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# LECTURE ON AERODYNAMICS.

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## Chapter I.

## Experimental Methods Employed in Studying Air Resistance.

General Statements.- The experimental methods employed in measuring the resistance of the air may be classed in two principal categories, according to whether the object of the investigation is stationary and subjected to the action of a current of air or whether it is moving through still air.

The first category (body in repose, air in motion) includes all of the methods which use a current of air produced by a fan. The device enabling the production and use of this current of air is called a "wind tunnel." The greater part of the experimental data on aerodynamics has been obtained by the use of wind tunnels, as this method is relatively easy to use and of high experimental efficiency.

The second category (body in motion, air in repose) includes the revolving arm (circular motion) and aerodynamic cars (rectilinear motion). The former method employs a horizontal arm revolving at a certain speed and carrying, by means of a suitable balance, the object of experimentation. It was originally employed by num-

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erous experimenters, but was later abandoned. Its abandonment is not entirely justified, since it should be the intermediate step between wind tunnels and aerodynamic cars. In wind tunnels the mass of moving air is relatively limited and is not usually free from turbulence. The conditions for the application of the principles of relative motion are therefore not entirely fulfilled. It may be stated that the phenomena set up in wind tunnels are not the same as those corresponding to the motion of a body through the air. Therefore a test on a revolving arm with the same body would enable the necessary verification with regard to the relative motion.

The whirling arm would also permit other methodical tests, but it is not so easy to use as a wind tunnel. The influence of the circular motion must be reduced by using an arm of great length. The centrifugal force is a drawback which must be considered, as also the speed imparted to the surrounding air.

Cars moving on a straight track constitute the only method giving results directly applicable in practice, since the conditions of motion and the dimensions are nearer to those of actual practice than with any other experimental device. The proximity of the ground and its interaction with the body under test is not a serious disadvantage, for both practice and theory show that this influence is very slight, if certain proportions of distance and dimensions are observed. The only disadvantage of this method is the loss of time, due to the necessity of operating in the absence of any appreciable wind. This method, therefore, should be devoted particularly to verification tests of results obtained with wind tunnels and whirling arms.

Wind Tunnels.- In the beginning we frequently employed wind tunnels in which the current of air produced by a fan was blown into the mouth of a shaft of appropriate dimensions. At the present time, practically the only types of wind tunnels employed are those in which the current of air is drawn in by a fan. The current of air obtained by suction is more regular than that obtained by direct blowing. The best arrangement for a wind tunnel is that indicated by Mr. Eiffel. It consists:

1. Of an entrance cone, in which the speed of the air current gradually increases with a minimum loss of pressure.

2. A cylindrical section or test-chamber, in which the speed of the air current is as regular as atmospheric and weather conditions permit.

3. An exit cone, diverging at an angle of 7 degrees, in which the speed diminishes gradually with a minimum loss of pressure. The fan is placed at the extremity of the exit cone.

This arrangement, which recalls that of the mouth of a Venturi tube, is advantageous, in that it enables a considerable speed to be obtained in the test chamber from a relatively small motive power. In other words, the efficiency of this arrangement is much higher than that of a cylindrical conduit of the same diameter as the test chamber.

At the outlet of the exit cone the air driven by the fan loses its speed on contact with the surrounding air. This loss of energy is less in proportion as the outlet section of the exit cone is greater. The air generally issues from the wind tunnel at an extremely low speed.

Sometimes the air is returned to the entrance cone through a tunnel (single or double) whose section is at least equal to the section of the outlet of the exit cone. In this case, the air returns to the entrance cone with a certain speed and a gain is realized in the motive power necessary to obtain the required speed in the test-chamber. The entrance cone is generally furnished with a "honeycomb" screen for the regulation and distribution of the components of the airstream in size and direction.

Frequently another screen is placed at the entrance to the test-chamber. Generally speaking, this screen and regulating grill produce turbulence in the center of the airstream, so that the regulation is accompanied by a more or less noticeable change in the flow of the fluid. This turbulence affects the reaction of the fluid on the body under test. It is particularly noticeable in the case of imperfectly streamlined forms upon which the filaments of air seem to strike at certain points of the contour (spheres, cylinders, ellipsoids, etc.).

The test-chamber may or may not have walls. In the first case, the wall forms a cylindrical or prismatic compartment of a length equal to two or three times its diameter. In the second case, the outlet end of the entrance cone and the intake end of the exit cone open into an air-tight chamber and the airstream traverses this chamber freely without noticeable expansion, if the length of the chamber in the direction of the stream is not too great (one or two diameters at most). This particularly ingenious and convenient arrangement was first employed by Mr. Eiffel in his old laboratory in the Champ de Mars. The elimination of walls in the test-chamber greatly facilitates the execution of tests.

The question arises as to whether the results obtained with the various devices are comparable and what relation they bear to the theoretical case of a fluid stream of infinite diameter. Experiments have been made for the purpose of answering this question. From certain German tests and in accordance with the theory established by Professor Prandtl, Director of the Aerodynamic Laboratory of Göttingen, it seems that, even for an object whose dimensions are small with respect to the section of the fluid stream, the limitation of the fluid stream modifies the pressure of the air against the object. This modification depends only on the relative dimensions of the stream and the object and is equal in amount but of contrary sign, according to whether the stream has walls or not. For example, for a given airfoil, the fluid stream without walls gives for a certain lift a little greater resistance than if the stream were unlimited. With the fluid stream of the same dimensions, that is to say, with all other things equal, the head resistance would be less by the same amount in relation to the theoretical resistance of an unlimited stream.

Tests executed at the Aerotechnical Institute of Saint Cyr have shown the accuracy of the corrections indicated by Prandtl. These corrections therefore apply to all experimental results. Thus, the results of various wind tunnels are comparable, on condition that other influences (turbulence, interaction of supports, etc.) are also comparable and as small as possible.

Aerodynamic Balance.- The objects to be tested are placed in the test-chamber and attached to the aerodynamic balance, enabling the measurement of the resultant of the action of the air in amount, direction and position.

In general, the balances are arranged so as to give the components of the reaction:

1. In the direction of the air current (head resistance or drag);

2. In a direction normal to the air current (lift).

The geometric sum of the two components gives the resultant in magnitude and direction. To arrive at its position, it is necessary to measure the moment of this resultant with respect to some given point (the leading edge, for example).

Various types of aerodynamic balances exist, but it is not possible to give a detailed description of them here.

Attention should be drawn to one very important point. The devices for attaching the model to the balance have a resistance of their own and an interaction with the model. The resistance of the supports themselves may be determined by direct measurement, but the interaction with the models should be null or negligible. This condition is often difficult to achieve and certain divergences between various laboratories are chargeable to these interactions which vary with the shape, size, direction and position of the supports. For this reason, models at the Aerotechnical Institute are connected to the balance by small taut wires.

Results obtained in wind tunnels, even when corrected for all parasite reactions (turbulence, limited airstream, interaction, etc.), relate to models of small dimensions (1/10 to 1/100 full size). Under these conditions, it cannot be stated that these results are directly applicable to full size by a simple application of geometric similitude. We do not yet know the laws of similitude applicable to aerodynamics. We only know that many phenomena (friction of the air, resistance of streamlined bodies, etc.) are a function of the product of the speed of the air by the characteristic dimension of the size of the body.

We have therefore endeavored in modern wind tunnels to increase as much as possible the speed of the air current and the size of the experimental models. We are, however, badly handicapped in this matter by the cost of such plants.

The principal wind tunnels in France are:

1. The wind tunnels of the Eiffel laboratory (61 rue Boileau, Auteuil) of which the principal one is 2 [6.56'] meters in diameter with a maximum speed of 30 [98.5 ft./sec.] meters per second; [$vl = 646$ ft²/sec.]

2. The wind tunnels of the "Institut Aerotechnique" at Saint Cyr, the principal one being 2 [6.56'] meters in diameter with a maximum speed of 48 [157.5 ft./sec.] meters per second; [$vl = 1033$ ft²/sec.]

3. The wind tunnels of the S.T.Aé. (Issy-les-Moulineaux), of

9.85 ft.

which the principal one is 3 meters in diameter and has a maximum

262.5 ft./sec.

speed of 80 meters per second. vl = 2584 ft²/sec.

Revolving Arm.- The object to be tested is attached to the end of this arm. It is then given a uniform relative motion with respect to the surrounding atmosphere, a suitable aerodynamic balance being used to measure the reactions.

As we have already said, the principal value of this method is that it fulfills, to a greater degree, the conditions of relative motion with respect to the air. The influence of the circular motion becomes negligible if the useful length of the revolving arm is from 15 to 20 times the span of the model under test. Moreover, the surrounding air acquires a slight rotary motion which rapidly becomes uniform and is therefore easily allowed for.

The greatest difficulty is the elimination of the effects of centrifugal force, which can only be accomplished by a suitable arrangement of the aerodynamic balance and the instruments for measuring the reactions of the air.

The revolving arm must be placed in a covered and closed building to eliminate the effects of the wind. It then has advantages over the aerodynamic car, since it can be used without regard to weather conditions.

The only revölving arm in France is that of the Aerotechnical

52.5 ft.

Institute. This has a useful length of 16 meters and a possible

91.1 ft./sec.

circumferential speed of over 100 kilometers per hour. It is en-

124.6 ft.

closed in a building 38 meters in diameter.

<u>Dynamometric Car</u>.- This is an especially equipped vehicle which moves along a rectilinear track, while carrying the body under test supported by a suitable aerodynamic balance.

The Aerotechnical Institute of Saint Cyr has a car for testing airplanes and other aircraft or their parts (cells, fuselages, wing structures, etc.). The aerodynamic balance consists of a system of jointed parallelograms enabling the direct measurement of drag and lift. A supplementary articulation enables the measurement of the moment of the resultant from which the position of the resultant is deduced.

This car, driven by a 120 HP engine, moves on a track 1300 meters long and can attain a velocity of 75 to 80 kilometers per hour.

There is a small amount of interaction due to the supports, but that due to the car and the ground is negligible for normal dimensions (wings or cells of 8 to 12 meters maximum span).

In the present status of aerotechnics it is of considerable interest to compare the results obtained on such cars with those furnished by wind tunnels and revolving arms. It is only from this comparison that we can deduce the laws of similitude applicable to aerodynamics. It is not improbable that the drag coefficients may be considerably smaller in the case of full-size experiments than the values given by the corresponding small models. The experimental confirmation of this fact would completely change the present conception and form of airplanes.

The Aerotechnical Institute also has a car for testing propellers, both lifting and propulsive. Either when stationary or when moving along the track, the tractive force exerted by the propeller, the power which it absorbs, the speed of rotation and the speed of translation may be measured. We thus have all the elements necessary to calculate the propeller efficiency. The electric motor, which drives the propeller, has a power of 80 HP and the speed of translation may reach 80 kilometers per hour.

Pressure Measurements.- In addition to the measurement of the resultant of all the air forces acting on a body, we can also determine the distribution of pressure (both positive and negative) over the whole surface. To accomplish this, a number of small orifices in the surface of the body are connected with a suitable micromanometer. This can be done in a wind tunnel or on an aerodynamic car.

Measuring Stability Coefficients.- For the various models we can also measure in a wind tunnel the various coefficients of stability by registering the curve of the oscillations about the axes passing through the center of gravity.

Measurements on an Airplane or Airship in Full Flight.- A certain number of measurements can be made on aircraft in full flight. These are particularly interesting as they contribute toward the establishment of the laws of similitude applicable to aerodynamics by comparing them with the results obtained on models.

## Chapter II.

Experimental Aerodynamics.- Experimental aerodynamics consists of all the results obtained in aerodynamic laboratories by the measurement of the action of the air on bodies of various shapes. It is impossible to give a complete exposé in this short lecture. We will therefore give only the latest data regarding supporting surfaces and briefly the data regarding other bodies.

The resistance of the air to a body in motion may be considered as being approximately proportional to the square of the relative speed and to the density of the air. Furthermore, the action of the air is proportional to the diametrical section (that is to say, to the square of the linear dimensions) for similar bodies oriented in the same manner with respect to the direction of motion.

The expression for this resistance is therefore the following:

$$F = K \rho S V^2$$

$F$ represents the total action of the air (in kilograms) on an object in motion with relation to it; $S$ represents the surface characteristic of the general dimensions of the object (for example, the surface of the master section in square meters); $V$ represents the relative speed of the object in relation to the air (meters per second); $\rho$ represents the density of the air (kilograms per cubic meter); $K$ represents the characteristic coefficient of the resistance to each shape of object, variable with the shape and orientation of the object and also with the characteristic value $E = V \times L$. We call this characteristic value $E$, the product of

$V \times L$ of the relative speed $V$ by a linear dimension $L$, characterizing the size of the object. This characteristic value is in some sort an abbreviation of the Reynolds number, which is equal to $\frac{VL}{\nu}$ $\nu$ being the kinematic coefficient of viscosity.

As the object is, in general, to compare the results of the tests made with the same fluid (the air), and under conditions varying only slightly as to density, we may, for the sake of simplicity, replace the Reynolds number $\frac{VL}{\nu}$ by the characteristic value $E = VL$. This variation of the coefficient $K$ with $VL$ is particularly important, In fact, the experimental conditions generally existing in the laboratories are such that the characteristic values, which one can attain there, are considerably inferior to the characteristic values in practical aviation.

If the coefficient $K$, which should be characteristic of the resistance of a body of a given shape and position, varies with $VL$, we could not rigorously apply laboratory results to full-sized aircraft. In order to do this, we would have to know the values of $K$ corresponding to the characteristic values $VL$ obtained with full-sized aircraft.

Resistance of Sustaining Wings.- The German laboratory at Göttingen has furnished some new data on the laws of resistance of sustaining wings which are particularly interesting. Theoretical considerations and methodical experimentation have led the German authorities to consider that the total drag (or head resistance) $T$ of either a monoplane or multiplane may be resolved into two parts: $T_o$ and $T_i$.

The first part ($T_o$) depends solely on the shape of the wing section of the airplane under consideration and is called the wing-section drag. For very good wing sections and small angles of attack, this drag $T_o$ may be considered, in the limiting case, as representing the resistance due to skin friction.

The second part ($T_i$) depends, for a given lift, on the dimensions, the plan contours and the juxtaposition of the surfaces composing the airplane cell under consideration, but it is independent of the profile of these surfaces. This is called the "induced drag." It is due to the descending current which results from the motion of the air on the surfaces and to the vortices at the lateral extremities of the wings. On studying the conditions for the formation of the descending currents induced by the wings in their motion through the air, we find that the induced drag $T_i$ is proportional to the square of the lift P and inversely proportional to the square of the span b. $T_1 = k \frac{P^2}{b^2}$

In other words, the values of $T_i$ are expressed by the abscissas of a parabola in terms of P, We may trace this parabola of the unit induced drag on the polar curve of any airplane cell. Then the coefficient relative to the wing-section drag is equal to the horizontal distance between the total polar and the induced parabola. The total angle of attack i is also equal to the theoretical sum of the angles of attack $i_o$, and the induced angle of attack $i_i$, that is:

$$i = i_o + i_i$$

The induced angle of attack $i_i$ is proportional to the lift and inversely proportional to the square of the span. $i_i = k \frac{P}{l^2}$

The drag $T_0$ and the angle of attack $i_0$ depend only on the shape of the wing section and we may calculate the differences between the drags and the angles of attack of two types (1 and 2) of airplane cells, using the same profile, by the following equations:

$$\begin{cases} T_2 - T_1 = T_{i2} - T_{i1} \\ i_2 - i_1 = i_{i2} - i_{i1} \end{cases}$$

In these equations, the values $T_i$ and $i_i$ are found by calculation. Methodical tests, undertaken for the verification of these laws have enabled the determination of the values of the parameters of induced drag for both monoplane and multiplane cells. Knowing these parameters, it is possible to calculate in advance, the polar of any cell when we have the polar curve of another cell using the same wing section.

Rectangular Monoplanes.- The induced drag and consequently the total drag for a given lift diminish constantly as the aspect ratio increases. The polar curves form a "fan" as shown in the accompanying figure.

Various Monoplanes.- The values of the induced drag depend on the contour (trapezoidal wings) and on the thickness of the wings. Experiments have enabled the determination of the corresponding parameters.

Straight Rectangular Biplanes.- The induced drag and therefore the values of parameters depend on the relation of the span b to the gap h. When the ratio b : h diminishes, that is to say, when the gap h increases for a given span, the value k increases and consequently the induced drag decreases. The variation of k may be represented by an approximate formula as a function of the ratio h : b. For staggered biplanes, with or without "interclinaison" (unfortunately called "decalage" in English), the perameters are more or less complex functions of the stagger and of the "interclinaison."

Lastly, for biplanes of unequal spans a calculation can still be made and there are in this case certain relative proportions of the two wings which give the minimum drag.

Triplanes and Multiplanes.- Formulas have been given which are well confirmed by experience. From what we have shown, it follows that interactions due to the superposition of wings can be determined, in general, with fair approximation. But there are also secondary interactions due to the fuselages, struts and exterior fittings. These interactions are very variable and must be determined experimentally in each particular case.

Wing-Section Drag and Skin Friction.- That which has gone before relates to the induced drag. The wing-section drag is due to the friction of the air and to the impacts and vortices. For very good wing-sections and angles of attack at which the fluid filaments do not leave the surface, the major part of the wing-section drag is due to skin friction. It is therefore very important to reduce this friction to a minimum! This is accomplished by using highly polished surfaces.

The tests show that on all polished surfaces the unit coefficient of friction is inversely proportional to the 0.15 power of the characteristic product VL(V = the speed and L = the length in the direction of the relative motion).

Thus, $Kf = \frac{0.000440}{(VL)^{0.15}}$

The total drag due to friction is given by the formula

$$F = Kf\, S_o\, V^2$$

$S_o$ being the total surface area under friction.

For example, a wing with a chord of two meters and a span of 12 meters, moving at a speed of 55 meters per second (200 kilometers per hour) will give a total friction drag of 31.6 kilograms, corresponding to 33 HP. With an unpolished surface this drag and the corresponding motive power might be doubled.

Note 1. The head resistance or drag of a good wing-section is due almost wholly to skin friction and the induced drag. Thus wing-section No. 430 of the Göttingen laboratory gives, for all angles from $-6^\circ$ to $+3^\circ$ (lift coefficient from 0 to 0.05), a constant wing-section drag equal to the friction ($K\,xf$ = 0.0007). Beyond this lift coefficient the wing-section drag includes, in addition to the friction, an additional resistance which is probably due to the increasing separation of the fluid filaments from the surface of the wing.

Note 2. As we have already said, the unit coefficient of drag varies somewhat with the magnitude of the relative speed V and with the dimension L of the body. We have only been able to determine these values for a limited range of the values of $V \times L$. However, the variations show that the coefficient of drag diminishes regularly as VL increases and that the lift coefficient remains strictly constant under the same conditions. It follows that the flow of the air around lifting wings improves when the speed or the dimensions increase. The efficiency of actual wings is therefore far superior to the efficiency of the corresponding small models.

## Laws of Resistance for Bodies of Various Shapes.

(a) Resistance of Cylindrical Bodies Perpendicular to the Air Stream.- The same as for spheres, the coefficient $K = \frac{R}{SV^2}$, referred to the diametrical section, depends essentially on the characteristic product V D. Mr. Eiffel has shown that when V D exceeds 1 square meter per second, the coefficient K shows a sudden variation such that its value passes from 0.061 (for VD = 1) to 0.02 (for VD = 3.5). This value remains constant at least up to VD = 6.

As in the case of spheres, there is also a change in the nature of the air-flow around cylinders. The value of VD, for which this change occurs, depends also on the degree of turbulence of the artificial air current employed. At Göttingen, the same phenomenon was observed, but the rapid variation of K did not begin until VD = 2.1.

The variation of the coefficient K for cylindrical bodies as a function of the characteristic number VD therefore shows two stages corresponding to very different values: $K_1 = 0.061$ to 0.065 and $K_2 = 0.02$.

This confirms what we have already said relative to the necessity of obtaining in laboratories high values of the Reynolds number and artificial air currents as free as possible from turbulence.

(b) Resistance of Streamlined Bodies Perpendicular to the Air Stream.- The employment of streamlined shapes for airplane fittings (struts, stays, etc.) has become general, because the drag coefficients of these shapes are much smaller than those of cylindrical shapes.

Mr. Eiffel found that starting with the aspect ratio S (ratio of the width at the master section to the depth in the direction of motion) good streamlined shapes all give a value of K = approximately 0.005. This value is about 1/12 of that found for cylinders.

At the limit, moreover, the resistance of good shapes tends toward that due simply to friction. This is why the degree of polish is extremely important in calculating these resistances. In addition, for the same reason, it would be useless to increase the dimensions of the body too much in the direction of the air stream.

Lastly, certain shapes give sudden variations of the coefficient K as a function of the characteristic number VL.

(c) Resistance of Spheres and Ellipsoids.- The resistance of spheres and ellipsoids presents interesting peculiarities due to the change in the flow of the air on the contour of the body. These changes depend on the characteristic product VR of the speed by the radius (or diameter) of the sphere. Thus, for a low speed and for spheres or ellipsoids such that the value of VR is less than 1, the flow is such that the fluid filaments are deflected a little in advance of the equator. For higher values of VR, the flow is less stable and the filaments are deflected on parallels situated at various distances back of the equator. Finally, for a sufficiently high value of VR, the flow becomes stable again and the fluid filaments are deflected at a certain parallel (about 25 degrees) back of the equator.

In the first case there is a negative pressure extending all over the rear half of the sphere. It is a case of high resistance in which the unit coefficient has a value close to 0.03.

In the second case there is a zone of negative pressure affecting only a portion of the rear hemisphere. It is a case of low resistance for which the unit coefficient has a value close to 0.012.

Mr. Prandtl, Director of the Göttingen Laboratory, demonstrated in 1914, that the condition of turbulence in the air current might have considerable effect on the course of the variations of the coefficient K with the characteristic value VD. For spheres, cylinders, ellipsoids, and all bodies from which the fluid filaments separate at a certain point, the rapid variations of the coefficient K, as a function of VD, are produced for as much higher values of VD as the current of air is less turbulent.

We have verified the results of Prandtl by measuring the resistance of the air on spheres at velocities running up to 80 or 90 meters per second (290 to 320 kilometers per hour). The wind tunnel employed was an Eiffel type not furnished with any regulating device.

Under these conditions, the current of air did not present any appreciable degree of turbulence, in spite of the high velocity attained. We have stated that the rapid decrease of the coefficient K is produced for all the spheres tested (diameter from 40 to 70 mm) in the neighborhood of a value of VR = 2.1, while in the experiments of Messrs. Eiffel and Maurain, this rapid decrease of K took place in the neighborhood of VR = 1.1. In the tests of Prandtl the same phenomenon was produced in the neighborhood of VR = 2.

By placing at the entrance of the wind tunnel a regulating screen, which produced a certain turbulence in the air current, we noticed a rapid decrease of the coefficient K for values of VR = 1.1.

(d) Resistance of Streamlined Bodies.- Small models of streamlined bodies correspond generally to the shape of airship hulls. It is customary to characterize the unit resistance of these bodies by two coefficients K and K'. The coefficient K is that of the usual shape

$$R = K\,S\,V^2$$

in which S is the area of the master section of the hull under consideration.

The coefficient K' is that in the formula

$$R = K' \, V_0^{\frac{2}{3}} V^2$$

in which $V_0$ is a volume of the hull. This expression for the resistance, proposed by Prandtl in 1910, agrees with the following consideration. For an airship, the ascensional force is proportional to the volume of the hull and it is this volume which must be considered in comparing the resistances of two hulls. The 2/3 power of the volume is homogeneous to a surface and the second formula is thus reduced to suitable dimensions.

Mr. Eiffel, in his last publication, gives the values of K and K' for many shapes of the hull. The smallest values were obtained for a hull with an aspect ratio of 3.65 (ratio of the length to the diameter at the master section) for which

$$K = 0.00306$$

$$\text{and} \quad K' = 0.00158.$$

However, previous tests have already shown that coefficients K and K' increase with the aspect ratio.

Note: In practice, aspect ratios as small as this are rarely utilized, especially in large airships. For the latter, the values of K and K' found by Mr. Eiffel, are particularly remarkable with a certain shape of hull (No. 2) having an aspect ratio of 6, for which K = 0.00414 and K' = 0.00164.

Influence of Aspect Ratio.- In spite of the diversity of hull shapes tested, results obtained by Mr. Eiffel show that the unit coefficients of drag for streamlined bodies increase with an increase of aspect ratio. Aspect ratios between 3 and 4 give the smallest coefficients of drag.

These results are confirmed by a series of other measurements on streamlined bodies whose forward and rear portions were quite different. The minimum value of K was found for a streamlined body with an aspect ratio of 3 forward and a symmetrically located rear section for which K = 0.0021.

(Minimum value of K' was found for an aspect ratio of 4 to be K' = 0.00150).

Influence of Velocity.- Forthese same models, Mr. Eiffel found that the coefficient K diminished as the speed increased. Here again the surface friction plays an important role. It was also found that the decrease of the unit coefficient with the velocity was sometimes due to the resistance of the shape itself, that is to say, to the resistance resulting from the dynamic pressures on the streamlined body. The portion of the drag due to friction on the hull can be determined. It depends on the shape and size of the hull. It is interesting to note that it frequently amounts to 50% of the total drag. The knowledge of the laws of variation of skin friction on streamlined bodies with a characteristic value of VL therefore assumes considerable importance. The coefficients of drag found for small models cannot therefore be applied rigorously to the corresponding full-sized hulls.

# Chapter III.

## Propellers.

Air propellers have been the subjects of numerous researches in aerodynamic laboratories. We will indicate the general properties actually established and the details of certain modern propellers.

1. Lifting or Vertical Thrust Propellers.- The problem of the helicopter causes a great interest to be attached to these propellers. All experiments confirm the practical accuracy of the laws enunciated by Colonel Renard, as defined by the following formulas:

$$F = a\ n^2\ D^4$$

$$T = b\ n^3\ D^5$$

F being the thrust of the propeller in kilograms;

T the power absorbed by the propeller in kilogram-meter per second;

n the number of revolutions per second;

D the diameter in meters;

a and b two coefficients which are the same for propellers geometrically similar and which are nearly constant for a given propeller within practical limits.

We may characterize the lifting power of vertical-thrust propellers by a coefficient such as that proposed by Mr. Margoulis -

$$K_F = \frac{a}{b}\ \frac{2}{3}$$

so that the thrust is given by the expression

$$F = K_F \times \sqrt[3]{T^2\ D^2}$$

For a given power T and diameter D, the propellers exerting the greatest thrust are those which have the best coefficient $K_F$.

A very complete series of experiments by Durand and Lesley on two-bladed propellers in the laboratory of Stanford University (18 families, each consisting of 3 propellers of different pitches) has shown that the thrust of two-bladed lifting propellers depends only on the diameter, the R.P.M., and the power absorbed, without regard to the cross-section, chord, contour, variation of pitch along the radius and the length of the radius, provided the relative pitch is less than 0.9.

Other tests by Bendeman and Schmid in the Lindenberg laboratory show that we may obtain a constant value of Kf within very wide limits of the power coefficient b, on condition that we employ, for the small values of b, narrow, flat, two-bladed propellers of low pitch. In proportion as b increases, we must increase the power of the propeller, either by hollowing out the blades or by increasing their chord and, finally, by increasing the number of blades.

The maximum value of Kf, resulting from the interpretation of these tests and of those made by the Aerotechnical Institute, is 0.48.

Note. The problem of the helicopter involves many other questions, in addition to the sustaining power of the propellers. These questions are, for example: the functioning of the propeller in a motion of forward translation (driving propeller) or translation backward (helicopter descending with engine running); the functioning of the propeller as an aeromotor (vertical or oblique descent with the propeller disengaged or braked). Some of these questions have already been studied experimentally, but the greater part must yet be undertaken methodically.

2. Driving or Horizontal-Thrust Propeller.- Propellers producing translation parallel to their axis of rotation are called driving propellers. A complementary characteristic of these propellers is their efficiency as defined by the following formula:

$$r = \frac{FV}{T}$$

V being the speed of translation with relation to the air. These experiments again confirm the practical accuracy of the laws of Colonel Renard.

$$F = a\ n^2\ D^4$$

$$T = b\ n^3\ D^5$$

But the coefficients a and b, as well as the efficiency r for a given propeller, are a function of the advance per revolution $\frac{V}{\pi nD}$, or more simply a function of $\frac{V}{n\ D}$. We find, in fact, that the thrust coefficient starting with its value at zero advance, diminishes constantly as V or $\frac{V}{n\ D}$ increases. For a certain value of $\frac{V}{n\ D}$ the thrust is zero and the efficiency is also zero. The coefficient of power b, diminishes as $\frac{V}{n\ D}$ increases and becomes zero for a value of $\frac{V}{n\ D}$ above that for which the thrust itself becomes zero.

The propeller efficiency r, starting from 0 for $\frac{V}{n\ D}$ (zero advance) passes through a maximum for a certain value of $\frac{V}{n\ D}$

and again becomes 0 for the value of $\frac{V}{n D}$ which gives zero thrust A very important point in the experimental study of propellers is the search for propellers with as great driving efficiency as possible.

1. Effect of Relative Pitch.- The relative pitch of the propeller is the ratio of the pitch to the diameter. When the pitch varies along the radius, the relative pitch is calculated by taking the value of the pitch for the section located at a distance from the axis of rotation equal to 3/4 of the radius.

The maximum driving efficiency increases as the relative pitch increases. The following table showing results obtained in the Eiffel laboratory gives an idea of the variation of the efficiency with the relative pitch.

| | | | | | |
|---|---|---|---|---|---|
| Relative pitch | h = 0.4 | 0.6 | 0.8 | 1 | 1.2 |
| Maximum efficiency | rm = 0.55 | 0.63 | 0.67 | 0.70 | 0.72 |
| | $\frac{V}{n D}$ = 0.375 | 0.54 | 0.72 | 0.87 | 1 |

Analogous results are given by the tests of Professor Durand (Stanford University, U.S.A.).

The influence of the profile of the sections of the propeller blade is more complex. However, it seems that the best propulsive efficiencies are given by curved sections of medium thickness.

The influence of the plan form of propeller blades is equally complex, but it seems that the best blades have a maximum chord equal to 0.16 R and located at 0.5 R (R being the radius), the chord decreasing towards the tip and the leading edge following a regular curve.

Effect of the Number of Blades.- Due to the interaction of the blades, the maximum propulsive efficiency decreases as the number of blades increases. The following table gives an idea of this variation:

| | 2-bladed propeller | 3-bladed propeller | 4-bladed propeller | 6-bladed propeller |
|---|---|---|---|---|
| Maximum efficiency r m = | 0.72 | 0.69 | 0.68 | 0.66 |

The conditions under which the propeller is fitted to the airplane are in reality very complex and include other things in addition to the consideration of the maximum propulsive efficiency. Thus, it may be necessary to adopt a 4-bladed propeller in order to obtain a diameter suited to the dimensions of the airplane.

Tandem Propellers.- On airplanes of large-carrying capacity, it has been found best to adopt lateral power plants, each composed of two like-powered engines, the forward engine carrying a tractor propeller and the rear one a pusher propeller. It was therefore important to investigate in the laboratory the conditions for the efficient functioning of tandem propellers.

Methodical tests undertaken by the Eiffel laboratory have completely solved the problem. The following are the general conclusions reached:

1. It is necessary to revolve the two propellers in opposite directions. This condition, moreover, fits in well with the arrange-

ment of the two engines. It has been found that the forward propeller is not appreciably influenced by the rear propeller, its power factor remaining the same as if it were alone and its efficiency being only slightly diminished. The rear propeller is affected and its efficiency is higher when the two propellers revolve in opposite directions.

2. There is no advantage, from the point of view of efficiency, in using front and rear propellers of different diameters.

3. There are no practical reasons for revolving the two propellers (if they are of the same diameter) at different speeds.

The problem of the adaptation of tandem propellers to an airplane is reduced therefore to the adaptation of the forward propeller and the determination of the pitch of the rear propeller. The relative pitch of the rear propeller depends on the relative pitch of the forward propeller. It is sometimes greater and sometimes smaller than the latter, according to whether there is a fuselage, or a fuselage and a cell interposed between the two propellers.

When a fuselage is interposed between the two propellers (general case in practice), it is found that the head resistance of this fuselage is considerably increased and that the thrust of the propeller is likewise increased. As a result, 3/4 of the increased drag of the fuselage is offset by the increased thrust of the rear propeller.

The presence of a fuselage and a cell between the two propellers produces similar results, the phenomena being more accentuated than when only a fuselage is interposed. The loss of efficiency of the rear propeller decreases as the relative pitches increase.

Note 2. In a general manner, the interaction between a propeller and a fuselage with or without wings is considerable. Thus, a tractor propeller placed in front of a fuselage, the wings being in place, increases the resistance of the fuselage for the thrust values corresponding to the normal R.P.M. Where the R.P.M. is such that the propeller gives zero thrust (gliding descent with propeller revolving at a suitable speed) the resistance of the fuselage is diminished.

## Chapter IV.

## Stability of Airplanes.

General Statements.- An airplane is stable when it can recover its position after its equilibrium has been disturbed.

Dynamic Stability, or stability of control, is that produced by the section of the rudder, elevator and ailerons.

Inherent Stability is due to the position, orientation and general proportions of the elements constituting the airplane (cell, fuselage, tail planes, etc.), all these being fixed in size, position and orientation. It is the stability of the airplane itself, when all the controls are locked. Inherent stability is, therefore, of an automatic nature and has principally to do with slight disturbances of equilibrium. It must not be made too great, since its exaggeration may destroy the maneuverability of the airplane.

The following stabilities are distinguished according to the nature of the disturbances to be overcome.

Longitudinal Stability, which controls pitching;

Lateral Stability, which controls rolling;

Directional Stability.

Longitudinal Stability.- This depends on the position of the center of gravity of the airplane with respect to the resultants of the action of the air on the whole airplane. It also depends on the direction of the propeller thrust.

When the line of thrust passes through the center of gravity of the airplane (the more general case), the longitudinal stability requires the center of gravity to be so placed that the resultants passing in front of the center of gravity correspond to a decrease in the angle of attack and the resultants back of it correspond to an increase in the angle of attack.

In order that the resultants may be so arranged, it is necessary for the horizontal tail planes to have certain proportions and orientations. The wings alone generally give an unstable set of resultants. The positions of the resultants are determined experimentally and this determination should be made for every possible position of the elevator. It is found that the set of resultants is stable when the general direction of the horizontal tail planes makes a smaller angle with the relative wind than the chord of the wings.

In general, the position of the center of gravity should be between 1/3 and 1/4 of the chord from the leading edge.

Lateral Stability.- The lateral inherent stability is generally obtained by raising the ends of the wings (dihedral). Lateral dynamic stability is obtained by the ailerons. The ailerons should be sufficiently efficacious not to require a very large angle of deflection, since this would produce a contrary effect to the one desired, by increasing the resistance of the wing which is lowered.

Directional Stability.- Directional stability is obtained in an appreciable degree by compensation of vertical drift areas. These areas are all the surfaces showing in the lateral projection of the airplane. Of course, these surfaces must be modified by a coefficient allowing for their resistance in an oblique wind. A plane surface is more effective in this respect than a cylindrical or streamlined surface. It is necessary for the moment of the air forces on all vertical surfaces in front of the center of gravity to be less than the moment of the air forces on the vertical surfaces back of the center of gravity.

This necessitates a vertical fin, back of the center of gravity, which is generally continued by the rudder. The latter enables dynamic directional stability and the corresponding maneuverability.

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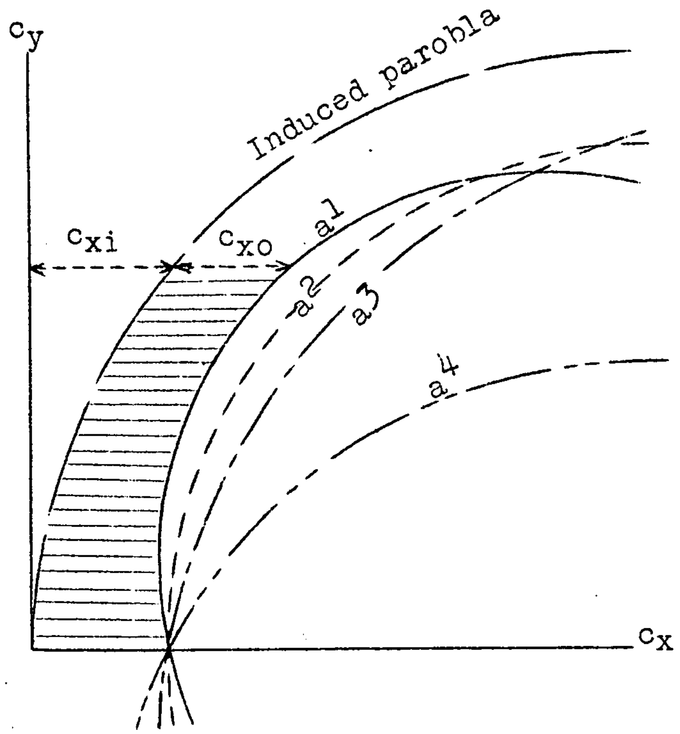


Polar curves of wings having various aspect ratios.