TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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By Oskar Schrenk

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EXPERIMENTS WITH A WING FROM WHICH THE BOUNDARY LAYER IS REMOVED BY SUCTION*

By Oskar Schrenk

Several years ago, when the idea of a technical application of the removal of the boundary layer by suction first arose, it was expected to obtain from this application the early realization of definite, technically desirable forms of flow, which had long been theoretically known as potential flows, but were impossible in practice, because the streamlines separated from the surface of the object in the strongly diverging fields of flow resulting from the great increase in pressure (e.g., on thick objects and on wings at large angles of attack).

The physical principle of preventing this separation by removing the boundary layer is simple and as old as the boundary-layer theory itself. The technical problem, however, could not be solved by a model test directly adapted to the special conditions, due to great difficulties of an experimental, hydrodynamic and purely technical nature. In part these difficulties manifested themselves in the fact that the requisite quantities of air to be removed appeared technically and fundamentally too great for removal by suction, an error which even clung to a few preliminary basic tests intended to show the effect of the boundary layer. After these experiments, the new tests were made very simple with the greatest possible improvement in the methods employed. We now have the results of the first investigation of this nature. It was indeed aeronautical, in that it dealt with airfoils, but the results are of very general application. In particular, the determination of the forces with the wind-tunnel balances is an especially simple way to arrive at conclusions regarding flow conditions along the surface of any object.

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*"Versuche mit einem Absaugeflügel." Zeitschrift für Flugtechnik und Motorluftschiffahrt, May 15, 1931, pp. 259-264. Published by R. Oldenbourg, Munich and Berlin.

Although not all the tests made in this investigation have led to conclusive results, and although great difficulties were encountered, nevertheless it was the first to yield reliable data regarding the characteristics of a wing profile from which the boundary layer is removed by suction. These profile characteristics are, moreover, considerably better than those obtained in previous tests.*

I. Apparatus

The wing model represented by Figure 1, contains all the suction apparatus, namely, two axial double fans, made especially for the tests and blowing outward through the end plates, and two high-speed three-phase water-cooled induction motors. A strip of the suction side of the wing (between M and N in Figures 1 and 3), extending throughout the whole span, is exchangeable, so that the suction openings, which are all located in this area, can be easily varied. The wing model is provided with end disks in order to obtain uniform lift distribution. A few tests were made, however, without the end disks. Tests were made with the single slots shown in Figure 2 and also with the perforated screens shown in Figure 3.

No direct measuring device, like a Venturi or Pitot tube, could be used in the limited space inside the model. This did not matter, however, since the amount of air expelled could be determined indirectly from the negative pressure in the model and the rotational speed of the blowers, on the basis of preliminary tests and calibrations. In Figure 1 the wires and pipes for operating and cooling the motor and for measuring the rotational speed and the pressures are seen to issue through the right-hand plate. In the wind-tunnel tests these wires and pipes were led through a conduit R, the connections with the wing consisting of very soft rubber tubes and metal springs. The conduit R, which approached to within one or two millimeters of the model and thus protected the external wires and pipes from all appreciable air forces, was not suspended from the wind-tunnel balance, but (with

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*O. Schrenk, "Tragflügel mit Grenzschichtabsaugung." Luftfahrtforschung, June 11, 1928. (For translation, see N.A.C.A. Technical Memorandum No. 534: Experiments with a Wing Model from Which the Boundary Layer is Removed by Suction.)

the aid of a suitable suspension) automatically followed all changes in the angle of attack of the wing, thus saving much time and greatly simplifying the tests.

This saving in time was important, in order to enable the completion of the comprehensive test program in the large wind tunnel and because the wear and the deterioration of some parts of the model due to the high revolution speed (mostly 30,000 r.p.m.) and the resulting vibrations were very great and, toward the end of the tests, necessitated increasingly frequent repairs.

II. Representation of the Results

1. As in the previous report,

Q = volume of air removed per second (suction volume),

$c_Q = \frac{Q}{vF}$ = nondimensional volumetric coefficient,

p = negative pressure in suction chamber,

$c_p = \frac{p}{\frac{\rho}{2} v^2}$ = nondimensional pressure coefficient,

v = wind velocity,

F = wing area.

2. The exhaust performance is composed of the true suction performance pQ and the discharge performance $\frac{\rho}{2} {v_b}^2 Q$, whose magnitude depends on the discharge velocity v_b. On the other hand, the propeller thrust and efficiency also depend on v_b, since, in order to utilize the reaction, the exhaust air is usually discharged backward. For technical reasons, however, this was not done in the model test. The calculation for $v_b = v$ yields the sum of the minimums of the two performances.*

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*This minimum calculation assumes identical aerodynamic efficiencies of the propeller and blower. A similar calculation can be made for unequal efficiencies and yields $v_b = v \frac{\eta \text{ blower}}{\eta \text{ propeller}}$.

In this case the performance factor is

$$c_{l_s} = c_Q\ (c_p + 1)$$

3. The reduction in the propeller load, which occurs in the correct backward discharge of the air, amounts to

$$\Delta c_W = - 2\ c_Q$$

and must be taken into consideration in connection with the data which serve as the basis for the evaluation of the test results.

4. As determined with the balance, the drag coefficient c_W consists of several components, one of which is the "sink resistance" with the coefficient

$$c_{W_Q} = 2\ c_Q$$

and is induced by the accompanying momentum of the discharged air. This component is peculiar to the suction model.

5. A portion of the profile drag resides in the "sink resistance" (loss of momentum in the boundary layer before the removal by suction) and requires no further consideration. The remainder could not here be determined in the usual way by means of the induced drag, for various reasons, but was determined for a series of test points according to the momentum method of Betz.* It was found to be very small and yielded a mean value of $c_{W_\infty} \approx 0.007$. Only such cases were investigated, with a favorable arrangement (fig. 2, slot III) and sufficient suction, as were of practical interest.

6. If the sum $c_{W_\infty} + c_{W_Q}$ is deducted from the measured c_W', the remainder consists of the induced drag and a small, not accurately determinable, secondary drag due to the end plates. These are of no importance, as

*A. Betz, "Ein Verfahren zur direkten Bestimmung des Profilwiderstandes." Zeitschrift für Flugtechnik und Motorluftschiffahrt, Feb. 14, 1925. (For translation, see N.A.C.A. Technical Memorandum No. 337: A Method for the Direct Determination of Wing Section Drag.)

they are both due to the special experimental arrangement. On the contrary, the value of $c_w' - c_{w_\infty} - c_{w_Q}$ is important in judging the accuracy of the test. If it is determined for all good test points under the general assumption of $c_{w_\infty} \approx 0.007$, the points for the various suction strengths and various good arrangements fall approximately in a single curve which therefore represents the course of the marginal and secondary drags. The slight scattering is probably due in part to small differences in the marginal and secondary drags. The remainder is the actual test scattering, which is divided between c_a, c_w', c_{w_Q}, and c_{w_∞}.

7. In the calculation of the total requisite performance for the profile itself (disregarding the induced drag) the former profile-drag coefficient was replaced by the profile performance factor

$$c_{l_\infty} = c_{w_\infty} + c_{l_s},$$

in which the components in paragraphs 3 and 4 cancel each other under the assumption of the most favorable discharge.

8. On account of the low aspect ratio of the test model at such high values of c_w, the lift itself needs to be converted for infinitely large aspect ratio. This is

$$c_{a_\infty} = c_a \frac{1}{\cos \Delta \alpha}$$

in which

$$\Delta\alpha = \frac{c_{wi}}{c_a}$$

III. Results Obtained with Slot III of Figure 2

Slot III of Figure 2, which was regarded from the first as the normal case for purposes of comparison, was very accurately tested and the results were frequently verified during the whole investigation. In the evaluation of the tests, moreover, the expectation was confirmed, that slot III is one of the most favorable cases investigated. Some of the other arrangements may be as good, but none of them is manifestly better.

The immediate test results are plotted in Figure 4 without regard to the theoretical considerations of the foregoing section. The accompanying table contains the mean suction values for each mark throughout the whole angle-of-attack range investigated. Some of the extreme values differed therefrom by several per cent.

On account of the various "sink resistances" (Section II, 4), it was to be expected that the test points of Figure 4 would be scattered over a wide strip. Only when $c_W' - c_{W_\infty} - c_{W_Q}$ is calculated according to II, 6, is there obtained a common curve, which replaces the formerly customary curve of the induced drag and which is represented by a line composed of long dashes.

The test points with $v = 10$ m/s (32.8 ft./sec.) are not plotted here, because they differ from the others in various ways. Due to very irregular flow conditions and to the smaller forces and pressures, they are very inaccurate, and the results are much worse than for 20 and 30 m/s (65.6 and 98.4 ft./sec.), between which there is no appreciably systematic difference. The results with $v = 10$ m/s are plotted in Figure 5 only for the sake of completeness. The difference between the two groups is thus rendered very obvious.

The transition from the laminar to the turbulent boundary-layer flow on the suction side of the wing is manifestly completed between $v = 10$ m/s and $v = 20$ m/s. The turbulent flow is considerably more favorable than the laminar flow for the removal of the boundary layer by suction. The poorer results of earlier investigations were probably due in part to the fact that the flow was below the "critical" velocity, without the possibility of determining the effect of the Reynolds Number. In the evaluation of the new results, the subcritical tests may be entirely eliminated, since they are of no practical significance.

Figure 5 shows the maximum lift corresponding to any volumetric coefficient. The curve a is the normal limit which can be reached by pulling up in the wind and generally also by starting the suction before the beginning of the motion, while the curve b is the limit which can be reached by suction after the flow has become detached. The dated points indicate previous measurements.

According to Section II, the direct measurements do not give a complete picture of the profile characteristics. The most important of all is the relation between c_{a_∞} and c_{l_∞}, in which the value 0.007 is taken as the basis for c_{w_∞}. This relation is shown in Figure 6, where the dash line indicates the location of the best values obtainable with this position of the slot. This curve lies somewhat above the test points for the following reason. It was not possible to determine the limiting values by careful experimentation with the rotational speed of the exhaust fan or with the angle of attack, due to the need of economy in time and material. The previously determined suction strengths and angles of attack (in stages of 6°) had to be used. Somewhere within the 6° from the last test point is the actual limiting point and the probable course of the limiting curve is obtained by the upward extrapolation of each test series by 3°. The same method was used to determine the limiting curves in Figure 5.

IV. Comparison of the Different Arrangements

No such close succession of test points as with slot III could be made with the other slot and screen arrangements. With them therefore only the greater differences could be recognized, and the results were sometimes obtained by the careful consideration of relatively few test points. The lack of a few accurate limiting points (cf. Section III) is especially regrettable, because the intervals between the individual angles of attack are here 12 or 18° instead of 6°, so that an extrapolation, as in Figure 6, is not very accurate. It is assumed that the polar of the wing from which the boundary layer is not removed by suction goes to $c_a \approx 1$ and has c_{w_∞} values between 0.05 and 0.1.

a) Comparison of the individual slots

As regards the location of the slots (I to III), position I is the least favorable and position III the most favorable. Consideration of c_p and c_Q shows that slot II is near the point of maximum suction and that slot

I is partially before it, which explains the considerable discrepancy.

Changing the width of the slot (III and IV), produces two opposing influences. The effect of the same quantity of removed air is lessened by increasing the width of the slot, but the quantity required for a given maximum lift may be greater, because the whole flow sacrifices some of its homogeneity and stability by the reduction in the pressure difference between the inside and outside. The results indicate, without sufficient test points, that both influences have their effect; $c_{a_{max}}$ over c_Q being obviously somewhat greater for slot III and $c_{a_{max}}$ over c_{l_s} being somewhat smaller than for slot IV. ($c_{a_{max}}$ is the maximum value attainable with every removal of the air by suction, as in Figures 5 and 6.) If this provisional result is confirmed, then the limiting curve in Figure 6 is not the best that can be attained with the previous arrangements.

Rounding the rear edge of the slot has no effect within the limits of accuracy hitherto attainable. (Slots III,b and III; III,c and III,a.) Rounding the front edge of the slot (III,a and III; III,c and III,b) has the same effect as increasing its width because, by preventing the contraction of the flow, it enables the utilization of the full width of the slot. (Fig. 7.)

b) The perforated screens (fig. 3)

These screens, which consist of two groups (I, II, III, with different slot widths and IV, II, V with different slot distribution over the suction area), show no systematic differences, so far as the test points go. None of them, however, is rightly located. Tests with the individual slots show that the screens should extend nearer the trailing edge.

It thus happens that the results obtained with the screens are nearly all poorer than with good slots, although logical considerations would indicate certain advantages from "continual" suction. The total amount of air removed should be diminished by the right slot distribution and, most important of all, a partially detached flow should be more readily restored. (Upper b curve in Figure 5.) No positive conclusion regarding the correctness of these considerations and no comparison of the screens with the individual slots is possible until further tests have been made.

c) Wings without end plates

For like values of c_Q, the values obtained for $c_{a_{max}}$ were over 30% smaller without end plates. Such a result was anticipated, because the wing tips with an outwardly decreasing lift distribution drew in too much air at the expense of the middle portion, although they really required the removal of less air. (Fig. 8.) In Figure 8 the pressure due to the tension $(p_a - p_i)$ for the inflow is greater at the wing tips than in the middle. p_a = outside pressure distribution at the suction orifices. p_i = pressure in suction chamber.

In practice this disadvantage can be avoided, even without end plates, by such means as tapering the slots or changing their location, changing the suction pressure, and using wing tips entirely without suction, according to Luftfahrtforschung, June 11, 1928, page 52.

V. Comparison of the Actual Flow with the Theoretical Nonviscous Potential Flow

From the boundary-layer theory it follows that the removal of the boundary layer by suction produces unusual forms of flow greatly resembling simple potential flows. In order that this conclusion might be confirmed by the new results, the tests were made with the theoretical Karman-Trefftz profile.* The four possibilities of comparison are drag, lift, moment and pressure distribution. The smallness of c_{w_∞} (Section II,5) with the slot 100 mm (3.94 in.) away from the trailing edge shows that, in these cases, there is very little deviation from the potential flow behind the slot.

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*Karman and Trefftz, "Potentialströmungen um gegebene Tragflugelquerschnitte," Zeitschrift für Flugtechnik und Motorluftschiffahrt, 1918, p. 111.

Figure 9 shows c_{a_∞} plotted against α_∞ (= $\alpha - \Delta\alpha$. See Section II,8) for slot III as compared with the theoretical lift. Though the calculation of the angle of attack in the tests is not very accurate, it is nevertheless evident that the discrepancies between the theoretical and measured c_a values are about the same as for ordinary wings in the zone of undetached flow.*

Figure 10 compares the experimental and theoretical travel of the center of pressure, which show satisfactory agreement. h_n is the distance of the center of pressure on the wing chord from the reference point of the moments.

All these observations show that the actual flow approximates the theoretical flow to the anticipated degree. The comparison of the pressure distribution about the profile has not yet been attempted, because its experimental and theoretical determination are beset with especial difficulties.

VI. Physical and Technical Importance of the New Results

a) Physical importance

The chief importance of the new tests is in the practical field, because the theoretical aspects of the removal of the boundary layer by suction had long been clear. Nevertheless, it does not seem entirely useless to establish the agreement of the latest results with the principles of the boundary-layer theory.

Furthermore, the experiments show that, in the removal of the air by suction, we are really influencing the flow with the aid of a thin boundary layer, i.e., by a kind of relay, instead of utilizing the direct cooperation of the main flow with the suction sink. The only direct action of this nature has already been included in the "sink resistance" (Section II,4). Moreover, according to the test results, the velocities induced by

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*O. Schrenk, "Systematische Untersuchungen an Joukowskyprofilen," Zeitschrift für Flugtechnik und Motorluftschiffahrt, May 28, 1927, p. 225. (For translation, see N.A.C.A. Technical Memorandum No. 422: Systematic Investigation of Joukowsky Wing Sections.)

the sink are very small in comparison with the wind velocity v and, according to the tests, amount to only about 2% of the circulation due to the induced velocities.*

That in fact only portions of the boundary layer, at any rate not more than the total boundary-layer quantity, is removed by suction, can be verified by comparison with more recent boundary-layer tests with an ordinary wing profile. This profile had, shortly before the separation ($c_a \approx 1.3$) on the rear half of the suction side, boundary-layer quantities 30 to 50° greater than the suction quantities necessary for the same value of c_a with our thick suction wing. When the boundary-layer exhaustion has attained sufficient practical importance, a more accurate investigation of the relation between the boundary-layer quantity, the suction quantity, the pressure increase and the boundary-layer profile will be necessary.

b) Technical interpretation

The practical interpretation of the new results, as already mentioned in the introduction, is based on the fact that we now have, for the first time, sufficient accurate data regarding the profile characteristics of a given suction wing which was never the case before, due to the many experimental difficulties. Progress, as compared with previous results, is shown, e.g., by the dated points of comparison in Figure 5. Moreover, test results have been compiled which are of general importance for the suction problem. Lastly, we now have data for the first time on the importance of the critical Reynolds Number (transition from the laminar into the turbulent boundary layer) for the removal by suction.

As regards the profile characteristics, it may be safely said, however, that we have not yet secured the best results obtainable with a suction wing. In the evaluation of the tests, various ways have been noted for further improvement of the profile characteristics (wide individual slots, two individual slots, better perforated screens, etc.). Only the tests with slot III (fig. 2) can yet be regarded as concluded. No final conclusion is pos-

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*$w_Q = v \frac{c_Q}{\pi} \frac{t}{r}$ is the induced velocity of the sink at the distance r from the sink (t = wing chord). $w = v \frac{c_a}{4\pi} \frac{t}{r}$ is the portion due to the circulation at the distance r from the center of the vortex.

sible for all the other investigated arrangements, due to the very limited number of test points.

Moreover, only a very definite profile type has thus far been tested, which was derived from an ordinary type simply by making it thicker. Some entirely different type (perhaps with greater pressure increase and maximum exhaustion) will yield still better results with removal of boundary-layer by suction.

As regards any direct aeronautic importance of the tests, the results indicate the possibility of reducing the wing chord of present airplanes without changing their other dimensions. The customary speed range would be attained at c_a values of 0.8 to 4.5. It is very doubtful, however, whether such an airplane would be satisfactory for all purposes, though it would offer two special advantages, namely, a very small travel of the center of pressure along the already rather short wing chord and a very great rigidity with respect to gusts. As a criterion for the excellence of the profile, we can take the ratio $c_{a_\infty}/c_{l_\infty}$ (Section II,7), which closely corresponds to the former profile lift-drag ratio and, in the vicinity of $c_a = 0.8$, has a value of 40 to 50 for slot III, according to Figure 6. During the measurements, this region received but little attention, so that the above-mentioned value is not very certain and should be verified by further tests.

The first applications of the removal of the boundary layer by suction may not be in the design of complete suction-wing airplanes, but in improving the flow about individual airplane parts (such as thick struts, cutaway wings, etc.), as the removal of the boundary layer by suction for the production of special forms of flow has already been introduced into general aerodynamic researches.

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

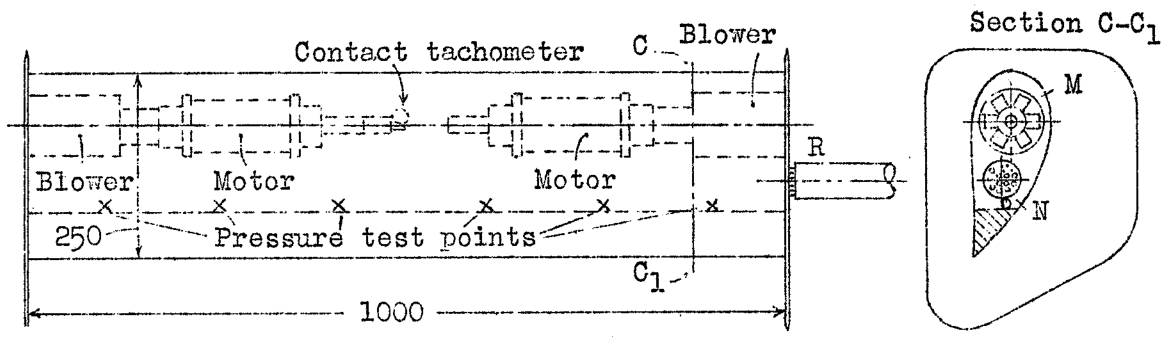


Fig. 1 The experimental wing.

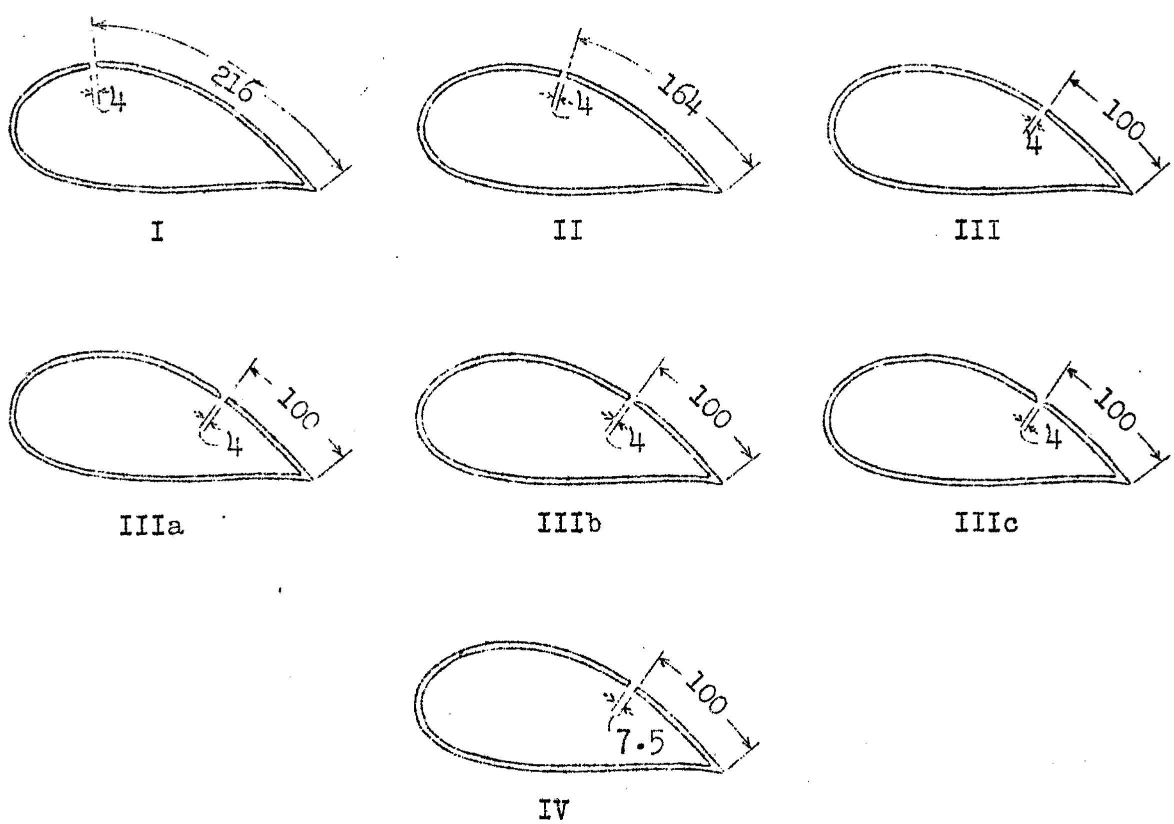


Fig. 2 Location, form and width of slot.

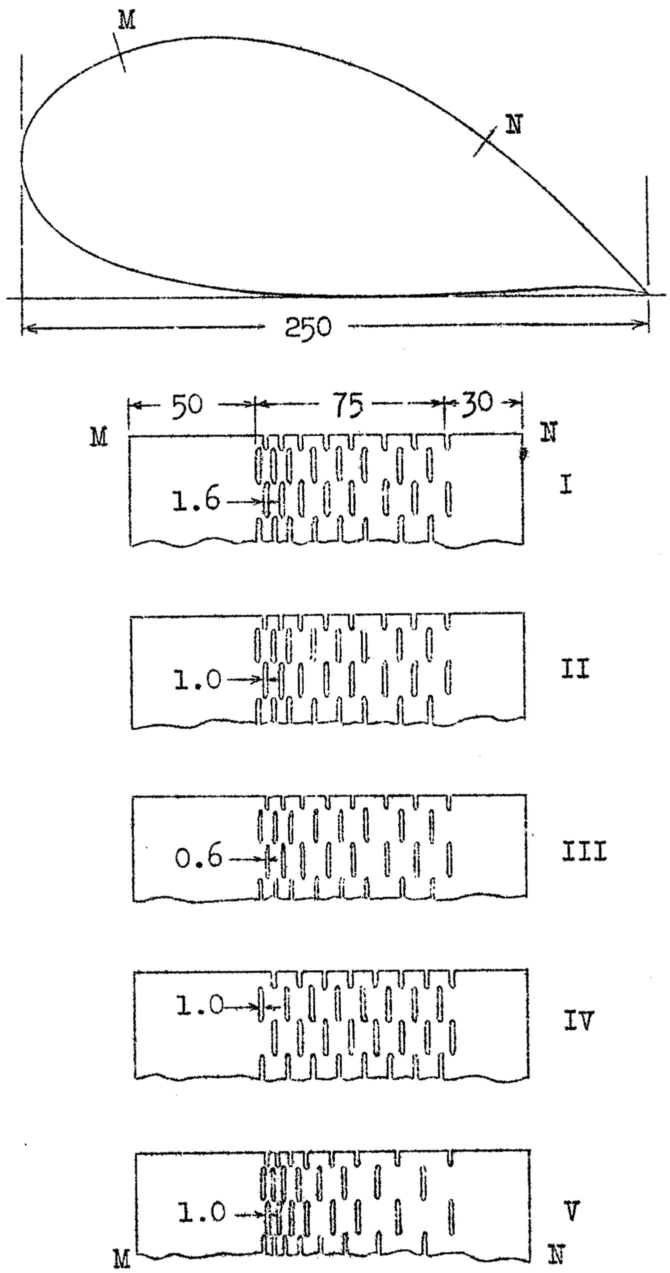


Fig. 3 Perforated shields.

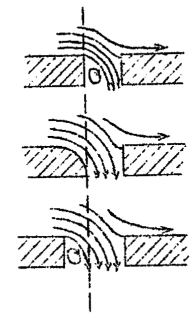


Fig. 7

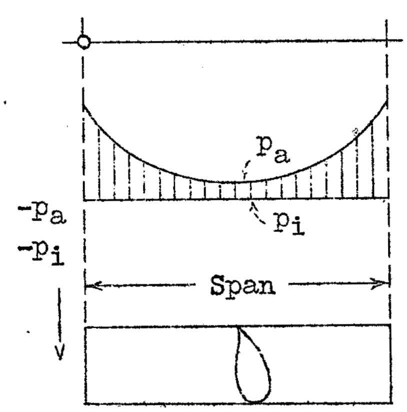
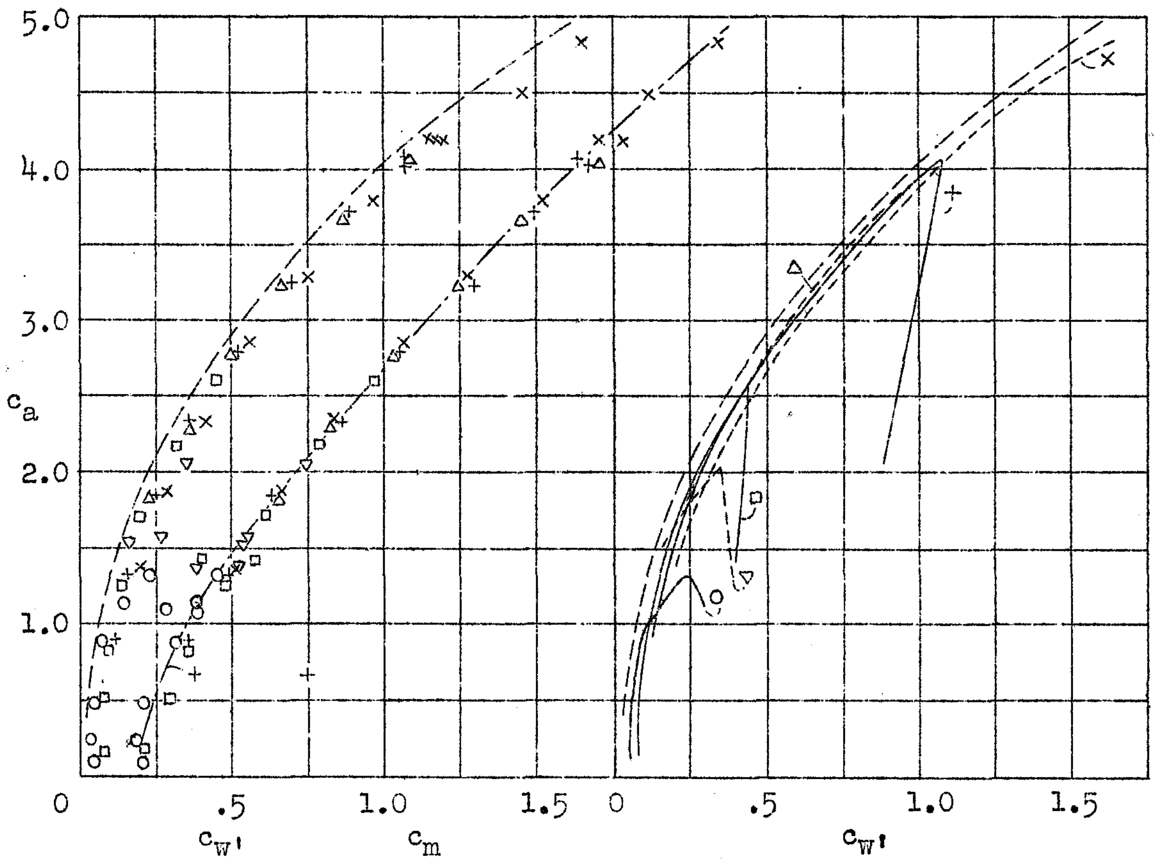


Fig. 8 Pressure distribution in suction wing with high c_a without end plates.



Symbol	v, m/s	n, r.p.m.	$\frac{n}{v}$ 10^{-3}	c_Q	$2c_Q$	c_p	$c_{l\,s}$
×	20	30000	1.50	0.038	0.076	16.0	0.660
△	20	20000	1.00	0.022	0.044	8.2	0.200
+	30	30000	1.00	0.024	0.048	8.0	0.210
□	30	20000	0.67	0.014	0.028	3.9	0.065
▽	20	10000	0.50	0.011	0.022	2.0	0.030
○	30	10000	0.33	0.005	0.010	1.0	0.010

Fig. 4 Test results with slot III.

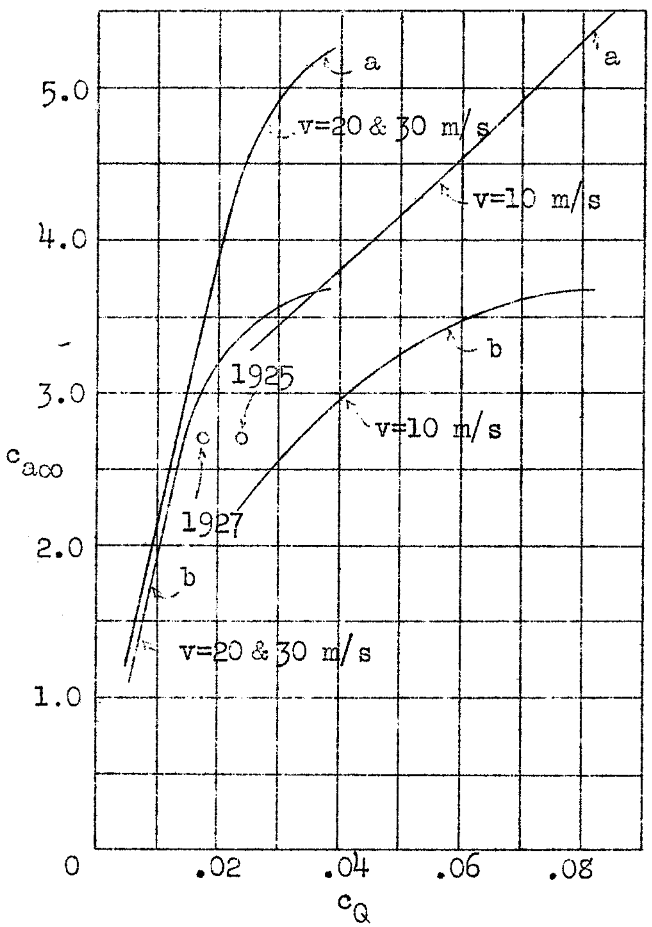


Fig. 5 Maximum lift values for different suction quantities.

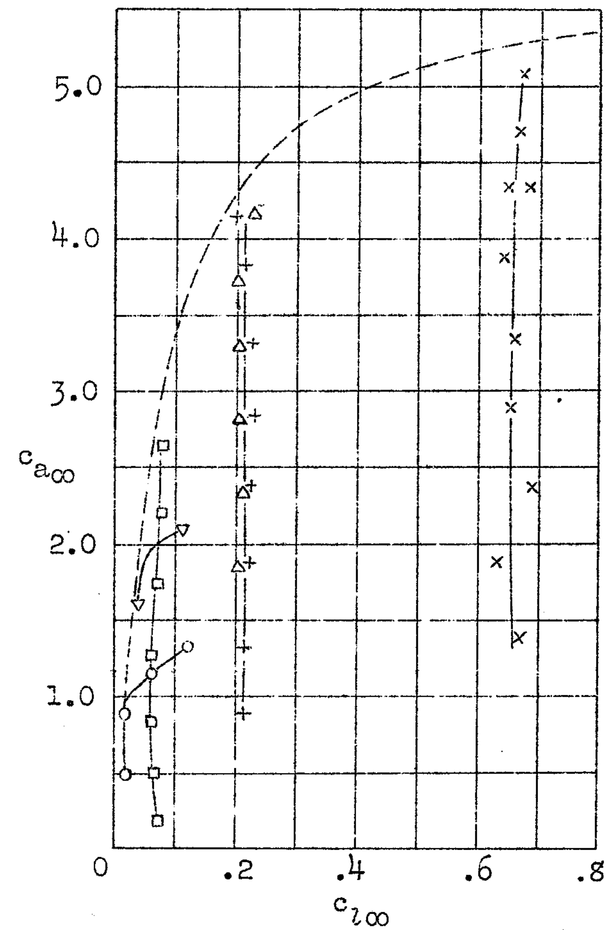


Fig. 6 (See Fig. 4 for designation of symbols.)

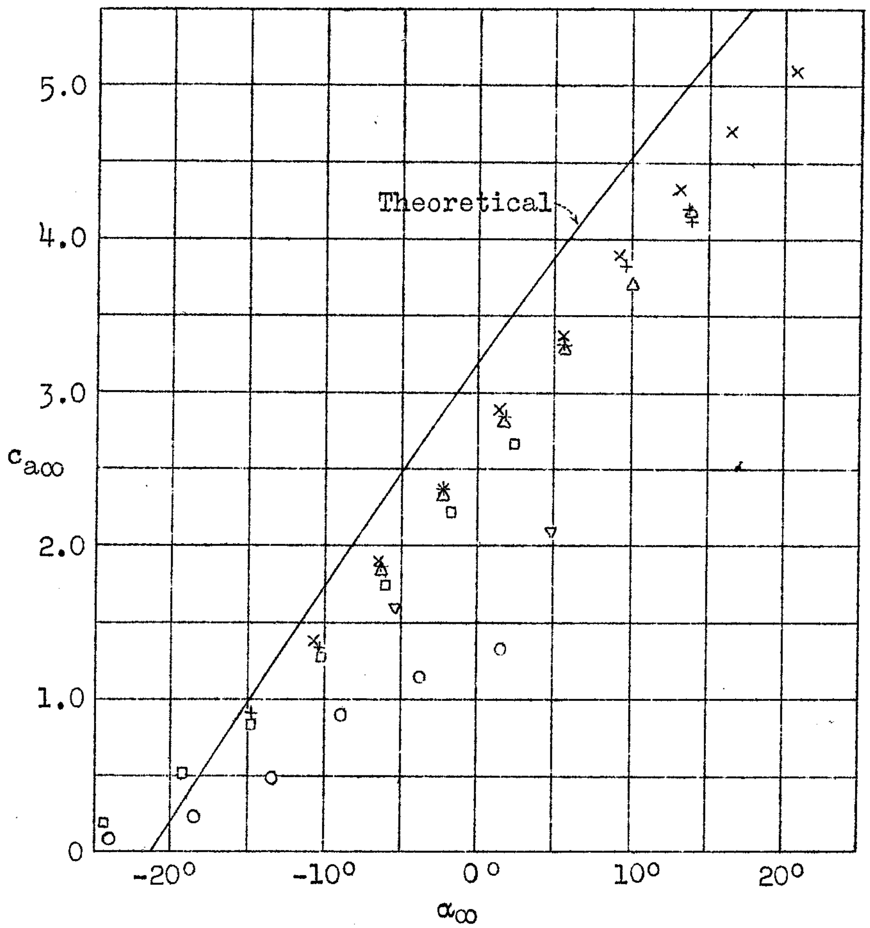


Fig. 9 Lift plotted against angle of attack, experimental and theoretical.
(See Fig. 4 for designation of symbols.)

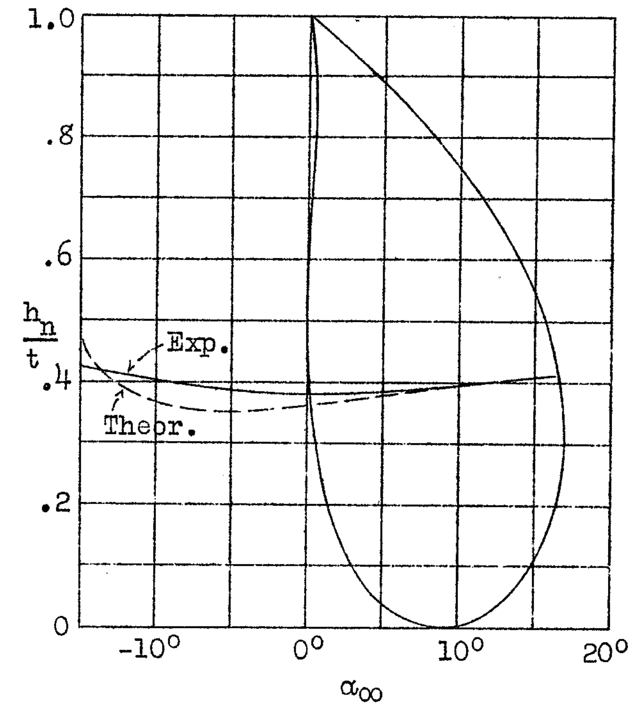


Fig. 10 Location of c.p., experimental and theoretical.