TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 323

NACA TN 323

RECENT EXPERIMENTS AT THE GÖTTINGEN AERODYNAMIC INSTITUTE.

By J. Ackeret.

From "Zeitschrift für Flugtechnik und Motorluftschiffahrt," February 14, 1925.

July, 1925.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL MEMORANDUM NO. 323.

RECENT EXPERIMENTS AT THE GÖTTINGEN AERODYNAMIC INSTITUTE.*

By J. Ackeret.

I will tell you today about a few recent experiments at the Göttingen Aerodynamic Institute. A short time ago the Institute had a hard struggle for existence, since it is not a Government institution and it did not receive much private or official aid during the reconstruction period. It was compelled, therefore, to seek commissions from manufacturing firms, in order to obtain money. However profitable this course might be for the firms assigning the tasks, there was generally no great advantage obtained in this way, because the experiments were necessarily unsystematic and the models were always made with regard to the constructive requirements. The scientific service for the past year is therefore not very large, in spite of the hundreds of experiments performed. The situation, however, has recently been somewhat improved. The "Kaiser Wilhelm Gesellschaft zur Forderung der Wissenschaften" (Emperor William Society for the Advancement of the Sciences) has again, by official and private assistance, been put in a position to give the Institute its support, so that in future we may expect more attention

* From "Zeitschrift für Flugtechnik und Motorluftschiffahrt," February 14, 1925, pp. 44-52. (Lecture delivered at a meeting of the W. G. L. at Frankfort, September 4, 1924.)

to be given to scientific research.

I will tell you about three series of experiments, which seem to me to be of general interest. It would naturally be of little use, in the short time at my disposal, to go very minutely into the details of the experimental arrangements and I will therefore confine myself to the essential points.

I. SYSTEMATIC EXPERIMENTS WITH JOUKOWSKI WING PROFILES.

I will first tell you about the systematic experiments with wing profiles. These consisted of a series of 30 so-called Joukowski profiles, in the form of rectangular wings of 20 cm (7.87 in.) chord and 100 cm (39.37 in.) span, which were tested in the usual way at 15 and 30 m/s (49.2 and 98.4 ft. per sec.). The airplane builder will ask: "Why use Joukowski profiles?" for he does not like their sharp trailing edges, which leave hardly room enough for the rear spar. The reason for this choice was the desire to be able to compare the experimental results with the theory and these profiles were well adapted to this purpose. They were named for a Russian aerodynamic engineer who died several years ago. Joukowski discovered a method which rendered it comparatively easy to compute the flow diagram about such a profile under the assumption of a frictionless flow without the formation of vortices.*

* "Zeitschrift für Flugtechnik und Motorluftschiffahrt," 1910, p. 281, and 1912, p. 81. The method of Trefftz is especially convenient (Z.F.M. 1913, p. 130). The drawings in the present article were taken from these.

Lift coefficients, location of center of pressure, pressure distribution and velocity distribution can all be accurately determined by it. There was also another reason for choosing them. For characterizing the shape of the profile, it is only necessary to have two numbers which are practically proportional to the ratio of the camber to the chord or of the thickness to the chord, hence two perfectly obvious parameters, the camber parameter being designated by o/l and the thickness parameter by $2\delta/l$. According to the expanded methods of Karman and Trefftz, Mises, Geckeler, Müller and others, it has indeed recently become possible to treat theoretically even very complex profiles, but the number of the parameters characterizing the shape is greater and therefore the number of the experiments which must be made for proving the theory, is greatly increased. Moreover, Joukowski profiles, notwithstanding the aforementioned defect, are often employed on airplanes.

Fig. 1 shows the tested profiles arranged according to these parameters. The camber parameter o/l increases, toward the right, from 0, corresponding to a symmetrical profile, until shapes are reached which are no longer practicable. The thickness of the profiles increases downward, thus increasing the thickness parameter $2\delta/l$. Very thin profiles are of little interest to airplane builders, but are very important for turbine makers, who prize the small resistance of such profiles.

For Fig. 2* a single profile was selected, with which I will show how closely the theoretical results approximate the values obtained by actual measurement. The wing resistance or drag was resolved into two essentially distinct components: namely, the induced drag, which is entirely independent of the shape of the wing section or profile and which increases as the square of the lift, and the profile drag, which depends very largely on the shape of the profile. Two parabolas were plotted for the induced drag, one of which corresponds to the usual assumption of elliptical distribution of the lift and represents the minimum of the possible induced drag. The abscissas of the other parabola were increased 4% by Mr. Betz, who showed that a rectangular wing with uniform angle of attack has no elliptical distribution of lift and therefore has a somewhat greater induced drag. The given increase of 4% has not yet been experimentally determined with absolute certainty, but probably comes nearer the truth than the computation with elliptical distribution. Two polar curves were plotted for 15 (49.2) and 30 m (98.4 ft.) per second. This is an effect of the so-called "in-

* The graphic representation of the ratio of lift to drag is termed the polar curve (or polar) of the profile. The lift and drag are computed according to the formulas:

$$L = C_L S \rho/2 V^2;$$

$$D = C_D S \rho/2 V^2.$$

The moment of the air forces about the foremost point of the wing chord is computed by the formula $M = C_M S \rho/2 V^2 c$, in which S = the projected area of the wing; c, its chord; ρ, the air density; V, the air velocity. See "Ergebnisse der A.V.A. (Aerodynamischen Versuchs-Anstalt zu Göttingen), Vol. I, where all these definitions are more fully explained.

dex value," defined as the product of the chord and wind velocity. We will recur briefly to this point later. The dash moment line was theoretically computed and agrees remarkably well with the experimental values. The agreement is not so good, however, for the more highly cambered profiles. The lift (Fig. 3) can also be plotted against the angle of attack. It is seen that the ratio between the theoretical and actual lift is quite constant at the smaller angles of attack, but undergoes a remarkable change at larger angles, due to the generally known fact that the flow no longer smoothly follows the top of the wing but separates from it, with the formation of powerful eddies or vortices. Theoretically the lift should reach its maximum at an angle of attack of 90°, but actually it is nearly zero at that angle. This enormous discrepancy could almost rob us of all hope of ever seeing the theoretical result fulfilled. In the last part of my lecture, we will find, however, that a very special Joukowski profile, namely, a cylinder, can, under certain conditions, almost attain the theoretical maximum.

In Fig. 4, two polars have been selected from the column of symmetrical profiles. The dash moment line again represents the theoretical straight line and here also the measuring points are quite well situated. The polars, however, are very different for the thick and thin profile. The latter evidently separates at relatively small lifts. The flow does not separate entirely, however, from the upper side of the wing, but seems to

cleave to it again farther back. With increasing angle of attack, the area of separation becomes continually greater, with a corresponding increase in the drag. Otherwise the course of the polars is entirely regular. The flow cleaves perfectly at first. When the separation occurs, however, the angle of attack is probably already too great, so that it cannot cleave again and the lift is greatly diminished, accompanied by a great increase in drag. In the good region, the profile resistance increases continually with the thickness.

Fig. 5 shows the results of a series of constant thickness but different cambers. With increasing camber, the whole polar moves toward higher C_L values. The moment line moves to the right, keeping almost parallel with itself, as required by the theory. Very great lifts can be obtained only at the expense of very great increases in the drag. The maximum seems to lie in the vicinity of $C_L = 1.9$. We see that, for all the polars, there is an enveloping curve, which can also be designated as the polar curve of a profile of constant thickness but variable camber. Polars of this kind are actually obtained by varying the camber (e.g. by means of flaps).

By plotting all the enveloping curves, we obtain a diagram which gives a comprehensive view of the whole series of Joukowski profiles (Fig. 6). Only the profile drags have been plotted on a correspondingly increased scale. We find that increased thickness always increases the profile drag. Thin,

slightly cambered profiles have the greatest lift-drag ratio. The best lift-drag ratio in this figure is 1 : 120. We obtain the greatest lift with profiles of medium thickness, very thick profiles being here also less favorable. With the aid of this series of curves, we can interpolate the values for the Joukowski profiles which have not yet been tested. Fig. 6 gives an approximate idea of the characteristics to be expected for differently shaped profiles.

I cannot here go into further details, but must refer you to a more detailed report, which will appear shortly. I will discuss only one other important problem, namely, as to how the results obtained from models can be applied to full-sized wings. Do the differences found in the properties of the models also exist in connection with full-sized wings? At present, we are quite far from any final solution of this problem of the "index value." Recently we performed further experiments in Göttingen with profiles of greater chord. (See "Ergebnisse der Aerodynamischen Anstalt," Vol. I, p. 54.) This kind of experimentation, however, has a characteristic difficulty. If, e.g., we wish to determine the profile resistance, we must deduct, from the measured drag, a correction which, like the induced drag of a finite wing, increases as the square of the lift. Hence we obtain what we wish, first as the difference between two quite large quantities, which is always a very unreliable method. The greater the chord, the more preponderant the correction will be.

However, there is perhaps another alternative. According to the Prandtl-Karman boundary-layer theory, the effect of the surface friction is confined to a very thin layer of air in immediate proximity to the surface. The surface friction practically retards only the fluid flowing within this marginal or boundary layer, so that conversely we can draw conclusions concerning the surface friction from our knowledge of the velocity distribution within this layer. It is conceivable that a process can be formulated with comparatively simple means, for finding the loss of force in the boundary layer and thereby the friction on the surfaces, probably with greater accuracy than by measuring the force. I believe, indeed, that we shall be able to make boundary-layer and profile-drag measurements during flight. In order to give you an idea of the thickness of the boundary layer, I am showing you, in Fig. 7, a few curves, which give the thickness of the boundary layer at different points on the surface for several angles of attack. It is evident that, in this case, the process of separation starts from the trailing edge, while, at large angles of attack, the thickness of the boundary layer greatly increases and gradually works forward.*

*The Joukowski profile tested was made of sheet metal and was hollow. From within outward there opened very small pressure tubes (0.25 mm inside diameter). The total pressure or energy was measured. The pressure distribution in the boundary layer could be directly recorded by a Wieselsberger manometer ("Ergebnisse der Aerodynamischen Anstalt," Vol. II, p. 5). Similar experiments are reported by Lachmann (Z.F.M. 1924).

II. EXPERIMENTS ON AN AIRPLANE MODEL WITH A BUILT-IN MOTOR AND FUNCTIONING PROPELLER.

We will now leave the profile experiments and devote our attention to a problem which has hitherto proved theoretically inaccessible and had to be approached from the experimental side. Every airplane manufacturer knows that the performances of an airplane may be greatly affected by the kind of propeller chosen. We have, in the American measurements of Durand and Lesley, excellent data on the propeller as such, but very little is yet known concerning the effect of the fuselage and wings on the action of the propeller. Experiments on full-sized airplanes are naturally of very great importance, especially when performed with hub dynamometers, but they are exceedingly expensive. It is therefore worth while to develop methods to enable the study of propellers on a small model. Such experiments in the Göttingen Laboratory will here be reported. An especial difficulty lay in the construction of small motors to give relatively high power, while still being capable of installation in the small body of the model. Some time ago we reported, through the Z. F. M. (1924, p. 101), the results of our labors in this direction. Here we will only discuss briefly the construction of the motors, which are built essentially according to the design of Dr. Betz.* Fig. 8 is a longitudinal section of the motor. It

*The first motors were made in his own workshop, but their manufacture has recently been assumed by the Göttingen "Elektro-Schaltwerk."

is driven by an alternating current, which has the advantage of a very simple rotor construction. It is very long in proportion to its diameter. The stator consists of thin metal sheets; the rotor, of a massive piece with inlaid copper rods. Worthy of note is the use of very large copper cross-sections and relatively small stator teeth, whereby the power could be greatly increased. The current density was made as high as compatible with the amount of heat produced. We obtained the best results with the three wires, which conveyed the current to the motor from without and which lie in the cooling current. With 0.7 mm diameter, they can carry as much as 30 amperes. The maximum revolution speed of the motors was 30,000 per minute and the power could be increased for a short time to 1.25 HP. (the motor weighing 1.8 kg), whereby, however, the heat was very noticeable. This is of little importance for experimental purposes, since some time always elapses between the individual experiments, thus allowing the engine to cool off somewhat. Larger propellers (20 to 25 cm diameter) are provided with gears.

The mutual action of propeller and airplane is manifestly of a very complex nature. The fuselage obstructs the propeller stream, thereby changing the angle of flow against the propeller blades and consequently the air forces. The blades, on their part, have a field of flow especially dependent on the angle of attack. The propeller stream is cut by the wings and obstructed by the fuselage. On the other hand, the surface friction of

the fuselage and tail is increased. We accordingly face a tremendous complexity of opposing forces and it will require long and systematic work to separate the individual forces as much as possible. Such work is being undertaken, but today I wish to show you, by means of an example, the resultant effect of those forces on which ultimately the most depends.

Fig. 9 shows a high-wing braceless airplane model with propeller. The Focke-Wulf Company has had experiments performed with it and has graciously allowed us to impart the results. The motor works on a spur gear, which reduces the revolution speed one-half. It is so installed that it can revolve around the propeller shaft, so that the torque can be measured from without. The revolution speed is read on a tachometer (placed behind the motor), which can be observed through a window in the fuselage. The lift, drag, longitudinal or pitching moment, propeller speed and torque are measured. Fig. 10 shows the experimental results in a series of polars, each of which corresponds to a definite degree of progress $\lambda = V/u$. (V = flight speed; u = peripheral velocity of propeller.) The polar without propeller is plotted in dashes and corresponds to the normal three-component measurement. The effect of the propeller is to change the lift, drag and pitching moment. At a small angle of attack, the lift is only slightly increased; more at larger angles of attack, partly because the propeller is pulling upward. The diminution of the drag is naturally the main effect we are striving

for. We have succeeded in entirely eliminating the drag of the model and still obtain impulsion. The points of intersection of the polars with the axis of the ordinates give the points where the resulting drag is 0 and hence horizontal floating is possible. The portions to the right denote sinking; to the left, climbing. We see immediately with what speed the propeller must revolve, if we know the load per unit area and the velocity V. The pitching moment is likewise noticeably changed, again partly because the propeller thrust produces a moment about the chosen point of reference (foremost point of wing chord in the plane of symmetry of the wing). The tail moment and the moment produced by the wing itself are likewise affected, though it is naturally impossible to pick out all the details from the figure. The slowly running propeller (large λ) offers considerable additional drag, as likewise the stationary propeller, which we have tested on other models. The braking effect of running the propeller backward was also tested.

For the sake of comparison, the propeller had also to be tested alone. For this test we used the same motor enclosed in a special housing to avoid disturbances of the air stream. The housing was then suspended like a pendulum in the wind tunnel and the thrust, torque and revolution speed determined. The arrangement is plainly shown in the photograph (Fig. 11), where half of the housing is removed. The driving gear is recognizable, as likewise the tachometer, the moment lever and the cur-

rent intake consisting of spiral strips of copper.

Fig. 12 shows the comparison between the free and the built-in propeller. Since, as already mentioned, it was not possible to separate the individual effects, we decided to cut the matter short by throwing all the burden on the propeller and defining its efficiency accordingly. The coefficients enable the calculation of the thrust, torque and efficiency according to the formulas:

Thrust $T = k_s \rho/2 u^2 S$; Torque $Q = k_d \rho/2 u^2 S D/2$;

Efficiency $\eta = k_s/k_d \lambda$, in which ρ = air density, S = area of propeller disk and D = propeller diameter.

In accordance with our earlier experiments, we adopted, as the useful propeller thrust, the difference between the drag without propeller and with revolving propeller at the same angle of attack. All the drag produced by the propeller was therefore counted as thrust. From the curves we find that the efficiency of the propeller running alone is rather low, due probably to the small index values and, possibly to the relatively rough surface of the wooden propeller. There is, however, quite a large difference between the dash-line curves of the free-running propeller and the plain-line curves of the built-in propeller. The efficiency falls off rapidly and there is a greater shifting of all the curves toward a larger λ, indicating that the air flow at the propeller was somewhat obstructed and that this was largely due to the wing. This signifies that, in choos-

ing a propeller for normal flight, we should allow for about 5% diminution of flow velocity, which diminution may increase to 15% in climbing flight. It is probably unnecessary to emphasize the fact that this method cannot be applied directly to other models without modification. By cumulative and systematic experimentation we may yet succeed in considerably diminishing the uncertainty in choosing a propeller.

III. THE ROTATING CYLINDER (Magnus Effect).

In connection with the above experiments with alternating-current motors built into the models, I would like to speak of still another series of experiments, which were likewise first rendered possible by these motors. This is the repetition of rather old experiments with new apparatus. In 1853, the physicist Magnus published, in Berlin, data on the lifting effect of rotating cylinders exposed to an air current at right angles to their axes. He made these experiments with especial reference to ballistics. Any projectile from a rifled gun is exposed to a side wind, as soon as its axis does not exactly coincide with the tangent to its trajectory. The rotation, however, in conjunction with this side wind, produces the above-mentioned lifting force, which acts perpendicularly to the trajectory and is naturally very objectionable to the gunner. Lord Rayleigh spoke, in a shorter article, of similar phenomena in connection with tennis balls. He thinks that there must be some sort of flow around the ball, without making any suggestions as to how it is

produced. Since very little was known concerning the magnitude of the lift, it was necessary to repeat the experiments of Magnus on a somewhat larger scale. Lafay performed similar experiments in Paris over ten years ago. We will return briefly to these later. After the first results had been obtained, the Flettner Company became much interested and very acceptably supported us in further researches. This company had in mind the possibility of more practical applications. Here, however, I wish to discuss only the physically interesting properties.

Fig. 13 represents a cross-section of one of the cylinders tested with a built-in motor. The length of the cylinder is 33 cm and its diameter is 7 cm. It is made from brass tubing. The rotor of the motor is connected with the cylinder walls, from which the stator is separated by a ball bearing. The stator is rotatable about its axis, in order to enable the torque (required for the rotation) to be measured from without. The drag and lift were measured on the regular balance. The electric current is conducted through three wires which pass through the axial hole. These wires run to three mercury contacts, which enable freedom of motion. The revolution speed is given by a tachometer. On the ends there are fastened two disks whose diameter is greater than that of the cylinder. These were put on at Dr. Prandtl's suggestion and are for the purpose of making the flow diagram approximate the theoretical as nearly as possible. If they are left off, the air presses from the sides into

the region of relatively great negative pressure or suction. We always have suction when lift is produced. In this case, as we shall show, the suction must be especially great. It has been noticed that the lateral introduction of air has a disturbing effect, even in drag measurements of rectangular plates exposed to a perpendicular air blast, in that the lateral introduction of air, which naturally produces a greater effect with square plates, considerably diminishes the drag of the same in comparison with the drag of an oblong (Wieselsberger, Ergebn, der A.V.A., p. 33).

Fig. 14 shows a few results. The curves appear very similar to normal polars, only it is to be noted that the same scale is used both for the lift coefficient and for the drag coefficient. The C_L coefficients refer to the dynamic pressure and the area of projection (diameter × length) of the cylinder. The great absolute lift and drag are noticeable at first. The polar of a good ordinary airfoil was introduced into the figure for comparison. The three plain curves correspond to two different disk diameters and to the cylinder without such disks. The effect is very pronounced and fully explains the great differences between our measurements and those of Lafay who obtained lift coefficients only up to about 2. It is not in itself strictly correct to devote our principal attention to the lift coefficients, while the induced drag in this case has a magnitude no longer negligible in comparison with the lift. It is

better to take into account the resulting force $C_R = \sqrt{C_L^2 + C_D^2}$. We now have a case before us, where the assumptions of the customary wing theory contain too great omissions. In particular, the downward velocity induced by the departing vortices is extraordinarily large, as likewise the bending of the lines of flow. Especially in cylinders which are relatively thick, in comparison with the span, very great derivations are to be expected, according to the calculations of Prof. Prandtl.

The induced drag is considerably reduced by the end disks, as a comparison of the curves immediately demonstrates. The departing vortices are, to a certain extent, spread out by the disks, whereby their kinetic energy is diminished. End disks reduce the drag even on ordinary surfaces. Many experiments in this connection are described in No. 2 (1925) of the "Vorläufige Mitteilungen" of the Göttingen Institute. In Fig. 15, C_L is plotted against the ratio u : V (peripheral velocity : wind velocity), which plays some such role as the angle of attack in normal profiles. Here also the effect of the disks is quite evident. In order to obtain the maximum lift, the peripheral velocity must therefore be about thrice the wind velocity.

Fig. 16 gives the results of the torque measurement. A coefficient is plotted which is proportional to the torque and dependent on the Reynolds number connected with the cylinder diameter and the peripheral velocity. In this case the air stream was discontinued, so that there was only rotation without lift.

With increasing Reynolds number, the torque coefficient fell off rapidly and the straight line (C_M and R being logarithmically plotted), falling somewhat below 45°, indicated that the flow in the boundary layer had a laminar character. The point at the lower right-hand corner was taken from a Lafay experiment and falls almost exactly on the straight line. Similar experiments by Riabouschinsky and Kampf ("Vorträge aus dem Gebiete der Hydro- und Aerodynamik," Insbruck, 1921, p. 168) on rotating disks, show, however, that laminar flow only occurs up to a certain Reynolds number, beyond which there is turbulence in the boundary layer. The decrease in the torque coefficient is then considerably less, there being possibly, at very large Reynolds numbers, no decrease at all. The dimensions of the tested cylinders were hitherto too small to solve these questions experimentally, but new experiments are now being instituted.

The theory is not yet prepared to furnish an accurate description of the actual flow phenomena. In particular, it has not yet succeeded in computing the force exerted in terms of u/V. Nevertheless, the boundary-layer theory of Prof. Prandtl gives a good qualitative idea of it.* This says that the frictional effect of the fluid is restricted principally to a very thin layer next to the object. The production of this boundary layer often prevents the formation of the flow required by the

* Föttinger has already applied the boundary-layer theory to the explanation of the Magnus effect ("Jahrbuch der schiffbautechnischen Gesellschaft," 1918).

potential theory. In the event of pressure increase along the surface of the object, the boundary layer soon separates, unless the pressure increase is a very gradual one, and the inert boundary layer is borne away by the outward flowing fluid. All these facts have been fully developed in a lecture of Dr. Betz before the W. G. L.* The formation of the boundary layer can be very largely diminished, however, if the relative velocity between the outflowing fluid and the surface of the cylinder is diminished. Here lies apparently the key to the explanation of the peculiar properties of the rotating cylinder. On top, where the cylinder surface moves with the flow, the boundary layer is very thin and shows no tendency to separate. On the bottom, however, the relative velocity is just so much greater, so that separation soon occurs. With the cylinder at rest, we know that the boundary layer separates more or less symmetrically soon after passing the region of greatest suction. With rotation, there is a strong dissymmetry of separation, accompanied by a dissymmetry of flow and by a lift. The more rapid the rotation, the greater the shifting of the separation point. On an ordinary profile, the lift is increased by changing the angle of attack, a process which is equivalent to the shifting of the two coincident separation points on the rear edge.

We will therefore not hesitate to discard, as unsatisfactory, the often expressed theory that the air is set in circula-

* A. Betz, "Die Wirkungsweise von unterteilten Flügelprofilen." (For translation, see N.A.C.A. Technical Note 100.)

tion in a broad circle by friction on the cylinder, and to conclude that the effect of the rotation is to free the boundary layer unsymmetrically. Hence the computation methods are wrong, according to which the circulation is supposed to be obtained by simply finding the product of the circumference and peripheral velocity, the actual relation being obviously much more complex.

We can, to a certain degree, follow theoretically the formation of the boundary layer in starting the cylinder. Fig. 17 shows the results of a calculation made by Dr. Tollmien at Göttingen. The figure is to be understood as follows: Imagine the fluid to be entirely devoid of viscosity, so that it does not cling to the cylinder. Then u : V must equal 1. After a given interval of time, its normal viscosity is suddenly restored to the fluid. Then a boundary layer will immediately form, as here shown on a highly magnified scale. With a wind velocity of 10 m/s and a cylinder diameter of 20 cm, the thickness of the boundary layer at the forward pressure point is about 0.67 mm. The chosen time unit corresponds to a turn of the cylinder through about 30° from the position where the viscosity set in. In spite of the fact that only very little time has elapsed, the entirely unsymmetrical flow in the boundary layer is clearly recognizable. The reversal of the lines of flow on the rear side would probably change to closed figures in a short time, whereupon, with the flowing away of this vortex

region, a circulation flow would set in and a lift be produced. The final flow diagram will again approximate the well-known diagram of a flow with circulation around a cylinder (Fig. 18), whose determination according to the methods of the potential theory is found in every text book of aerodynamics. In the present status of the boundary-layer theory, however, it is not yet possible to follow this transition mathematically.

Postscript.- The former sailing vessel "Buckau" has now been provided with rotating cylinders and has made its first trial trips. So far as we can yet tell, the wind tunnel results have not been contravened. Regarding the history of its origin, it may be said that Mr. A. Flettner originally contemplated the use of metal airfoils instead of sails. Since the area of these metal sails would have been only a little less, the danger of upsetting in a storm could not be disregarded. Rotating cylinders, as made in Göttingen, are much less dangerous in this respect. Mr. Flettner therefore immediately abandoned his original plans and, with the aid of the German Shipyard at Kiel, carried through with great energy the conversion of the "Buckau" on the new basis.

For further details on the Magnus effect and the rotor ship, you are referred to a small pamphlet by the writer, soon to be published by Vandenhoeck and Ruprecht, Göttingen. (See also N.A.C.A. Technical Memorandum No. 310: The "Magnus Effect," the

Principle of the Flettner Rotor," by A. Betz.)

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

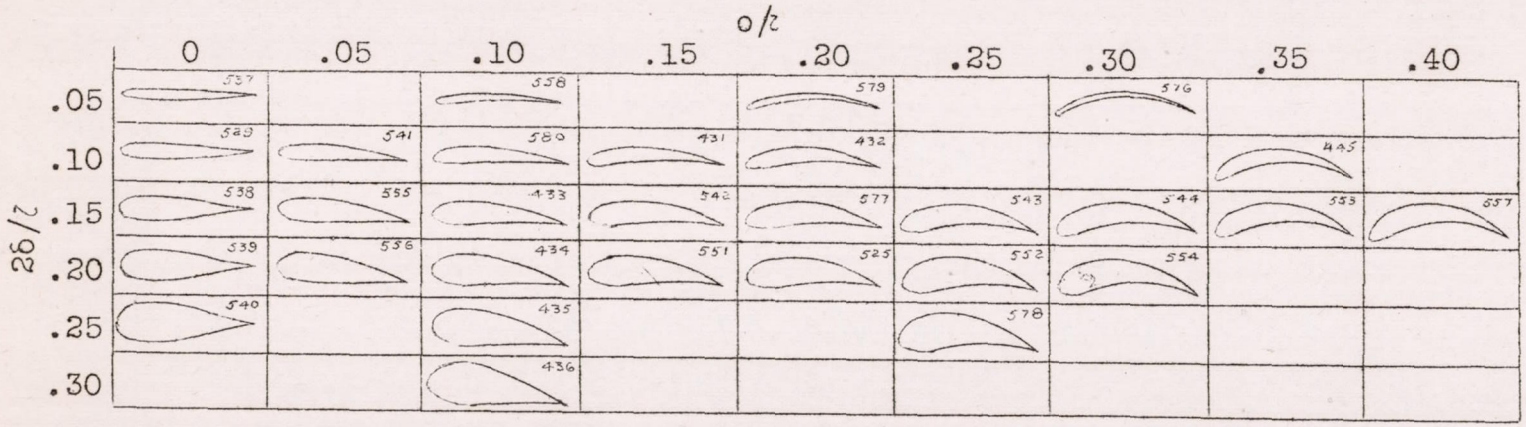


Fig.1 Joukowski profiles of varying camber and thickness.

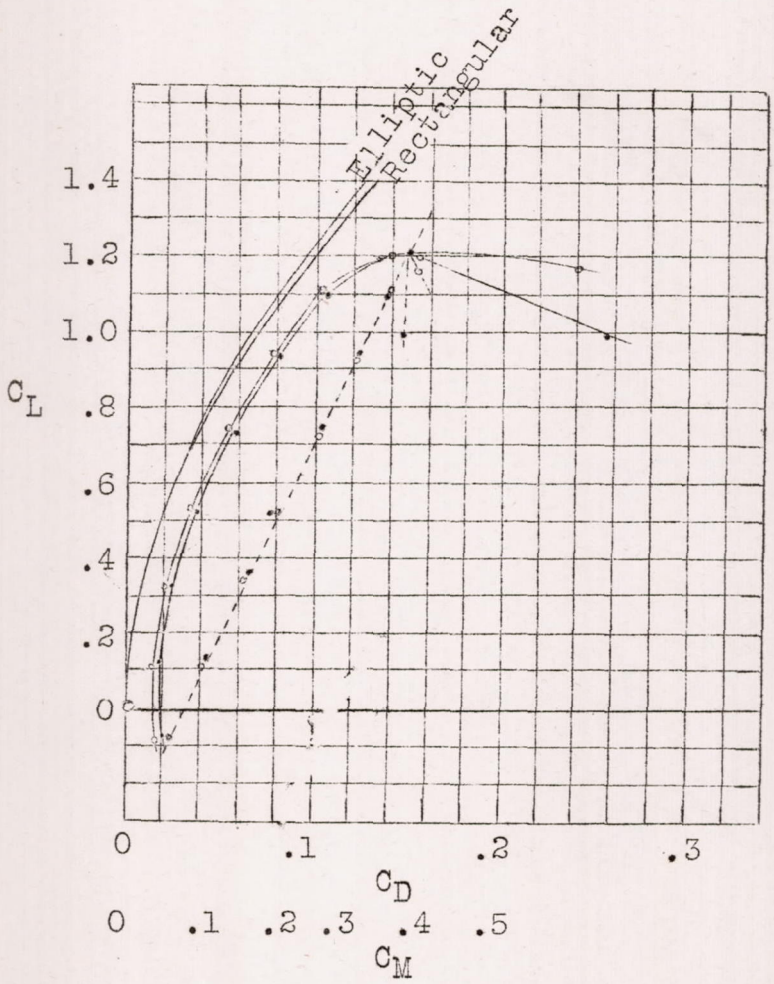


Fig.2 Polars of a single airfoil.

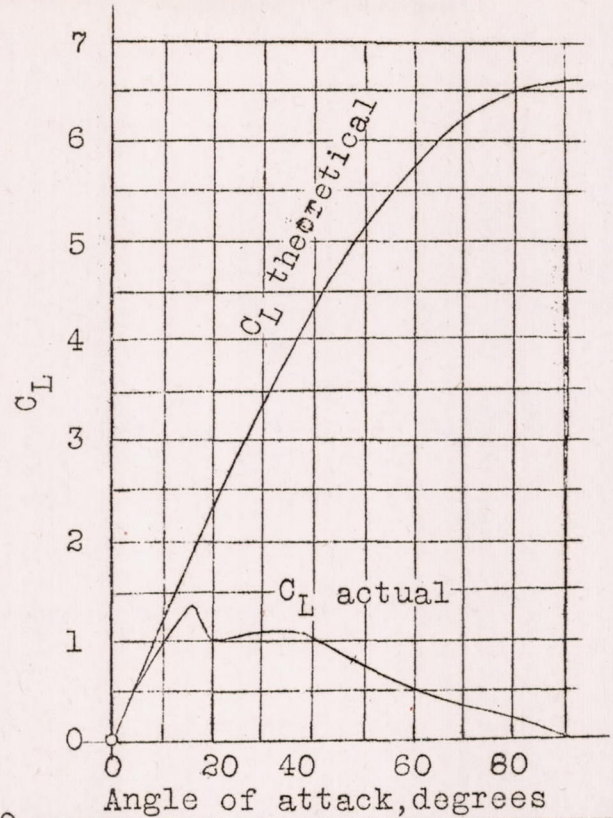


Fig.3 Lift plotted against angle of attack.

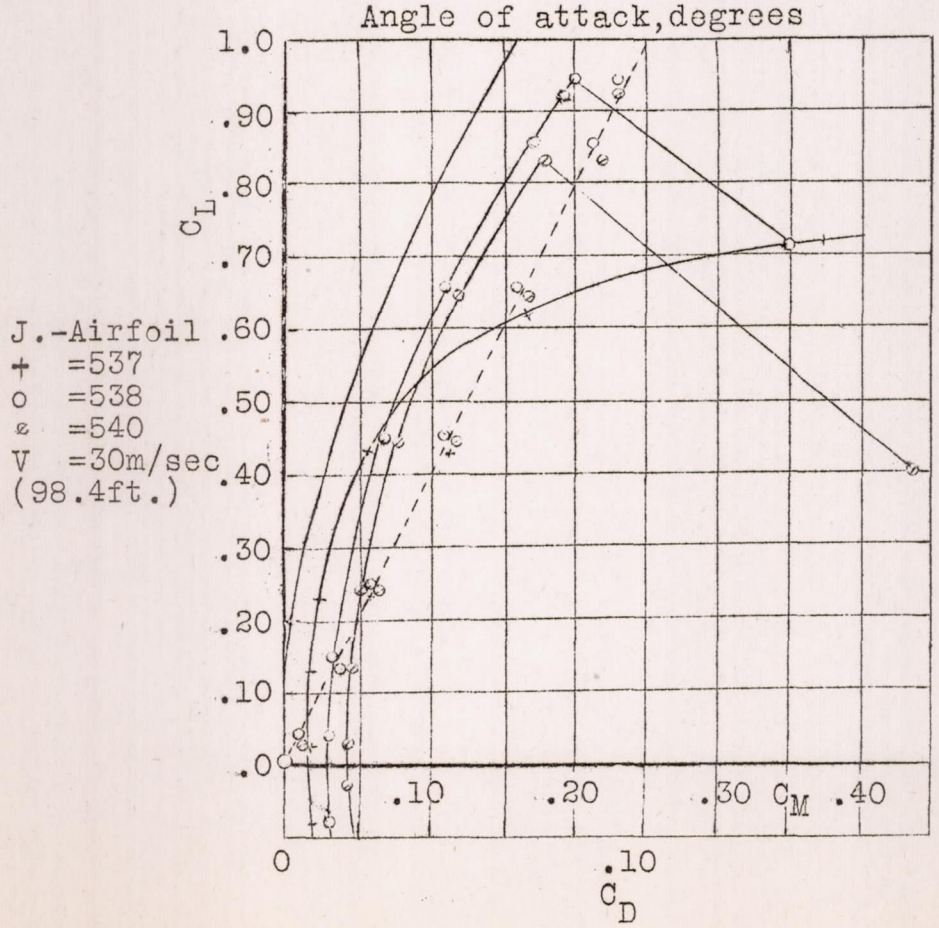


Fig.4 Airfoils having same camber but different thickness.

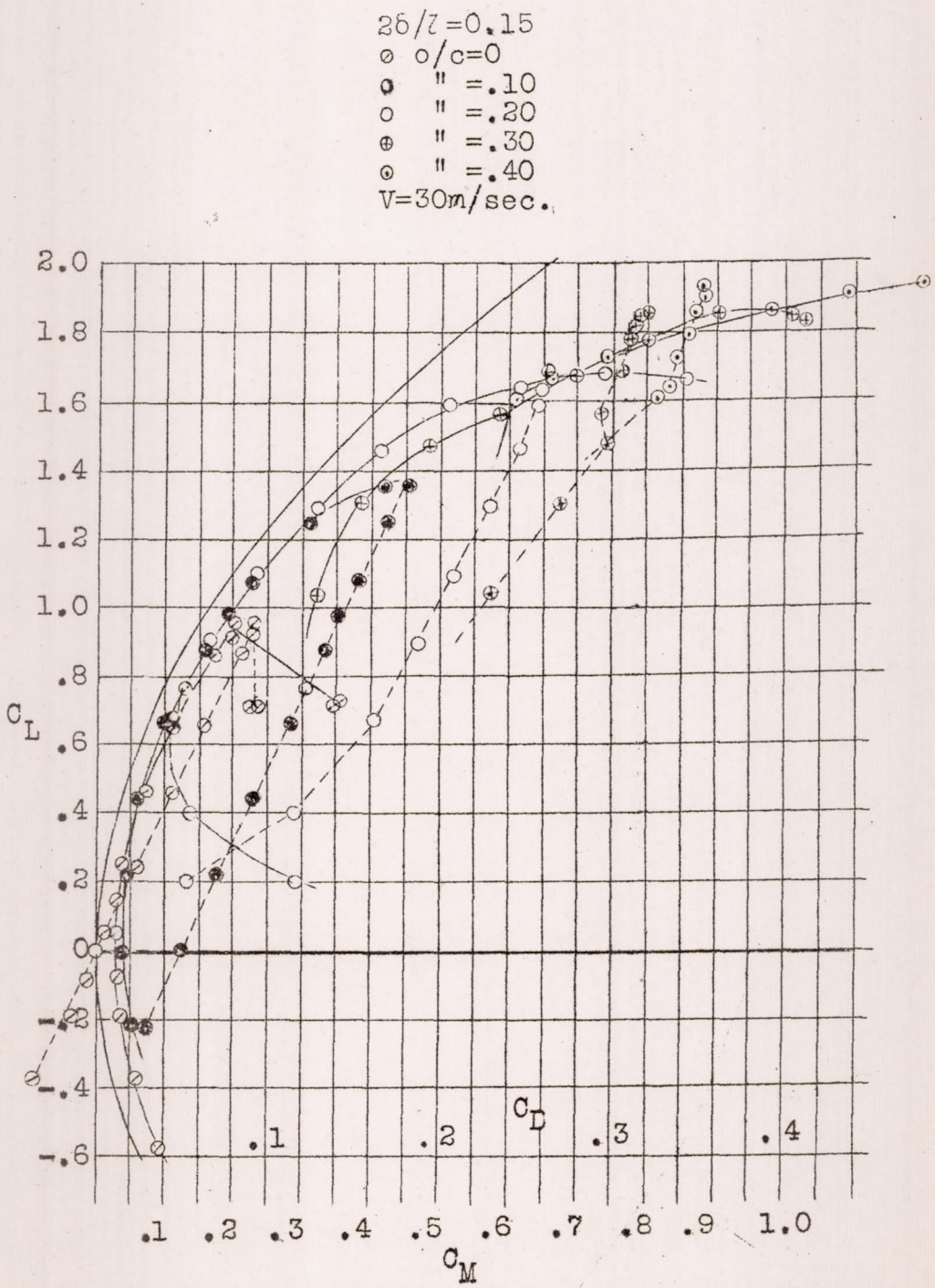


Fig.5 Joukowski airfoils having same thickness but different camber.

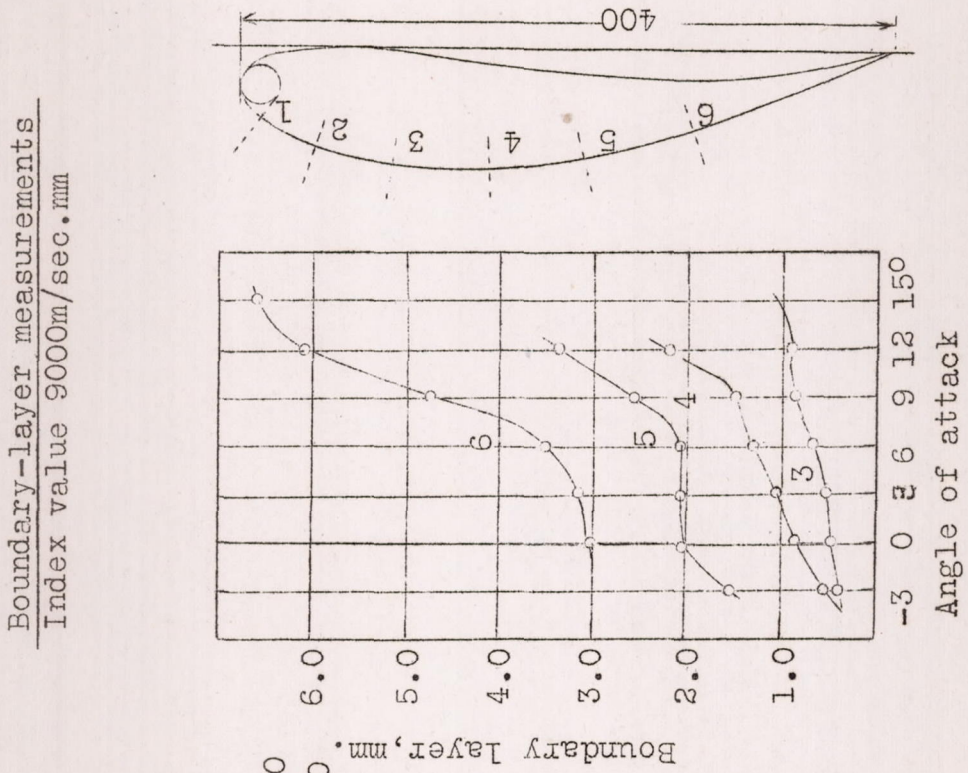


Fig.7 Thickness of boundary layer on top of a Joukowski airfoil.

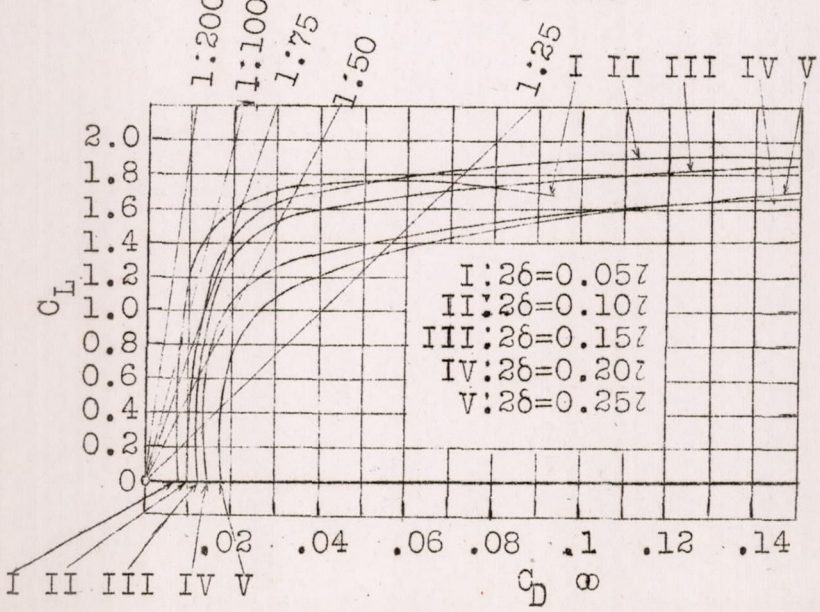


Fig.6 Profile drag of Joukowski airfoils. Index value 6000m/sec.mm.

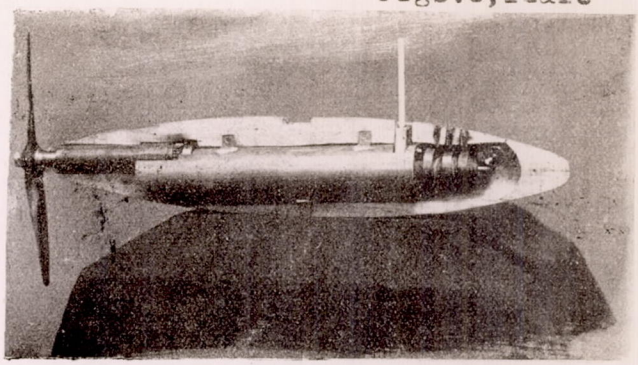


Fig.11 Motor housing for propeller tests.

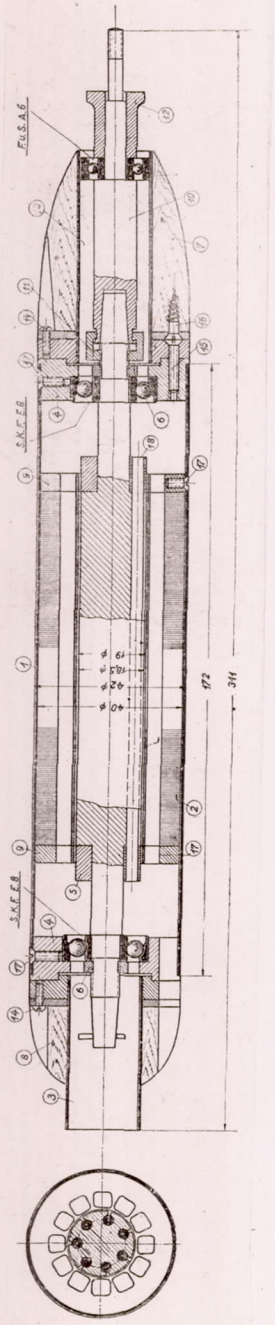


Fig.8 Small rapid alternating current motor.

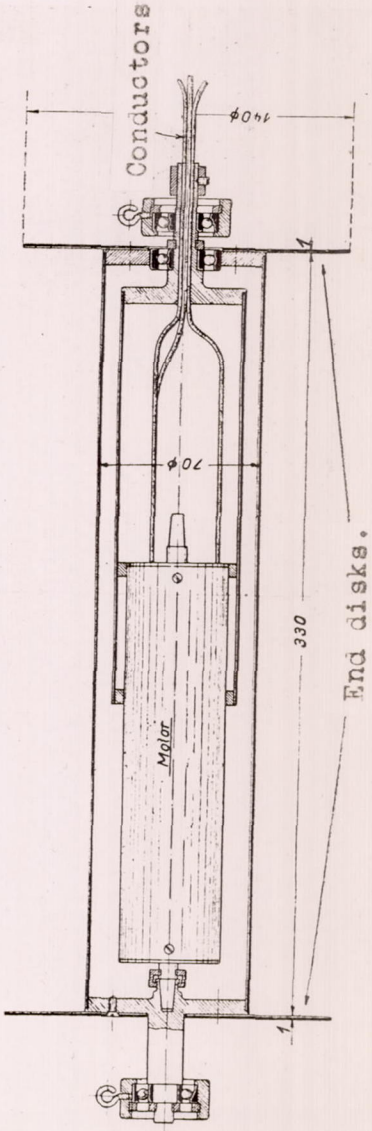


Fig.13 Rotating cylinder.

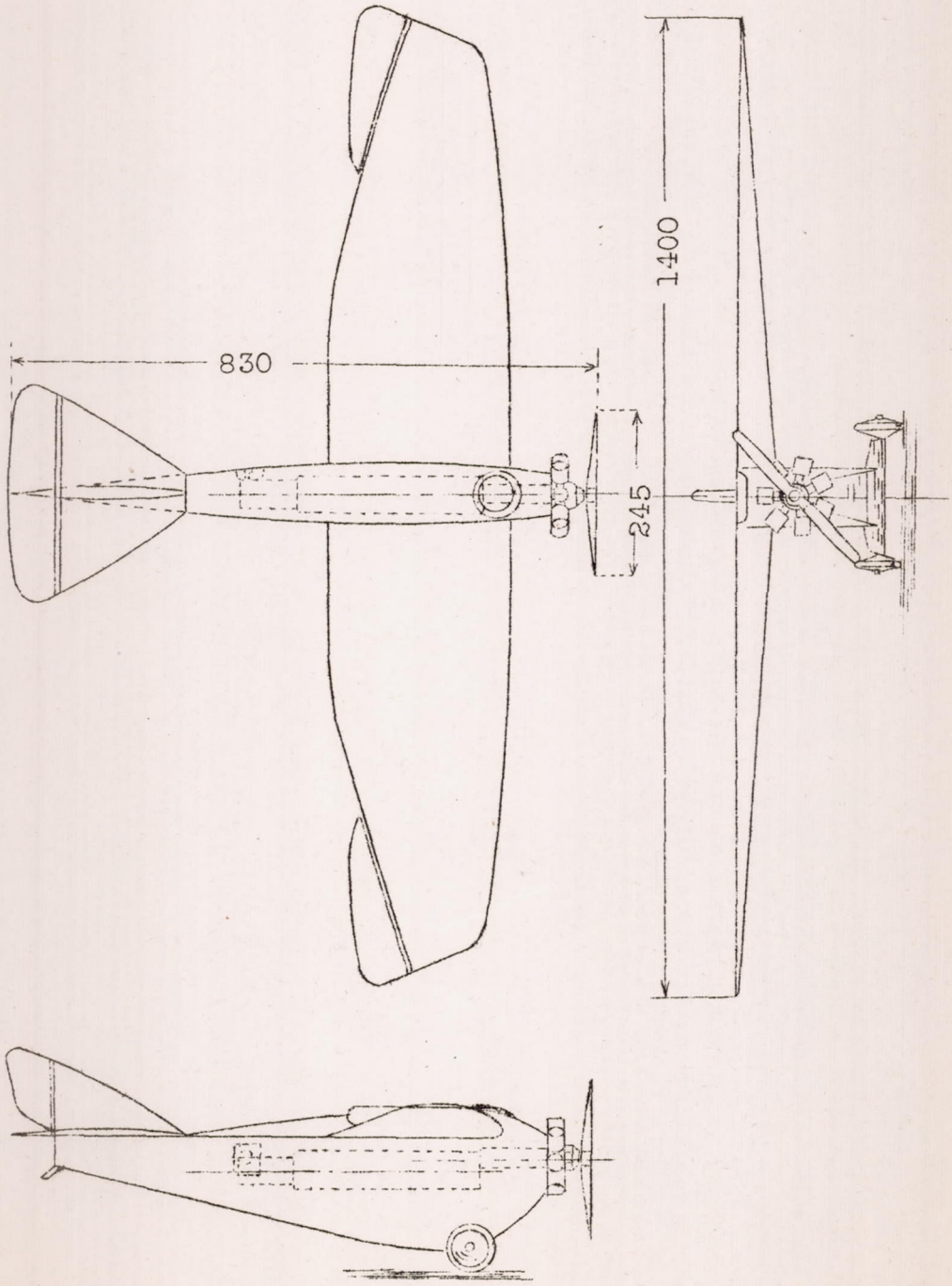


Fig.9 Airplane model with propeller and interior motor.

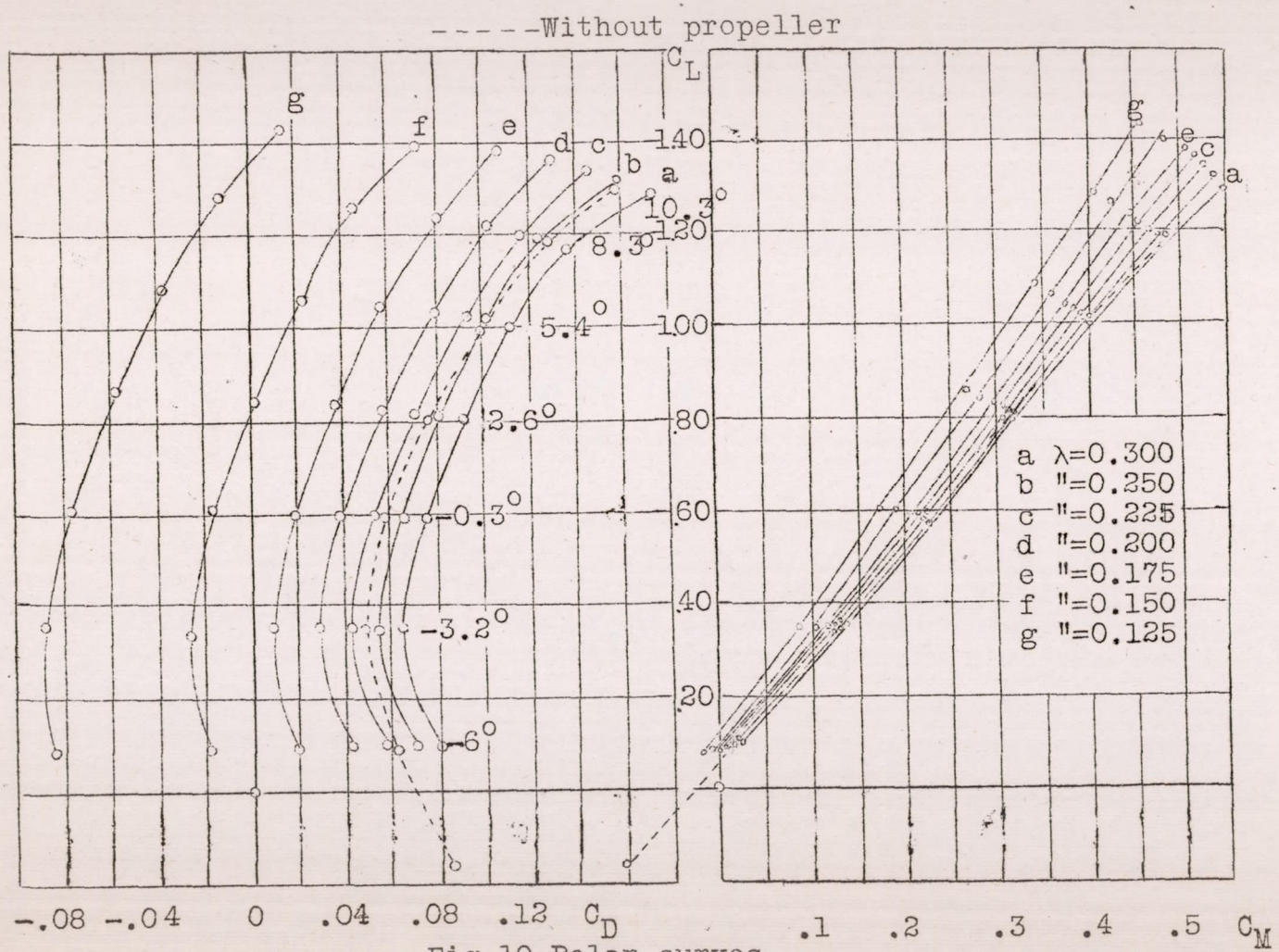


Fig.10 Polar curves.

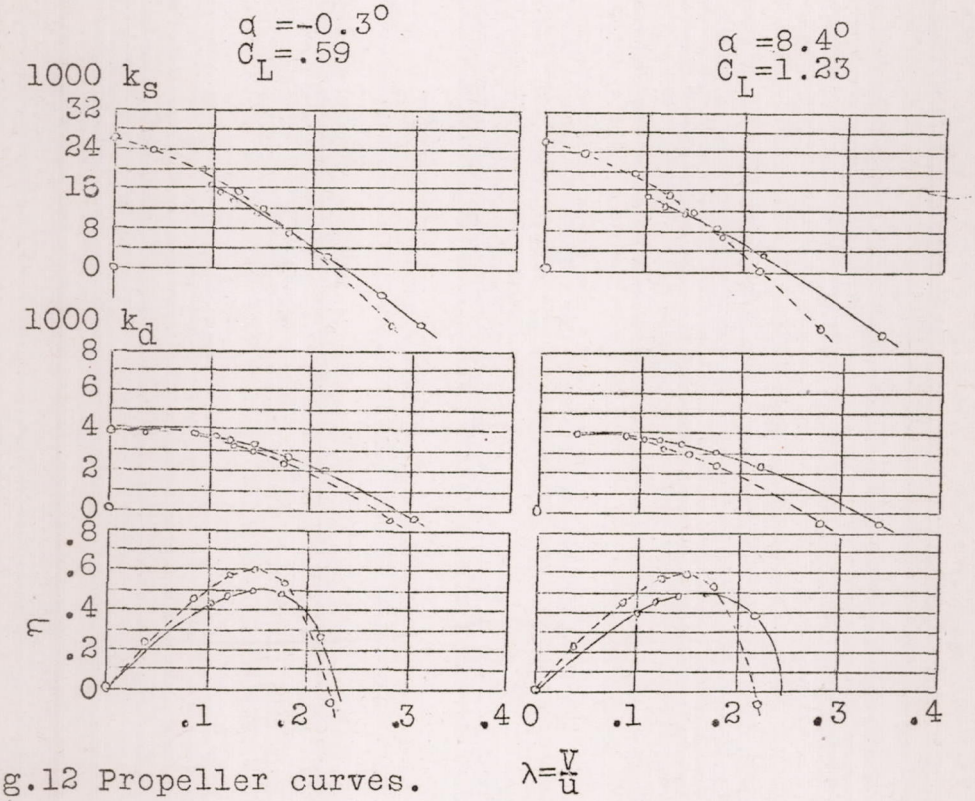


Fig.12 Propeller curves.

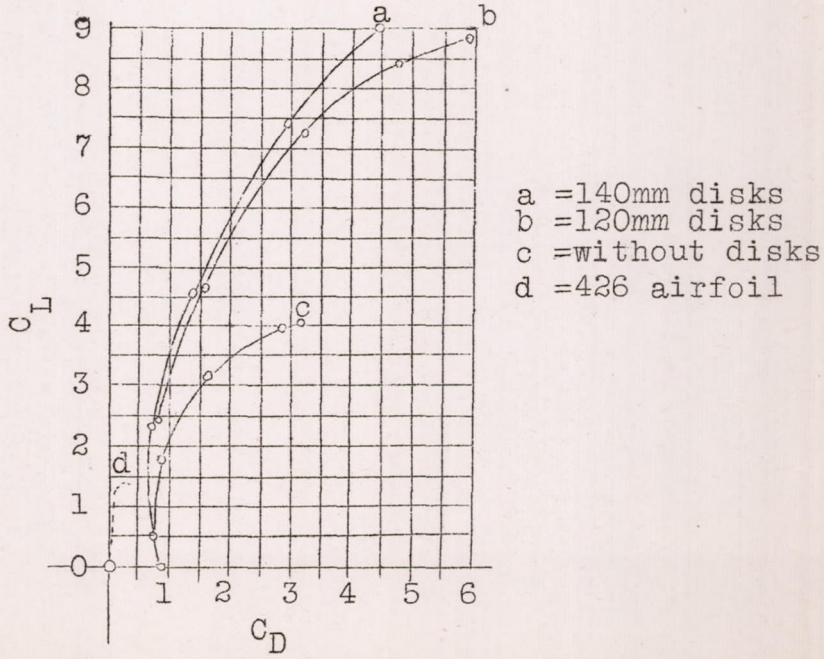
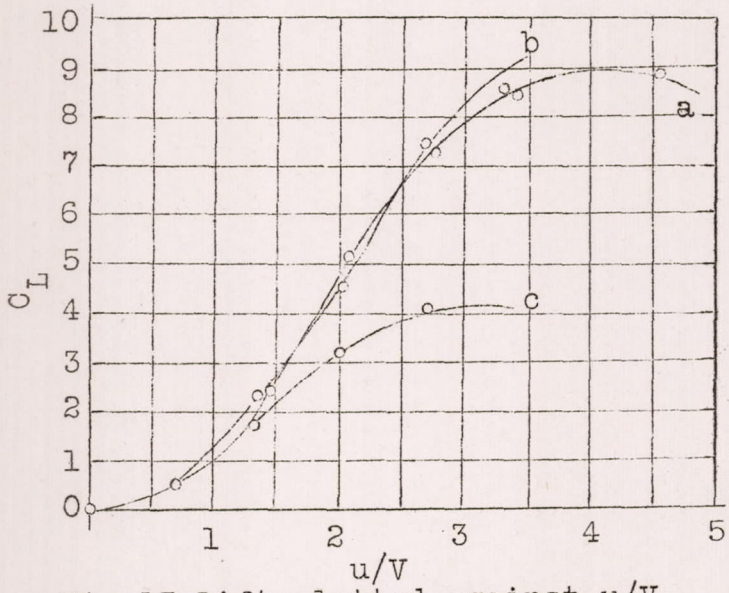
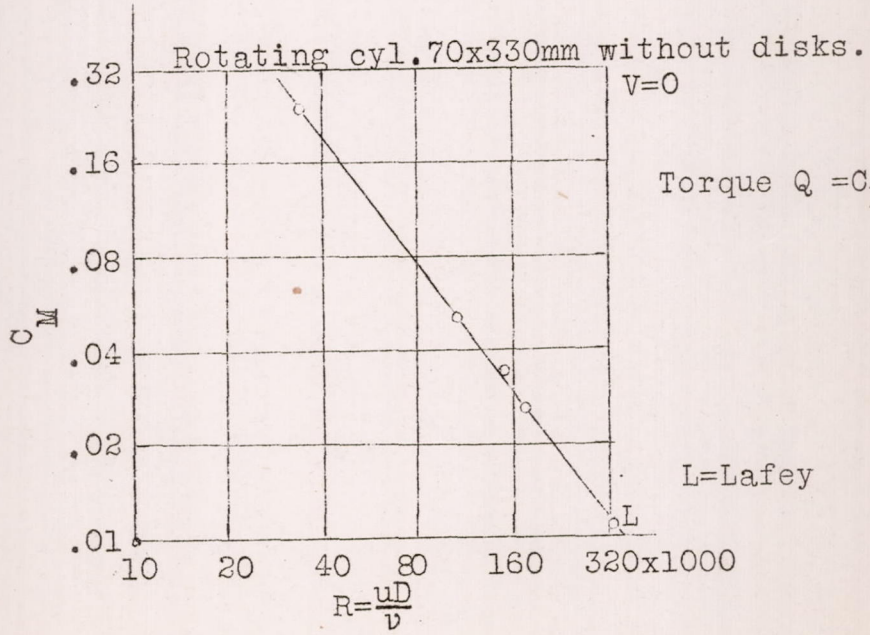


Fig.14 Polars of rotating cylinder.



a =120mm disks
b =140mm disks
c =without disks

Fig.15 Lift plotted against u/V



Torque $Q = C_M \frac{\rho}{2} u^2 S \frac{D}{2}$

Fig.16 Resisting torque.

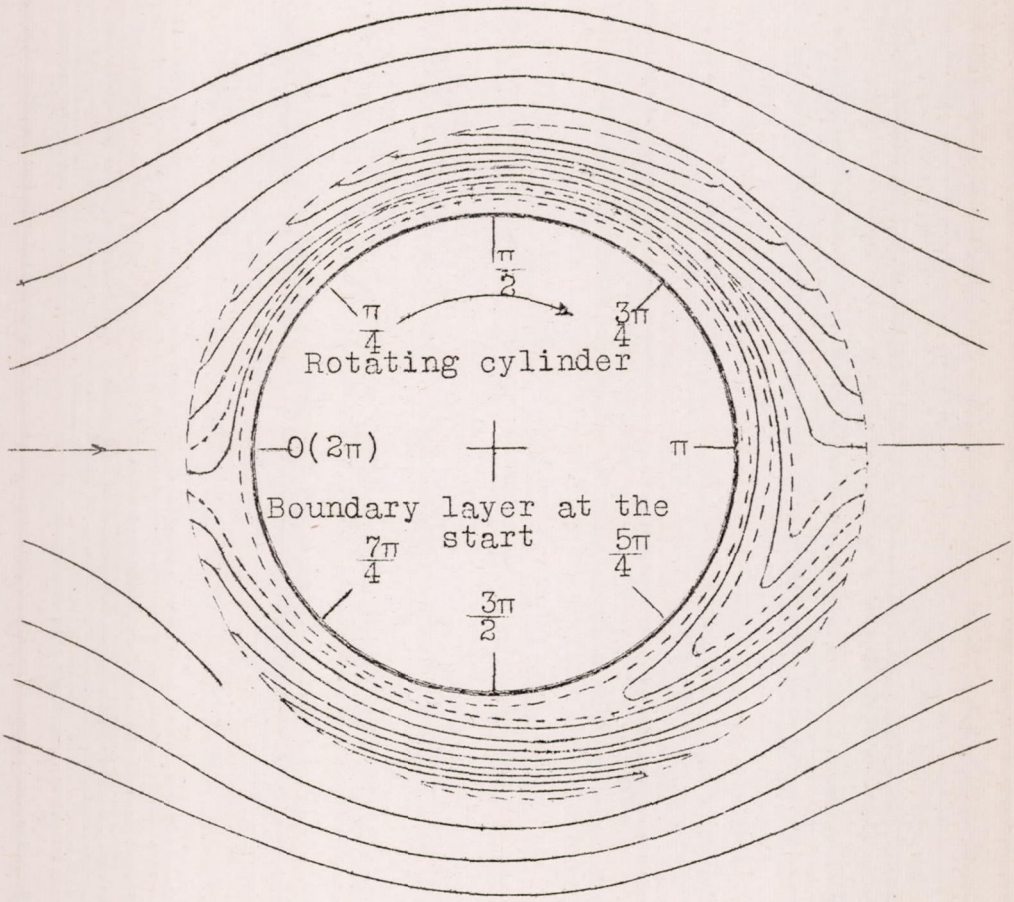


Fig.17 Boundary layer on rotating cylinder according to Tollmien.

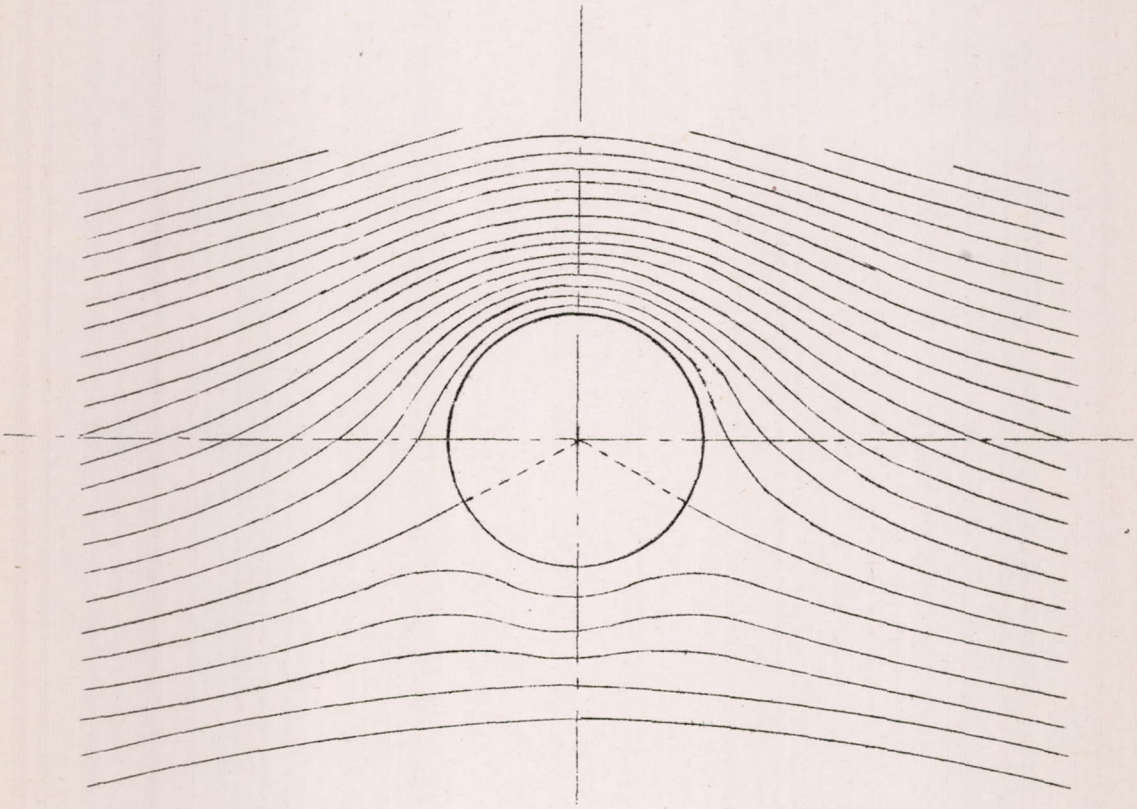


Fig.18 Flow about a rotating cylinder according to the theory of frictionless potential flow.