TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 264

A METHOD FOR THE INSTANTANEOUS DETERMINATION OF THE VELOCITY AND DIRECTION OF THE WIND.

By E. Huguenard, A. Magnan and A. Planiol

From "La Technique Aéronautique": 1923, Nov. 15 and Dec. 15;
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A METHOD FOR THE INSTANTANEOUS DETERMINATION OF THE VELOCITY AND DIRECTION OF THE WIND.*

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The experimental investigation of all aerodynamic phenomena rests on the determination of the velocity and direction of the wind with relation to the surfaces it encounters. A knowledge of the velocity and direction of air currents is also necessary for the determination of the mechanism of soaring flight. Especially in soaring flight with a horizontal wind, a practical solution of the problem can be reached only by seeking to determine the available portion of the wind's energy and by thus discovering the probable amplitude and period of the variations in the velocity of a given wind. In fact, when the law is discovered, which gives the velocity of a wind, supposedly horizontal and of constant direction, as a function of the time, it will be possible to calculate the energy a bird or a soaring airplane can draw from such a wind, on condition of having determined the piloting maneuvers to be made at each instant.

Unless proper instruments for the instantaneous determination of the wind's direction really exist, instruments for measuring its velocity cannot, in their turn, give accurate results.

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* From "La Technique Aéronautique": 1923, Nov. 15, pp. 798-806; Dec. 15, pp. 854-862; 1924, Jan. 15, pp. 7-16; Feb. 15, pp. 47-58.

We have already shown, among other things that, for small velocities of only a few centimeters per second, the functioning of ordinary anemometers is uncertain, by reason of the small air stresses. In a feeble wind, an anemometer starts with difficulty on account of the excessive friction. After starting, it does not closely follow the fluctuations of the wind, because it generally has considerable inertia. We find, in fact, that for an initial velocity of 5 m (16.4 ft.) per second, some anemometers require two seconds to stop in still air from the effect of friction. Hence it follows that, if the intervals of time between the gusts registered by the instruments are relatively near enough to those actually existing in a natural wind, the amplitudes of the velocity variations are, on the contrary, considerably smaller than normally. For this reason the anemometer records do not correspond to the reality, but are more or less distorted.

Instantaneous Determination of the Wind's Velocity

For the purpose of making an accurate study of the motions of the air, not from the viewpoint of their mean manifestations but rather from that of their instantaneous phenomena, we have invented several recording instruments based on the employment of hot wires, which are much more sensitive and accurate and which have the additional advantage of introducing into the wind to be studied only a very small object, which does not affect its character. We have prosecuted our researches partly in the Laboratory of Experimental Mechanics of the Faculty of Sciences, and partly in the Physical Laboratory of the "Conservatoire national des Arts et Métiers," thanks to the very great kindness of Messrs. Koenigs and Violle, members of the Institute; Auclair, President of the Committee on Mechanics at the Patent Office; and Lemoine, Associate Professor at the "Conservatoire des Arts et Métiers" (Conservatory of Arts and Crafts).

Previous Work.- Researches had already been made on this subject, during the past 15 years, in Germany, Italy and especially in England. We will mention only the researches touching the question of the instantaneous determination of the wind's velocity by the aid of hot wires.

Bordoni ("Nuovo Cimento," April, 1912, p.241) constructed a Wheatstone bridge, which is in equilibrium when the anemometer wire, inserted in one of the arms, is cold. After the wire is heated by an alternating current under a constant efficacious tension, the galvanometer readings l_1 and l are taken, the former in still air and the latter in air having a velocity of v. The ratio $\gamma = l/l_1$ depends, according to Bordoni, only on the velocity v, if the temperature of the wire is not too high. Bordoni employed copper wires heated about 15°C (27°F) above the temperature of the surrounding air. Figure 1 shows a calibration curve obtained by him with a copper wire of 0.11 mm (0.0043 in.) diameter.

Gerdien ("Berichte der deutschen physikalischen Gesellschaft," 1913, No. 20) placed in an air current two arms of a Wheatstone bridge, consisting of a long zig-zag platinum wire, so that the air current first struck the portion of the wire forming the first arm, became heated and passed to the second arm, which, being cooled less, remained warmer and destroyed the equilibrium of the bridge, so that the galvanometer needle was deflected. Gerdien resorted to this method, in order to make the zero of his galvanometer more constant. This explanation shows that he was troubled by the excessive sensitiveness of his instrument for very feeble air currents, which is its immediately apparent characteristic. Figure 2 shows the calibration curve he obtained.

Louis Vessto King ("Transactions of the Royal Society," London, 1914, p.273, and "Phylosophical Magazine," 1915, p.556) studied the question from the theoretical viewpoint and showed that, for a difference of θ° in temperature, the quantity of heat q taken from the wire by an air current of velocity v is $q = \theta\ (a + b\sqrt{v})$, a and b being constants and the a verified experimentally.

For these measurements King used a Kelvin bridge and platinum wires. Figure 3 is a diagram of the arrangement a, b, α and β, being great resistances in comparison with d and c, which is the platinum wire. We have $a = b$ and $\alpha = \beta$ and the bridge is in equilibrium when $c = d$. P is a battery, A an ammeter, G a galvanometer and R an adjustable resistance. R is adjusted so as to reestablish equilibrium in the bridge, while causing the ammeter A to vary, which indicates that King worked at constant temperature. The calibration gives $i^2 = i^2_\theta + K\sqrt{v}$, in which $v = 10$ m (32.8 ft.)/sec., $i = 2^a$ (about) and $\theta = 10000$ (about). It may be deduced that the platinum wires employed had a diameter of 0.1 to 0.15 mm (0.0043 - 0.0059 in.).

The foregoing leads to the conclusion that the object pursued by the persons mentioned was very different from ours and that their methods are not applicable to the problem under consideration. In fact, Bordoni's method combines with the very unfavorable calibration curve a serious difficulty as regards temperature correction, since, in order to obtain accurate results, the temperature of the air must be known to a very fine degree of precision.

Gerdien's method, without being quite so unsatisfactory, is not perfect from this viewpoint. Moreover, it is of no use in a wind of variable direction.

Lastly, the method of Vessot King is not applicable to the case in hand, since it explicitly assumes that equilibrium must be established between the two arms of the Wheatstone bridge, which involves the necessity of a uniform flow of gases. Moreover, the sensitiveness of his device decreases rapidly, as the wind velocity increases.

It is therefore important, in order to solve this new problem of the instantaneous determination of the wind, to invent a new device, capable of always meeting the requirements from the viewpoints both of precision and sensitivity. The results of our studies in this connection are given below.

Conditions of the Problem.- The apparatus must record automatically, without any assistance from the operator, the different values of the wind velocity, follow the fluctuations of the velocity in their most rapid changes and be, in so far as possible, sensitive only to the velocity.

Hence it was necessary to employ only very fine platinum wires, in order to obtain static equilibrium in a very short space of time and also to heat these wires very strongly, in order to avoid the necessity of making corrections for variations in the temperature of the air. The latter condition necessitates the employment of platinum, the only metal with a high melting point and specific heat which is not affected by a high temperature in the presence of air. Unfortunately, fine platinum wire, being but little used, is made in only a few sizes, namely: 0.025, 0.05 and 0.1 mm (0.001, 0.002 and 0.004 in.). In order to avoid difficulties in obtaining wires, we limited ourselves to these diameters, which complicated the question somewhat.

Lastly, the electric instruments and, more especially, the galvanometers employed had to be capable of following the thermal, and hence electric, variations of the wires. We were therefore obliged to have sensitive instruments, of short period and suitably damped.

Numerous tests have already put us in possession of two different methods for solving the greatest difficulty of this problem, which is to obtain an instrument with sensitiveness independent of the velocity, a new condition which we have adopted and which does not seem to have received the attention of our predecessors.

In fact, if we confine ourselves to joining in series a source of electricity, an anemometric wire heated by the current from said source and an instrument for measuring current intensity, we find that the latter increases with the velocity of the wind, at first very rapidly and then more and more slowly, as shown by Figure 4. The sensitivity of the instrument, represented by the slope of the tangent to this curve, decreases in the ratio of 24 : 1 when the velocity increases from 0 to 16 m (52.5 ft.) per second. The scale derived from this curve for the graduation of the instrument is manifestly almost non-utilizable beyond very restricted limits. We corrected this defect by making our anemometers compensative, the first one having been the subject of a communication to the Academy of Sciences (Huguenard, Magnan and A. Planiol, "Sur un anémomètre à fil à compensation," C. R. de l'Académie des Sciences, January 29, 1923).

Anemometer with Compensation by Wire.- Figure 5 shows the arrangement we adopted. A battery B_1 produces a current i_1, which traverses and heats the platinum anemometer wire F. A fine platinum wire S is mounted in the circuit, forming a shunt to the terminals of the galvanometer G. A second battery B_2, in opposition to B_1, is connected to the terminals of S, with the interposition of a variable resistance R, thus rendering it possible, when no wind blows on F, to annul the current in the fine wire S, which then has the temperature of the surrounding air.

If we suppose the resistance R to be very great in comparison with all the others, thus requiring a very large electromotive force for B_2, we may neglect the variations in the intensity i_2 of the current passing through the shunt B R_2. Then the intensity i_1, of the current passing through the anemometer wire F, will vary under the influence of the variations in the resistance of F due to its cooling. Let us therefore assume i_2 to be constant, with the value of i_0, which is the value of i_1 for $v = 0$.

The current passing through the fine wire S will accordingly be $i_1 - i_0$ and the amount of energy expended on S will be $r(i_1 - i_0)^2$, r being the resistance of the shunt S. Its increase, in terms of $i_1 - i_0$, will be very rapid, when v increases, by reason of the correlative elevation of the temperature of S, which greatly increases its resistivity.

Experience has demonstrated the necessity of:

1. Making S long enough, so that the loss of heat at the ends of the wire will not too greatly affect the mean temperature of the whole;

2. Making S short enough, so that its resistance will be small in comparison with that of F;

3. Making S of smaller diameter than F, so that it will

promptly follow the variations of F and be sufficiently heated by the current $i_1 - i_0$ passing through it.

With an anemometer wire F of 0.05 mm (0.002 in.) diameter, the best results were obtained by making the shunt S from a wire of 0.025 mm (0.001 in.) diameter, with a length of 10 mm (0.4 in.). Figure 6 shows the curve experimentally obtained, under these conditions, by letting the abscissas represent the velocity of the wind in meters per second and the ordinates represent the excess of the difference of potential e, at the terminals of the shunt, for the velocity v, over the initial value e_0 for $v = o$, the arbitrary unit being taken equal to $e_{14} - e_0$.

The electromotive force of the batteries B_1 and B_2, is respectively 24 and 96 volts. We then have $i_0 = 0.7$ ampere for $v = o$ and $i_1 = 1$ ampere for $v =$ about 15 m (49 ft.) per second. The resulting value of R is about 140 ohms. The variation of the current i, furnished by B_2, is, in this case, reduced to only a few milliamperes at the most and exerts no unfavorable influence on the output of S. A comparison of the curves of Figures 4 and 6 shows the advantage of this method. The scale of graduation in wind velocities (Fig. 6) is almost regular and the ratio of the slopes of the extreme tangents has here fallen to 1.4.

The records, represented by Figure 7, obtained during the first compensation experiments, are among the most interesting, because they show how promptly the hot wire follows the variations in the velocity of the wind. The anemometer wire was placed near a propeller blowing toward it and driven by an electric motor. The record was made, on a drum covered with smoked paper, by a hollow glass stylus drawn very fine and carried by the movable coil of the recording galvanometer.

When the propeller was motionless and the air calm, the stylus traced the horizontal line at the top of Figure 7, whereas the record made while the propeller was running, indicated, by its perpetual oscillations, the irregularity of the air current supplied by the propeller, the mean velocity of the air current being also measured by a wind-wheel anemometer.

It can be easily demonstrated from Figure 7 (which is a photographic reproduction of the original record, without retouching) that the number of oscillations, in any given section, is proportional to the revolution speed of the propeller.

On the other hand, the motor and propeller, mounted on a concrete base at about ten meters (32.8 feet) from the recording apparatus, transmitted no mechanical vibration to the latter. It is therefore well demonstrated by these facts that the oscillations in the record are due alone to the temperature variations of the hot wire caused by the variations in the velocity of the air current produced by the propeller. The coil employed, when placed in the field of a permanent magnet and brought, for these records, to the critical damping point, possessed, in fact, a period proper of 0.13 second, a period which would have put it in resonance with the passages of the propeller blades revolving at about 230 R.P.M. It may be remarked that it is impossible to show on the record any exaggeration of the amplitude at 234 R.P.M., which practically corresponds to the resonance, which in turn shows that perfect damping of the coil was obtained. It is also observed that the sensitivity of the latter was sufficiently great to enable it to follow at higher revolution speeds, though with a somewhat smaller amplitude, velocity variations of a shorter period than its free oscillation. The first instrument constructed on this principle was exhibited at the last "Salon de l'Aeronautique."

Since that time we have not ceased to make improvements. We first replaced the method of recording directly on lamp-black by the photographic method of Poggendorf, consisting of a small mirror attached to the galvanometer coil and projecting a spot on a strip of bromide paper, which is unrolled at the proper speed.

We employed a much smaller coil, whose moment of inertia was about 0.23 g/cm^2 (.0033 lb./sq.in.), with a period of only 0.02 second, while that of the coil for direct recording was 0.13 second. The first result was obtained by means of a test instrument, whose coil contained only a relatively small number of turns (less than a thousand) of quite large wire and was mounted in the air-gap of a not very suitable electromagnet. It is evident that only a specially calculated galvanometer can render it possible to reduce the period greatly and, at the same time, increase the sensitivity, i.e., the consequent damping upon which the accuracy of the records depends.

This instrument satisfactorily fulfills the conditions required for making instantaneous records of the wind velocity. It is practical and convenient, since the adjustments are easily verified by means of two ammeters giving the intensities i_1 and i_2. Two voltmeters may also be advantageously employed for obtaining the differences of potential at the terminals of the wires F and S. It is quite certain that, if the current in the two wires is always referred to the same initial value in calm air, the instrument will always be found consistent. The wires F and S may be made removable and immediately replaceable in case of rupture.

Anemometers with lamp compensation.- For various researches on the field, requiring light instruments, we decided to make a more portable instrument and employed the triple-electrode lamp used in radio. The many and valuable properties of this lamp enabled us to arrive at a good solution of the problem.

We took as the basis of this experimental study, the properties of the characteristic curves of thermo-ionic emission of the filaments of this lamp at a variable temperature and at a constant tension of the plate. In fact, when we join the plate and the grid of a triple electrode lamp and establish a constant difference of potential between this system and the filament and then vary the heating current of the latter, we obtain for the intensity i of the current in the plate, a curve which increases very rapidly in terms of the intensity I in the filament of the lamp, whose curve A is given in Figure 8. Since the intensity curve, in a hot wire cooled by a current of air, follows an inverse course (curve B of Fig. 8) in terms of the velocity of this current, we were able to combine the two phenomena in such manner as to obtain a perfectly rectilinear representative curve $i = \Phi (v)$ of the plate current, in terms of the velocity, so as to give the instrument a constant sensitivity throughout the whole extent of its zone of functioning.

The apparatus is connected up as shown in Figure 9. A battery B simultaneously heats the anemometer wire A and the filament F of the lamp shunted by a suitable resistance R, thus rendering it possible to regulate the intensity I of the current passing through F and consequently its temperature. The grid G and the plate P are together connected with the plate battery B' and with the filament by a recording galvanometer E, attached to the terminals of a shunt S.

In this apparatus, we have a choice of independent variables for attaining the object sought. For any given lamp, these are:

Electromotive force of battery B;

Electromotive force of battery B';

Resistance of R;

Resistance of S;

Length of anemometer wire A;

Diameter of anemometer wire A.

In our system we used French lamps of the regular military radio type, which are the most readily obtainable. The most advantageous curves were obtained with an initial heating intensity, in the filament, of 0.485 ampere in calm air, the intensity in the anemometer wire, at this instant being 0.615 ampere. The latter was a platinum wire 0.05 mm (0.002 in.) in diameter and 124 mm (4.88 in.) long. The electromotive forces for B and B' were respectively 16 and 32 volts. The scale of graduations in wind velocities deduced from this curve (Fig. 10) is absolutely regular and the sensitivity is independent of the velocity.

This part of the program has therefore been very satisfactorily carried out, still better than with the system of compensation by wire. The lightening of the apparatus is likewise considerable. In fact, while it requires storage batteries weighing about 75 kg (165.3 lb.) for operating the anemometer with wire compensation 20 hours, it is necessary to have storage batteries with a maximum weight of only 20 kg (44.1 lb.) to operate the anemometer for the same length of time with a radio lamp. The weight may be reduced about one-half by replacing most of the storage batteries with dry cells. The weight may be still further reduced by using lamps requiring less current.

By reason of the several variable elements enumerated above it is probable that we will yet discover other combinations of the values of these elements which will render it possible, either by maintaining a constant sensitivity, or by allowing a slight variation of the latter with the velocity, to make still greater savings in the energy to be furnished and hence in the weight of the batteries used and thus make the apparatus still more portable, without impairing the permanence of its adjustment.

Certain combinations render it possible to operate, in fact, with a constant heating of the filament, so as to eliminate the inevitable delay resulting from the establishment of thermal equilibrium in the lamp filament, when it is desired to undertake the study of phenomena with extremely short periods.

For example, the filament of a triple electrode lamp is heated at constant intensity by a battery B (Fig. 11). Another battery B', of suitable electromotive force, furnishes the tension of the plate. Between the poles of the latter battery a resistance R and the anemometer wire A are mounted in series. The grid G of the lamp is put in communication with the point common to A and R and the plate P is connected with the pole of the battery B' opposite to the pole connected with the filament F.

When the velocity v of the wind blowing on the wire A varies, its resistance also varies, as likewise the difference in the potential at the terminals, which decreases as v increases. Since the potential of the grid varies with relation to the potential of the filament, the intensity of the plate current recorded by the galvanometer E will undergo variations according to the known amplificative properties of the lamp. These variations in the current intensity are instantly recorded, since the establishment of equilibrium in the electronic flux of the lamp takes place instantly. It is obvious from this example, both from the viewpoint of the sensitivity and from that of the speed of recording, that the hot-wire anemometer possesses almost unlimited possibilities, due to the faculty of deriving advantage from all the different ways of assembling and from electrical and optical devices.

Recording Galvanometer.- The galvanometer, designed to be used with lamp-compensation anemometer, must be able to follow faithfully all the variations of the current, whose intensity is rendered proportional to the wind velocity by the compensative device, and to record these variations simultaneously.

For this purpose, its own period must be shorter than the duration of the most rapid variations of the wind and its adjustable damping must suffice to prevent the variations from entailing, in any event, oscillations of the movable recording arm. This damping may be weak if the period is very short, provided the instrument is not sensitive to the vibrations which it is often difficult to avoid in an instrument designed to function under so many various circumstances. Lastly, the instrument must be strong, easily transportable and as light as possible. The compensation conditions give, in fact, sufficient available energy for actuating the recording device, of which it is consequently unnecessary to require a very great sensitivity.

For this purpose, we constructed a galvanometer with a movable iron core, which enabled us to meet the various requirements very satisfactorily. Its essential part is a small tongue P of electrolytic iron (Fig. 12) placed in the narrow air-gap N S of a permanent magnet A and supported by a knife on the pole piece N. The magnetic attraction holds it firmly in place and oriented in the N S direction of the lines of force of the air-gap field.

A coil B, whose axis is perpendicular both to the lines of force and to the edge of the knife with the tongue, creates, under the action of the current to be recorded, a variable field which may be reinforced by a suitable iron core and which, by modifying the air-gap, changes the orientation of the position of equilibrium of the tongue. The latter carries a small concave mirror m, which reflects the image of a metal-filament lamp on the unwinding photographic strip.

The instrument has neither pivot, torsion wire, nor spring. Furthermore, the tongue can be immersed, to a greater or lesser depth, in the oil of a small oil cup located in the air-gap, so as to bring its damping to the desired value.

On voyages, a device renders it possible to separate the tongue from the pole which supports it, so as to lift the knife from its support, the same as for the beam of a precision balance.

The current furnishedby the compensative system is always in the same direction. It causes displacements of the tongue, which are all on the same side of its position of equilibrium. Under these conditions and, in spite of the hysteresis of the iron of the tongue and of the core of the spool, the graduation of the instrument is practically constant and its zero quite stationary. This is due, in the first place, to the employment of electrolytic iron and an open magnetic circuit for the coil B and, in the second place, to the fact that the photographic recording reduces the variations in the magnetization of the iron to a minimum value. These variations are always much less than the ones allowed in the instruments with movable iron cores universally employed.

The coil B with lamp compensation, used for recording the wind, has a resistance of 6500 ohms. The resistance of this coil, which we did not make for this purpose, seemed to be rather large. We also used a coil of 30 ohms, with which we obtained Figures 13-16, which are given here to illustrate better the properties of our galvanometer.

Figure 13 shows the vibration of the undamped instrument. The tongue is set in vibration by a series of current impulses in the coil B. The image of the source of light traces on the unwinding photographic paper a sinuous line, which must be examined from right to left, since the paper is unrolled from left to right at a speed of 113 mm (4.45 in.) per second. Examination of this line shows that the frequency of the oscillations is about 143 per second. The same periodicity is found in the sinuosities of the left part of the figure, which sinuosities are caused by heavy blows on the table supporting the instrument.

Figure 14 is the record obtained by the interruption of the current in the coil B, the galvanometer being partially damped by immersion of the tongue in the oil up to half its height.

Figure 15 is the record which shows the same phenomenon with stronger damping, while Figure 16 was obtained under the same conditions, but with a speed of unrolling of about 2 cm (0.79 in.) per second, about the same as that employed by us in making records of the natural wind. It should be remarked that the table supporting the instrument vibrated strongly under the action of the motor employed to unroll the photographic paper and that these vibrations can be easily avoided.

The currents employed in the coil B for these different records began with 0.05 ampere for the 30 ohm coil. The maximum deviation, 35 mm (1.38 in.) to 1 m (3.28 ft.) of the galvanometer, was obtained with the 6500 ohm coil, with less than 10 milliamperes.

The first galvanometer used by us, at the beginning of our researches, was mounted on a pivot and had an oscillation period of 0.13 second. The second galvanometer was mounted on a torsion wire, with a movable frame like the preceding, and had a shorter period of about 0.02, but was very sensitive to exterior vibrations and had, moreover, the disadvantage of requiring a strong current for the electromagnet serving to create the magnetic field. The galvanometer, just described, does not have these disadvantages, but is a permanent magnet with a period of only 0.007 second and is less sensitive to exterior vibrations than most of the recording instruments used on airplanes. We have not tried to shorten its period further. The period of the first galvanometer, about 0.1 second, is excellent for recording winds, when it is desired to obtain a record showing the general structure of air currents and particularly of gusts. The latter galvanometer, with a permanent magnet, is adapted, on the other hand, to the study of the more rapid vibrations of natural winds, due to their inner structure. It is also adapted for determining the vibrations of air currents in ordinary wind tunnels, with a mean velocity of less than 100 m (328 ft.) per second.

It is possible to diminish still further the period of the instrument with the movable iron core, but the very fine hot wires, which would have to be used, would be entirely too sensitive for recording natural winds.

Transmission of the Indications of a Hot-Wire Anemometer by Radio

In studying the instantaneous velocity of the air, above the sea and particularly of high altitudes, it may prove inconvenient to carry the additional weight of the apparatus.

We have invented a means for solving this difficult problem, a device rendering it possible to dispense with the insulated wire conductors, which are always very heavy. With this device, we have succeeded in transmitting by radio the indications furnished by the hot wire.

The anemometer transmitter is attached to the cable of a balloon or kite. Since this cable constitutes a metal connection between the transmitting and receiving stations, only a very small power is required.

The transmitting instrument is the same as that of a wireless telephone station with emission modulated by the hot wire, which can affect either the heating of the filament or the potential of the grid.

The reception of the variable waves, emitted on a fixed length, is accomplished by the usual methods, while taking into account the particular conditions of the problem. Furthermore, the amplification, if necessary, is carried only on the high frequency, to a detector which transforms the alternating current into a continuous variable current passing through the recording galvanometer. The intensity of this continuous current may be brought to the desired value by employing any suitable amplifier.

The power of the transmitting station and the number of amplification stages of the receiver are chosen in such fashion as to make the lamps work in the regions of their characteristics, which determine variations of the emission proportional to the velocities of the wind striking the hot wire. This is easy to accomplish, when the compensation is effected by the methods indicated in the devices for measuring the velocity.

The curve furnished by the recording device gives, therefore, the relative value, at any instant, of the velocity of the air current past the anemometer wire which modulates the emission, the scale of the ordinates being undetermined. To remove this indeterminateness, a relay, inserted in the circuit of the hot wire, serves to interrupt the emission, whenever the intensity of the current exceeds a definite value, i.e., whenever the wind attains a known velocity, e.g., 5 m (16.4 ft.) per second. The recording galvanometer therefore returns suddenly to zero, for a very short space of time, whenever the wind exceeds 5 m (16.4 ft.) per second, which is recorded on the strip. The other velocities are marked by the proportional ordinates.

Transmitter.- A hot-wire anemometer (Fig. 17), 0.05 mm (0.002 in.) in diameter and 20 mm (0.79 in.) long, is mounted in series with an ordinary radio lamp in the circuit of a 6-volt heating battery B_1. One pole of the battery is connected with one of the poles of an induction coil S, the other end of which is connected with the plate P of the lamp through the intermediation of a 200-volt battery B_2. The grid G is connected, in its turn, with an intermediate point of the induction coil S. The portion of the latter included between this point and the negative pole of the 200-volt battery is shunted by a variable condenser C. When the wire moves at a speed of several decimeters per second, the alternating current varies by several milliamperes.

Receiver.- Since the distance of transmission did not exceed 10 meters (32.8 feet), we used no antenna, either for sending or receiving. The receiver (Fig. 18) comprises an alternating circuit C of a single 1.2 m (3.94 ft.) turn connected with a variable condenser c of about 1/10000 microfarad. The filament F of the lamp is heated by a 6-volt battery B_1, while the plate P has a potential of 100 volts furnished by the battery B_2. A recording galvanometer G and a 2000 ohm telephone receiver T are added. The reaction is magnetic.

This device renders it possible to hear very clearly, a whistling sound whose pitch changes when the temperature of the sending lamp varies, due to the effect of the variations in the velocity of the wind striking the hot wire. Furthermore, it is easily regulated so that the sound becomes louder when the wind blows more strongly against the anemometer wire. There is then produced in the telephone receiver a noise comparable with that made by the wind blowing against the telegraph wires in the country.

The reception is sufficiently strong for the galvanometer to record directly the variations of the continuous plate current. Figure 19 clearly shows the precision of the photographic records thus obtained with a coil galvanometer of at least 1000 turns of a large enough wire mounted in the air-gap of an electromagnet. We attached a hot wire to the end of a pendulum C at about 60 cm

(23.6 in.) from the axis of oscillation (photograph, Fig. 20), the oscillation period of which was 2 seconds and the amplitude 15 cm (5.9 in.), the maximum velocity of the air current being about 21 cm (8.3 in.) per second. The curve traced on the photographic paper demonstrates the extreme sensitivity of the instrument and the excellence of the method employed. In this experiment, the hot wire was not compensated; otherwise it would have traced a sinusoid. Figure 21 shows this sensitivity still better, since it is the record of a wind whose velocity did not exceed 40 cm (15.75 in.) per second, notwithstanding which, all the slight variations in the velocity of the wind are recorded with remarkable clearness.

Researches on Thermal Inertia of Anemometer Wires

Theoretical Study.- The employment of any instrument, in order to be rational, necessitates a preliminary study of the causes of error, susceptible of impairing the results, and also a numerical determination, either theoretical or experimental, of the corresponding corrections. The following observations were made for this purpose.

Since nearly all our experiments have been performed with anemometer wires of 0.05 mm (0.002 in.), we have employed the data thus obtained as the basis of our calculations.

Measuring the intensity of the current in the hot wire with a known difference of potential in a wind of known velocity, makes it possible to determine the resistance and, consequently, the temperature of this wire, the temperature coefficients of platinum being known with satisfactory precision.

The experiments performed with the wire-compensated anemometer already described furnished the following data:

Velocity of wind	v	0	1.6	5	10	15	m/sec.
Temperature of wire	θ	1285	908	738	616	558	degrees C.
Heat lost in wire per unit of time and per unit of length.	q	0.249	0.296	0.306	0.316	0.316	small cals.

It may be noted in passing that the quantities of heat q, removed by a wind of v velocity from a wire of $\theta^\circ C$, conform very satisfactorily to the expression formulated by Vessot King, $q = \theta\,(a + b\sqrt{v})$, which reads, with the numerical values of its coefficients, $q = 10^{-4}\,\theta\,(1.94 + \sqrt{v})$.

If we represent on the abscissas the velocity v of the wind and on the ordinates the quantities of heat q dissipated in the wire, we find that the latter quantity may be regarded as constant, except for very small velocities, when it diminishes a little (Fig. 22).

It is therefore easy to calculate the thermal exchanges between the wire and the air, by taking into account the fact that the absorption of heat furnished by the current is independent of the variations in velocity and by disregarding the difference between the temperature of the air and that of the wire.

If the wire is in thermal equilibrium at the temperature θ' in an air current of velocity v' and we suddenly give this air current a velocity v greater than v', the temperature of the wire, instead of falling suddenly from the value θ' to the value of the new equilibrium with θ smaller than θ', keeps on falling gradually to this new value, by reason of the thermal inertia of the wire.

The expression, in terms of the time t elapsed since the diminution of the velocity of the wind and of the instantaneous temperature τ acquired by the hot wire at this instant, will give an accurate measure of the errors due to the thermal inertia.

Designate by:

γ, the heat capacity of one centimeter of platinum wire;

q, the quantity of heat lost in this length per unit of time;

τ, the temperature of the wire at the instant t.

Since the temperature excahnges are proportional, other things remaining equal, to the difference in the temperatures of the bodies in contact, the heat removed from the wire by the air, at the instant t and during the time dt, is $q \frac{\tau}{\theta} dt$, while the quantity of heat received in the same time is $q\,d\,t$. Hence the wire loses, from the fact of the variation in the velocity of the air, a quantity of heat $q \frac{\tau-\theta}{\theta} dt$ more than it receives. This additional amount of heat lost is due to the variation in the internal heat of the wire, which is $\gamma\,d\,\tau$. Hence we have

$$\gamma\,d\,\tau = -q\frac{\tau-\theta}{\theta}\,dt \quad \text{or} \quad \frac{d\tau}{dt} = -\frac{q}{\gamma\,\theta}(\tau-\theta).$$

On taking as variable the excess of the momentary temperature of the wire over its equilibrium temperature $T = \tau - \theta$, we have $dT = - \frac{q}{\gamma\theta} dt$, or, by integrating, $LT = - \frac{q}{\gamma\theta} t + LT$. Since T_0 the initial value of the difference in temperature, is equal to the difference of the temperatures before and after the variations in velocity, we have $T_0 = \theta' - \theta$. The above equation may be written: $T = T_0 e^{-\frac{q}{\gamma\theta} t}$. It gives the temperature difference between the state of the wire at the instant t after the variation and its final state of equilibrium.

The anemometer is graduated, however, in wind velocities and not in degrees of temperature. Hence the important thing to know is the error in the determination of the wind velocity at the instant t. For this purpose, let us consider the curve giving the temperature θ of a wire in equilibrium in an air current in terms of the velocity of this current, $\theta = \Phi(v)$ (Fig. 23). On referring to it and beginning with the ordinate of the point v under consideration, the difference of the temperature at the instant t, it is easy to see the value of the error in the wind velocity caused by this difference in temperature.

Moreover, a simplification is immediately introduced into the calculation by the fact that we are here studying small variations corresponding to the errors of the instrument, on the one hand, and that, on the other hand, the calculation is only for the purpose of determining the value of a quite small correction, which it is therefore unnecessary to know with very great accuracy. Under these conditions, the curve $\theta = \Phi(v)$ may be assimilated to its tangent at the point v in the proportion which occupies us. We then have $u = \frac{dv}{d\theta} T$. On remarking that $T_0 = u_0 \frac{d\theta}{dv}$, the logarithmic equation giving T may be written

$$LT = LT_0 \frac{d\theta}{dv} - \frac{q}{\gamma\theta} t$$

and the corresponding value of u is

$$Lu = L \frac{dv}{d\theta} + L\, u_0 \frac{d\theta}{dv} - \frac{q}{\gamma\theta} t = L\, u_0 - \frac{q}{\gamma\theta} t$$

whence we deduce $u = u_0 \cdot e^{-\frac{q}{\gamma\theta} t}$.

We thus find that the time required to attain a given limit of error u, depends, for a given value of variation of velocity u_0, only on the final equilibrium temperature of the anemometer wire and is proportional to it, since the quantity of heat q lost is regarded as constant. The establishment of equilibrium is therefore more rapid at high velocities than at small ones, but the difference is of small importance, since, in passing from one to the other, the temperature of the wire hardly doubles.

Let us trace the curve $u = \psi t$ which is likewise the curve $T = \frac{d\theta}{dv} \psi(t)$, as we have seen (Fig. 24). Let us consider the tangent to this curve at the point of the abscissas t. Its slope $\frac{du}{dt}$ represents an acceleration. The error u in the measurement furnished by the anemometer, at this instant t, is the one we would have in the record of a wind of constant and uniform acceleration at $\frac{du}{dt}$ at the moment when the velocity of this wind would be equal to the value v chosen for the establishment of the curve u, which depends on the velocity v of the wind after the disturbance. Since the same calculation may be made for any point of the curve u and, since the curve u can be established for any value of the velocity v, we see that it is possible to construct an abacus giving, for any values of the variables, the velocity and acceleration of the wind, the value u and the corresponding error.

The possibility of making this correction in all cases was important to demonstrate, but it would be superfluous to give the complete results here. It will be shown in fact, further along, that its calculation is practically useless in the study of atmospheric winds, by reason of the very slight errors due to the thermal inertia in such winds, their accelerations always being relatively small.

Computation of Errors.- Let us consider an anemometer consisting of a platinum wire of 0.05 mm (0.002 in.) diameter, whose thermal characteristics have already been given. In this case, we find the following characteristics:

Section, 2×10^{-5} square centimeters;

Specific gravity of platinum, 21.4;

Weight of wire, 4.3×10^{-4} g per sq.cm of wire;

Heat capacity $\gamma = 1.3 \times 10^{-5}$ per cm of wire;

Temperature coefficient of platinum (Landolt)

$r = r_0(1 + at + \beta t^2)$, $\alpha = 3 \times 10^{-3}$ and $\beta = - 5.8 \times 10^{-7}$.

Let us assume that this anemometer wire is placed in a wind whose velocity $V' = 9$ m(29.6 ft.)/sec., which, at the instant

$t = 0$, suddenly changes to $V = 10$ m(32.8 ft.)/sec. We then have $u_0 = 1$ m(3.28 ft.)/sec. The final temperature $\theta = 616^\circ C$ is 18° lower than the initial temperature θ and we deduce

$$T_0 = \theta' - \theta = 18^\circ \text{ and } \gamma\theta = 8 \times 10^{-3} .$$

The amount of heat lost per cm of wire and per second is $q = 0.316$ cal., whence $\frac{q}{\gamma\theta} = 39.5$. We then obtain, by passing from the lower logarithms to the vulgar logarithms,

$$\log T = 1.255 - 17.13\, t \quad \text{and} \quad u = \frac{1}{18}\, T.$$

We accordingly obtain the following values:

t = 0.01	0.02	0.05	0.10	0.15	seconds;
T = 12.1	8.20	2.50	0.35	0.05	degrees C;
u = 0.70	0.45	0.14	0.019	0.003	m per sec.;

which show that the establishment of temperature equilibrium in the wire is very rapid (Fig. 24).

An example will demonstrate this fact more clearly by the computation of the error in the record of a natural wind gust. The examination of the records already obtained makes the irregularity of a wind possessing an acceleration of 10 m(32.8 ft.)/sec.^{2} (either positive or negative) appear desirable. The results given above enable the calculation of the error in the record of this gust, at the instant its velocity was 10 m(32.8 ft.)/sec. and we have seen that this error would be slightly less at greater velocities and greater at lower velocities.

For this purpose, let us draw the tangent of slope to the curve u (Fig. 24) equal to 10 in absolute value. The coordinates of the point of contact are: $t = 0.036$ sec. and $u = 0.24$ m(.79 ft.)/s. Thus the anemometer gives a record of this violent gust, which is exact to within 2% at the given instant. This error represents the practical limit of the recording method actually adopted. We obtain, in fact, for a velocity of 10 m/s a deviation of about 20 mm (.79 in.) on the photographic record. An error in the velocity 0.24 m/s then corresponds to a deviation of 0.5 mm (.02 in.) or about the width of the mark made by the projection of the spot.

It does not, therefore, seem to be of any practical importance to make this correction, which is of the same order of magnitude as the errors proceeding from other causes, such as the variation of the temperature or heat capacity of the air, the variation of the e.m.f. during an experiment, the sources of electricity employed, etc., whose exposition would exceed the scope of the present article.

Experimental Investigation.- We decided to investigate directly as to whether the wires of the diameters hitherto employed in our anemometers are sufficiently sensitive to air pulsations much more rapid but less ample and hence more difficult to record than the pulsations of the natural wind.

For this purpose, we chose the periodic variations of velocity produced by the sound waves at the free end of an open sonorous tube vibrating in half-waves and consequently presenting a center of velocity at this extremity, where we placed the hot anemometer wire.

The tube, after being set in vibration by compressed air, was traversed by a uniform current, coming from the output of excitation air, to which were added the periodical velocity variations due to the sound waves. With the aid of a lens O (Fig. 25), we obtained, at I, an image of the anemometer wire F placed perpendicularly to the plane of the figure inside the sonorous tube T, set in vibration by compressed air entering at A. This image was formed on a sensitive film, while a chronograph C produced, each second, a brief eclipse of the source of light. Figure 26, a direct reproduction of the film, shows the results obtained.

Notwithstanding the slight velocity variation due to the sound waves and in spite of their high frequency, the anemometer wire underwent such temperature changes that the film was strongly affected, as shown by the white spots constituting the successive images of the wire at the instant of minimum velocity of the air current, corresponding to the maximum temperature and luminosity of the wire. This experiment likewise constituted a direct determination of the vibration period of the tube, which Figure 26 shows to be 1/130 = 0.0077 second.

There is certainly no likelihood of encountering, in the study of natural winds, any phenomenon so difficult to record as the sound waves in a small organ pipe. The above experiment demonstrates, however, by its very simplicity, the possibility of making such a record with anemometer wires of customary size, without amplification of the variations of the thermal condition of the wire, which are already large enough to be shown directly by photography. The employment of more complicated means and much smaller wires enabled the recording of aerial vibrations incomparably smaller.

During the war, the Tucker microphone, employed by the listening stations (Bull-Weiss system), composed of platinum wires of 0.01 mm (.0004 in.) diameter, registered perfectly waves from the detonation of German howitzers of mean caliber at a distance of ten kilometers (6.2 miles) by means of a cord galvanometer.

More recently, by employing a powerful instrument with extremely small wires and by amplifying several thousand times the current variations obtained, Lee de Forest succeeded in recording photographically, in a remarkable manner, at several meters distance, the highest notes of the human voice. He even carried his researches up to frequencies of 30000 periods per second.

We may also mention, in the same order of ideas, the invention, before the war, of the Abraham telephone, entirely thermal, in which both transmission and reception were effected by means of extremely fine hot wires.

In order to show how the hot wire and galvanometer, simultaneously employed, behave in the recording of rapid velocity variations, we repeated the experiment with the organ pipe, this time recording the galvanometer indications on a rapidly moving film.

Figures 27-29 show, not only that the sensitivity of the instrument has been increased sufficiently to give to the record a suitable amplitude, but also that the damping of the galvanometer, reduced to about one-third of its maximum value, and the thermal accuracy of the hot wire rendered it possible to show the variations in the pitch of the pipe.

The second film (Fig. 27) shows the fundamental tone of the pipe (130 periods per second), as also the irregularities in the amplitude of the motion.

The third film* (Fig. 28) represents the superposition of a harmonic on the fundamental tone, with almost regular vibrations.

The last film (Fig. 29) shows, on the right, a queer and very sudden exaggeration of amplitude, so strong that the whole upper part of the record of this oscillation has disappeared, by reason of the excessive velocity of the spot furnished by the galvanometer. The motion is also the resultant of two sounds of different periods.

The ability to analyze the sonorous motions of the air, demonstrated by the preceding, represents, for an anemometer designed for the study of atmospheric currents, a really new property and an enormous excess of sensitivity over that which will be actually required of it under conditions of practical employment. We have shown that this represents only a part of the possibilities from the employment of hot wires. We may, therefore, rely on this method to be always and very easily equal to all practical needs.

Oscillographic Study of Hot Wires

After having studied theoretically the errors due to the ther-

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* The original was almost a blank.

mal inertia of hot wires and after having demonstrated by the records that the sensitivity to the short vibrations of the air conformed well with the conjectures based on the calculations, we decided to determine directly the effects of this thermal inertia and, consequently, the time required to establish equilibrium in the wires. We determined this period of time by evaluating the time necessary for the establishment of the current in the wire, when subjected to a wind of known velocity.

The employment of the Dufour cathode oscillograph renders it possible to obtain the value of the current in the wire with a delay surely not attaining one/thousandth of a second under the given conditions, which enable it to trace an entirely satisfactory curve of the current intensity in the wire, in terms of the time. For this purpose, we proceeded in the following manner, thanks to the kindness of Mr. Beaudouin the constructor of the Dufour oscillograph and Mr. Gondet, his engineer, who assisted us in employing this instrument.

The anemometer wire F (Fig. 30), exposed to the wind V, is inserted in a circuit comprising a variable resistance R with neither induction coil nor temperature coefficient, a source of electricity A and two coils B_1 and B_2 of several turns each, designed to produce the magnetic field for deflecting the cathode ray C furnished by the vacuum tube T and provided with the necessary high-tension devices (not shown in Fig. 30, for the sake of clearness).

This cathode ray, deflected perpendicularly to the plane of the figure, displaces its point of impact on one of the generatrices of the revolving cylinder bearing the sensitive film S and contained in the vacuum tube E. This cylinder can be driven at any speed, but was set at 2 m (6.56 ft.)/sec. for the experiments in question.

After adjusting the temperature of the wire to a suitable velocity, by means of the resistance R, and after bringing the air current to the chosen velocity V, we started the cylinder S and then suddenly closed the switch I.

The current was established throughout the whole apparatus in an exceedingly short space of time, the time constant of the circuit being very small, then decreased to the value corresponding to the thermal equilibrium obtained in the wire and then remained at this value. The experiment was then terminated.

The curve of decrease of the current, in terms of the time, rendered it possible to calculate the intensity in the wire at any given instant.

Knowing, on the other hand, the difference of potential at the terminals of the wire and the length of the wire, it was easy to deduce the unit resistance, whence the temperature of the wire at that instant was determined by the means previously explained.

Records were made with wires of 0.05 and 0.025 mm (0.002 and 0.001 in.) diameter at wind velocities of 15 m (49.2 ft.) per second and at 0. Since the 0.05 mm wire had been the object of the preceding theoretical and practical researches, it was again employed in this method. It would be of no interest to recall here the method of computation employed and we will simply give the temperature curve (Fig. 31), in terms of the time, deduced from the curve of current intensity.

This curve relates to a wire of 0.05 mm (0.002 in.) diameter and 27 mm (1.063 in.) long exposed to a wind of 15 m (49.2 ft.) per second and traversed by a current of equilibrium of 0.95 ampere. The corresponding temperature of equilibrium is a little below 550°C (1022°F). Representing this temperature by T_e, we can easily find on the curve that the difference $T_e - T$ between the temperature of equilibrium and the temperature at any instant is divided by 2, when the time increases 0.02 second, which shows that the curve is probably of an exponential nature, as anticipated by the theory.

By referring to Figure 24, in which the computed variations in temperature are plotted against the time, we find that, for the same 0.05 mm (.002 in.) wire, the computed variations decrease one-half for each time increase of 0.018 second.

The agreement of the theoretical and experimental results is all the more satisfactory, because the wire, after serving for the cathode oscillograph records, was cooled to a temperature 20°C lower than that which served as the basis of the calculation, which evidently rendered the calorific changes less active. On the other hand, the resistances outside the wire were proportionally greater in this case than previously, which caused a further decrease in the sensitivity. We may therefore assume that the results of the above-mentioned computation have been experimentally verified as well as we could wish.

Figure 32 is a direct reproduction of the cathode record made by a 0.025 mm (.001 in.) wire exposed to a wind of 15 m (49.2 ft.) per second. Figure 33 is a similar record without wind. Considerable increase is easily noted in the rapidity of the reaction of the wire with the velocity of the wind. The time required for obtaining thermal equilibrium of the wire is about 0.015 second in Figure 32 and twice as long in Figure 33. The same fact, anticipated by the computation, was also verified for the 0.05 mm (.002 in.) wire whose reaction time was triple that of the 0.025 mm (.001 in.) wire.

Comparison of the records furnished by the two wires shows the very great superiority of the 0.025 mm (.001 in.) wire, from this viewpoint, over the 0.05 mm (.002 in.) wire which we have already shown to be satisfactory for the study of phenomena of longer duration than 0.1 or 0.05 second and which accordingly remains the normal diameter for the study of natural winds and most of the irregularities in ordinary wind tunnels.

Apparatus for the Instantaneous Determination of the Direction of the Wind

The results obtained in recording variations in the velocity of the wind, with the aid of hot wires, incited us to use the same wires for recording fluctuations in the direction of an air current. The customary instruments are, in fact, very imperfect and require much longer to reach a state of equilibrium than our hot anemometer wires.

The employment of a single wire for finding a direction in a plane does not seem impossible at first thought, if we note that a wire heated electrically, when struck obliquely by a wind, is traversed by an electric current which varies with the direction of the wind. This method must, however, be rejected, for the reason that the variation of the current depends on two variables: the angle of incidence α of the wind to the direction of the wire F (Fig. 34) and the velocity V. In assuming that, at constant velocity, the electric current is a definite function of the angle α, which presupposes for the hot wire a perfect constancy of form, and that the turbulence of the air remains constant, the use of this method would require the preliminary determination of the velocity of the wind. If this velocity is known, the value of the current in the wire defines the direction. But if we employ recording devices based on this principle for studying the structure of the wind, the curves obtained can only be utilized after a laborious transcription, which will give the direction, if, at the same time, we take into account the corresponding points of the two curves of wind velocity and current in the direction wire. Lastly, since the variations of the current in the wire, in terms of the incidence of the wind, are very small in comparison with those due to variations in velocity, the method in question is ill adapted to accurate determinations of direction. For attaining our object, we preferred another method for which we have devised apparatus with two hot wires.

By placing two equal hot wires F_1 and F_2 (Fig. 35), near the points a and b respectively, and located symmetrically with reference to the meridian xy of a cylindrical body containing the mean direction of the wind, we obtain a simple device, which has very great advantages. In fact, if a wind strikes this cylindrical body in a direction parallel to the plane xy, the points a and b, placed symmetrically with reference to this plane, and consequently the two hot wires F_1 and F_2 each receive air filaments of approximately the same velocity, so that their resistance to the passage of the electric current remain the same. If the direction of the wind changes (Fig. 36) the same wires find themselves in air currents of different velocities, so that they are differently cooled and their resistance is no longer the same.

Figure 37 shows the simple arrangement we employed for determining these variations of resistance and consequently the variations in the direction of the wind. The wires F_1 and F_2 form two arms of a Wheatstone bridge, supplemented by two equal resistances R_1 and R_2 and a galvanometer G. A storage battery B supplies the bridge at a constant tension. R_1 and R_2 respectively adjoin the hot wires F_1 and F_2.

The bridge being in equilibrium in calm air with the wires at

1200 to 1300 C (2200 to 2400°F), the equilibrium continues so long as the wind blows in the plane of symmetry of the system of hot wires and of the obstacle behind them, whatever may be the velocity of the wind, and the galvanometer shows no deviation. If, however, the direction of the wind changes the inequalities in the velocity of the filaments of air striking the two wires produce resistance variations in F_1 and F_2 and cause electric currents to pass through the galvanometer, whose needle is deflected to the right or left, according to which side of the plane of symmetry of the hot wires the direction of the air current lies.

We will see, further along, that it is easy to contrive a device of this kind, which gives a current of one milliampere in the galvanometer, when the wind is inclined one degree to the plane of symmetry xy of the hot wires. A galvanometer is easily constructed so as to be sensitive to a current one thousand or one million times smaller. It is therefore simply the regularity of the wind which determines the accuracy with which this device indicates the direction of this wind of supposedly constant velocity. In fact, if the galvanometer shows no deflection in calm air and if, in a uniform air current in the plane of symmetry of the instrument, the deflections are less appreciable, the greater the parallelism of the air filaments, in a natural wind, on the contrary, the velocity variations, due to the turbulence of the wind, produce variations in the resistance of the wires. Hence, by reason of the extreme sensitivity possible for the galvanometer to attain, it will always be possible to obtain a permanent oscillation of this instrument, since an airflow in parallel filaments is only a conception of the mind.

But if the wind is variable, the galvanometer must be able to follow its variations promptly, which limits its sensitivity. The determination of a direction can be made to within 0.1° with an instrument whose period is 1/20 to 1/30 second. We do not think artificial air currents, any more than natural winds, have a sufficiently definite direction to utilize all the sensitivity of the instrument.

There is a device employed on airplanes, as indicator of sideslip, the principle of which is somewhat analogous to the one on which our direction finder is based. This principle operates as follows: If a wind strikes a round body (sphere or cylinder), the two points, a and b, placed symmetrically with reference to the meridian of the body, are struck by two air currents of equal velocity and undergo equal pressures. If the direction of the wind changes, the same points, a and b, of the body will find themselves in currents of different velocities and will support unequal pressures. A differential manometer taking the pressures at a and b, will therefore remain at zero so long as the direction of the wind is in the meridian of symmetry of a and b. This instrument becomes practically useless, if we try to deduce from it the inclination of the wind to its plane of symmetry, because the pressure difference given by the differential manometer is then simultaneously a function of this inclination and of the velocity of the wind. The instrument lacks, moreover, sensitiveness to velocities below 20 m (65.6 ft.) per second and does not lend itself directly to rapid registrations.

The instrument with two hot wires, which we have invented, offers very great advantages over the preceding. Within certain limits, it gives indications concerning the direction, independently of the velocity of the wind. If, thus far, our device, as a zero instrument, seems to present, over the manometric device, only the advantage of great sensitivity, it has, on the other hand, as will be shown by what follows, the property of enabling the measurement of the inclination of the wind to the plane of symmetry of the hot wires.

If we direct against our device an oblique wind of constant direction α (Fig. 36) but of increasing velocity (e.g. from 0 to 20 m (65.6 ft.)/sec.), we find that the deflection of the galvanometer needle, in terms of the velocity of the wind, is represented by the curve of Figure 38.

At zero velocity, no current passes through the galvanometer and the bridge remains in equilibrium. When the velocity reaches about 1 m (3.28 ft.) per second, the current increases rapidly to 18 milliamperes, passes to a maximum of 20 milliamperes when the wind blows 6 m (19.7 ft.) per second and then gradually decreases, At 20 m (65.6 ft.) per second, the current returns practically to its value at 1 m/sec. If the velocity of the wind became infinite, the wires F_1 and F_2 would have practically the same temperature and the current i would fall to zero. On this curve, we find that, between 1 and 20 m (65.6 ft.) per second, the galvanometer deflection remains between 18 and 20 milliamperes for an inclination of 9° of the direction of the wind to the plane of symmetry of the hot wires.

In this simple form, the device suffices for studying the direction of natural winds. The current i is practically proportional to the inclination α, so long as the wind does not make an angle, with the plane passing through both hot wires, differing too much from a right angle.

We have tried to increase the precision of this instrument by compensating the decrease in the current i, produced when the temperature of the wire fell too low. We have experimented with two methods. The first consisted in employing an instrument whose indications depend simultaneously on the difference and sum of the currents i_1 and i_2 passing through the wires F_1 and F_2. When the wind velocity increases greatly, i_1 and i_2 increase, but their difference $(i_1 - i_2)$ becomes small. If the movable coil of a differential galvanometer has two loops traversed in opposite directions by the currents i_1 and i_2, it will become proportional to $i_1 - i_2$. On adding a third loop traversed by the current $i_1 + i_2$, it is possible to modify the sensitivity of the differential galvanometer, so as to keep its deflection constant within certain limits, when $i_1 - i_2$ decreases under the action of a very strong wind.

It is an instrument of this kind that we have used since our first experiments in recording direction in both vertical and horizontal planes (See Huguenard, Magnan and Planiol: "Sur un appareil donnant la direction instantanée du vent," C.R. de l'Académie des Sciences, Vol. 176, March 5, 1923). The instrument comprises two shunts (Fig. 39) of the same circuit of a source of electricity B, each having a galvanometer coil. A platinum wire 0.05 mm (.002 in.) in diameter and 3 cm (1.18 in.) long is inserted in each shunt and heated electrically, both wires F_1 and F_2 being mounted near a wooden cylinder obstructing the passage of the air current. When the direction of the latter is in the plane of symmetry of the instrument, both wires are cooled alike and the galvanometer marks zero. On the other hand, as soon as the direction of the wind leaves the plane of symmetry, the flow of the air filaments no longer takes place in the same manner, since one wire is more protected from the wind and cooled less than the other.

Consequently, the resistances of the two wires are no longer equal and the galvanometer indicates the direction of the air current with reference to the plane of symmetry of the instrument. This indication would be of little value, however, if it depended on the momentary velocity of the air current. Being given the constants of the instrument, the difference in the intensities of the electric current $(i_1 - i_2)$ increases in the zone of velocities considered, namely, 0 to 15 m (0 to 49.2 ft.) per second.

We were able to effect the compensation by the aid of a special galvanometer.

The current, which traverses the wire F_1, passes through the first turn d_1 of a differential galvanometer, then through one of the halves of a compensating coil c mounted at right angles on the same axis as the coil of the differential galvanometer (Fig. 39). The wire F_2, on the other shunt, is traversed by a current, which passes through the second turn d_2 of the differential galvanometer and then through the second half of the compensating coil c.

The object of the latter is to prevent an increase in the velocity of the wind from causing a corresponding increase in the deflection of the coils entailing a change in the indication of the direction. In fact, this coil, being traversed by the sum of the currents $(i_1 + i_2)$, increases the recall couple resulting from its presence in the magnetic field, when both these currents increase as a result of the cooling of the hot wires. This recall couple renders it possible to annul the increase in the couple furnished by the two differential coils d_1 and d_2.

The compensation can be effected in another way. We can leave, for example, the galvanometer in its simple form and prevent the too rapid decrease of the current $i_1 - i_2$ by utilizing the properties of the Wheatstone bridge and by employing resistances or shunts with a strong temperature coefficient, placed at suitable points of the instrument. We do not insist on this method of compensation. It renders it possible to effect the independence of the galvanometer indications from the influence of the velocity of the wind, when this velocity is comprised within certain limits, which can be varied at will by modifying the adjustable resistances R_1 and R_2 (Fig. 37). It is also possible to make an instrument capable of being, at any wind velocity, quickly adjusted to its best functioning conditions for this velocity, its graduation being previously determined for the various adjustments of R_1 and R_2. Figure 40 gives the curves, for various values of the incidence α and of the wind velocity, of an instrument supplied with a constant current $i_1 + i_2$. Since the device with two hot wires has not been made absolutely symmetrical, equal deflections in both directions have not, in these experiments, given absolutely equal currents in the galvanometer, which defect can be easily remedied in the construction of instruments for use on the field.

The employment of two such instruments mounted at right angles, one showing the ascension and the other the azimuth, renders it possible to determine the direction of the wind with very great precision.

We recorded the variations in the direction of a natural wind with our differential galvanometer apparatus. Since we deemed it necessary to compare variations in velocity and direction produced in the wind at a given instant, we endeavored to record simultaneously, on the same film, both the velocity and the direction of the wind. This was easily accomplished by the use of prisms which, when suitably arranged, directed the rays, from the same luminous source, against the mirrors of the velocity and direction galvanometers, whence they were reflected on the slot in front of the same unrolling photographic film in such manner that, in the absence of any atmospheric motion, the luminous point made by the mirror of the velocity galvanometer would be at one end of the slot, thus marking the zero of velocity and oscillating, according to the velocity of the wind, between this zero and the other end of the slot, and so that the luminous point furnished by the mirror of the direction galvanometer would be in the middle of the slot, in calm air, thus marking the line of zero inclination and oscillating to the right or left, according to the nature of the variations in direction, when the wind is blowing.

The tracings contained in the photographic records, reproduced in Figures 41-44, show that the direction of the wind studied changed continually, both in the vertical and in the horizontal plane. It appears from the record (Fig. 43) that the wind alternately ascended and descended. The records show, moreover, that the duration, both of the ascending and of the descending periods, was from four to five seconds. It appears, however, from our experiments, that these periods were controlled by no definite law, since we found both shorter and longer ascending periods. The records show, furthermore, that, while the wind was ascending or descending, on the whole, there were vertical oscillations lasting from one-half to one second.

The amplitude of the oscillations on either side of the zero line of inclination also varied greatly. In a general way, neither the amplitude of the ascents nor descents exceeded ten degrees, the mean amplitude oscillating about five degrees. The amplitude of the oscillations was not fixed, but varied from one to ten degrees and sometimes, though only for a half-second, passed from plus ten to minus ten degrees, returning to plus eight and then to minus eight degrees, which signifies that the wind ascended and descended twice in one second.

We recorded the momentary velocity and direction of the wind on the same strip, in order to find whether any relation exists between these phenomena. This does not appear probable from the records thus far obtained, since the periods of ascending wind correspond successively to periods of increasing and decreasing velocity and the same holds true of the periods of descending wind.

We also obtained records of the variations in the momentary direction of the wind in the lateral sense. Thus we found that there were also variations of momentary direction in the horizontal plane, but there did not seem to be any well defined periods of variation in either direction. The lateral variations appear rather like a succession of oscillations of variable amplitude of a few degrees not often lasting more than a few tenths of a second.

Only repeated records of the momentary variations in the direction of the wind in different vicinities and at different altitudes can determine whether any general laws govern these variations.

Conclusions

For the purpose of studying the structure of the wind and, among other things, to explain the soaring flight of birds in a wind called horizontal and to try to imitate it with the airplane designed by Magnan, we constructed a series of instruments, which made it possible to record rapid variations of the wind in both magnitude and direction.

The laboratory instruments, which we often constructed with makeshift means, gave encouraging results and showed that they could satisfactorily meet the required conditions. By limiting ourselves to the employment of hot wires of 0.05 mm (0.002 in.) diameter, we obtained instruments which faithfully followed all the wind fluctuations of over 0.1 second and even much more rapid variations without any very great error.

Moreover, they are not limited to this object alone, but can also be employed in laboratories for studying air motions in wind tunnels or along wings or hulls, the small size of the measuring wires rendering it possible to place them easily wherever desired. It should be noted, in fact, that our instruments can stand considerable ranges of velocity, e.g., from 0 to 20 m (65.6 ft.)/sec. Though compelled to reduce the heating current, when the velocity falls below a certain high value, we can considerably increase their sensitivity at very high velocities, since the wires then stand much stronger currents.

Their use renders it possible to determine the momentary direction and velocity of an air current at different points, to obtain a numerical evaluation of its turbulence and to reveal the disturbing motions within it by introducing only very small objects.

Lastly, when associated with rapid dynamometers, they render it possible, in a natural wind, to determine the characteristics of flexible airfoils or of full-sized airplanes by the method we have recently described - (Huguenard, Magnan and Planiol: "Sur l'Etude aerodynamique des ailes d'oiseaux et des voilures souples" - C.R. de l'Academie des Sciences, Vol. 178, January 7, 1924).

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

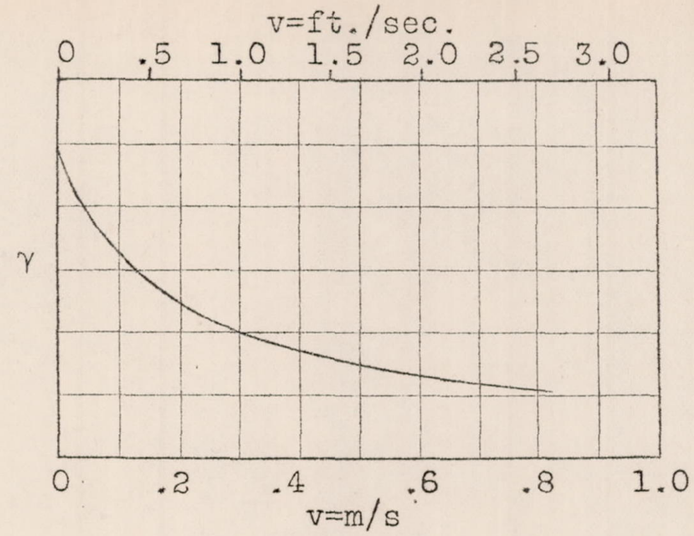


Fig.1.

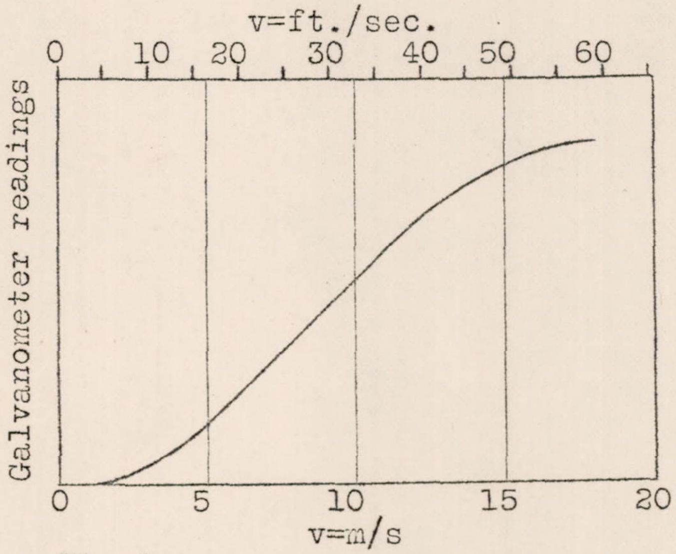


Fig.2.

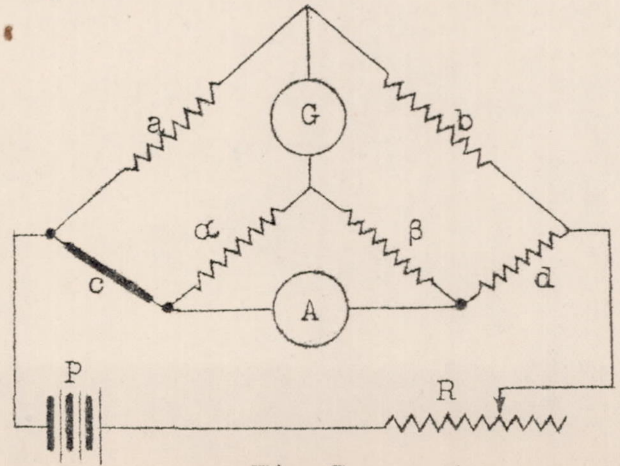


Fig.3.

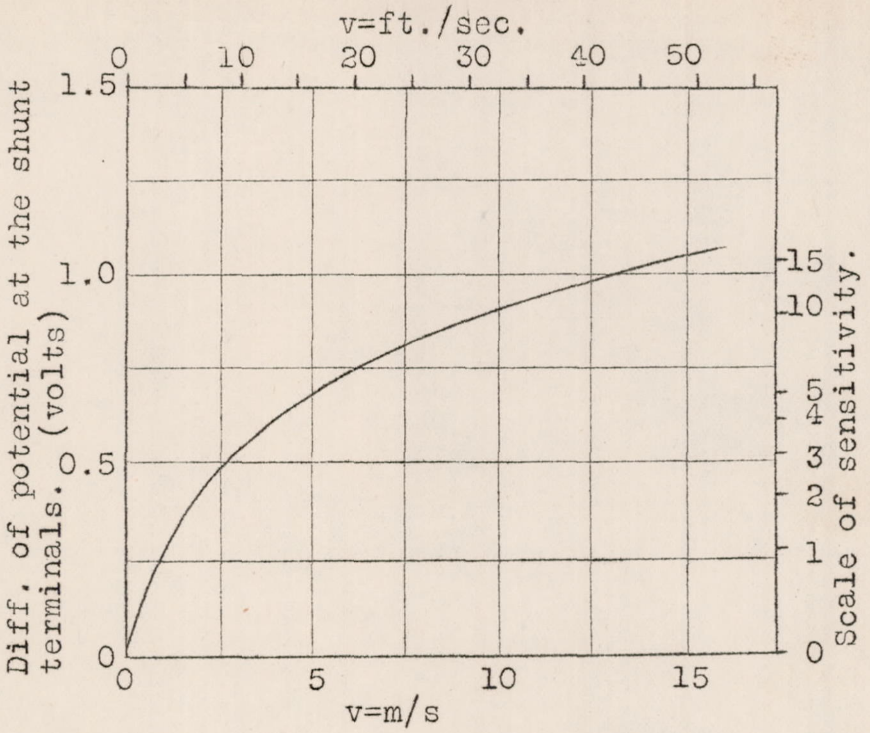

v=ft./sec.
0
10
20
30
40
50
1.5
1.0
0.5
0
Diff. of potential at the shunt terminals. (volts)
15
10
5
4
3
2
1
0
Scale of sensitivity.
0
5
10
15
v=m/s

Fig.4.

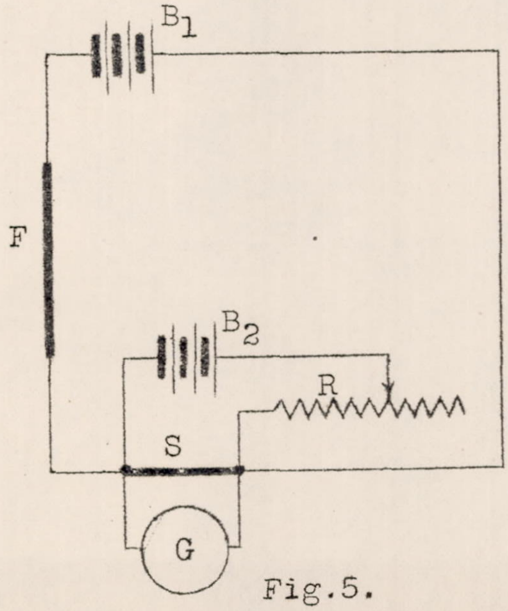

B1
F
B2
R
S
G

Fig.5.

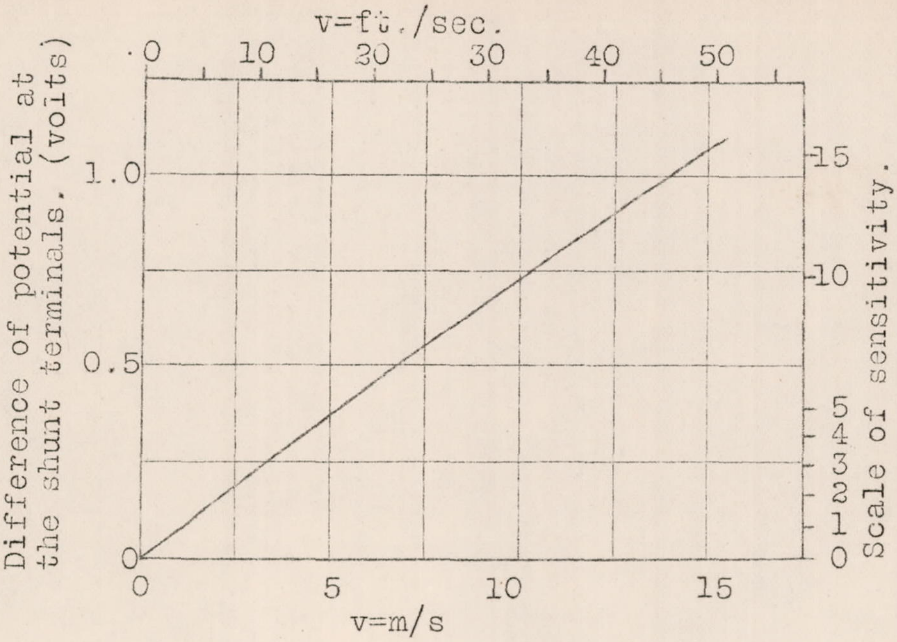

v=ft./sec.
0
10
20
30
40
50
Difference of potential at the shunt terminals. (volts)
1.0
0.5
0
Scale of sensitivity.
15
10
5
4
3
2
1
0
0
5
10
15
v=m/s

Fig.6.

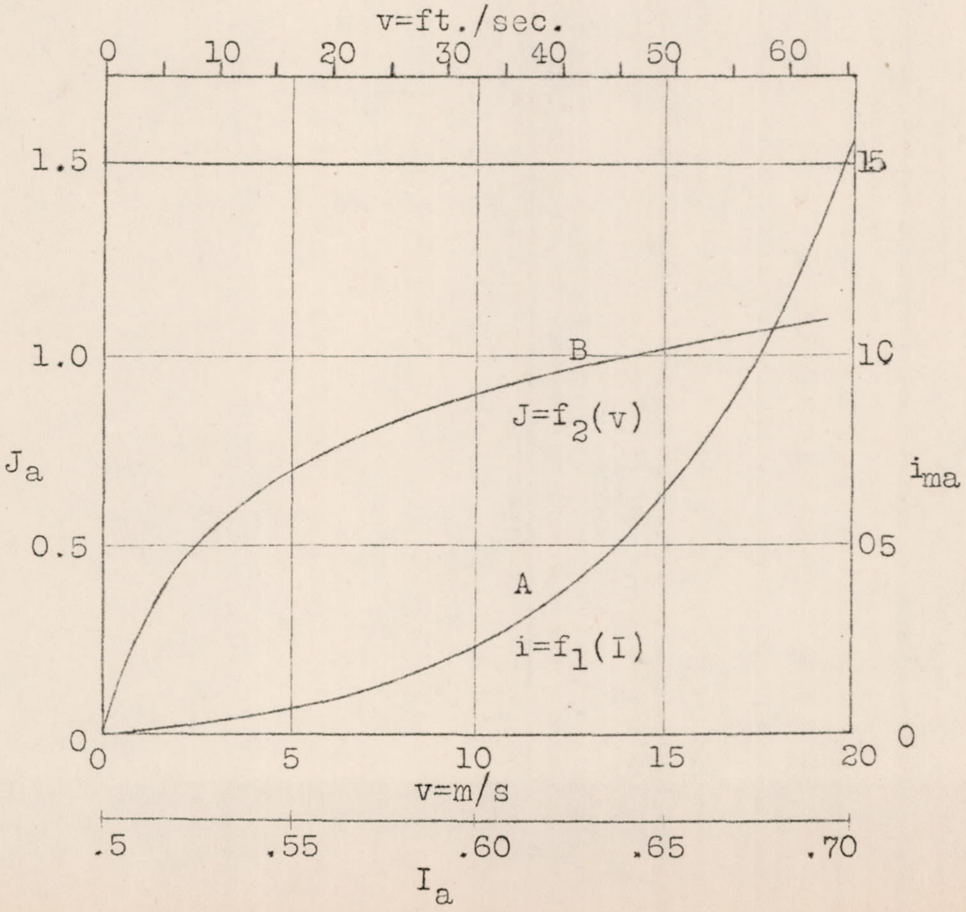

v=ft./sec.
0
10
20
30
40
50
60
1.5
1.0
0.5
0
Ja
15
10
05
0
ima
B
J=f2(v)
A
i=f1(I)
0
5
10
15
20
v=m/s
.5
.55
.60
.65
.70
Ia

Fig.8.

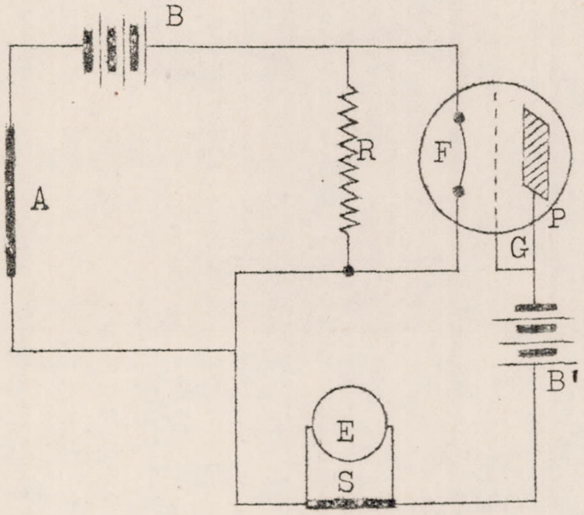

B
R
F
A
P
G
B'
E
S

Fig.9.

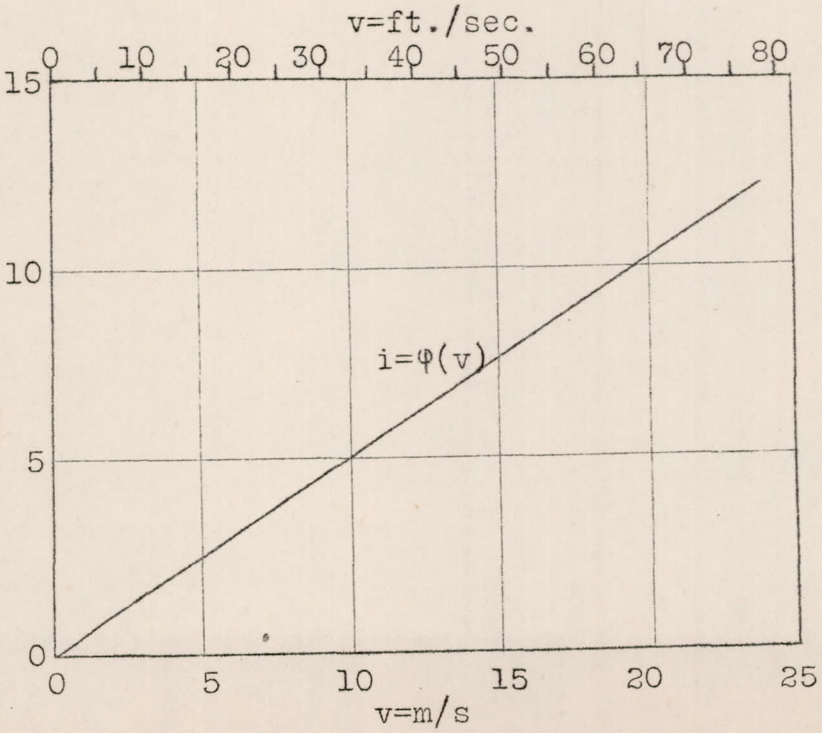

v=ft./sec.
0
10
20
30
40
50
60
70
80
15
10
5
0
i=φ(v)
0
5
10
15
20
25
v=m/s

Fig.10.

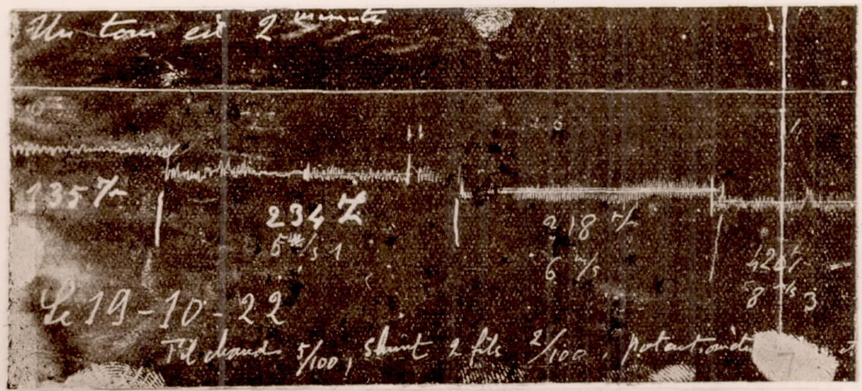


Fig.7 Record of wind produced by a propeller, by means of a hot-wire anemometer with with partial compensation.

Fig.13

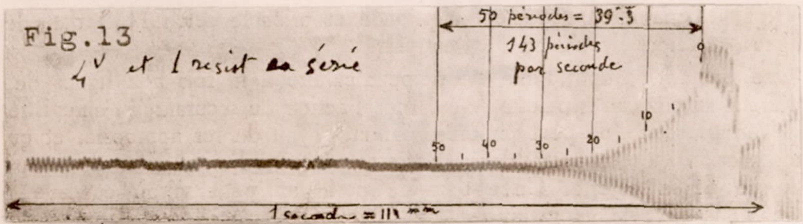


Fig.14

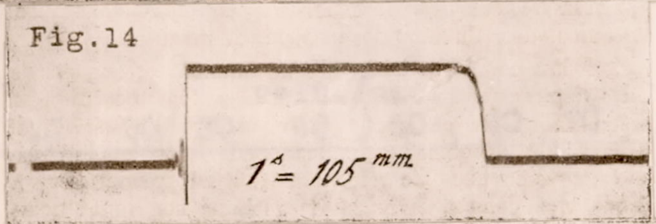


Fig.15

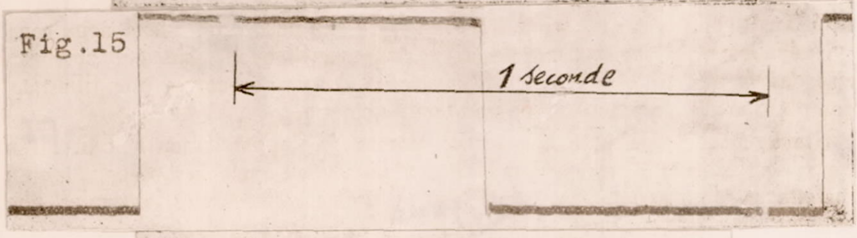
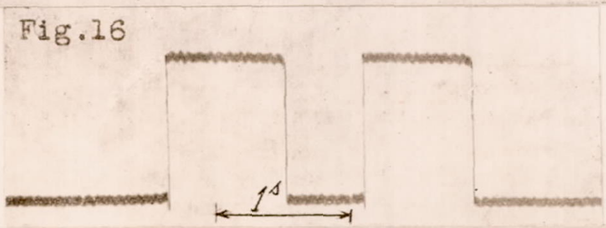


Fig.16



Figs.13,14,15,16 Diagrams showing the galvanometer with a movable core.

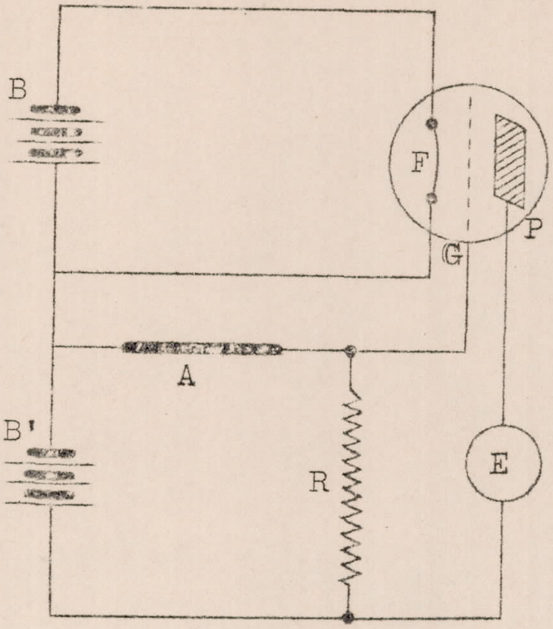


Fig.11.

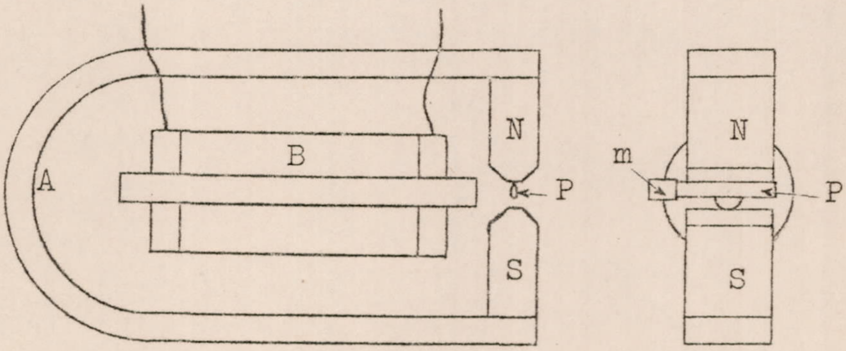


Fig.12.

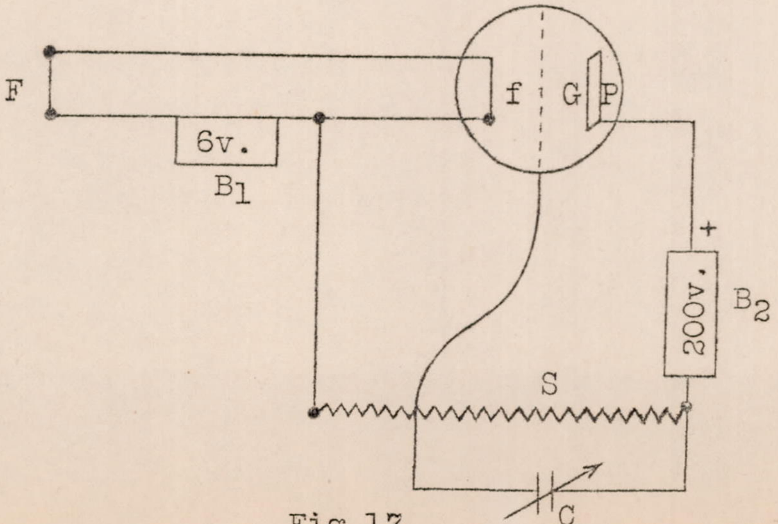


Fig.17.

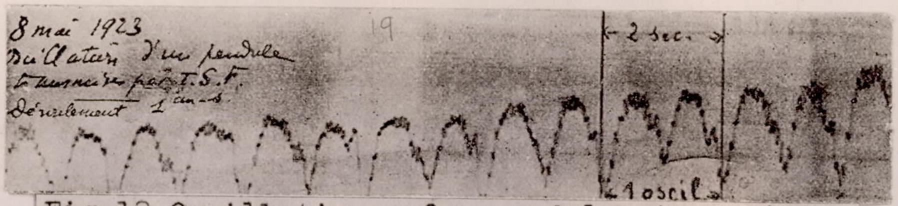


Fig.19 Oscillations of a pendulum transmitted by radio motion of photographic paper 1 cm (0.4 in.) per second.

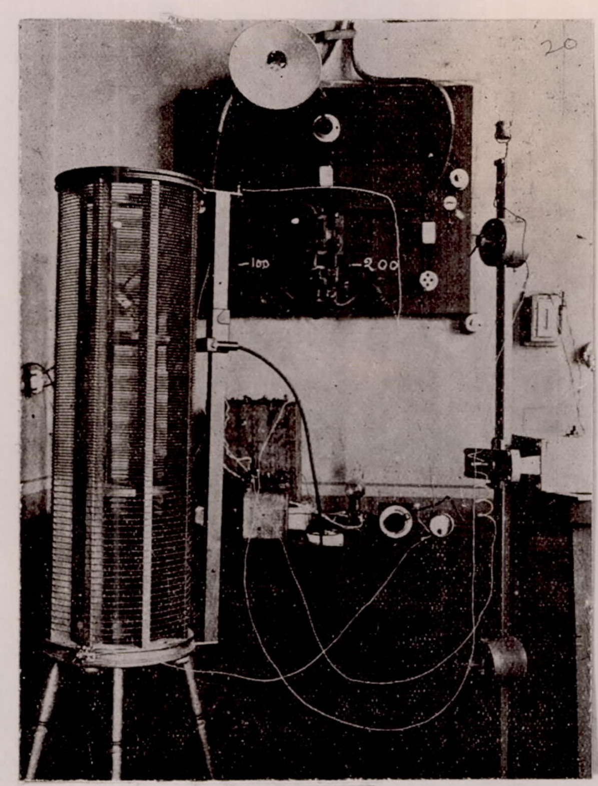


Fig.20

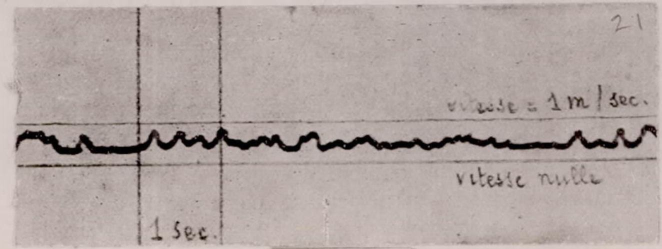


Fig.21

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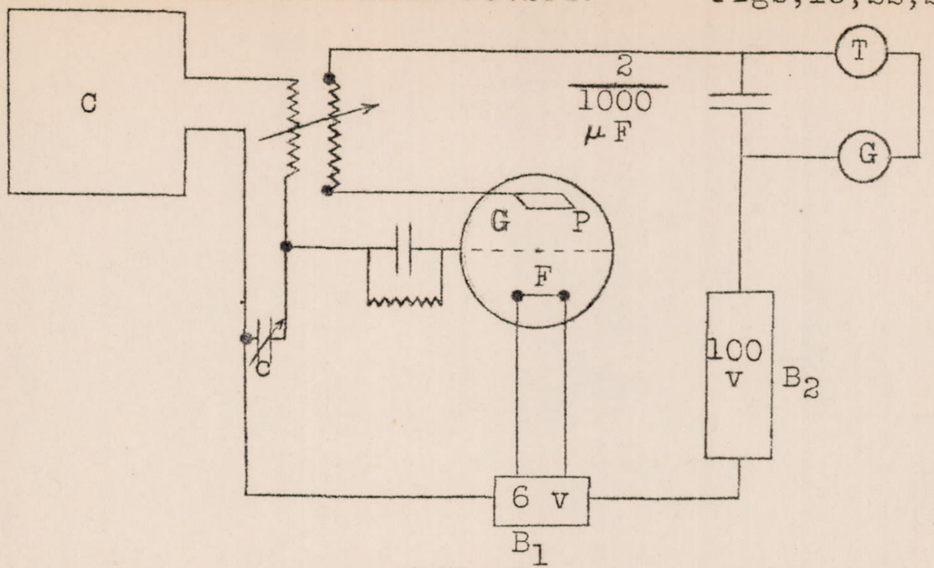


Fig.18.

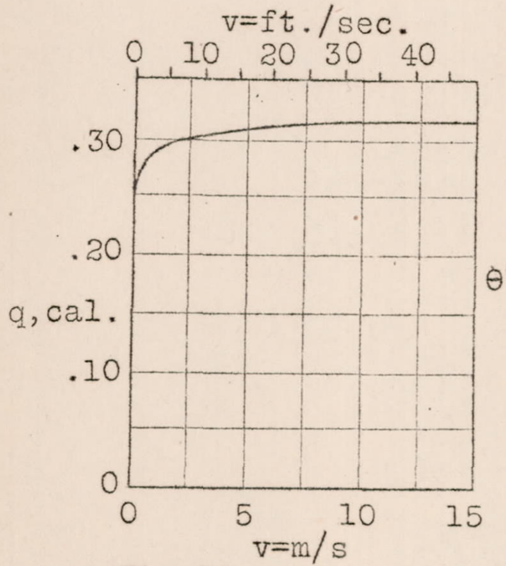
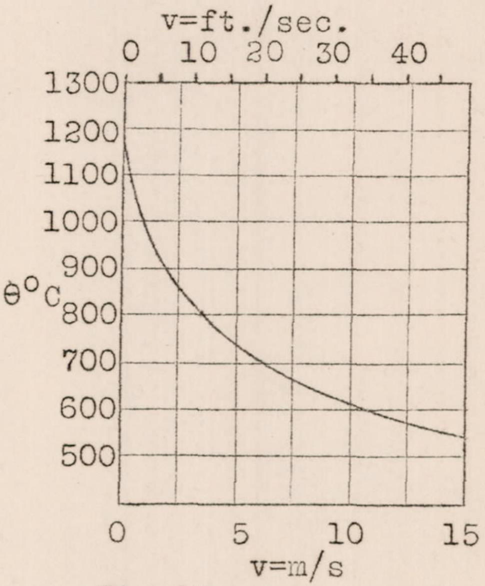


Fig.22.



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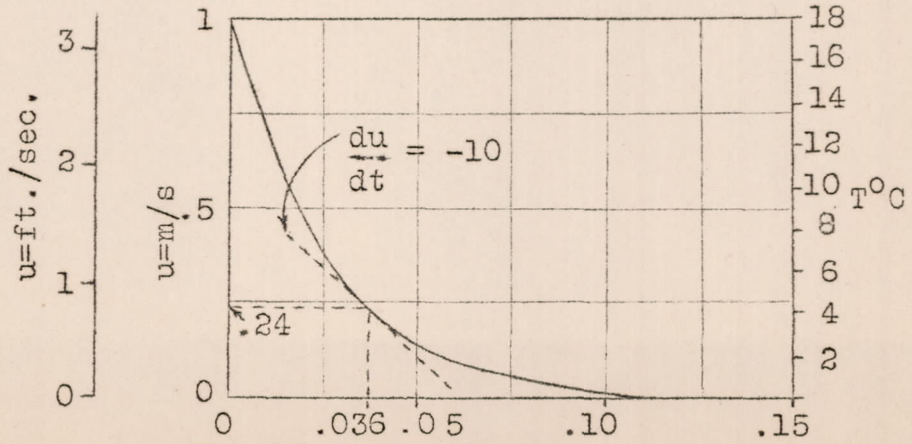


Fig.24.

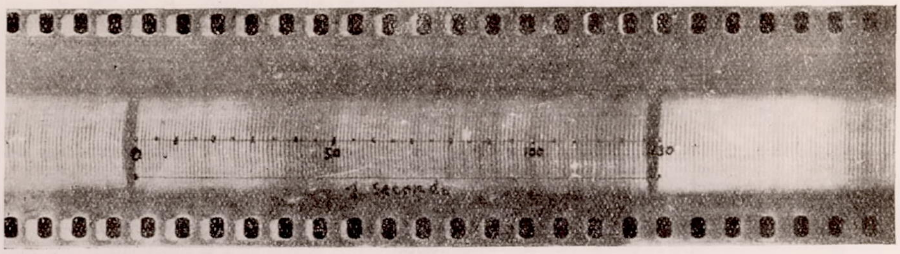


Fig. 26

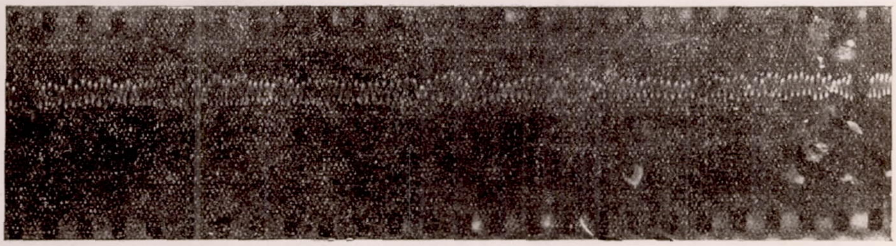


Fig. 27

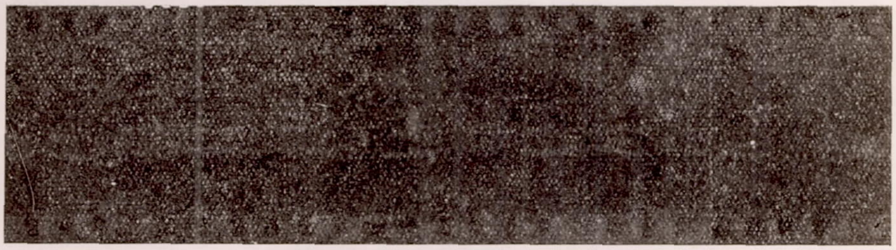


Fig. 28

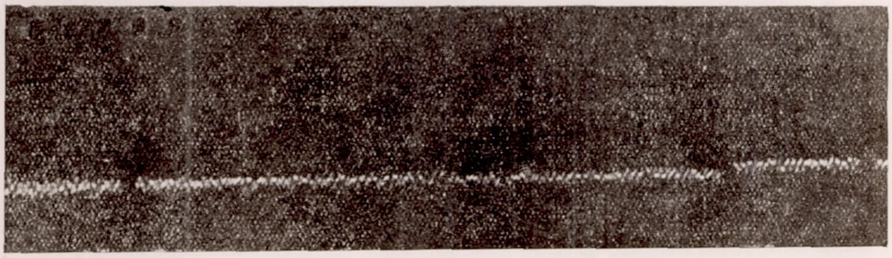


Fig. 29

N.A.C.A.
11506 A.S.

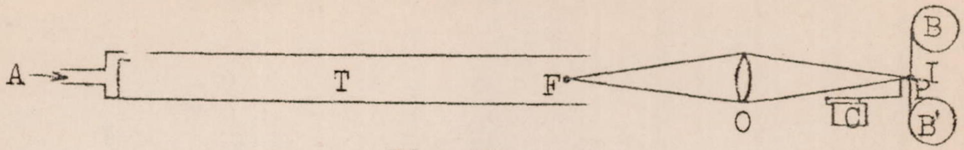
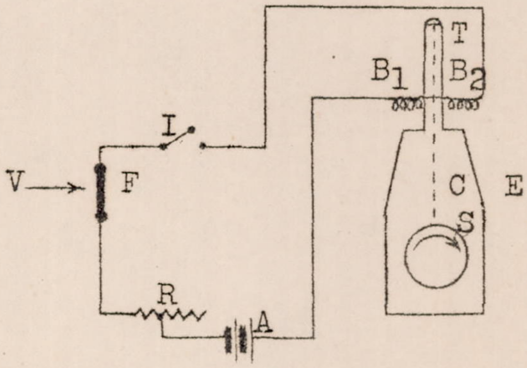


Fig.25.



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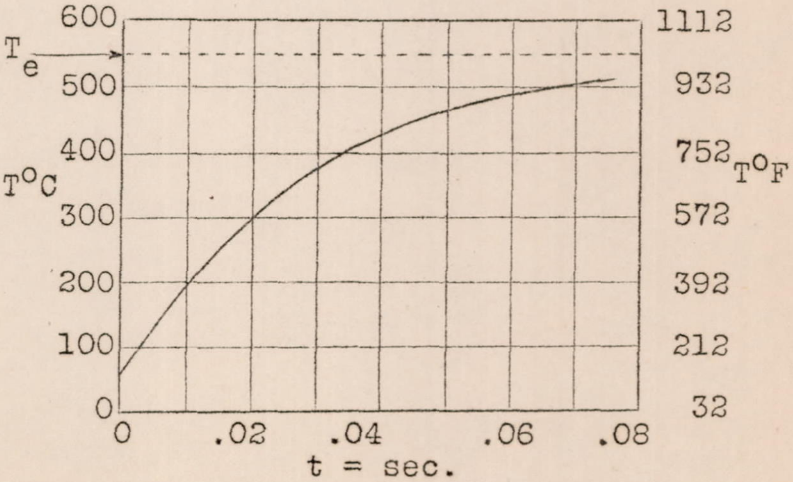

Fig.31.

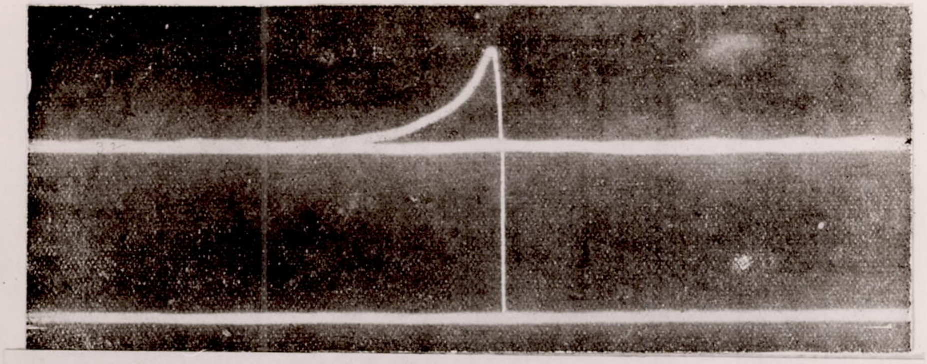

Fig.32 Establishment of thermal equilibrium in a platinum wire of 0.025 mm (.001 in.) diameter exposed to a wind of 15 m (49 ft.) per second, as recorded by the Dufour cathode oscillograph. Unrolling speed 2 m (6.56 ft.) per second.
Scale:- 395 : 550

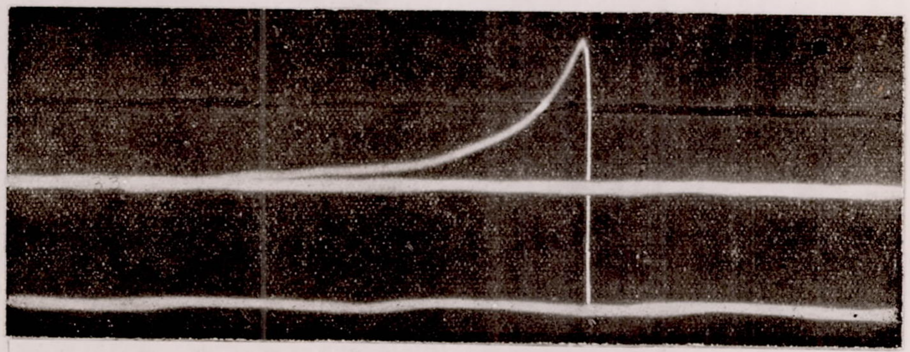

Fig.33 Establishment of thermal equilibrium in a platinum wire of .025 mm (.001 in.) diameter, in still air, as recorded by a Dufour cathode oscillograph. Unrolling speed, 2 m (6.56 ft.) per second.
Scale:- 385 : 535

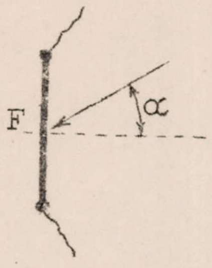

Fig.34.

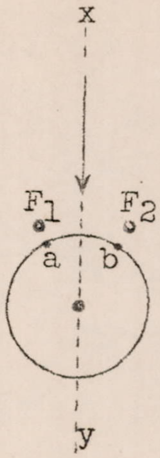

Fig.35.

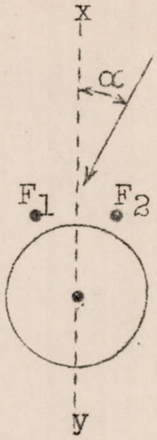

Fig.36.

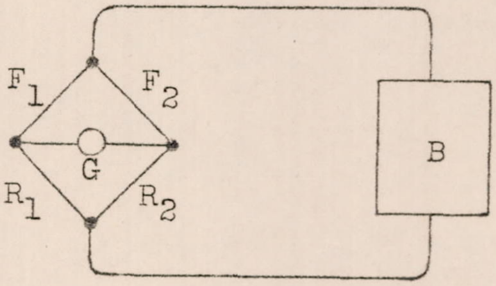

Fig.37.

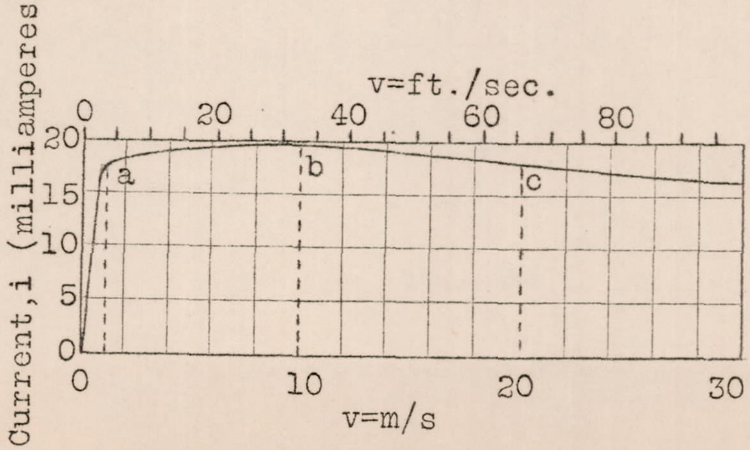

Fig.38.
Inclination of wind, α = 9°

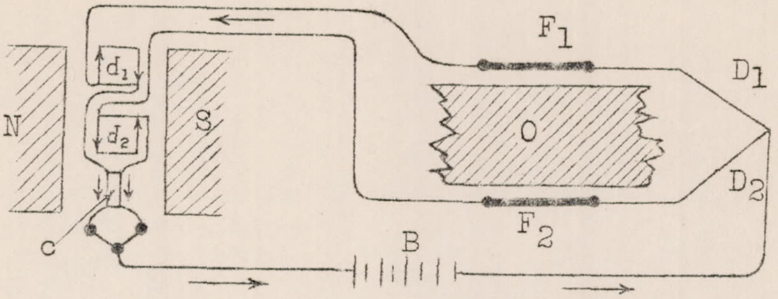
F_1
D_1
N
d_1
d_2
S
O
D_2
F_2
c
B

Fig.39.

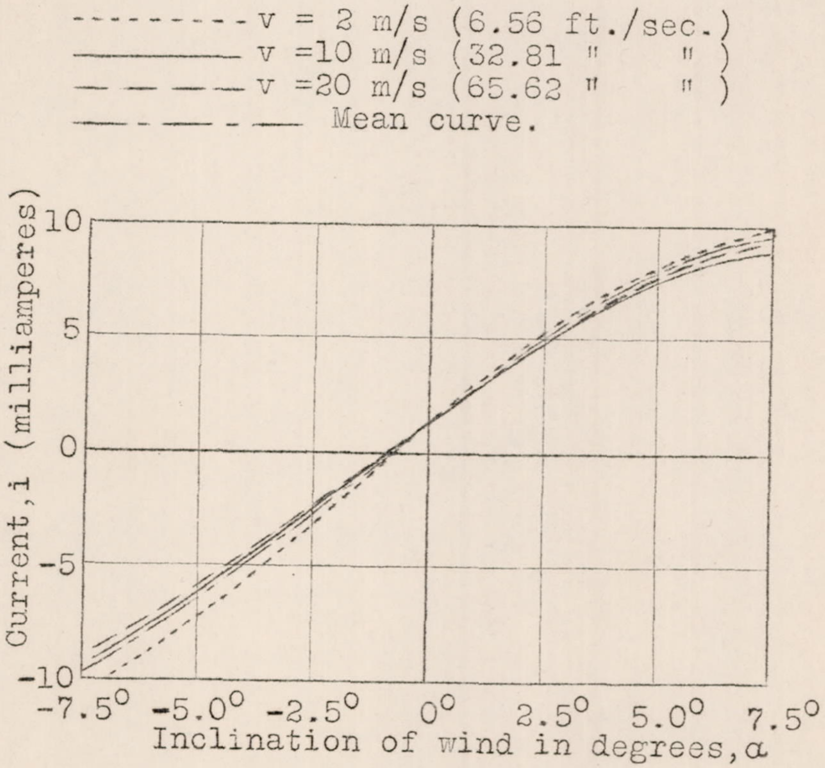
---------- v = 2 m/s (6.56 ft./sec.)
———— v =10 m/s (32.81 " ")
— — — — v =20 m/s (65.62 " ")
—— - —— - —— Mean curve.
Current, i (milliamperes)
10
5
0
-5
-10
-7.5°
-5.0°
-2.5°
0°
2.5°
5.0°
7.5°
Inclination of wind in degrees, α

Fig.40.

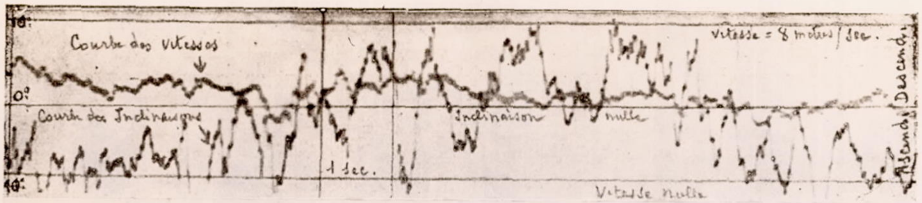

Fig.41 Velocity 26.2 ft./sec.

Curve designations

Courbe des vitesses . . . . Wind velocity
" " inclinaison. . . . . " inclination

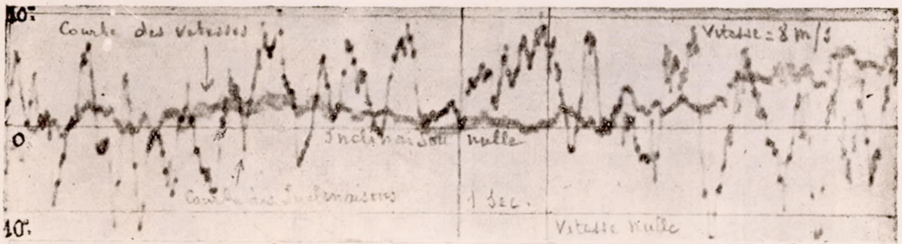

Fig.42 Velocity 26.2 ft./sec.

Curve designations

Inclinaison nulle . . . . Zero inclination
Vitesse " . . . . " velocity

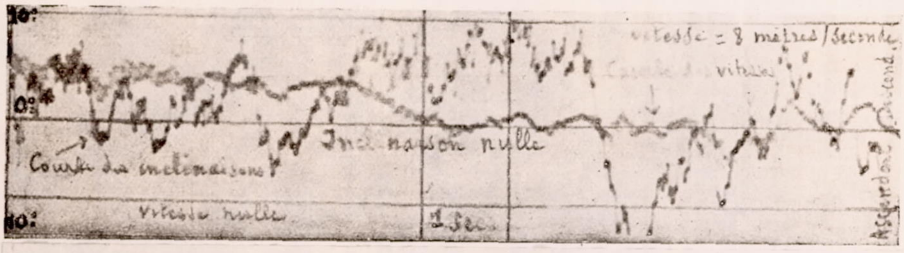

Fig.43 Record of variations in velocity and direction of a natural wind in the vertical plane.

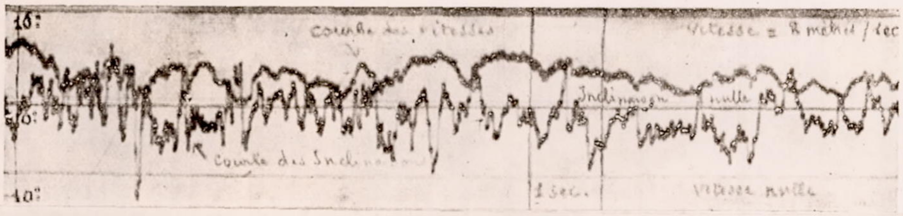

Fig.44 Record of variations in velocity and direction of a natural wind in the horizontal plane.

N.A.C.A.
11508 A.S.