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WINGS WITH NOZZLE-SHAPED SLOTS

By Richard Katzmayr

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By Richard Katzmayr.

Aerodynamic engineers have always sought to discover devices which would produce the greatest lift with the least possible drag. Their first successes were obtained by giving a suitable shape to the wing profile. This device failed, however, at large angles of attack (18-21°), so that it appeared impossible to obtain greater maximum lifts than $2\ c_{A_g} = 150$. Only after the cause was found for the sudden decrease in the lift after reaching a certain angle of attack, were means adopted which enabled a further increase in the lifting effect of a wing. The lift decrease was found to be due to the loss of energy which finally takes place in the so-called "boundary layer" of the air flow. This occurs in connection with a rapid and excessive pressure increase and causes the boundary layer to separate from the upper surface of the wing, thus leading to a partial reversal of the direction of flow and finally to the formation of vortices. The most obvious way to counteract this evil is to replace the lost energy in the boundary layer. This can be accomplished in various ways.

In the case of "rotors," for example, the energy is added by causing the surface of the rotor to move in the direction of

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*"Düsenflugel," from Berichte der Aerodynamischen Versuchsanstalt in Wien, Vol. I, No. 1 (1928), pp. 57-75.

the main flow, thereby imparting, through friction, a supplementary acceleration to the air near its upper surface.

With the "slotted wings" of Lachmann and Handley Page, the boundary layer on the upper side is accelerated by the additional air flowing through the slots. The kinetic energy of the additional air is derived from the pressure difference between the upper and the lower side of the wing. The energy transformation is effected with the least loss in nozzle-shaped slots.

In Göttingen an attempt is being made to reach the same goal in a third way. This consists in removing the boundary layer from the top of the wing by suction into the inside of the wing, a method which also means nothing but an acceleration of the boundary layer, since a pressure drop is produced on the upper side of the wing by creating a negative pressure inside the wing. This pressure drop accelerates the flow of the surrounding air.

The direct use of rotors as airfoils is very uneconomical, since the considerable transverse force produced by them is accompanied by a great drag in the main direction of motion which requires considerable energy to overcome. For constructional reasons, on the other hand, it is not possible, in the case of unsymmetrical bodies like airplane wings, to employ the method used with rotors. Experiments with wings having rotors fitted into their leading edge showed that no considerable lift increase can be thus obtained.

With slotted wings, however, a considerable increase was found in the lifting power, especially in the maximum lift. It was found, however, that a corresponding drag increase occurred at small and medium angles of attack, so that slotted wings are of practical importance only when the slot openings can be regulated during flight.

The results of only a few laboratory experiments with suction are yet available. They indicate, however, a considerable increase in lifting power without change in drag. Even before the publication of the results of the Göttingen experiments on the removal of the boundary layer by suction, experiments with nozzle-slotted wings were begun, at the suggestion of Josef Mickl, in the Vienna Aeromechanical Laboratory. A report of these experiments will be given here.

With this type of wing the additional energy is supplied to the boundary layer on the top of the wing by a current of air flowing out through a slot parallel to the leading edge and tangent to the wing profile. Only toward the end of this investigation did it become known to the writer that this method of investigation had been proposed in other countries, e.g., by Professor Baumann in Germany, by Professor Lafay in France, and by Professor Stroescu in Roumania. I do not know whether experiments with such nozzle-slotted wings were actually instituted in the above-mentioned countries. In Vienna special importance was laid, from the first, on the correct form of the passages at the outlets. They were made nozzle-shaped, in order to effect the completest possible conversion of the potential energy of the compressed air inside the wing into kinetic energy at the mouth of the slots. The nozzle shape of the air passages led to the use of the expression "nozzle-slotted wings" to designate this type. It differs from the ordinary slotted wing in that the air is not taken from the lower side of the wing, but from the inside of the wing, to which it can be constantly supplied in any desired manner. Thus it is possible, independently of the angle of attack, to impart to the auxiliary air the velocity of discharge best suited to each particular case. Moreover, the slot openings can be located at those points of the wing profile where they will be most effective. Lastly, it is possible to regulate the discharge of the auxiliary air without movable parts on the wing itself, as in the case of ordinary slotted wings.

In order to obtain an idea of the effect of the discharge of the compressed air tangentially to the wing surface on the magnitude and direction of the resultant aerodynamic force, experiments were first tried with a cylinder. This cylinder had a diameter of 150 mm (5.91 in.) and a length of 990 mm (39 in.). It was made of sheet brass 0.2 mm (0.008 in.) thick and was provided with twelve slots parallel to the cylinder surface, and 0.75 mm (0.03 in.) wide. Sheet-brass tubes led the air to these slots, as shown in Figure 1. The cylinder surface was stiffened by two rings a and b, between which the width of the slots was fixed by soldering in short pieces of wire c. The end walls e and f (Fig. 1) were provided with connecting tubes g and h, of 65 mm (2.56 in.) diameter and 100 mm (3.94 in.) length, through which the compressed air could flow into the cylinder.

Since the passages to the discharge slots all led in the same direction, the outflowing air formed an envelope around the cylinder circulating in a definite direction. In order to determine the effect of the circulating supplementary air on the magnitude of the air force on the cylinder, it was exposed to the air stream in a wind tunnel and the drag and transverse force (i.e., the lift) were measured.

For this purpose the cylinder was suspended on two wires from the drag balance and connected with the lift balance by means of four levers. It was also necessary to make further provisions, to enable the delivery of the compressed air to the cylinder without hampering the action of the two balances. Lastly, it was necessary to eliminate the effect of the finite cylinder length on the results. The air supplied to the cylinder was highly compressed by a centrifugal blower. The compressed air was led through pipes to the border of the artificial air stream and thence into the cylinder by means of two thin-walled rubber tubes of 1 meter (3.28 feet) free length and the connections g and h. Since the thin rubber tubes were not strong enough to withstand the internal air pressure, they were enclosed in nets of fine thread, which kept them from bursting without diminishing their flexibility. This device proved satisfactory and did not hamper the operation of the balances, even when the rubber tubes were fully distended. In order to protect the rubber tubes from the action of the air stream, they were enclosed in sheet-metal pipes of 150 mm (5.9 in.) diameter. These pipes were brought close to the ends of the cylinder and firmly secured by stay wires against the action of the air stream. Since the protecting pipes had the same outside diameter as the cylinder, they all formed one continuous body of uniform cross section passing transversely through the whole air stream. The effect of the finite cylinder length on the results was thus eliminated. Figure 2 shows the whole installation as viewed from the lift-balance side, and Figure 3 as viewed from the air-pipe side.

The quantity of air flowing from the cylinder could not be determined by means of a measuring orifice (Staurand), because the straight sections of the air pipes were not long enough. The quantity of air was estimated from the exit velocity at the slots. The pressure in the cylinder was also measured occasionally. The experiments were conducted at different dynamic pressures and exit velocities both with all the slots open and with only a part of them open.

The cylinder was first subjected to the air stream without causing any air to flow from the slots. The tests were made at six dynamic pressures and consequently at six different Reynolds Numbers R. The results, as given in Table I and Figure 4, show the characteristic decline in the drag coefficient with increasing values of R. The drag coefficients are based on an area $F = 0.99 \times 0.15 = 0.1485$ m² (1.6 sq.ft.). The relatively high value of $2\ c_W$ for $R = 214,300$ is ascribable to the peculiar character of the cylinder surface.

Table II and Figure 5 give the results obtained with air issuing from the slots in the cylinder, diagrams a to e (Fig. 6) show the number and distribution of the slots open during the experiments, the rest of the slots being closed with wax. Figure 6 shows the number of the open slots and their location with respect to the direction of the air flow. In case a, all the slots were open. From Table II and Figure 5, it is seen that, as the ratio u/v increases, the transverse force (lift) increases, while the drag first decreases and then increases. The curves in Figure 5 are similar to the characteristic curve of an ordinary wing. In analyzing them, it should be noted that the same scale was used for $2\ c_A$ and $2\ c_W$. If the characteristic curve obtained for the slotted cylinder is compared with the curve obtained in Göttingen with a rapidly revolving finite cylinder of 70 mm (2.76 in.) diameter and 330 mm (13 in.) length between two terminal disks of 140 mm (5.5 in.), the great similarity of the results is apparent (Fig. 5, curve b).

The drag coefficients are smaller throughout for the slotted cylinder than for the plain cylinder compared with it. This is probably due to the infinite length of the cylinder used in the Vienna experiments. It should be noted that, from the stationary end cylinders enclosing the rubber air tubes, no air flowed out tangentially to their surface, so that the flow diagram around the cylinder suspended from the drag balance was not quite like the one around the stationary end cylinders. Hence the resulting $2\ c_W$ values are probably too high. The Vienna lift coefficients are very similar to those obtained in Göttingen.

This fundamental experiment showed that the compressed air flowing out tangentially to the cylinder had an effect very similar to that of the circulatory flow produced by the surface friction of a plain rotating cylinder.

The results given in sections b to e of Table II and in Figure 5, show that closing part of the slots causes a diminution of the transverse force (lift) and also of the drag. It is noteworthy that the latter has smaller values throughout than in the case of a cylinder from whose surface no air flows. Comparison of d and e shows, moreover, that the location of the slots with respect to the direction of the main flow greatly affects the results. The effect of the additional air is all the greater, the more of it is blown into the dead-air space behind the obstacle, a result not apparent in the following

wing investigations.

It should also be mentioned that the ratio u/v was so changed that the velocity of the main flow varied, while the outflow of the supplementary air remained constant. It would probably have been better, at the highest possible wind velocity, at $p =$ about 30 mm (1.18 in.) water column, to increase the velocity of the flow from the slots by a corresponding pressure increase inside the cylinder, since the various measurements would then have been made for one and the same index value. The centrifugal blower at our disposal did not furnish, however, the high pressures required and we had to adopt the previously mentioned expedient.

After the above-described experiments showed that transverse forces could be generated by the tangential flow of compressed air from slots in the surface of a cylinder, the same as with rotors, we also investigated the effect of objects with wing-shaped cross sections. The performance of these experiments was much more difficult than those with the cylinder. We had to abandon the introduction of the air from the sides on account of the necessary changes in the angle of attack. The air duct was transferred to the center of the lower side of the wing. Great pressure drops in the intake pipe had to be accepted, since its small size necessitated high velocities, and since it had several sharp bends. The central position of the intake pipe was also unfavorable for the uniform distribution of the outflowing air throughout the whole span, which has to be taken into consideration in the analysis of the results. The intake pipe is shown in Figure 7. It was a streamlined pipe and was fastened to the upper central support of the lift balance. The end toward the wing model was tapered and was connected with the latter by means of a short thin-walled rubber tube and a tubular connection on the model. This flexible union was necessary because changes in the angle of attack shortened the lower part of the tube. The end toward the model carried a 90° elbow with its free arm extending upward. The center of curvature of the elbow was so located that the direction of the mean centrifugal force of the air flowing through the pipe passed through the fulcrum of the lift balance. Any impairment of the lift values by this reactionary force was thus avoided. To the free end of the elbow there was fastened a thin-walled rubber tube 700 mm (27.6 in.) long and 70 mm (2.76 in.) in diameter, which, as in the experiments with the cylinder, was protected against bursting by a net (Fig. 7). The connection with the centrifugal blower is completed by means of another elbow, a tapering piece and a pipe 120 mm (4.7 in.) in diameter. A measuring orifice had been introduced at 2/3 the length of the vertical part of the pressure pipe. The quantity of air delivered could be varied by throttling on the suction side of the centrifugal blower. A small tube, which passed through the large elbow near the balance into the inside of the wing, enabled the measuring of the pressure on a micromanometer shown in the right foreground of Figure 8. The wing models were supported in the usual manner by two wires from the drag balance and were connected with the lift balance by three rods.

Tests were made with four models which differed from one another in their cross-sectional shape and in the number and distribution of the outflow slots. Three of the models were "normal wings" while the fourth was a monoplane model. Two different wing sections or profiles were used for the normal wings, one of which will be designated by I (Fig. 9). The compressed air could escape through three slots, two of them being on the upper side and the third one on the lower side of the wing. Their location, shape and size are shown in Figure 9. The slots extended the whole length of the model (900 mm ≐ 35.4 in.). The channels were closed at the ends of the model by metal plates. The leading edge of the model was connected with the trailing edge by an iron plate which had a row of large holes for the passage of the air. The rear channel was connected with the channel in the lower portion of the wing by a series of hollowed-out passages. The slots were covered with cardboard strips 12 mm (0.47 in.) wide, glued firmly to the wood on one edge. The compressed air pumped into the wing raised the cardboard strips and flowed from the slots almost tangentially to the wing profile. The strips were attached in such manner that the escaping air could flow only toward the rear on the upper side of the wing and only toward the front on the lower side.

The second profile shape was the Göttingen 398. Models were made of two normal wings of this shape 900 × 150 mm (35.4 × 5.9 in.). One of these had three slots and will be designated by II (Fig. 10). The other model had nine slots and will be designated by III (Fig. 11). Model II, like model I, had two slots on the upper side and one on the lower side, while model III had six on the upper side and three on the lower side. The slot openings were parallel to one another and extended the whole length of the models. These models were made of seasoned wood and differed from model I principally in the shape of the inside passages to the slot openings. As shown by Figures 10 and 11, the passages tapered toward the surface so as to form nozzle-shaped slots, through which flowed regulated air streams. The flow losses were thus considerably reduced and the flow velocity was the maximum for the given internal pressure. Model II consisted of three separate parts held together by a number of plates throughout the span. Model III consisted of nine parts. In the middle of the span, where the inlet tube for the compressed air was attached to the lower side of the model, the parts were held together by a metal band 50 mm (about 2 in.) wide passing entirely around the model, the slots being interrupted for this width. As in the case of model I, cardboard strips 12 mm (0.47 in.) wide were glued at one edge to the wood parts so as to cover the slots. The opposite edge was lifted by the compressed air and released thin air jets during the tests.

Due to the small dimensions of the model, the inside channels could not be perfectly shaped. In particular, the free section of the main channel in the middle of the spam was relatively too small, thus occasioning considerable flow losses. Special attention is called to this point, because these unfavorable conditions, which do not exist to so high degree in full-scale wings, must be taken into consideration in the analysis of the final results.

Many tests were made with the above-described models, but only the most important ones will be referred to here. The tests cover the determination of the lift and drag coefficients at different angles of attack. The tests were made both with and without air flowing from the slots. In the former case, as in the case of the cylinder, the ratio of the discharge velocity u to the air-stream velocity v was varied. This could be done only by varying the velocity of the air stream. The number and location of the open slots were varied by gluing silk paper over some of the slots, in order to determine the effect of the air jets flowing from the slots.

Tables III-IV and Figures 12-13 give some of the results obtained with model I. The wing model was first subjected to an air-flow pressure of 5 mm (0.2 in.) and then of 20 mm (0.8 in.)

water column. In both cases the tests were made with all the slots closed, then with all the slots open, and finally, with the front upper slot open and the other two closed. The characteristic curves for the case with all the slots closed show relatively small lift values and quite high drag values, both being due to the cardboard strips which unfavorably affected the surface of the wing model, abnormally thickened the boundary layer, and increased the skin friction. The lift values were 20 to 25% smaller than for the wing with a smooth surface. The characteristic curve, which was obtained at a small Reynolds Number, shows, moreover, the sudden characteristic fall in the lift values.

The characteristic curves for the model with the air jets issuing from the slots show, throughout, a considerable increase in the lift values, which, in contrast with the well-known ordinary slotted wings, extends over the whole range of the angles of attack and is connected with a moderate increase in the drag at small angles of attack

It is obvious that the test results required some corrections, in order to represent accurately the effect of the outflowing air jets. First it was necessary to determine the additional drag produced by the inlet tube and to make allowance for it in the evaluation. For this purpose, the model was tested both with and without the inlet tube and the additional drag was determined from the difference in the results. Furthermore, the reaction force of the air jets was measured for various jet velocities with the main air stream stopped, but with the compressed-air pump still working. It was likewise deducted in the subsequent correction of the measured drag values. The forward thrust was repeatedly measured at medium angles of attack and large u/v ratios. It might have been allowable not to deduct from the test results the forward thrust produced by the reaction of the air jets, because this thrust was due to the system chosen and not to the arrangement of the experimental apparatus.

As in the case of the slotted cylinder, it is possible to establish the dependence of the magnitude of the effect of the air jets on the ratio of their velocity of discharge to the velocity of the main air stream (i.e., u/v). The larger this ratio is, the larger the lift values will be. The unfavorable flow ratios, mentioned at the beginning, permitted no value of u/v greater than 0.803. This value was obtained at a pressure of $p = 5$ mm (0.2 in.) water column with an open slot on the upper side of the wing model. It is about twice as large as the value (0.402) obtained at $p = 20$ mm (0.8 in.) H_2O and, at a medium angle of attack α, increases the lift about 20%.* The absolute increment in the lift values, based on those of the wing model without the air jets but with the glued cardboard strips, is about 80% for medium angles of attack. It has been

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*It must not be forgotten that the two tests were made at different Reynolds Numbers.

demonstrated that the number and location of the slots in the wing profile are of importance. It has been found that the effect of a slot on the lower side of the wing is to reduce the drag. It is quite important at a large u/v ratio and small angles of attack α (Fig. 12). At large angles of attack, however, a slot on the lower side of the wing does not increase the lift values so much as one on the upper side. Experiments have shown that the effect of an air jet issuing from a slot near the leading edge is greater than the effect of a similar jet behind the thickest portion of the wing. In particular, the tests made with the nine-slotted model III confirmed the correctness of this phenomenom as observed in the tests with models I and II.

The jet velocities u, given in the tables, are mean values, since they vary considerably throughout the span. One of the portions tested is represented in the left part of Figure 14. The maximum u_g is about 2/3 of the distance from the center of the span, the magnitude of u decreasing from this point in both directions. Negative flow velocities were observable in the middle third of the whole span for some of the slot arrangements. Even the direction of the flow from the slots was in no case perpendicular to the trailing edge of the model throughout its whole length. In the middle of the model the directions diverged up to about 45°. At the position of the u_g they were mostly perpendicular to the trailing edge, while at the wing tips the direction of the u again diverged 10-15° toward the middle of the wing, as shown in the right portion of Figure 14.

In the experiments with models II and III the pressure distribution on the upper surface was also measured at different angles of attack. The measurements were made at 12 points on the periphery in a plane situated 180 mm (7.1 in.) from the plane of symmetry of the model. We are giving here only the results obtained with model III at the angle of attack $\alpha = 0$ and under the two dynamic pressures $p = 5$ mm and 20 mm (0.2 in. and 0.8 in.) water column. The location of the measuring points and that of the six slots is shown in Figure 15. The three slots on the lower side of the wing were closed in these tests. The results are given in Table V and Figure 15. They show that during the discharge of the compressed air from the slots, a reduction in the negative pressure occurs in the vicinity of the leading edge, but a considerable increase in the negative pressure toward the trailing edge. This is particularly noticeable for $p = 5$ mm (0.2 in.) water column, whereby u/v had a value of 0.402.

Before giving the results of the experiments with a nozzle-slotted monoplane model, I will compare the results obtained with ordinary slotted wings and with nozzle-slotted wings. Figure 16 shows the characteristics of these two types plotted side by side. I is the L/D curve of the slotted wing as derived in a modified form from the Göttingen wing profile No. 422 by the introduction of nozzle-shaped slots. II is the L/D curve for the unchanged wing profile 422.* III is the envelope curve of the characteristic curves given in Zeitschrift fur Flugtechnik und Motorluftschiffahrt, 1924, p. 175. This wing tapered toward the tips both in width and thickness. It had an adjustable auxiliary wing on the leading edge and a movable flap on the trailing edge. IV and V are the characteristic curves of the nozzle-slotted wing (with and without air jets), as taken from Figure 12. In order to enable direct comparison, the results were converted to the standard aspect ratio of 6.

The relative position of the curves clearly demonstrates the superiority of the nozzle-slotted wings, especially at small and medium angles of attack. Curve III passes above curve IV only after the angle of attack exceeds 16°. Curve IV, which, for lack of space, is only partially shown, continues to climb up to $2\ c_A = 292$ at $\alpha = 24^\circ$. The tests showed that the lift A continued to increase even beyond this angle of attack. It is also worth noting that the lift values of curve IV were reached at a smaller α than those of curve III, which is of practical importance in landing.

The good results obtained in experiments with normal wings furnished the reason for testing a nozzle-slotted wing in combination with a fuselage. Drawings of the wooden model are

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*These curves were taken from "Ergebnisse," Vol. II, pp. 61-64, and Vol. I, p. 109.

shown in Figure 17. The fuselage was hollow and made in two parts joined in the plane of symmetry. The two parts were held together by two screws with the interposition of a thin rubber plate. The side of the fuselage facing the lift balance was provided with a short connection for the compressed-air pipe. The two wings were joined to the fuselage at about half its height. They were made of wood and had three nozzle-shaped slots on the upper side, the openings being covered with cardboard strips glued at one edge. The slots were perpendicular to the plane of symmetry. They began at the fuselage and ended about 15 mm (0.6 in.) from the wing tips. Each wing consisted of three parts. One part formed the leading edge, lower portion and trailing edge of the wing. The two other parts lay between the slots. They were joined to the lower part at two points of the span.

The tests were made at the three dynamic pressures of p = 5, 10 and 20 mm (0.2, 0.4 and 0.8 inch) water column. By closing some of the slots, the effect of their number and position was tested. The pressure of the air was regulated by throttling at the suction side of the centrifugal blower. In order to determine the effect of the compressed-air tube on the drag, the model was tested in the air stream, like an ordinary wing model, both with and without this tube. The additional drag due to the tube was thus determined, and allowance was made for it in the calculations. The reaction effect of the outflowing air was also deducted in the same way as for ordinary wings.

The "angle of attack" was measured between a reference line drawn on the side of the fuselage and the direction of flow of the air stream. The angles formed by the wing chords with respect to this reference line are indicated in Fig. 17. The wing area F, required for calculating the forces per unit area, was 1056 cm^2 (1.1367 sq.ft.).

From the great number of tests made with this monoplane model, only the results obtained at pressures of 5 and 10 mm water column, with air flowing from all three slots, are given here (Table VI and Fig. 18). In both cases, the mean jet velocity u was 7.15 m/s (23.5 ft./sec.), making u/v 0.8 in one case, and 0.565 in the other.

The experimental results indicate that, when air is flowing from the slots, the lift values increase about 80% over the whole range of the angles of attack. The corresponding drag values decrease but little, however. The maximum lift values are obtained at greater angles of attack than with ordinary wings. Naturally the maximum values of the coefficient of glide (L/D ratio) and of $c_A{}^3/c_W{}^2$ are very large. If, for example, $u/v = 0.8$, we then have $(c_A/c_W)_g = 29.8$ and $(c_A{}^3/c_W{}^2)_g$, as compared with 11.15 and 123, respectively, in the case of a wing without air jets.

Also in the case of a monoplane model, the pressure distribution was measured on the upper side of the wing in a cross section 200 mm (7.87 in.) from the plane of symmetry of the model. Table VII and Figure 19 give the negative pressures for $p = 5$ and 10 mm (0.2 and 0.4 in.) H_2O at $\alpha = 0$ and 12°. It is apparent that the lift increase is ascribable to the very considerable lessening of the pressure reduction toward the trailing edge.

The velocity distribution of the outflow and its direction throughout the span is much the same as for normal wings, i.e., a rapid reduction in the velocity of the outflow near the fuselage and a great divergence in its direction.

Taken collectively, the experiments show that, as regards increasing the lift values, the effect of the air flowing from the nozzle-shaped slots is similar to the effect produced in the case of ordinary slotted wings. The high lift values are attained, however, at the smaller angles of attack employed in ordinary flight. The drag values are only a little greater than for wings of simpler construction. In this regard it does not matter whether air is flowing from the slots or not. Unlike ordinary slotted wings, nozzle-slotted wings require no movable parts for regulating the effect of the slots, it being necessary only to vary the outflow velocity of the air. The number and location of the slots in the wing profile greatly affect their aerodynamic action. The outflowing air imparts energy to the boundary layer and consequently delays its separation and the formation of vortices. Simultaneously, the distribution of the negative pressure on the upper surface of the wing is improved toward the trailing edge.

Note.- While the magazine from which this article was taken was in press, the writer learned that experiments were being instituted in Germany and in Switzerland with the object of increasing the maximum lift by removing the boundary layer from the upper surface of the wing. In Germany, Mr. Seewald of Berlin, published the results of such experiments in Z.F.M., 1927, p. 350.* The results of the investigations by Mr. Wieland of Basel, are given in the same magazine, p.346.**

In both cases, compressed air was released on the upper side of airfoils parallel to the leading edge. The results were similar to those given above, in that both investigators observed a considerable increase in the c_{A_g} values. The German experiments were performed at very high pressures inside the airfoil (up to 4 atmospheres gauge pressure), which probably could never be used in practice. Values of $2\ c_{A_g}$ up to 335 were obtained at $\alpha = 30°$. Wieland also used very high pressures. It should be noted, however, that both experimenters measured the pressures a long way from the outflow openings on the upper surface of the airfoils. The results were there-

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*For translation, see N.A.C.A. Technical Memorandum No. 441: "Increasing Lift by Releasing Compressed Air on Suction Side of Airfoil."

**For translation, see N.A.C.A. Technical Memorandum No. 472: "Experiments with a Wing from Which the Boundary Layer is Removed by Pressure or Suction."

fore affected by the considerable pressure losses in the delivery pipes, which had to be made quite small. Seewald also mentions this fact in his treatise.

Wieland found, in agreement with our investigations, that the magnitude of the drag was hardly affected by the location and operation of the slots. The increase in the lift values even at small and medium angles of attack, as uniformly observed in the numerous Vienna experiments, differed from the experimental results of Wieland and the theoretical conclusions of Seewald.

TABLE I.

R	87,800	123,800	152,000	175,600	196,000	214,300
p	5	10	15	20	25	30
v	8.95	12.7	15.5	17.9	20.0	21.9
2 c_W	94.6	73.0	60.0	57.0	51.0	47.5

TABLE II.

p	v	u	u/v	a		b	
				$2c_A$	$2c_W$	$2c_A$	$2c_W$
5	8.95	19.6	2.19	416	73.1	343	68
10	12.7	19.6	1.54	261	63.6	215	61
15	15.5	19.6	1.26	160	59.1	138	55.3
20	17.9	19.6	1.09	116	54.0	104	51
25	20.0	19.6	0.98	94	57.0	79	52.9
No. of slot			open closed	12 0		9 3	

TABLE II (Cont.)

p	v	u	u/v	c		d		e	
				$2c_A$	$2c_W$	$2c_A$	$2c_W$	$2c_A$	$2c_W$
5	8.95	19.6	2.19	274	60.5	261	60	131.5	53.1
10	12.7	19.6	1.54	158	52.5	154	53	84	45
15	15.5	19.6	1.26	104.9	46.4	105.8	46.5	67	40.1
20	17.9	19.6	1.09	78.4	44.5	80.6	42.7	57.1	38.7
25	20.0	19.6	0.98	57.5	46.1	62	45.2	48.6	40.8
No. of slot open				7		5		5	
No. of slot closed				5		7		7	

TABLE III.

Wing model I.
Normal wing, 900 x 150 mm (35.4 x 5.9 in.), rectangular plan.
$F = 1350\ cm^2$ (1.453 sq.ft.)
Dynamic pressure p = 5 mm (0.2 in.) H_2O
Wind velocity v = 8.98 m/s (29.46 ft./sec.)
2 slots on upper side of wing, 1 on lower side.

	All slots open		All slots closed		Only front upper slot open	
Jet velocity u	0 m/s		6.45 m/s		7.2 m/s	
u/v	0		0.72		0.803	
α^o	$2c_A$	$2c_W$	$2c_A$	$2c_W$	$2c_A$	$2c_W$
-6	7.46	7.61	35.8	18.05	43.4	21.1
-3	17.18	4.48	51.5	5.81	70.9	6.87
0	32.8	4.48	71.6	4.37	95.5	6.12
3	50.0	5.57	97.8	4.40	123.0	6.56
6	64.2	7.16	122.1	5.98	146.0	8.36
9	79.1	10.0	149.0	9.35	173.0	14.2
12	71.6	14.45	172.0	15.2	199.0	22.6
15	85.2	20.9	197.0	24.5	224.5	33.1
18	–	–	218.0	37.1	248.0	46.6
21	–	–	243.5	56.8	270.0	65.0
24	–	–	257.0	–	292.0	–

TABLE IV.

Wing model I.
Normal wing, 900 x 150 mm (35.4 x 5.9 in.) rectangular plan.
$F = 1350\ cm^2$ (1.453 sq.ft.).
Dynamic pressure $p = 20$ mm (0.8 in.) H_2O.
Wind velocity $v = 17.9$ m/s (58.7 ft./sec.)
2 slots on upper side of wing, 1 on lower side.

	All slots open		All slots closed		Only front upper slot open	
Jet velocity u	0 m/s		7.05 m/s		7.2 m/s	
u/v	0		0.394		0.402	
α^o	$2c_A$	$2c_W$	$2c_A$	$2c_W$	$2c_A$	$2c_W$
-6	1.49	7.46	30.2	13.85	21.6	9.6
-3	10.81	3.92	45.6	6.09	36.7	6.82
0	24.6	4.18	58.6	5.195	68.0	5.32
3	38.4	5.23	79.5	5.62	91.4	6.84
6	53.0	7.77	97.0	6.81	111.0	8.95
9	64.2	10.43	116.8	8.75	130.0	11.58
12	73.75	13.06	131.2	10.75	145.0	14.25
15	82.8	15.7	145.0	14.08	162.5	19.2
18	92.0	19.0	155.0	18.5	179.0	24.0
21	99.5	22.2	161.2	22.7	188.0	29.75
24	107.0	16.95	165.0	27.8	197.0	35.4

TABLE V.

Wing model III.
Angle of attack $\alpha = 0^\circ$.
$\bar{p}_1$ = static pressure in mm H_2O.
+ = positive pressure.
– = negative pressure.

Dynamic pressure p =	5		20	
Measuring point No.	Without	With	Without	With
	Air jet		Air jet	
1	+2	+ 1.6	+ 8	+ 8
2	-4	- 2.5	-16.4	-15
3	-6	- 5.4	-22.4	-23
4	-6	- 6.4	-24	-27
5	-6.5	- 7.2	-24.6	-28
6	-7	- 7.6	-25.4	-28.6
7	-6.5	- 8.4	-25.5	-28.6
8	-6	-10.2	-23.7	-28.6
9	-4.6	-12.7	-19	-23.3
10	-3.4	-13.1	-11.6	-20.5
11	-0.6	-10.6	- 4	-11.8
12	-0.2	- 7.6	- 1	- 8.9

TABLE VI.

Monoplane model.
F = 1056 cm² (1.1367 sq.ft.)
3 slots on upper side of wing

Dynamic pressure p Wind velocity v Jet velocity u u/v	5 mm H_2O 8.98 m/s 7.15 m/s 0.8		10 mm H_2O 12.63 m/s 7.15 m/s 0.565	
	All slots closed		All slots open	
α°	$2c_A$	$2c_W$	$2c_A$	$2c_W$
-6	8.6	3.4	34.8	5.4
-3	31	3.8	60.5	3.4
0	55.6	5.0	89.2	3.3
3	80	7.2	118.6	4.4
6	103	9.4	150.0	7.0
9	115	11.6	175.2	10.0
12	116	15.2	198.4	15.8
15	108	25.4	213.0	23.6
18	90	36.0	190.4	39.0
21	82	40.8	149.6	40.6

TABLE VI (Cont.

Momoplane model.
F = 1056 cm² (1.1367 sq.ft.)
3 slots on upper side of wing

Dynamic pressure p Wind velocity v Jet velocity u u/v	5 mm H_2O 8.98 m/s 7.15 m/s 0.8		10 mm H_2O 12.63 m/s 7.15 m/s 0.565	
	All slots closed		All slots open	
α°	$2c_A$	$2c_W$	$2c_A$	$2c_W$
-6	7.5	3.7	26	4.5
-3	30.8	3.8	53	3.4
0	55.0	4.8	80.8	2.9
3	78.5	6.3	116.8	4.6
6	98.5	8.8	142.3	7.4
9	108.5	11.5	162.6	10.9
12	111	15.2	179.2	16.0
15	110	24.0	178.5	23.5
18	95.5	34.5	165.7	35.8
21	86.5	41.0	127.3	40.4

TABLE VII.

Monoplane model.
$\bar{p}_1$ = static pressure in mm H_2O.
\+ = positive pressure.
– = negative pressure.

Angle of attack α	0°				+12°			
Dynamic pressure p	5		10		5		10	
Measuring point No.	Without	With	Without	With	Without	With	Without	With
	Air jet		Air jet		Air jet		Air jet	
1	-0.5	- 5	+ 3	- 2.5	-10	- 9.5	-14	-21
2	-8	-10	-13	-16	- 9.5	-14	-14	-25
3	-8	-10.5	-13.5	-17.5	- 9	-13.5	-16	-24
4	-7.5	-10.5	-12.5	-18	- 5.5	-13.5	- 9	-23.5
5	-5.5	-11.5	-10	-18.5	- 2.5	-14.5	- 4.5	-22
6	-3	-13	- 4	-20	- 2	-15.5	- 4	-21
7	-1	-15.5	- 1.5	-22	- 1.5	-17.5	- 3.5	-21.5

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

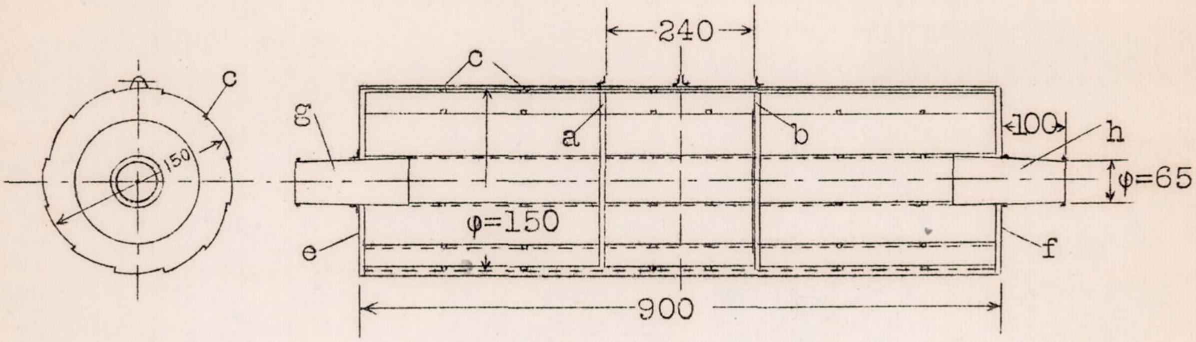

c
150
g
240
c
a
b
100
h
φ=65
φ=150
e
f
900

Fig.1

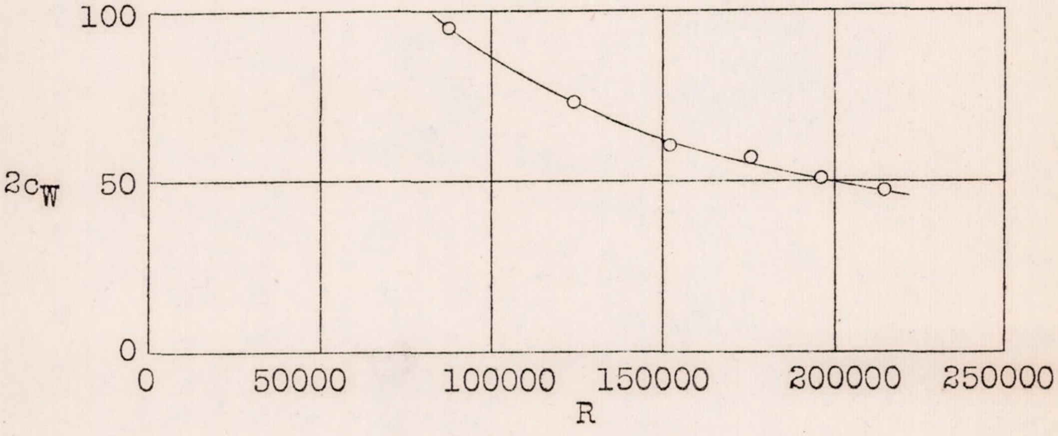

100
50
0
2c_W
0
50000
100000
150000
200000
250000
R

Fig.4

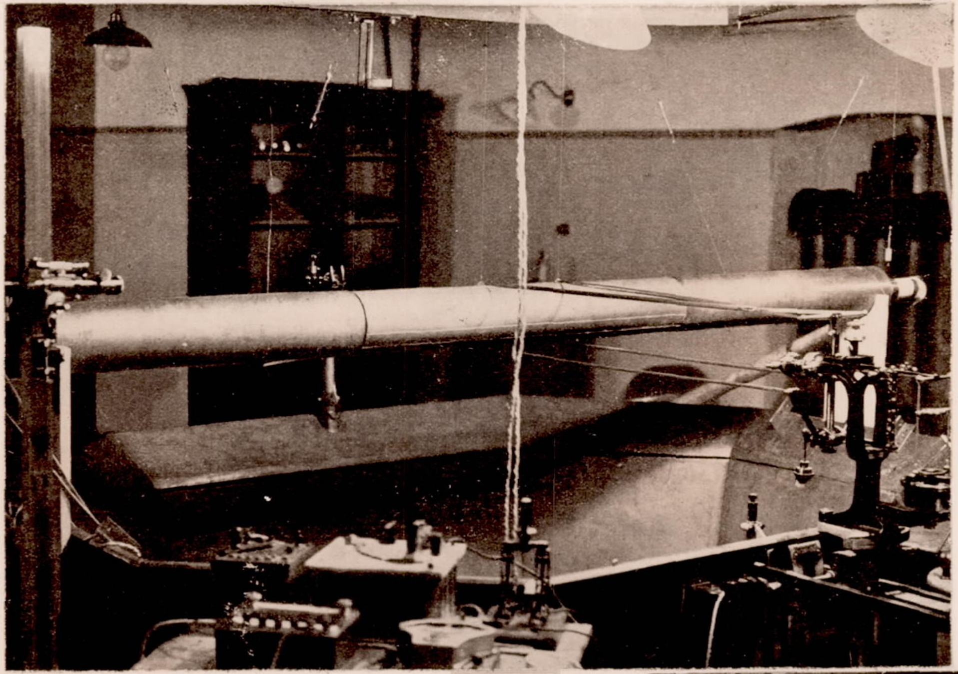


Fig.2

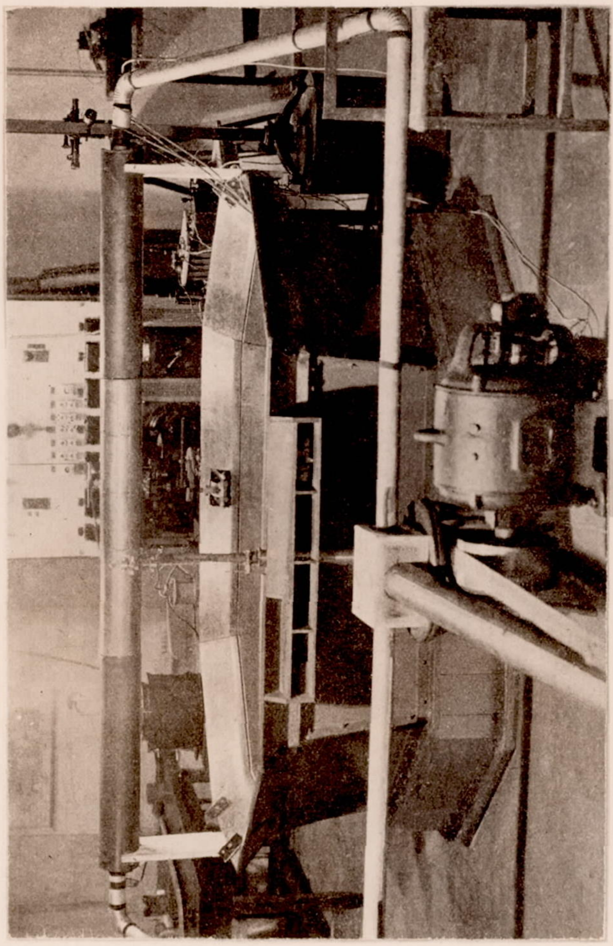


Fig.3

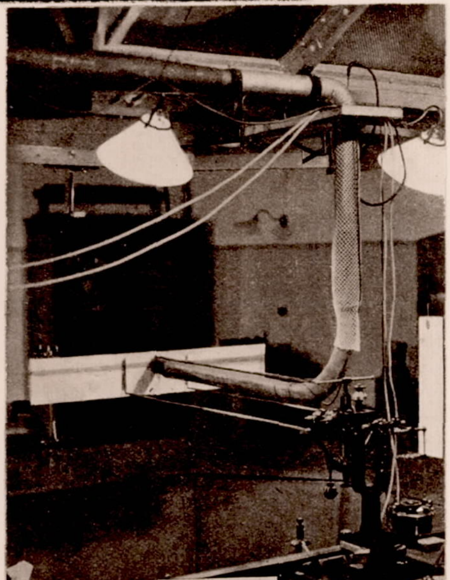


Fig.7

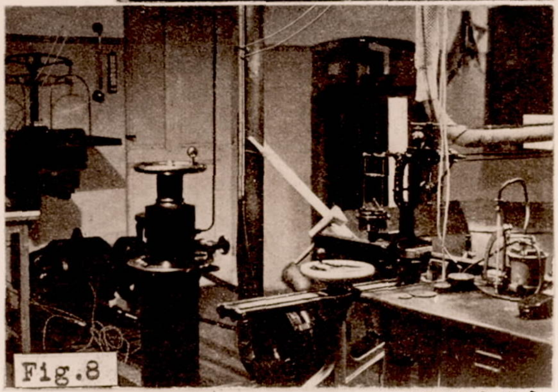
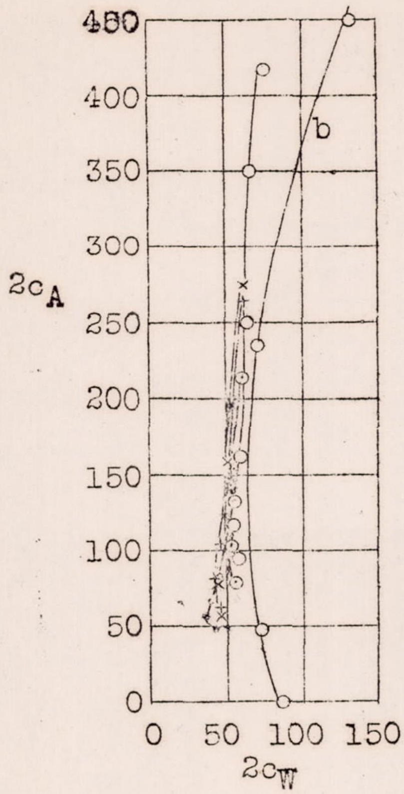


Fig.8

13052 R.S.



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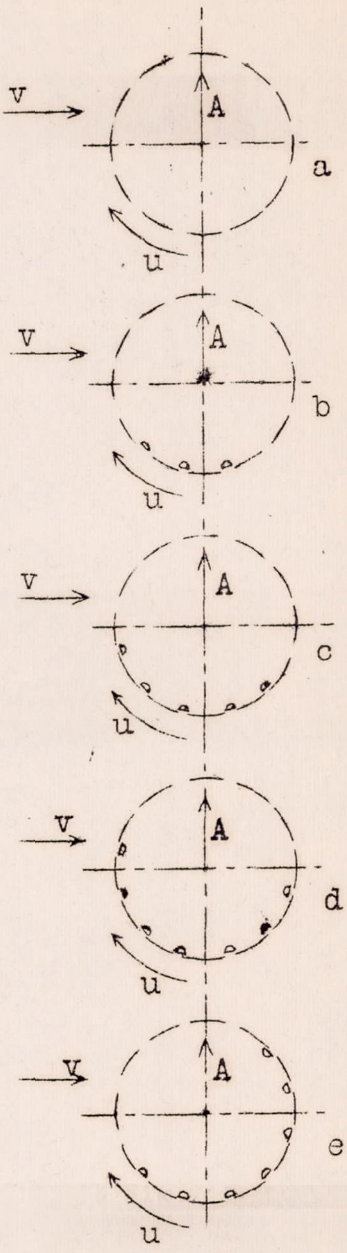
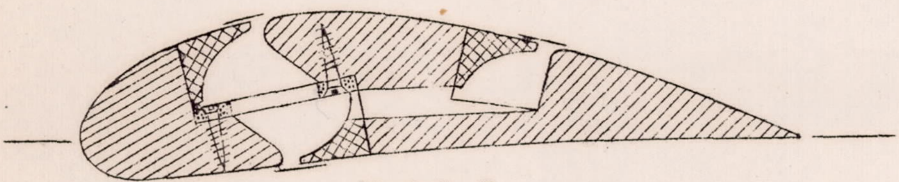


Fig.6



Model I

Fig,9

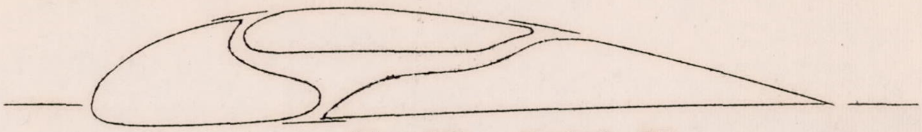


Fig.10 Model II

Fig.11 Model III

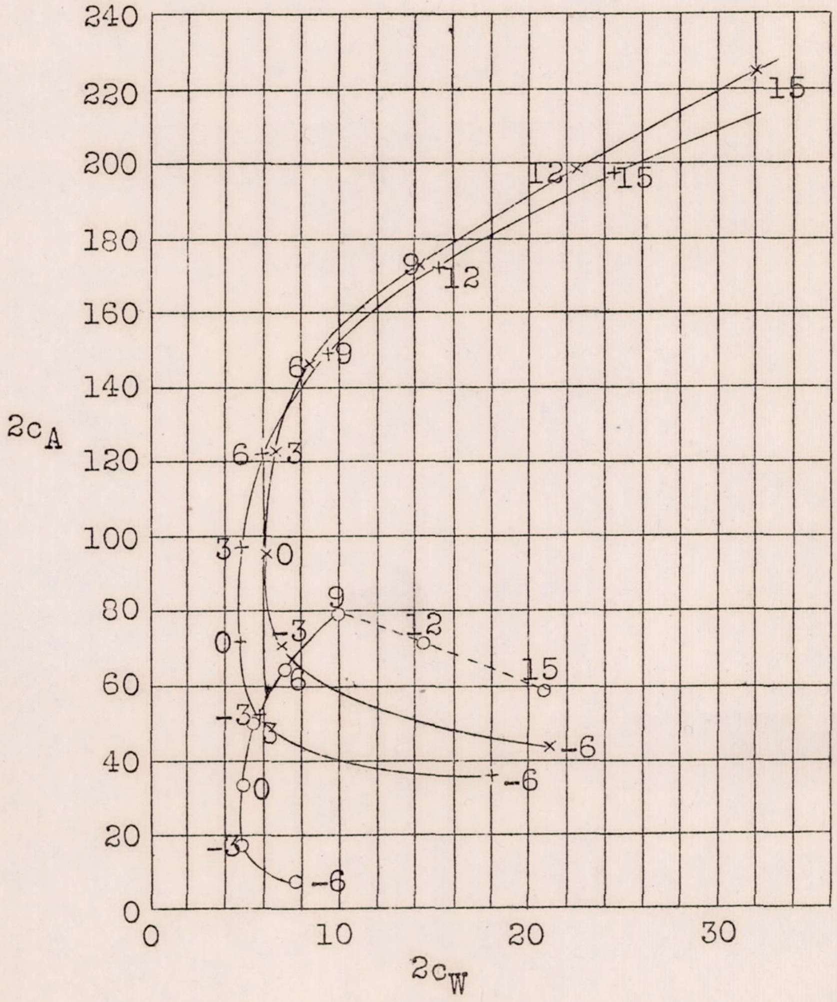


Fig.12

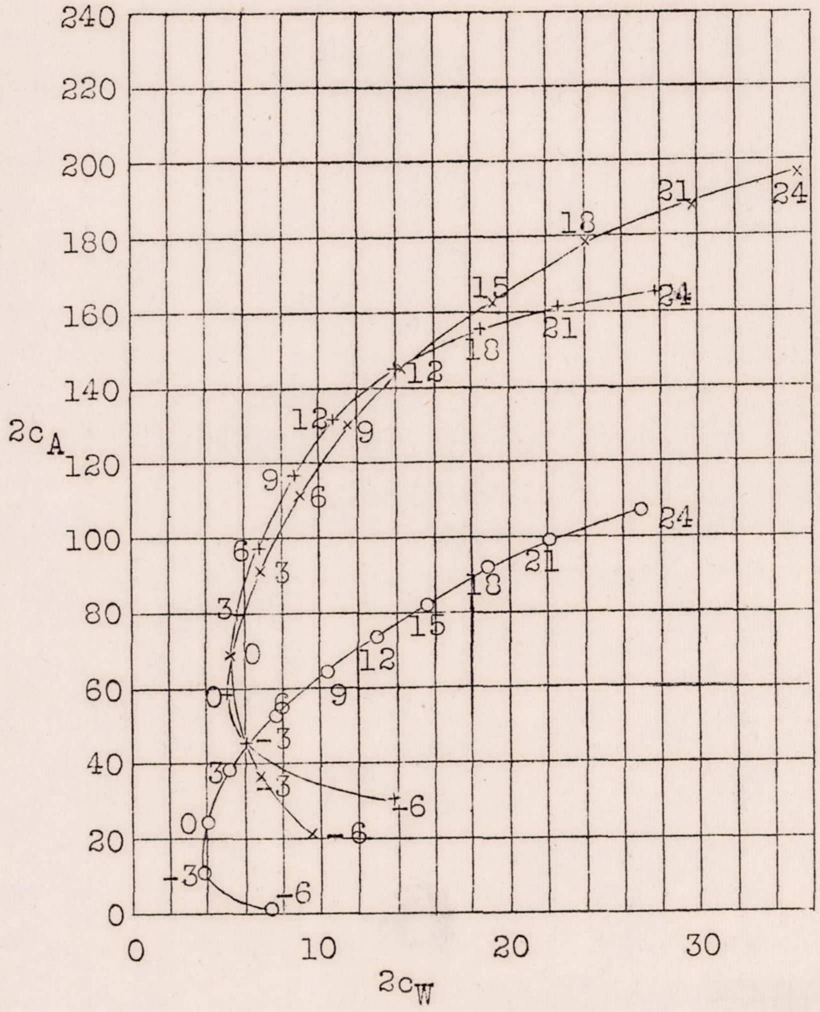
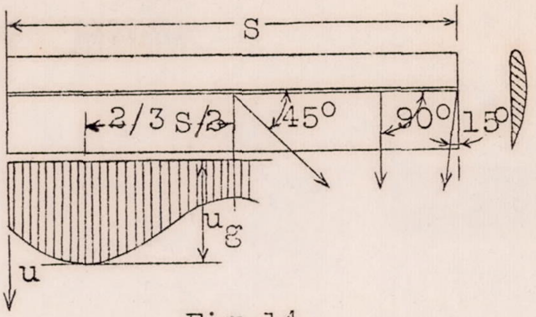
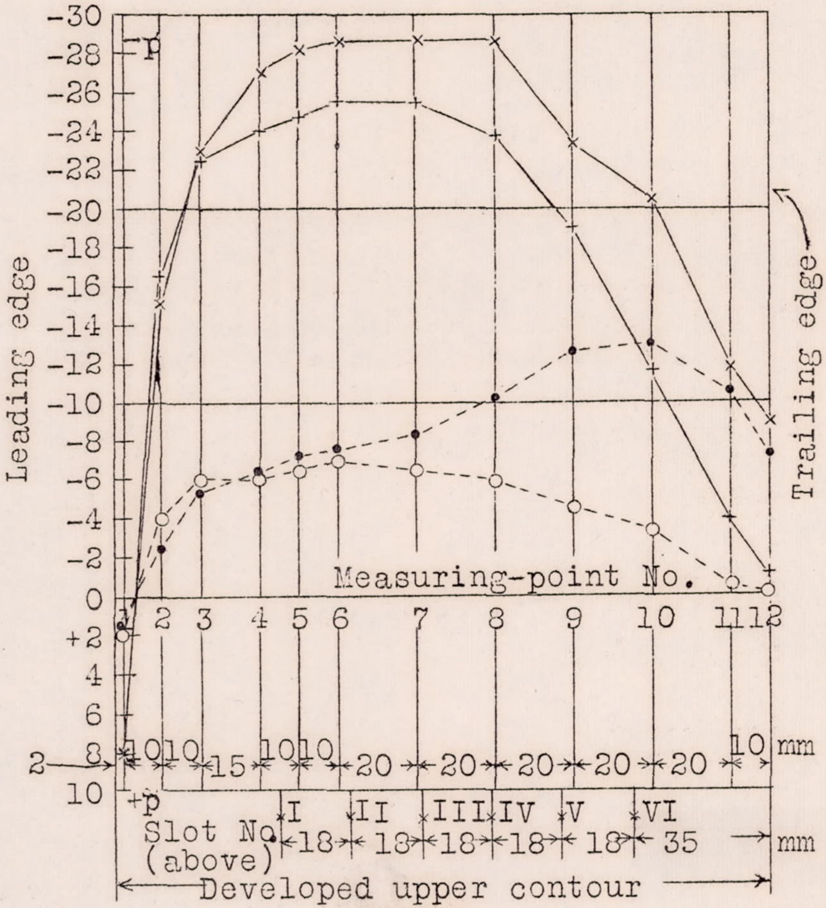

240
220
200
180
160
140
120
100
80
60
40
20
0
2cA
0
10
20
30
2cW
-6
-3
0
3
6
9
12
15
18
21
24

Fig.13



S
2/3 S/2
45°
90°
15°
u
u_g

Fig.14



-p
+p
Leading edge
Trailing edge
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
4
6
8
10
Measuring-point No.
1 2 3 4 5 6 7 8 9 10 11 12
2 10 10 15 10 10 20 20 20 20 20 10 mm
Slot No. (above)
I II III IV V VI
18 18 18 18 18 35 mm
Developed upper contour of wing.

Fig.15

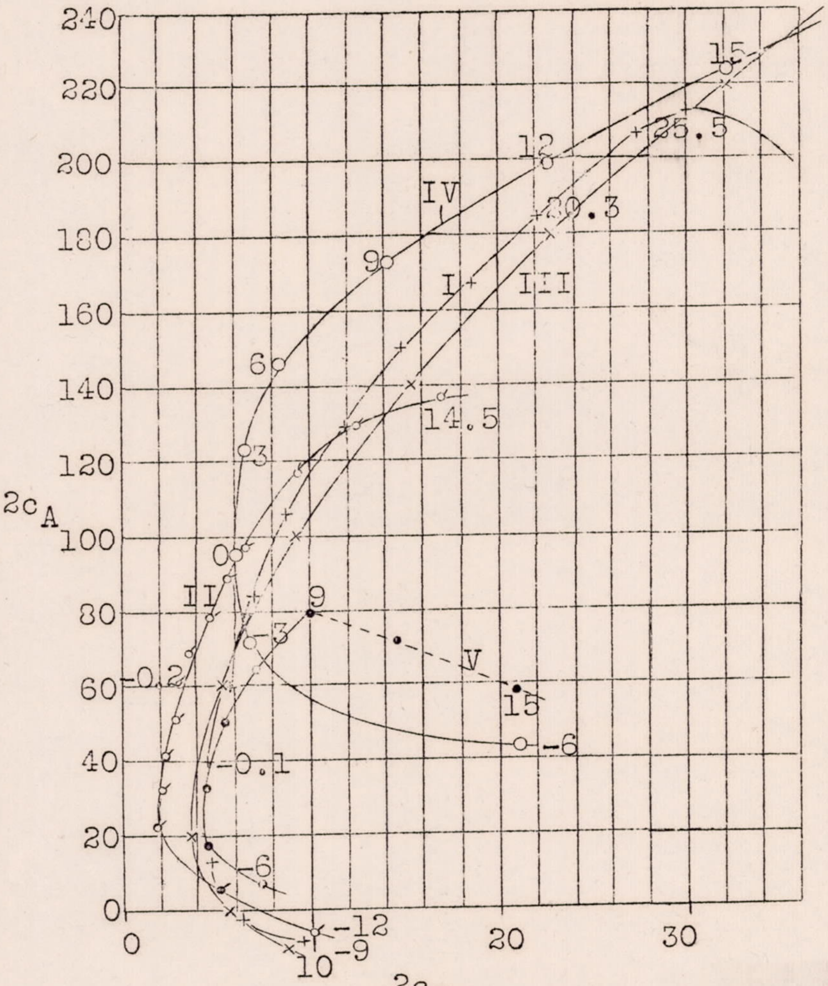

240
220
200
180
160
140
120
100
80
60
40
20
0
$2c_A$
0
10
20
30
$2c_W$
IV
I
III
II
V
15
12
9
6
3
0
-3
-6
25.5
20.3
14.5
-0.2
-0.1
-6
-12
-9
10
9
15

Fig.16

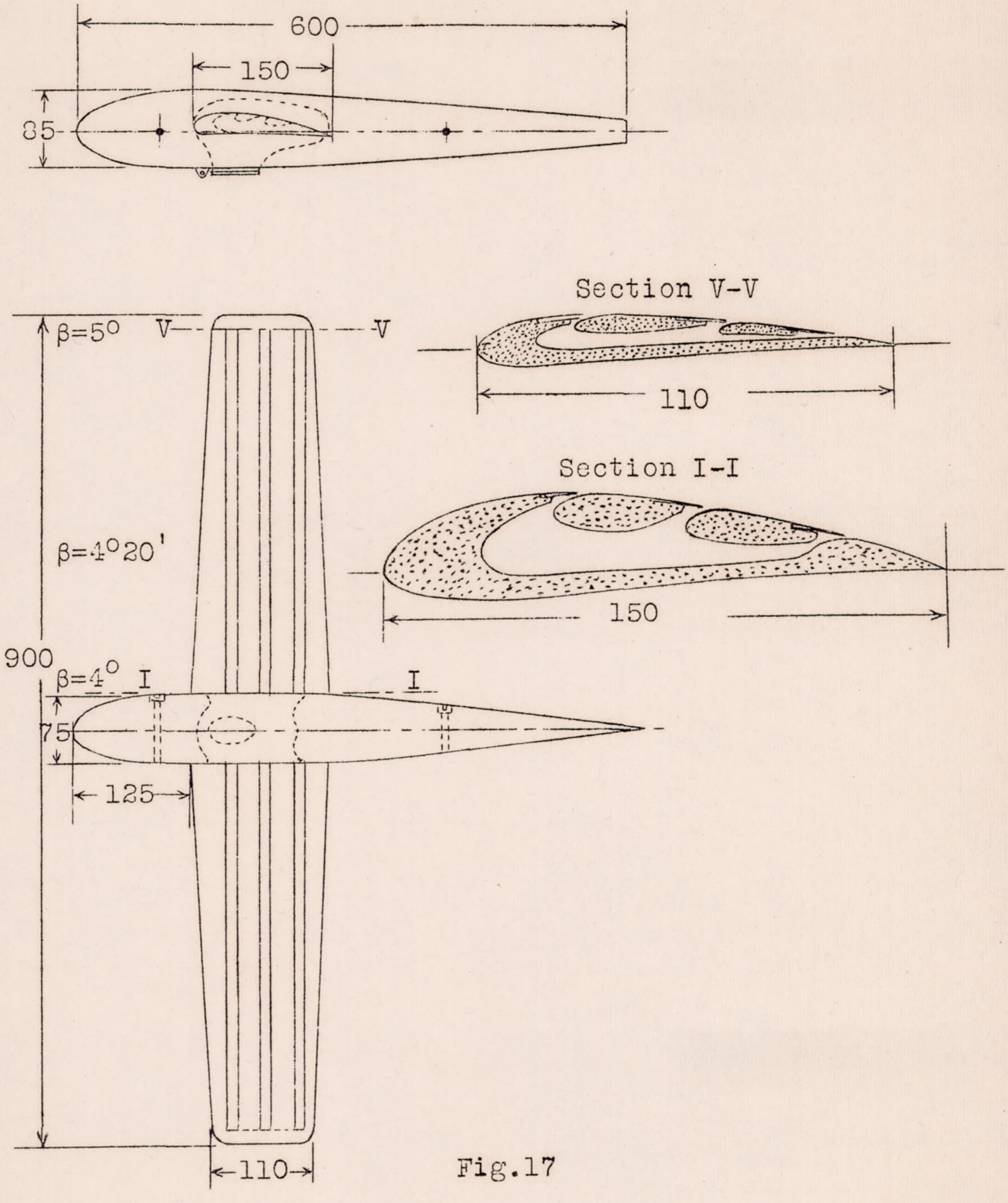

600
150
85
Section V-V
110
Section I-I
150
β=5°
V
V
β=4°20'
900
β=4°
I
I
75
125
110

Fig.17

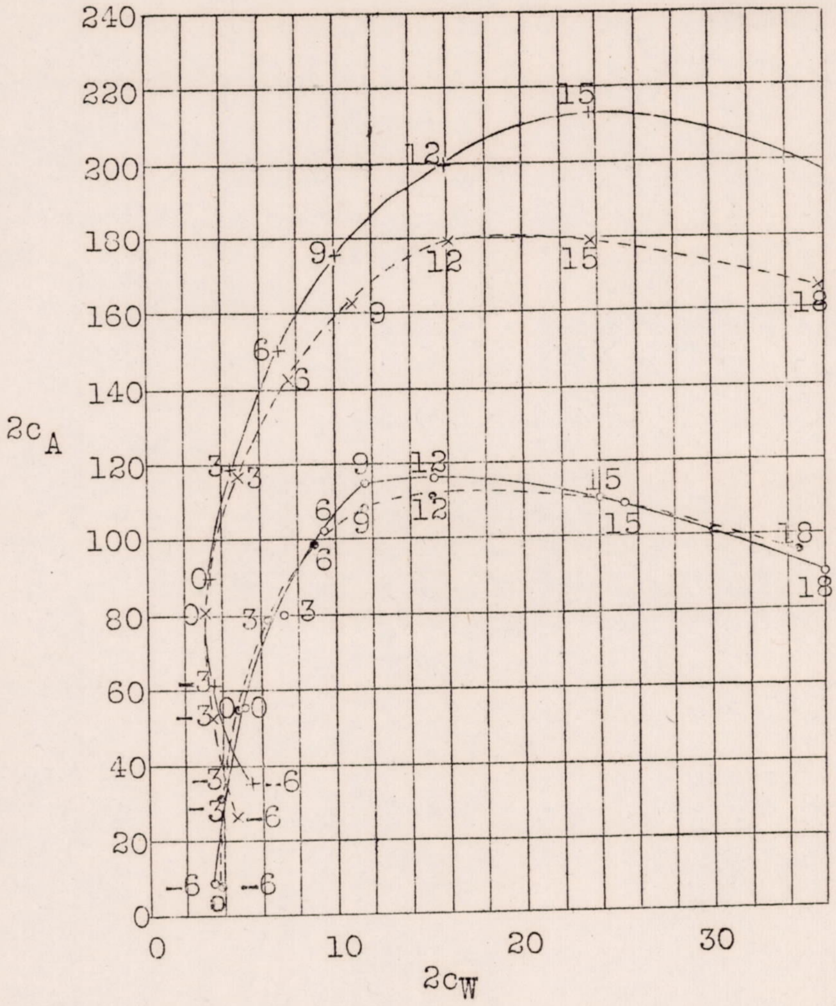

240
220
200
180
160
140
120
100
80
60
40
20
0
2c_A
0
10
20
30
2c_W
15
12
9
6
3
0
-3
-6
18

Fig.18

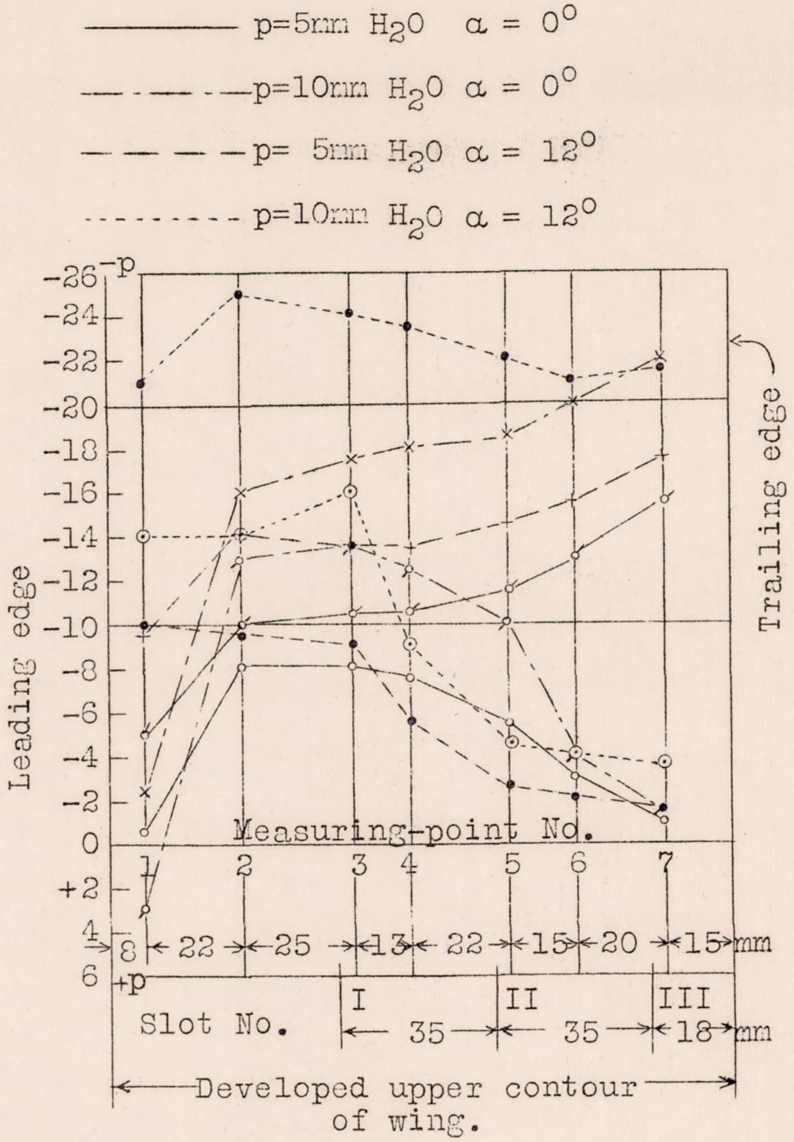

p=5mm H2O α = 0°
p=10mm H2O α = 0°
p= 5mm H2O α = 12°
p=10mm H2O α = 12°
-p
-26
-24
-22
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
4
6
+p
Leading edge
Trailing edge
Measuring-point No.
1
2
3
4
5
6
7
8
22
25
13
22
15
20
15 mm
Slot No.
I
II
III
35
35
18 mm
Developed upper contour of wing.

Fig.19