movement of the center of gravity will not be made here. Similarly the very evident fact that the expected increase in velocity and height resulting from away-stroke from the wing materialized only much later (namely during the return stroke!) shall only be mentioned here. For the given distribution of forces during wing off- and back stroke shown in figure 10 the average velocities of both movements (such as for many birds) approximately agree with each other. However, a somewhat smaller, but distinct delay is noticed at the upper reversal position of the wing motion: the model remains somewhat longer in the stationary flight position with raised wings than in the unstable position with lowered wings.

In the following table in addition to several general facts concerning the model, a number of evaluated data for the average flight path of the curve in figure 13 are presented.

Table

span width 2 s	0.8 m
wing area F	0.07 m^2
weight G	0.007 kg
wing loading G/F	0.1 kg/m^2
engine power N	0.00035 horse power
power loading G/N	20 kg/horse power
stroke angle	60^o
average ascension angle	18^o
average frequency n	2.7 sec^{-1}
average velocity of center of gravity $\bar{v}_s$	1.8 m/sec
average velocity of wing tip	3 m/sec
α_o at base of wing	$\approx 15^o$
α_1 at base of wing	$\approx 5^o$
α_o at wing tip	$\approx 3^o$
α_1 at wing tip	$\approx 17^o$
average lift coefficient $\bar{c}_a$	0.49
average drag coefficient $\bar{c}_w$	0.37
average thrust coefficient $\bar{c}_s$	0.52
reduced frequency $\nu = ns/\bar{v}_s$	0.6
Reynolds number Re = $\rho \bar{v}_s F/2\mu s$	10^4

For the low weight the area loading of the model is smaller by an order of magnitude than that of birds of corresponding size. In connection with that the average velocity of the center of gravity is also noticeably smaller. This, however, causes a relatively high reduced frequency for the given stroke frequency which is not reduced to the same extent. It shall be the job of the future to produce swing models which, with respect to area loading, velocity - and thus Reynold's number - as well as with respect to reduced frequency agree with those of flying animals.

Compared to values conventional in airplane construction (2 to 8 kg/HP) the power loadings seem to be extraordinarily high. Here one should note, however, that this value is a function of the absolute size. If we denote the ratio of the linear dimensions of two airplanes under consideration with $\chi = l_{model}/l_{airplane}$ then it is customary to assume that the weights vary as χ^3. In our case, however, the weight of the model is so small that for G one should employ a change of at least the 5. power of the length dimensions. If we assume that the air forces are comparable for both cases, then we can show by the methods of similarity mechanics, which we cannot discuss here in detail, that in our case the ratios of the power loadings* must be $\chi^{-3/2}$. In this way we obtain, starting with the model, an airplane with a power loading below 1 kg/HP; this means that the model has an extraordinarily large engine compared to its size. - In addition this consideration shows that flying machines and flying animals, as long as the air forces remain comparable, achieve the same flight performances for decreasing absolute /360 size with a less powerful engine relative to their weight.

The laws of similarity mechanics, touched upon here, can also be of service in other areas. Thus with their help it is possible to evaluate many data obtained from aircraft construction in the analysis of animal flight and, on the other hand, to compare different flying models.

The relatively straight-line motion of the center of gravity, despite its low weight and slow flapping frequency, allows one to conclude that the vertical force fluctuates only little during a swing. This brings us to the problem, mentioned above, of the division of functions along the wing span width. LILIENTHAL** had already assumed that in birds the wing area near the body preferentially provides steady lift while the wing tips provide

*If we assume that the weights vary as χ^3, then the power loadings vary as $\chi^{-\frac{1}{2}}$.

**O. LILIENTHAL, Flight of birds as a basis for the art of flying, 3rd edition, Munich and Berlin 1939.

forward thrust. Although our evaluation method has not attained the desired accuracy in this connection*, we can see indeed in our example that the zone near the body functions with a low angle of attack amplitude and a large angle of attack while, reversely, the wing tip functions with a large angle of attack amplitude and a low average angle of attack. The angle of attack ratios in our case thus qualitatively correspond, at the base of the wing, to those of figure 9e (those of the dashed curves) and at the wing tip to those of figure 9c. This shows that, on the outer wing zone, the incident flow during the return stroke is from above thus providing not only forward thrust but also negative lift.** This negative lift, however, is partially compensated by an additional lift by the zone near the body. Between the wing tip and the body there is a wing cross section against which the incident flow occurs at an angle of attack equal to zero (figure 9d); this location moves, on wing contact (with the body) starting with the tip first to the inside and then back again. - As the wing flaps away, we obtain lift and forward thrust at all positions of the span width; the latter is produced here mainly by the wing tip since this has the highest stroke amplitude.

The example shown here represents an average case insofar as an additional increase of the wing section experiencing negative onflow during wing contact as well as a decrease of the same toward zero is possible. In the first case we approach a shaking flight mode in whose extreme case, stationary flight, the entire

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*Since for the models used by us to date the mechanically produced motion of the wings was still modified by its elasticity, a completely accurate determination of the motion is only possible with the aid of time exposures.

**Let us mention again that figure 9 is valid only for the theoretical case where each incremental area of the span width produces the same motion. For a quantitative statement one would have to take into account, in our case, the mutual effects of the individual wing cross sections (which have different motions).

surface experiences alternately positive and negative flow; in the other case we approach a flying mode which occurs for probably many birds (surely ring doves) in fast horizontal flight. Final determinations in this regard have yet to be made.

The given air force coefficients $\bar{c}_a$, $\bar{c}_w$, and $\bar{c}_s$ were not obtained from a quasi-stationary theory in the above sense, but from equilibrium conditions for the stationary ascending flight. If γ_o is the average path angle, the average lift $\bar{A}$ of the weight components $G \cdot \cos \gamma_o$ must maintain equilibrium and also the average thrust $\bar{S}$ must be equal to the average drag $\bar{W}$ increased by the weight component $G \cdot$ sine γ_o:

$$\bar{A} = G \cdot \cos \gamma_o$$

$$\bar{S} = G \cdot \text{sine}\, \gamma_o + \bar{W}$$

In these equations G and γ_o are known, as well as S which can be calculated from the engine power N (in HP) and the average velocity $\bar{v}_s$ of the center of gravity:

$$\bar{S} = 75\, \eta N / \bar{v}_s$$

Let us now assume an efficiency of 0.5 since this also includes operating losses, etc. In this way we obtain $\bar{A}$, $\bar{W}$, and $\bar{S}$ and from them their coefficients. This can be explained, among others, by the steepness of the flight path (the path angle at every point is considerably greater than was assumed in the quasi-stationary theory) whereby a not lower component of the lift, referenced to the average path direction, appears partially as drag and partially as thrust. It should be mentioned that a coarse estimate using a quasi-stationary theory leads to similarly high values. As a comparison, figure 14 shows a short flight path of another model with an ascension angle of 40^o. The still steeper path (the flying mode already approaches the shaking mode) with a reduced frequency $\nu = 0.9$ gives still

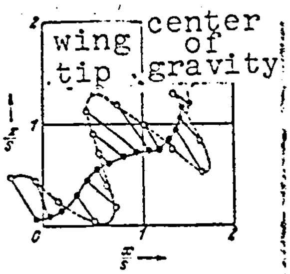

Figure 14: Motion of the center of gravity and the wing tip in space during ascending flight of another flight model. Details as in figure 13.

greater coefficients: $\bar{c}_a = 1.2$; $\bar{c}_w = 1.1$; $\bar{c}_s = 2.4$. All these coefficients are referenced to the average velocity of the mass center of gravity.

VI.

Let us add a few short thoughts to the discussion of the wing movement itself and its effects concerning the stabilization of the entire flight apparatus. Since the wing, as we saw, /361
had to execute an accurately dosed rotation about its longitudinal axis the question arises, above all, how the thus arising torques about the transverse axis of the flying animal resp. the flight model are compensated. Observations of nature have taught us that for larger or at least more slowly flapping flight animals essentially two possibilities have been realized. Either a special surface, separated from the wings has been attached - the tail for birds and the main plate for certain flying lizards with long lizard tail - at the rear end (figure 15 a-c); or the rear mid-zone itself of the wing surface assumes the stabilizing function as shown by bats and also by other flying lizard types as well as by the larger butterflies which, in this regard, fly like bats (figure 15 d-f). Both types of stabilization can also be simulated in the flight model. Our tests to date in this direction showed that, for the second type, the corresponding rear wing zone, although capable of producing the up and down motion of the wing, could naturally not take part in any rotation about the longitudinal axis of the wing (compare figure 12 where one can recognize in the photos taken from the side this movement

of the "tail-part" of the wing). Furthermore it was shown that, for the flight model, the size of this area section could not go below a certain minimum so as not to destroy the stability of the transverse axis (for the "only flying" model of figure 12 b, for example, a reduction of this rear wing section by one third prevented a stable flight). In comparison this zone can be reduced considerably more for flying animals (many bats and presumably also flying lizards); birds are still able to fly even with a complete loss of the tail surface. In this connection the birds are clearly superior because they can master even an unstable flight position by means of reflex corrections. There are several means which they can employ here; exactly how they do this can only be determined with the aid of good moving pictures.*

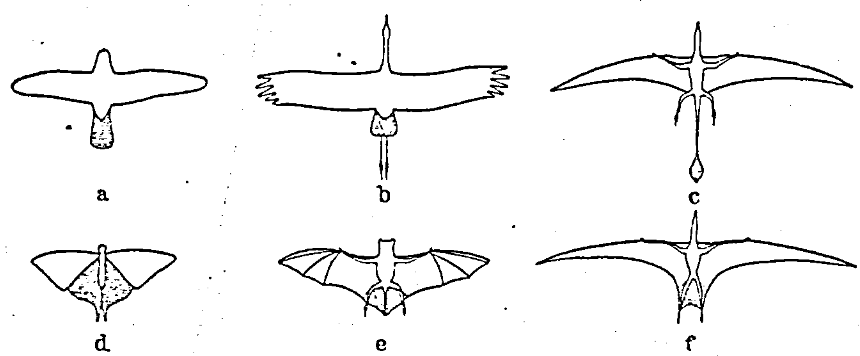

Figure 15: Position of stabilizing surface (cross-hatched) for various flying animals; a) and b) birds c) flying lizards of the type Ramphorhynchus, d) butterflies, e) bats, f) flying lizards of type Pteranodon.

Furthermore the mass of the body can contribute in different degrees to the torque equalization about the transverse axis. For birds with long neck and long legs the stretching of these members in a forward and backward direction, i.e., far removed from the point of rotation, can play a certain, although subordinate

*K. Lorenz writes that a tailless buzzard could fly with definite difficulty (with stabilizing forward and backward motion of the wing) while tailless crows could fly without any visible impairment.

role. (figure 15 b). In flight positions where, for the lack of sufficient flow the tail surface can hardly be effective, such as flight in place, the center of gravity (at least for more slowly beating types) is located as low as possible (figure 4 b). In very many insects which specialize in this "in place" flying mode, a special stabilization is not even present.

Special attention must be paid in this connection to the flight of the dragonflies which, as is well known, possess /362 the capability to move their two wing pairs in opposite senses, i.e., with timed phase intervals of a half swing. The advantage of such a flying mode lies in the fact that the differences in the effect of away-and-return stroke are mutually compensated since both motions are carried out simultaneously by one pair of wings each. The mass center of gravity can thus, in contrast to the flying mode of birds, bats etc., describe a straight-line path with almost equal velocity. The disadvantage lies in the appearance of a considerable angular momentum about the transverse axis because of the distance, in the longitudinal axis direction, of the pressure points* of both pairs of wings (cf. figure 16 a).

The dragonflies first compensate this disadvantage by a very strong stretching of the body mass - the typical thin, long dragonfly body is, without a doubt, a correlative of the flying mode - and then, as it appears, by maintaining a relatively high flap frequency; for smaller required air forces the amplitude is obviously reduced preferentially, and not, as otherwise customary, the frequency.

The flying mode of the dragonflies can be simulated in the flight model considerably more easily than that of the birds. The relatively slow flap frequency of the models built by us to date (span width not below 30 cm) really requires the installation

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*Here the pressure point means the center of gravity of the lift distribution of the right and left wing, taken separately.

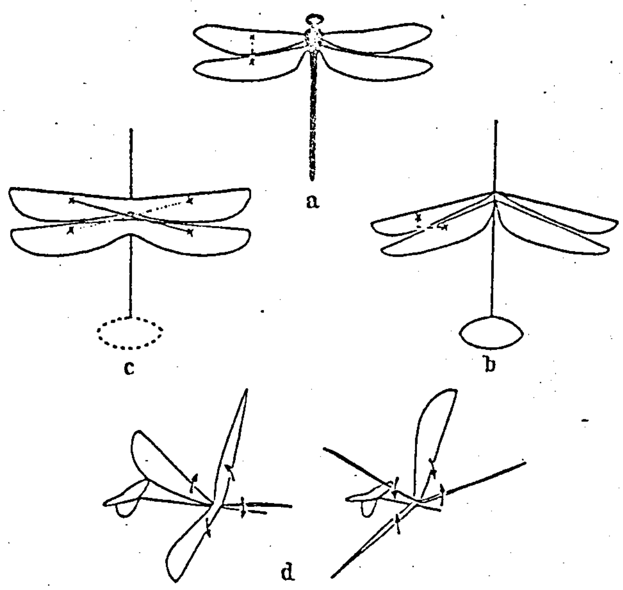

Figure 16: a) Physical appearance of a dragonfly; b) and c) flight models according to the dragonfly flight principle. In b) the flight pairs are moved alternately as for the dragonfly, and in c) alternately cross-wise. The crosses denote the given positions of the pressure points. d) sketches of two typical wing positions of the model c) (from movies); the small arrows denote the flapping direction, at the moment, of the wings.

of a tail surface for additional momentum equalization. One can reduce this torque greatly by allowing the wings to slant toward the rear (figure 16 b) which makes possible to bring the pressure points closer in the direction of the longitudinal axis; it can be eliminated by allowing the wings to flap toward one another in a crossing mode (figure 16 c,d). In this case a stable flight (for not too low a flap frequency) is entirely possible even without any additional surface, such as for the dragonflies themselves. For larger construction sizes, however, a certain moment about the vertical axis necessitates at least a vertical stabilization surface while an additional horizontal one increases flight safety.*

These brief dissertations concerning what has been achieved to date in swing-model construction were intended only to show that a definite starting point for exact measurements has been achieved; however, a thorough continued development of models for particular measurement purposes is required. In conjunction with a theory still to be established it would then be possible to determine the effect of the peculiarities of wing motions, the role of the absolute size, of the shape of the wing and wing loading, and thus, in connection, the reduced frequency and the Reynolds number, the effect of force distribution, the mutual effects of several surfaces (fore-wings, slot wings, double wings of dragonflies and grasshoppers, etc.), the various possibilities for control and stabilization, and many others. Thus the necessary exact foundation would be provided for a future development of human flight technology in this direction - a possibility which can neither be proven nor disclaimed today.

It is hoped that close cooperation between biological and physiological, physical-technological and aerodynamic methods and viewpoints would soon lead to the formation of a new fruitful branch of German science, flight biophysics; this should be forthcoming from this area of research which offers many interesting facets in various directions and which till now has been greatly neglected either because of the difficulties or because of objections to rather uncritical, optimistic presentations or because of the feeling that man is finally superior to nature. It is hoped that this presentation will furnish inspirations in this direction.

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*A flight model of this type with 0.5 m span width was able to carry out, at the above-mentioned Breslau contest, steep flights of 6-7 m above starting height and of up to 44 sec duration.