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No. 424

DISCUSSION OF THE RESULTS OF THE BOUNDARY-LAYER TESTS OF AN AIRFOIL FITTED WITH A ROTARY CYLINDER

By E. B. Wolff and C. Koning

Report A 130
of the Rijks-Studiedienst voor de Luchtvaart," Amsterdam
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DISCUSSION OF THE RESULTS OF THE BOUNDARY-LAYER TESTS OF AN AIRFOIL FITTED WITH A ROTARY CYLINDER.*

By E. B. Wolff and C. Koning.

The results of the velocity measurements in the boundary layer described in Report A 129** are here discussed in greater detail, and a program is developed for further research.

The measurements made by Van der Hegge Zijnen of the velocity distribution in the vicinity of an airfoil model fitted with a rotary cylinder were undertaken for the purpose of obtaining a closer insight into the phenomena observed in experimenting with this model. In Report A 129 the results of these experiments were briefly discussed from this standpoint. It is desirable, however, to consider some aspects in greater detail, especially because some of the results have a wider application aside from the special problem here investigated, in that they also explain the phenomena which occur in the flow around an ordinary airfoil in immediate proximity to the surface and therefore in the boundary layer.

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*"Beschouwingen naar aanleiding van de grenslaagmetingen aan het model met draaiende rol." From Report A 130 of the "Rijks-Studiedienst voor de Luchtvaart," Amsterdam. (Reprint from "De Ingenieur," Dec. 25, 1926.)

**For the translation of Report A 129, see N.A.C.A. Technical Memorandum No. 411: Determining the Velocity Distribution in the Boundary Layer of an Airfoil Fitted with a Rotary Cylinder.

With the establishment, by means of the boundary-layer measurements, of the previously assumed explanation of the effect of the rotary cylinder in the wing, the preliminary investigation of this problem may, in a certain sense, be considered closed. The time has now come to develop a program for the eventual continuation of the tests. For a more systematic investigation, a division of the problem seems desirable.

Flow Around an Ordinary Airfoil

Of the groups of measurements with the cylinder at rest (B and C), only the latter group will here be considered, because in group B the slot or gap between the cylinder and the after portion was not closed and produced so great a disturbance in the flow, that the model in this condition could hardly be regarded as an "ordinary airfoil." In group C, on the contrary, the gap was carefully closed, thus producing a smooth surface.

The results of the tests (Figs. 3 and 4) confirm the customary assumption in the boundary-layer theory that the flow around an obstacle can be divided into two overlapping regions.* The first region, where the viscosity or internal friction prevails, embraces only a thin boundary layer. Here the relative velocity falls off rapidly and becomes zero at the wall. The

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*For the literature on this point, see footnote 4 in "Rapport A 105" on p. 181 of "De Ingenieur" for March 6, 1926 (or N.A.C.A. Technical Memorandum No. 354, p. 11).

second region embraces the rest of the field of flow, in which there is generally a small loss in velocity. At the foremost measuring points (I - V) the separation of the two regions is very sharp, the thickness of the boundary layer being here about 1-1.5 mm (0.04 to 0.06 in.). Farther aft, the separation becomes less distinct, while the region in which the velocities are small (i.e., the boundary layer) becomes thicker. At the point VI its thickness is about 5 mm (0.2 in.); at VII, about 12.5 mm (0.5 in.). Probably a separation of the flow occurs on the aftermost portion of the surface, even at the small angle of attack at which the measurements are made, whereby a turbulent region with a small mean velocity is developed, which increases in thickness toward the rear. The possibility of this phenomenon has already been demonstrated by Betz in his explanation of the difference between the actual and the theoretical circulation around an airfoil.*

The same phenomenon occurs at a large angle of attack, but the separation point is then so far forward that the turbulent region is very great and the whole character of the flow is changed.

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*Betz, "Untersuchung einer Schukowskyschen Tragfläche." From "Zeitschrift für Flugtechnik und Motorluftschiffahrt," 1915, p. 173.

Effect of the Rotary Cylinder

Although in the tests with the rotating cylinder (A), the gap between the cylinder and the after piece was open, the general character of the flow still conformed closely to that in the case of the model with the cylinder at rest and the gap closed (C) (Figs. 1 and 4). This confirms the conjecture that the cylinder, as regards the general character of the flow, can offset the effect of the gap or at least greatly reduce it. The gap does not prevent local disturbances, however, which here have no effect at the small angle of attack, but may have detrimental consequences at larger angles of attack.

On comparing the velocity distribution in cases A and C (Fig. 4), it appears that the cylinder considerably increases the velocity in the boundary layer. At the foremost measuring points (III - V) the velocity increase is only local and is confined mostly to the portion of the flow lying within 2.5 mm (0.1 in.) of the surface. These differences increase toward the rear. Behind point V there is developed a slight difference in the opposite direction in the region between ij = 2.5 mm (.1 in.) and ij = 10 mm (0.4 in.), which has not yet been explained.

The measuring points VI and VII give the impression that the original character of the boundary-layer flow is maintained farther back; that the separation of the flow here occurs later;

and that the turbulent region is smaller. The thickness of the disturbed region is about 3 mm (0.12 in.) at the point VI, but can be estimated at about 10 mm (0.4 in.) at point VII, where the line of separation is very indefinite.

This is completely confirmed by the explanation of the action of the cylinder in Report A 105. The momentum of the air in the boundary layer is increased by the cylinder. This increase is noticeable along the entire surface and opposes the separation of the flow at the rear. In cases where the separation occurs so far forward that a considerable turbulent region is developed and the whole flow is thus disturbed (at large angles of attack), the cylinder reduces the disturbance and thus increases the lift while diminishing the drag.

At the points II and III, the curves exhibit a yet unexplained phenomenon. Since these points lie on the cylinder, it is to be expected that, for $y = 0$, the velocity of the air will be the same as that of the cylinder, 18.6 m (61 ft.) per second, just as in the remaining points the velocity for $y = 0$ seems to be near zero. This is not the case, however, above $y = 1$ mm (0.04 in.) when the velocity diminishes, which at this point is 9.9 m (32.5 ft.) or, 10.4 m (34.1 ft.) per sec., although less rapidly than in case C (cylinder at rest). At the point VIII (Fig. 6), on the contrary, which is located on the lower side of the cylinder, the velocity increases with rotating cylinder on approaching surface.

The results obtained at the points VIII and IX on the lower surface make it very probable that a contrary flow is developed here in the vicinity of the model, in that the air is taken along with the cylinder in a direction opposite to the general direction (Fig. 6). In determining the velocity distribution at point VIII, the hot-wire anemometer gives the velocity, but not the direction of the flow. The portion of the curve between $y = 0$ and $y = 2.5$ mm (0.1 in.) must therefore be here given the negative sign, to indicate the direction of the flow. There is therefore a turbulent region between the two regions of opposite flow. Since the anemometer in this region gives the absolute magnitude of the velocity, without taking account of the direction, no turning point can here be quickly indicated. At point IX, which is located on the fixed part behind the cylinder, no contrary flow is noticeable, but there is a strongly retarded layer of about 10 mm (0.4 in.) in thickness.

Effect of Gap with Cylinder at Rest

The results of group B (Figs. 2 and 5), on comparison with group C, clearly show the considerable effect of the gap when the cylinder is at rest. Only at the point III in front of the gap is there any retardation noticeable. On the contrary, at both the following points, IV and V, the velocity for $ij < 3$ mm (0.12 in.) is considerably diminished, and at point

IV it is combined with some increase in the velocity in the outer region. It thus seems as if the flow were here forced away from the surface, probably by a slight turbulence developed by the sharp edge. The points VI and VII show what effect this disturbance has on the flow over the remaining portion of the surface. At both points the disturbed region is considerably greater than for the model without gap (C). For the case B the thickness at the points VI and VII can be estimated at 10 and 20 mm (0.4 and 0.8 in.), respectively, while for case C, on the other hand, it is 5 and 12.5 mm (0.2 and 0.5 in.), respectively.

These results confirm the conclusion reached in previous experiments,* that a small and seemingly unimportant irregularity on the surface of an airfoil, which causes a local disturbance of the flow, may have a great indirect effect and considerably affect the whole course of the flow.

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*See Report A 51, "Experiments with a Device for Shortening the Glide and Landing Run of an Airplane" (N.A.C.A. Technical Memorandum No. 272). Report A 29, "Investigation of the Effect on the Aerodynamic Properties of Cutting Away Part of the Leading Edge of a Fokker F III Wing" (N.A.C.A. Technical Memorandum No. 103). From "Verslagen en Verhandelingen van den Rijks-Studiedienst voor de Luchtvaart," Amsterdam. Part II, 1923.

Program for Further Research

The theoretical side of this problem has been considerably advanced by the explanation of the effect of the rotating cylinder in the airfoil, which was determined through boundary-layer measurements. The making of further boundary-layer measurements on the existing or on a similar model, e.g., at other angles of attack or other ratios between the peripheral velocity of the cylinder and the velocity of the wind, is at present of very little value, since the results would probably be very similar. These would repay the trouble of the very tedious experiments, only if a correspondingly quantitative treatment were possible. The investigation method hitherto followed, in which the combination of airfoil and cylinder is treated as a unit, makes the problem too complex, however, for such a treatment. It is therefore desirable to divide the investigation in such a way that each part offers the possibility of quantitative results and of drawing conclusions which can be applied to the combination of airfoil and cylinder. Lastly, an experimental confirmation of the correctness of this application is necessary. Such a division also has the advantage that different parts of the investigation can give results, which may be of interest for more general problems.

The following is a possible program embodying these ideas:

a) Boundary layer of an ordinary airfoil, i.e., without cylinder;

b) Separate cylinder;

c) Boundary layer of a fixed body behind the cylinder:

1. Transition of the accelerated boundary layer to the fixed body;
2. Behavior of the accelerated boundary layer farther along this body.

d) Model with rotary cylinder, designed on the basis of the results of a - c.

Since the purpose is to influence the flow in the boundary layer of the airfoil with the aid of the rotary cylinder, the first question regards what happens with an ordinary airfoil (point a). An impression of this is obtained from the measurements already made, but the available data are far from sufficient for obtaining a complete picture of the phenomena produced. Moreover, the airfoil here used is not suitable for comparing an actual flow with the one obtained by theoretical calculations, since these calculations are very complicated for an arbitrary airfoil section. The investigation should therefore be carried out with an airfoil suitable for these calculations, whereby the flow at different angles of attack must be investigated and special attention given to the circumstances under which the separation of the flow occurs at large angles of attack.

Another point of great importance is the question as to how the cylinder affects the surrounding flow, and what factors are here important, such as the degree of roughness, the ratio of the peripheral velocity to the wind velocity and the value of Reynolds Number (point b). Hereby an explanation must also be sought for the phenomena mentioned in point c, as now observed in the neighborhood of the rotating cylinder.

After the cylinder has accelerated the air in its vicinity, this air must be brought over the fixed part behind the cylinder with as little loss in velocity as possible (point c1). In this transition, the gap between the two parts is very important, especially as regards its width, since a portion of the boundary layer passes through it unused. Attention must also be given the shape of and any irregularities on the edge of the rear portion. The part placed behind the cylinder may be given as simple a shape as possible, e.g., it may be a flat plate.

For determining the effect of the accelerated boundary layer on the fixed rear part, it is desirable to know how such a layer generally behaves, when flowing along a stationary wall (point c2). Hence a flat surface can be chosen for the experiments, in order to make them as simple as possible.

The last point of the program necessitates the combining of the results and their adaptation to the combined airfoil and cylinder.

Such a division of the investigation requires a comprehensive program, if the experiments are not to be made at random. It remains an open question, however, as to how far the given program can be carried out with the limited available time and means.

The first point (a) is to be handled through the kindly cooperation of Professor Burgers, since, on the one hand, a suitable model is available and, on the other hand, this part of the investigation promises important results of more general interest. The model, which had already been designed by the R.S.L. ("Rijks-Studiedienst voor de Luchtvaart"), was made for the purpose of more thoroughly investigating the flow around an airfoil by determining the pressure and velocity distribution in the boundary layer. The cross section or profile of this airfoil was so chosen as to enable the calculation of the theoretical flow and its comparison with the actual flow. This investigation is deemed very important, because the boundary-layer phenomena apparently have a momentous effect on the principal properties of an airfoil, such as the profile or wing-section drag, the influence of Reynolds Number and all the phenomena connected with the critical angle of attack. For lack of time, this investigation can not now be carried out by the R.S.L. Since, however, it has again become prominent as the basis of the above-mentioned program, it will now be made by Van der Hegge Zijnen in the laboratory of Professor Burgers at Delft in cooperation with the R.S.L.

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

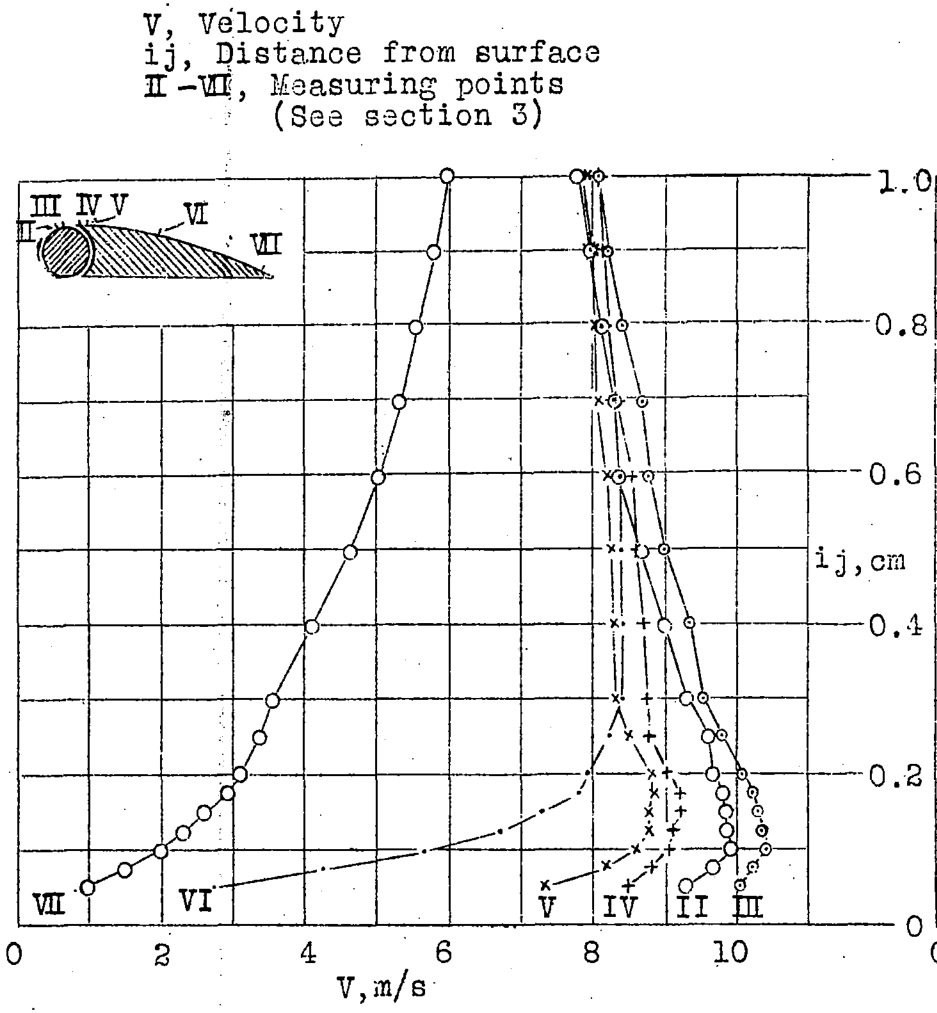


Fig.1 Velocity distribution with cylinder rotating (A).

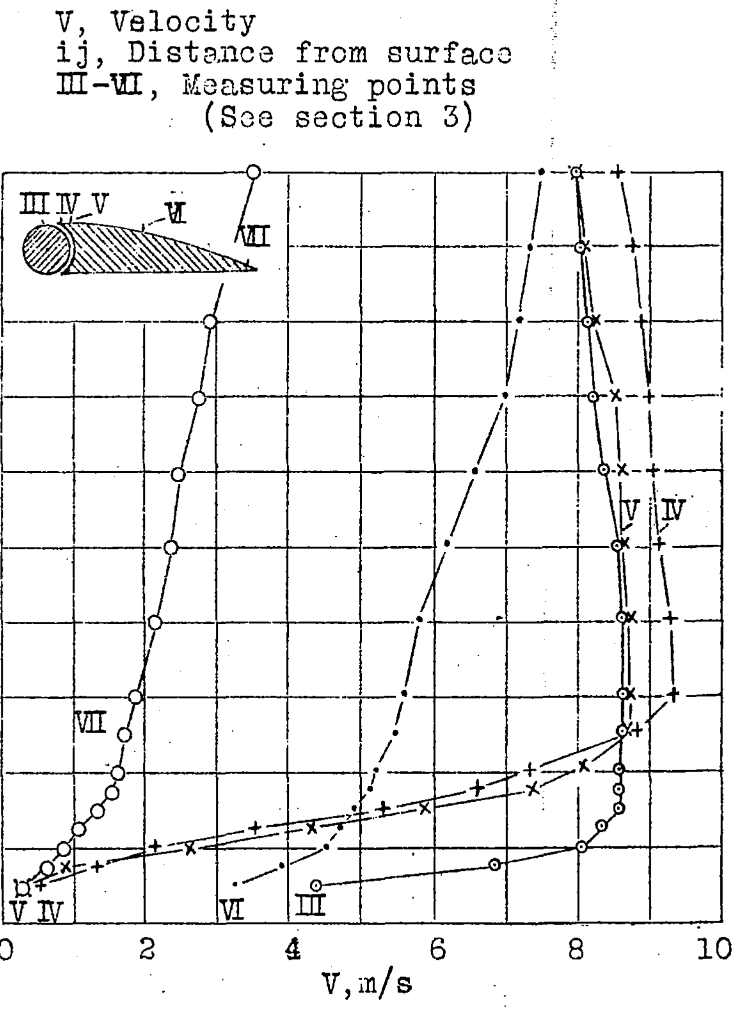
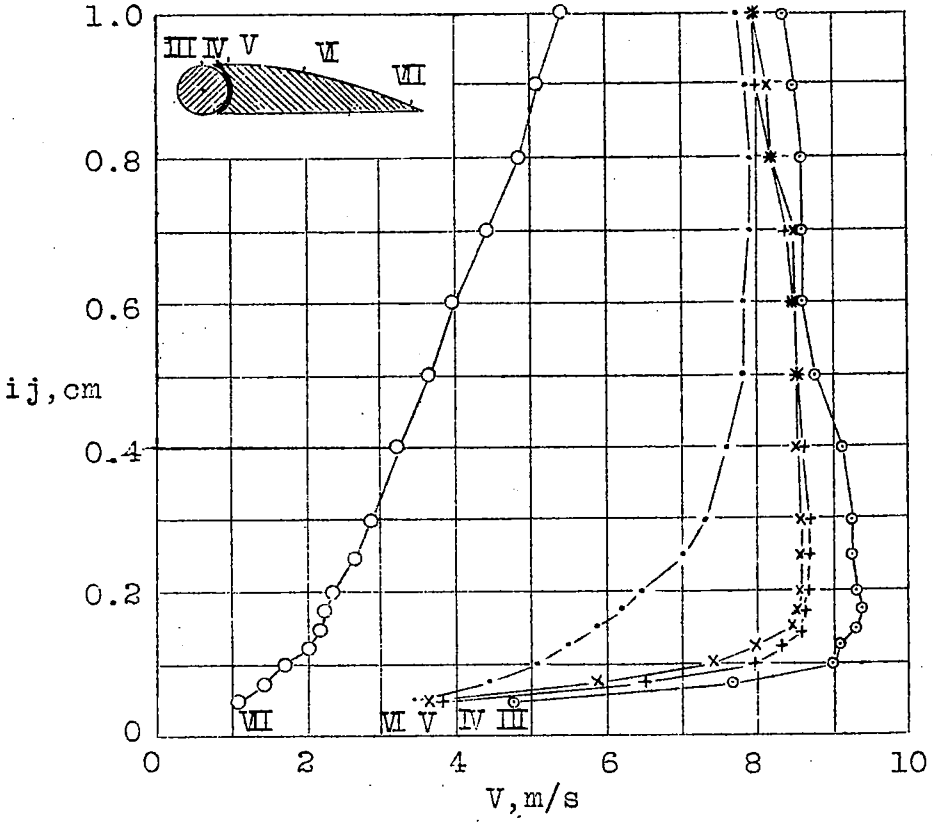


Fig.2 Velocity distribution with cylinder at rest (B).

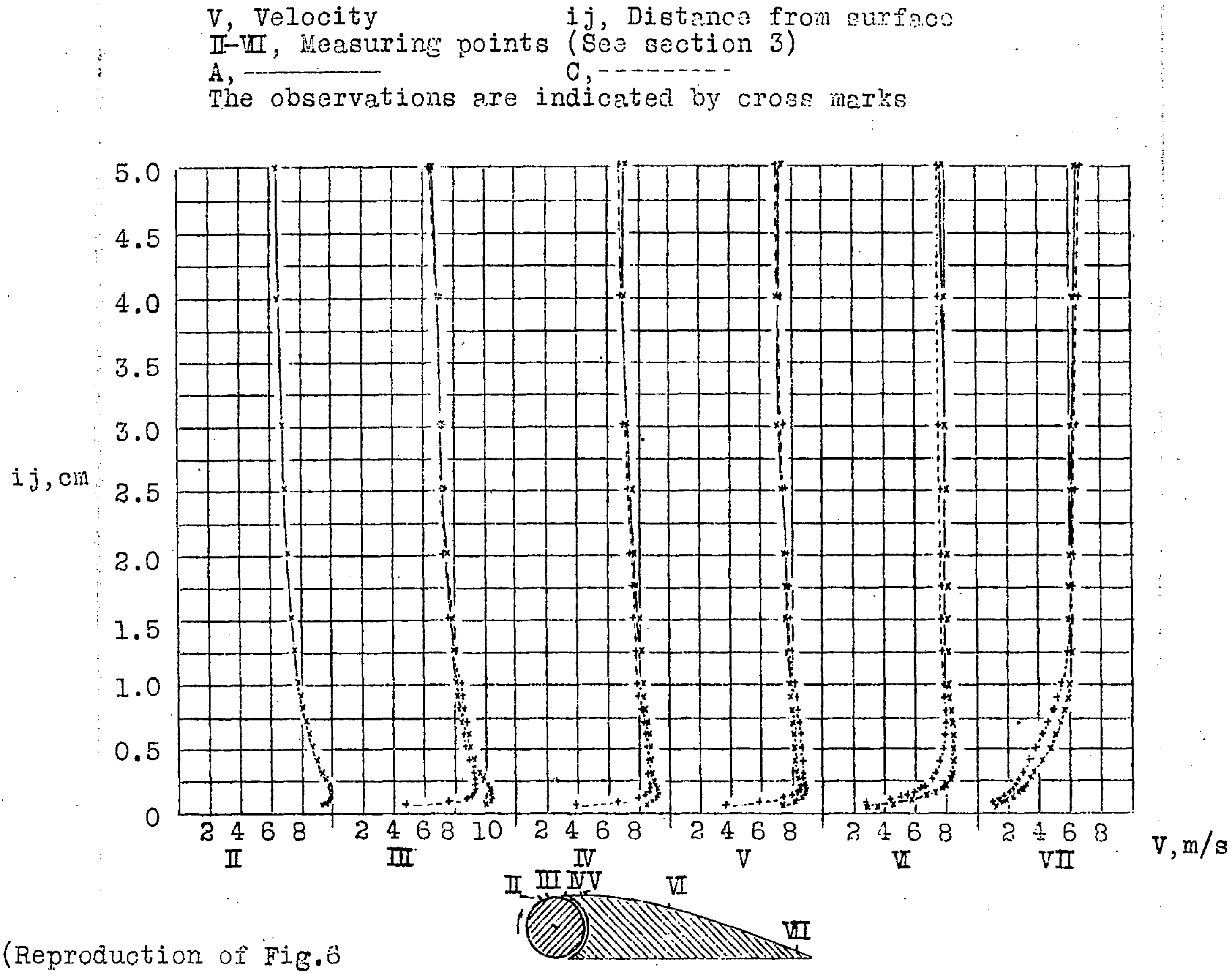
(Reproduction of Figs.3 & 4 of T.M.411)



V, Velocity
ij, Distance from surface
III-VII, Measuring points
(See section 3)

Fig.3 Velocity distribution with cylinder at rest and gap closed (C).

(Reproduction of Fig.5 of T.M.411)



(Reproduction of Fig.6 of T.M.411)

Fig.4 Comparison of the velocity distribution on the surface of the model with cylinder rotating (A) and that with cylinder at rest and gap closed (C).

V, Velocity
ij, Distance from surface
III-VII, Measuring points
(See section 3)
B, ————
C, - - - - -
The observations are indicated
by cross marks

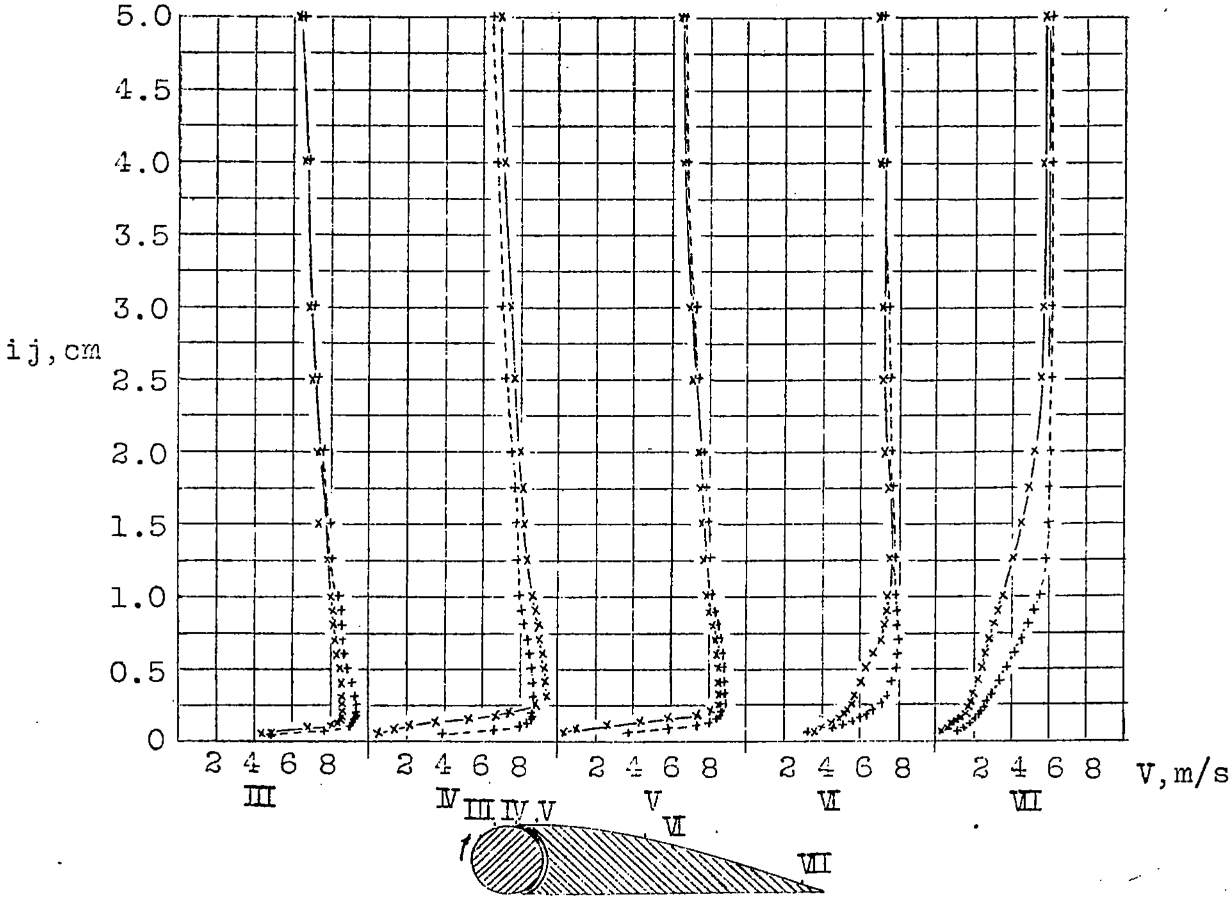


Fig.5 Comparison of the velocity distribution on the surface of the model with cylinder at rest(B) and that with cylinder at rest and gap closed(C).

(Reproduction of Fig.7 of T.M.411)

V, Velocity
ij, Distance from surface
VIII-IX, Measuring points (See section 3)
A, ————
B, - - - - - - -
The observations are indicated by cross marks

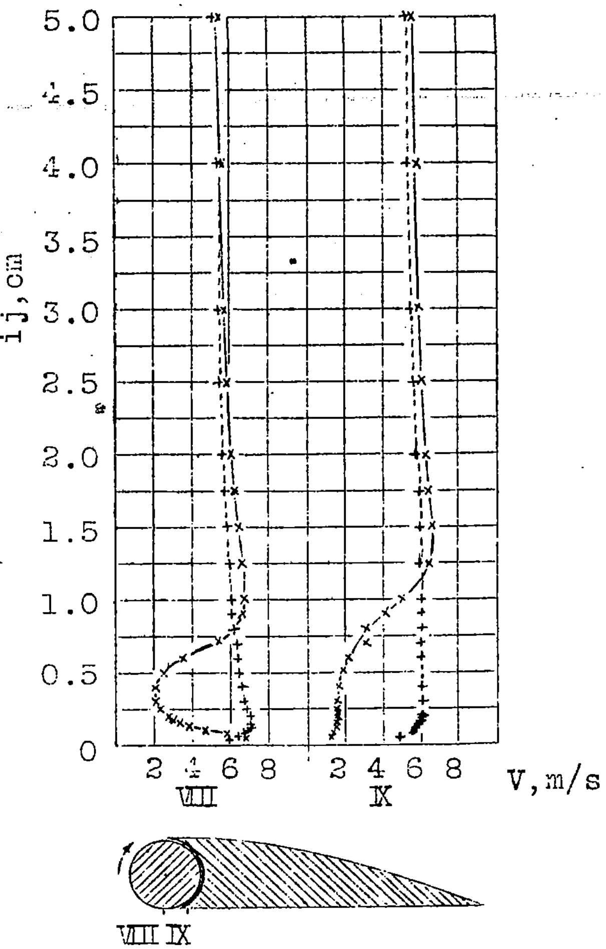


Fig. 6 Comparison of the velocity distribution on the surface of the model with cylinder rotating (A) and with cylinder at rest (B)

(Reproduction of Fig.8 of T.M.411)