NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL MEMORANDUM NO. 411.

DETERMINING THE VELOCITY DISTRIBUTION IN THE BOUNDARY LAYER OF AN AIRFOIL FITTED WITH A ROTARY CYLINDER.*

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Summary

In the closer investigation of the results obtained from a wing model with a rotary cylinder mounted in its leading edge (N.A.C.A. Technical Memorandum Nos. 307 and 354), the velocity distribution in the vicinity of the surface of the model was determined by means of a hot-wire anemometer. The results confirmed the belief that the rotary cylinder had considerable effect on the air flow, but demonstrated the fact that the direct influence of the cylinder is confined to a very thin layer in immediate proximity to the surface.

1. Introduction

It was seen from the reports A 96 (Technical Memorandum No. 307) and A 105 (Technical Memorandum No. 354) on the tests for determining the effect of a rotating cylinder in the leading edge of a wing model, that the cylinder could greatly affect

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*"Metingen van de snelheidsverdeeling in de grenslaag aan een draagvlakmodel, waarin een draaiende rol is aangebracht." Report A 129 of the "Rijks-Studiedienst voor de Luchtvaart," Amsterdam, in collaboration with the Delft Technical High School Laboratory for Aerodynamics and Hydrodynamics. Reprint from "De Ingenieur," October 23, 1926.

the air flow. These experiments were limited to the measurement of the forces acting on the model. As stated in Report A 105, it was desired to make a more thorough investigation of the air flow around this model, in order to obtain a better understanding of the phenomena exhibited and to determine the correctness of the assumption that the decisive factor was the effect of the cylinder on the boundary layer. In addition to the velocity measurements in the vicinity of the model, the pressure distribution on the surface of the model was also determined.

2. Method

a) In General.- The experiments were performed in the aerodynamic laboratory of Professor Burgers at Delft. The velocity distribution in the boundary layer was determined with a hot-wire anemometer, which is preferable to the very small Pitot tube used by Stanton.

b) Model.- The wing model No. 38a (without the leading edge), described in Report A 105, was used. For the determination of the pressure distribution, a pressure tube was introduced into the surface of this model, as explained in Report A 33 (Technical Memorandum No. 300).

c) Mounting the model and rotating the cylinder.- In contrast with the horizontal mounting of the model employed by the R.S.L. ("Rijks-Studiedienst voor de Luchtvaart") it was now mounted vertically. Considering the vibrations of the model, which, at the start and especially at the critical revolution speed of the cylinder, can be very strong, and in combination with the accurate adjustment and often very slight distance of the hot-wire anemometer from the model, the mounting was made as rigid as possible. Since the span of the model was 1 meter (39.37 in.) and the inside height of the tunnel was hardly 0.8 m (31.5 in.), the tips of the model projected beyond the tunnel. These tips were attached by means of iron fittings to an iron framework which was fastened to the side of the tunnel and which also supported the holder of the hot-wire anemometer. On account of the vibrations, it seemed necessary, however, to support the trailing edge of the model by wooden rods on both the upper and lower sides. The cylinder was driven by means of a cord, by an electric motor outside the tunnel. On account of the large size of the model, the whole of the driving cord was also outside the tunnel. Fig. 1 shows the arrangement of the apparatus.

d) Determining the revolution speed of the cylinder.- A method was adopted which was the same in principle as the one used by the R.S.L. The stroboscope, however, was not used to look through, but only to interrupt at regular intervals the light from a tungsten lamp which illuminated the outer end of the cylinder (Fig, 1).

When the cylinder and stroboscope synchronized, the former appeared to stand still. This was also the case when the revolution speed of the cylinder was a multiple of that of the stroboscope. The revolution speed of the cylinder was determined approximately with a tachometer, the disk of which was pressed against the surface of the cylinder, and the stroboscope was further used for accurate adjustment.

e) Measuring the velocity in the boundary layer.- The hot-wire anemometer was used to determine the velocity of the air flow in the boundary layer along the surface of the airfoil. (See Reference No. 5.)

Its action depends on the cooling (and thus on the variation of the electric constants) of an electrically heated platinum or platinum-iridium wire by the fluid whose velocity it is desired to know. Before using it as a measuring instrument, it is customary to calibrate it, i.e., to determine the energy loss as a function of the velocity to be measured. This is a disadvantage in comparison with the direct measurement of the velocity with a Pitot tube, but the hot-wire anemometer has the advantage, on account of its small dimensions, of affecting the local flow less, the wire itself usually having a diameter of only a few hundredths of a millimeter. In the experiments here described, the temperature of the wire which had a diameter of 0.05 mm (0.002 in.) and, consequently, its electrical resistance were kept constant. Before the experiments, and as often thereafter as was found necessary, the wire was calibrated with the aid of a standard Pitot tube of the Prandtl type.

The distance between the hot wire and the surface of the model (in a direction perpendicular to the chord) was measured by a micrometer screw having a scale divided into hundredths of a millimeter. The maximum distance the wire could be withdrawn from the surface of the airfoil was 5 cm (1.97 in.). The zero point could be found by moving the wire inward until it met its image reflected in the polished wood surface of the model. In the experiments in the vicinity of the metal parts of the model, the zero point was determined by the electrical contact of the wire with the metal surface. From previous experiments with a flat glass mirror (See Reference No. 6), it was found that the error in determining the zero point by this method did not exceed 0.05 mm (0.002 in.). The wire could be shifted in the direction of the chord by means of a second micrometer screw placed at right angles to the first. For greater distances, the whole was moved by hand.

The observations were then made so that the wire was moved by stages perpendicularly to the tunnel axis and hence perpendicularly to the chord of the model and, at each distance from the surface, the velocity of the air flow was measured. The velocity outside the boundary layer was determined by means of a Pitot tube and an alcohol micromanometer. The velocity was kept constant by regulating the motor which drove the tunnel propeller. In general, the mean of six readings was found. If four readings in the same position showed no special discrepancies, no more readings were taken; otherwise, a greater number was taken, especially on the under edge of the model and in front of the gap between the cylinder and model. Series III B was repeated as a whole, as likewise series IV B and V A. Table I gives the mean results of these measurements. The accuracy of the velocities thus determined, with the corrections described in section f, can come within ±2.5%.

f) Corrections.- In the immediate vicinity of the wall of the model a quantity of heat was absorbed by the surface in addition to that absorbed by the air itself, the amount being greater the nearer the wire to the surface. If no allowance were made for this loss of heat, too great a value would be obtained for the velocity of the air. Hence it is necessary in the inner portion of the boundary layer, to make a correction for the cooling of the anemometer wire.

The method whereby the energy absorbed by the wall in still air was subtracted from the energy absorbed by the wall and by the air stream together, gives, as found by experiments with a plain glass mirror (Reference No. 6, page 15), in the immediate vicinity of the surface, a still smaller velocity than one would expect on the basis of the velocity reduction on the wall. At greater distances the results of this correction were satisfactory. The whole cooling region, as the result of the heat absorption by the surface, extended in still air over a distance of about 0.25 cm (0.01 in.). The distance at which the "overcorrection" was noticeable, was previously, at an air velocity of 4 m (13 ft.) per second, not over 0.05 cm (0.02 in.) and, since here, on account of the vibrations of the model, no measurements were made nearer than 0.05 cm of the surface, it is not probable that the velocity measurements in the boundary layer were much affected by the heat absorption by the wall.

g) Measuring the pressure distribution.- These measurements were made as described in Report A 33 (Technical Memorandum No. 300). Fig. 2 is a diagram of the arrangement used.

3. Measurements Made

In the measurements of the air velocity in the boundary layer of the wing model 38a the angle of attack was 0°. The cylinder had a constant velocity of 9600 R.P.M. The air velocity outside the boundary layer, as found by a Pitot tube (Fig. 1e) was 5.44 m (17.8 ft.) per second. Since the diameter of the cylinder was 37 mm (1.46 in.), this makes the ratio of the peripheral velocity of the cylinder to the wind velocity 3.42.

In the following table, the distance from the wire to the surface of the model is designated by y; to the leading edge of the cylinder by x. The following series of measurements were made:

Series	I	II	III	IV	V	VI	VII
x	-1	10	5 mm before gap	5 mm behind gap	35	93	176 mm

These points are located on the convex side of the model, V being at the place of greatest thickness, VI at the center of the chord, and VII one centimeter (0.4 in.) from the trailing edge. Two additional series of measurements (VIII and IX) were made on the flat side, 5 mm before and 5 mm behind the gap.

All the measurements (except series II) were made both with the cylinder rotating (A) and with it at rest (B). Series III was also measured at the points farther back, after the gap had been closed and made as smooth as possible (C). At point II, moreover, a measurement was made in still air with the cylinder rotating (D). The pressure measurements were likewise made at zero angle of attack and a wind velocity of 5.4 m (17.7 ft.) per second. Three measurements were made with the model in the abovementioned A, B, and C arrangements. With the cylinder rotating, the R.P.M. was 9600.

The width of the gap was not determined, since this varied considerably from place to place, due to the oscillations of the cylinder, and consequently was affected by the centrifugal force.

4. Results of the Experiments

a) Velocity measurements.- The results are given numerically in the table and graphically in Figs. 3-8. However, only the velocity, not the direction, of the wind is here known. In the figures, the velocity vectors are plotted parallel to the direction of the motion at a great distance from the model. In Figs. 3-5 they are plotted together for each arrangement of the model. Figs. 6-7 show a comparison of the model with the cylinder rotating (A) and at rest (C) and also of the model with cylinder at rest and with gap open (B) and closed (C). Fig. 8 shows the results for both points on the lower surface.

It appears that the rotating cylinder imparts considerable momentum to the air flow in immediate proximity to the surface. The effect of the cylinder extends over the whole chord of the model, but the principal action is confined to a very thin layer whose thickness is of the same order of magnitude as that of the boundary layer. Except in the series of measurements which were made on the flat side of the model 5 mm before the gap, no return flow of the air was found in the boundary layer.

Although it is not possible to determine the direction of the flow with the hot-wire anemometer, the velocity curve for the last-mentioned series indicates a back flow in the boundary layer and hence a dragging along of the air by the cylinder in the general direction of motion. Due to the strong velocity fluctuations, however, it was not possible to determine just where the change in direction took place. In the experiments with the air at rest (II D), the flow was more turbulent, so that it was difficult to obtain very accurate results.

b) Pressure measurements.- The results of these are given in Table II and in Fig. 9. It appears that, with the cylinder rotating (A), the suction in the boundary layer on the foremost portion is noticeably increased, but that the effect on the rear portion is slight. The great negative pressure in the foremost portion of the boundary layer is very noticeable with the cylinder at rest and the gap open (B), probably due to the formation of vortices by the sharp edge of the stationary rear portion.

Conclusions

The rotating cylinder imparts, in the foremost portion of the surface of the airfoil, to the air in immediate proximity to the surface, a great momentum, the effect of which is noticeable over the whole, while the direct velocity increase is confined to a very thin layer.

Although the experiments covered only one angle of attack and one ratio of the R.P.M. of the cylinder to the wind velocity, they confirm the explanation in Report A 105 (Technical Memorandum No. 354) of the effect of the cylinder on the forces acting on the airfoil. It appears, in fact, that we here have to do with a boundary-layer phenomenon.

TABLE I.

Wing Model No. 38a.

Velocities in cm/sec.

i.j mm/100	Upper Surface												
	I		II		III			IV			V		
	A	B	A	D	A	B	C	A	B	C	A	B	C
0	425	310	–	–	–	–	–	–	–	–	–	–	–
25	435	320	–	–	–	–	–	–	–	–	–	–	–
50	434	331	930	–	1005	436	475	849	50	380	731	27	366
75	441	346	967	437	1024	684	767	880	130	650	818	88	586
100	454	358	992	400	1043	804	900	906	212	795	859	262	740
125	–	–	986	400	1037	832	908	911	350	830	877	430	795
150	–	–	986	372	1030	855	930	922	532	858	877	586	847
175	–	–	980	376	1024	855	936	922	661	858	882	738	855
200	520	392	967	380	1011	857	930	906	734	864	880	805	858
250	–	–	961	357	980	861	924	880	883	864	850	870	858
300	525	436	930	324	955	861	924	875	934	864	832	870	858
400	558	459	900	310	936	861	912	870	930	858	829	870	852
500	595	480	864	259	900	855	876	860	913	852	826	860	852
600	630	522	835	259	880	836	858	855	906	847	820	860	847
700	636	542	829	234	870	823	858	835	900	838	808	855	847
800	658	568	812	210	842	815	858	822	891	818	804	822	818
900	680	576	795	202	822	806	847	816	880	800	800	810	812
1000	688	596	778	177	810	800	835	810	860	795	787	800	795
1250	711	630	761	128	793	794	795	800	831	784	771	789	784
1500	732	640	740	100	778	736	784	793	820	778	763	771	778
1750	740	658	718	74	758	761	773	771	807	773	760	755	767
2000	740	676	707	52	742	744	745	758	787	751	755	749	751
2500	732	670	696	28	729	718	718	738	768	718	728	738	734
3000	711	670	681	21	711	704	713	722	743	713	703	702	715
4000	691	670	655	16	680	682	686	692	716	686	694	676	692
5000	688	670	650	14	670	661	660	688	698	660	686	670	671

Table I (Cont.)

Wing Model No. 38a.
Velocities in cm/sec.

ij mm/100	Upper Surface						
	I		II		III		
	A	B	A	D	A	B	C
Cylinder R.P.M.	9600	-	9600	9600	9600	-	-
Barometer mm	767	770	761	760	768	763	769
Temp. °C.	15.4	17.3	16.0	18.6	17.6	15.6	17.7
x mm	-1		10		5 mm before gap		

ij mm/100	IV			V		
	A	B	C	A	B	C
Cylinder R.P.M.	9590	-	-	9600	-	-
Barometer mm	761	763	769	760	768	766
Temp. °C.	18.1	15.9	17.6	17.1	17.3	15.7
x mm	5 mm behind gap			35		

I-IX: measuring points (See section 3).

A : Cylinder rotating.
B : " at rest.
C : " " " with gap closed. } V_o = 5.44 m/sec.
D : " rotating, $V_o = 0$.

Table I (Cont.)

Wing Model No. 38a.
Velocities in cm/sec.

ij mm/100	Upper Surface						Lower Surface			
	VI			VII			VIII		IX	
	A	B	C	A	B	C	A	B	A	B
0	–	–	–	–	–	–	–	–	–	–
25	–	–	–	–	–	–	–	–	–	–
50	273	324	342	96	27	106	676	590	123	488
75	425	388	441	150	60	142	581	666	139	548
100	565	450	506	200	86	169	462	686	144	566
125	670	471	548	231	106	202	384	702	154	588
150	728	489	586	260	134	216	328	702	159	591
175	780	511	620	292	152	225	292	787	161	595
200	794	520	645	310	162	234	276	702	161	601
250	820	548	700	338	172	266	237	681	156	605
300	840	561	729	356	186	289	213	661	154	605
400	840	581	756	411	216	324	204	658	169	605
500	840	620	780	466	240	369	246	655	196	605
600	836	660	780	505	253	400	353	645	228	605
700	830	701	790	535	280	445	534	627	313	605
800	820	720	790	558	296	488	615	618	317	605
900	794	735	784	581	317	511	660	615	424	605
1000	790	751	773	595	354	543	671	605	506	605
1250	790	751	767	595	396	581	661	601	645	605
1500	790	758	762	595	450	595	645	586	658	605
1750	782	751	762	595	484	600	620	576	645	601
2000	782	735	756	595	520	600	605	563	630	595
2500	782	724	751	595	558	610	590	560	615	576
3000	780	720	740	595	576	615	576	560	595	570
4000	758	720	729	600	581	625	563	560	588	563
5000	735	720	713	600	594	625	557	560	586	560
Cylinder R.P.M.	9600	–	–	9600	–	–	9600	–	9600	–
Barometer mm	757	757	748	750	750	747	758	756	756	757
Temp. °C	15.1	15.0	17.9	15.0	17.1	18.0	18.2	17.8	16.3	15.8
x mm	93			176			5 mm before gap		5 mm behind gap	

TABLE II.

Wing Model 38a.
Pressures in millimeters of water.

Hole No.	A	B	C
1	0.075	0.075	0
2	0.225	0.175	0.075
4	0.425	0.425	0.425
6	0.800	0.600	0.675
8	1.300	1.00	1.08
10	1.83	1.33	1.50
12	2.20	1.70	1.90
13	2.50	1.88	2.18
14	2.80	2.45	2.48
14.5	2.98	3.20	2.55
15	3.05	3.30	2.70
15.5	3.20	3.55	2.90
16	3.25	3.70	3.05

V_0 = 5.44 m/sec.

Barometer = 757 mm Hg

Temperature = 16.4°C.

The numbers in Column 1 represent the distance of the hole from the trailing edge of the model, as measured in centimeters along the surface.

A : cylinder rotating (n = 9600 R.P.M.).

B : " at rest.

C : " " " with gap closed.

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2. Wolff, E. B. and Koning, C. : "Voortgezet onderzoek van een draaiende rol, aangebracht in een vleugelprofiel." R.S.L. Report A 105. "De Ingenieur," March 6, 1926. (N.A.C.A. Technical Memorandum No. 354.)

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Translation by Dwight M. Miner,
National Advisory Committee
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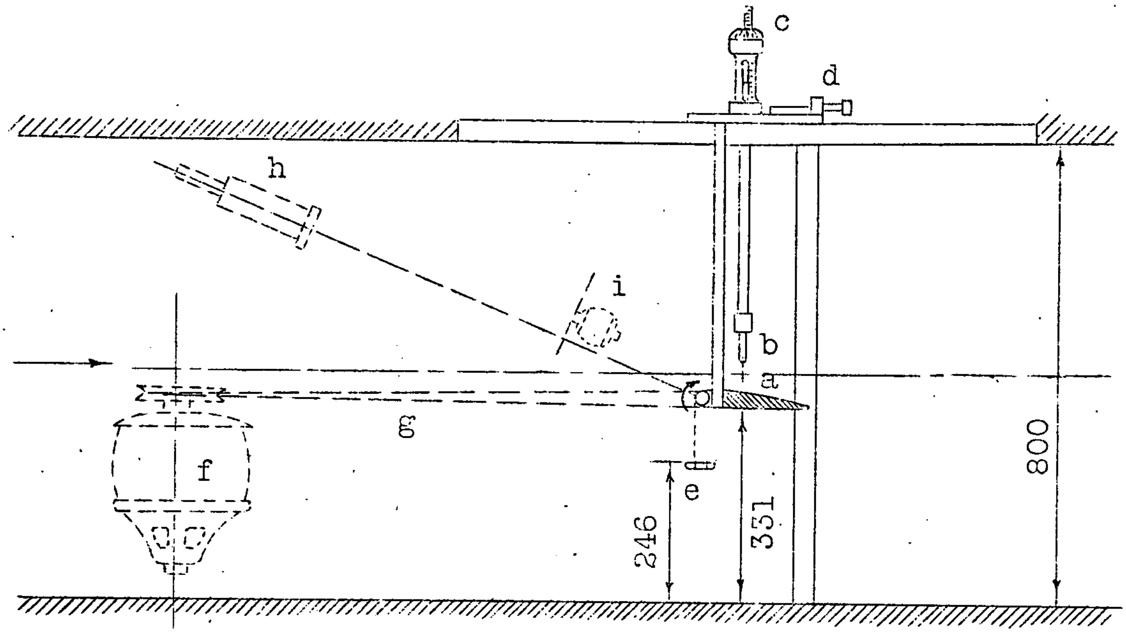
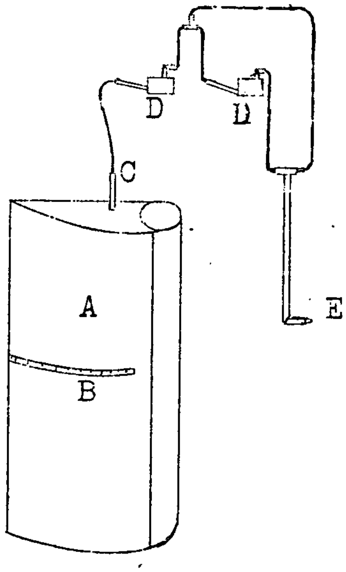
a, Model b, Hot-wire anemometer
c, Micrometer screw for adjusting wire perpendicular to chord
d, Micrometer screw for adjusting wire parallel to chord
e, Pitot tube
f, Electric motor for driving the cylinder
g, Driving cord
h, Tungsten lamp
i, Stroboscopic disk with motor

Fig.1 Arrangement of apparatus in velocity measurements.





A, Model
B, Perforated tube set flush and connected with tube C
D, Hot-wire anemometer
E, Pitot tube
The cylinder is mounted and driven and its revolution speed measured the same as in Fig.1

Fig.2 Arrangement of apparatus for pressure-distribution measurements.

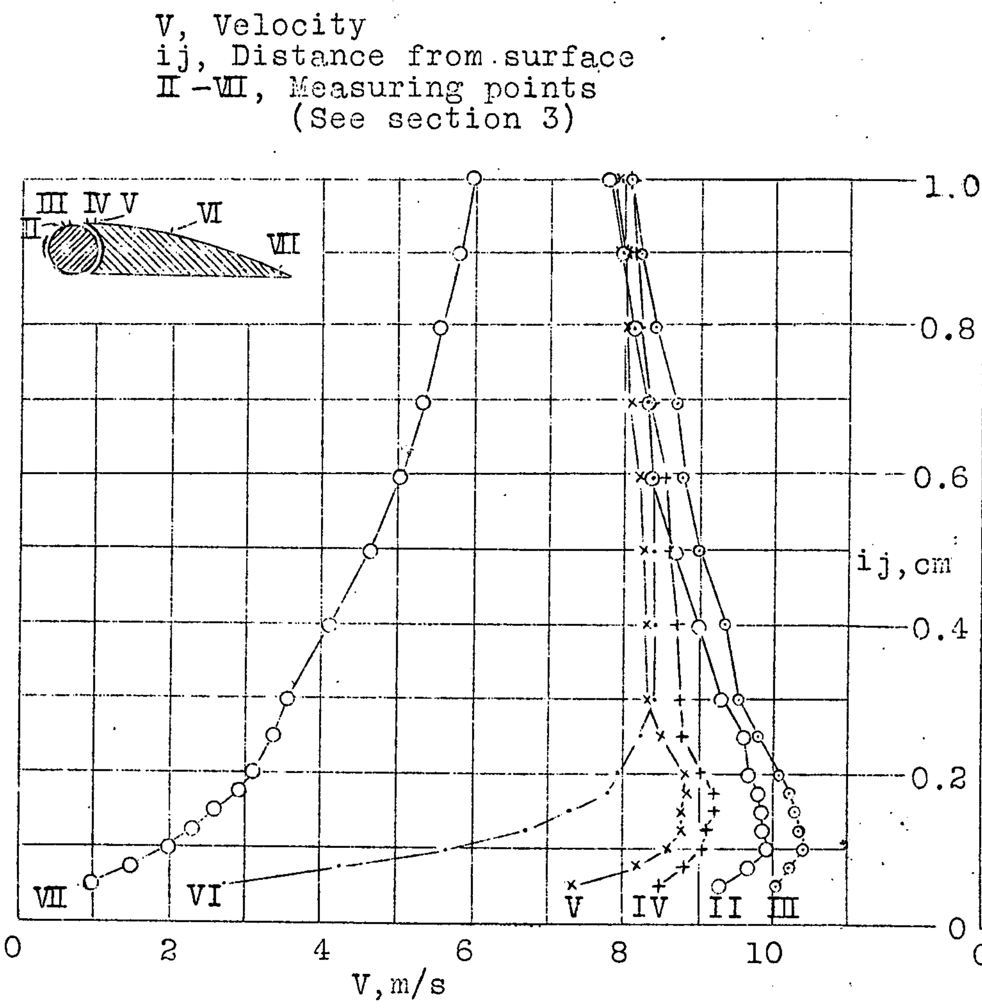


Fig.3 Velocity distribution with cylinder rotating (A).

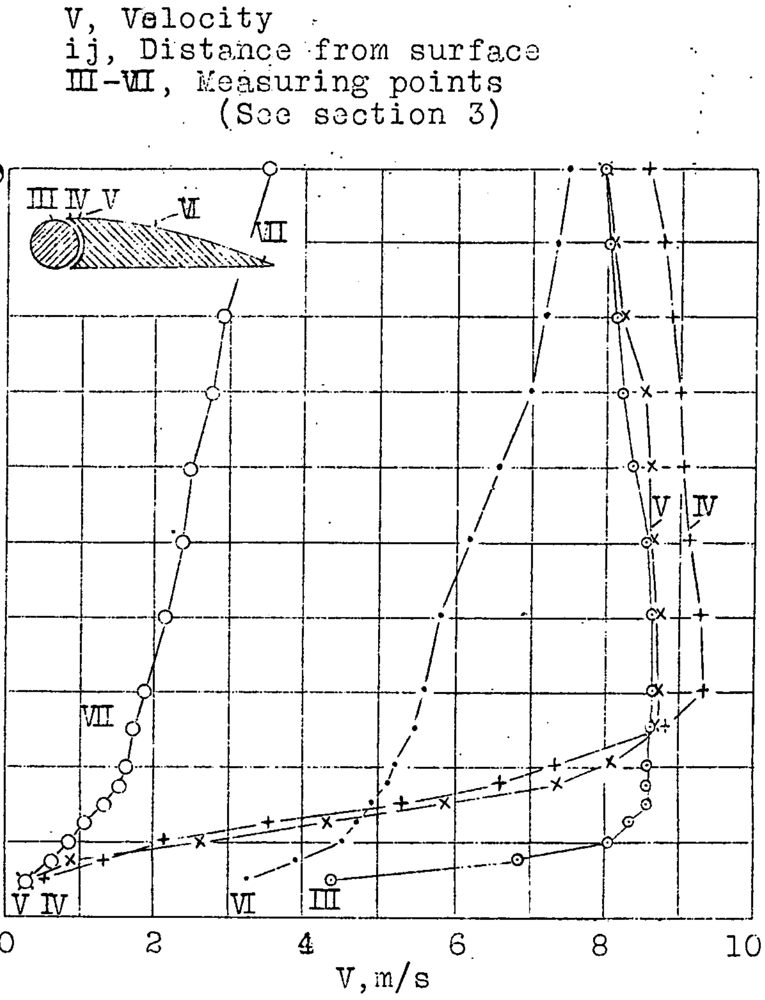
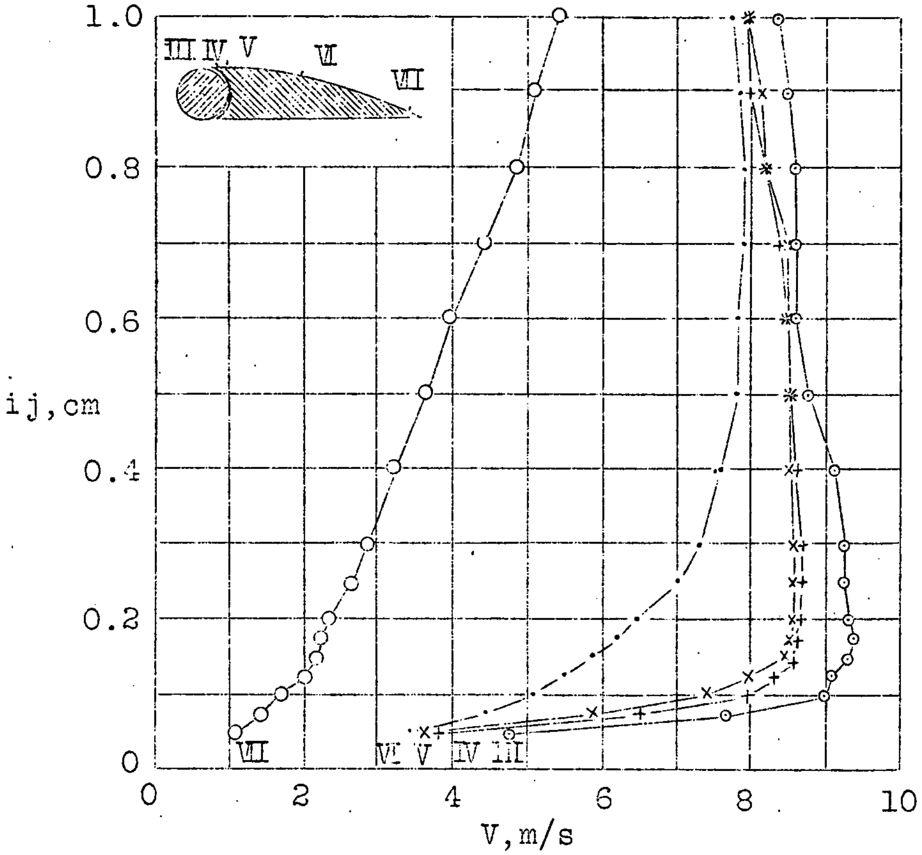


Fig.4 Velocity distribution with cylinder at rest (B).



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

Fig.5 Velocity distribution with cylinder at rest and gap closed (C).

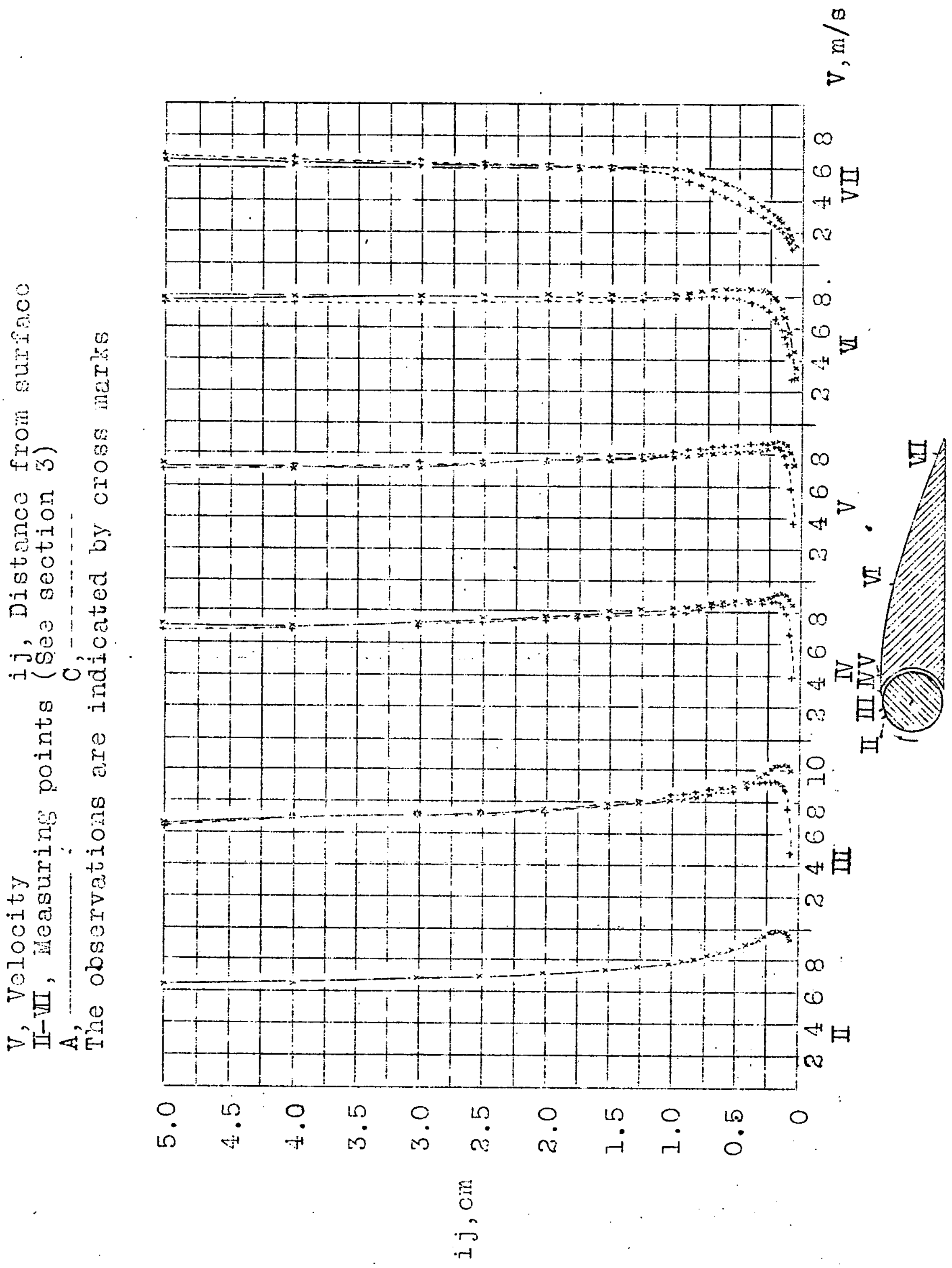


Fig.6 Comparison of the velocity distribution on the surface of the model with cylinder rotating (A) and that with cylinder at rest and gap closed (C).

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

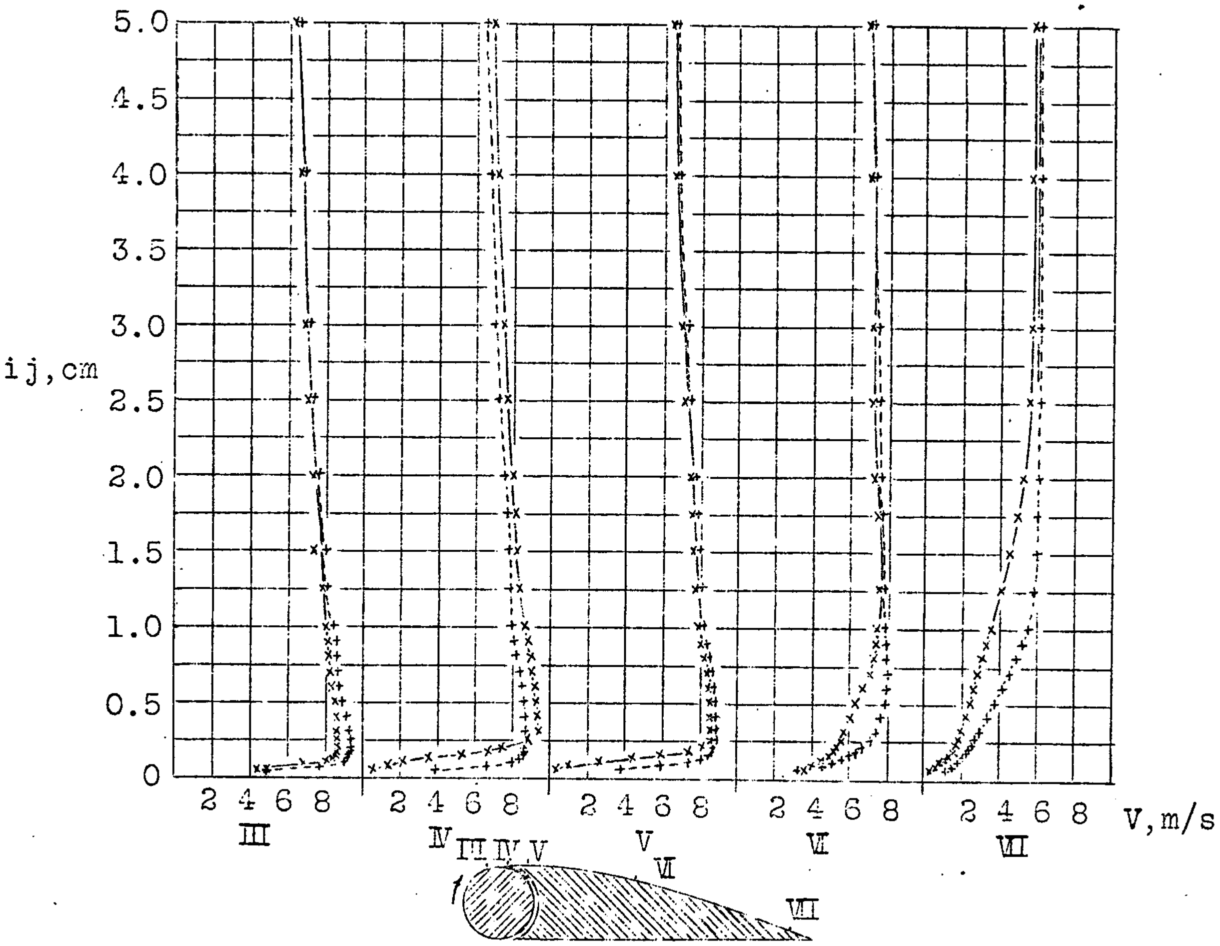
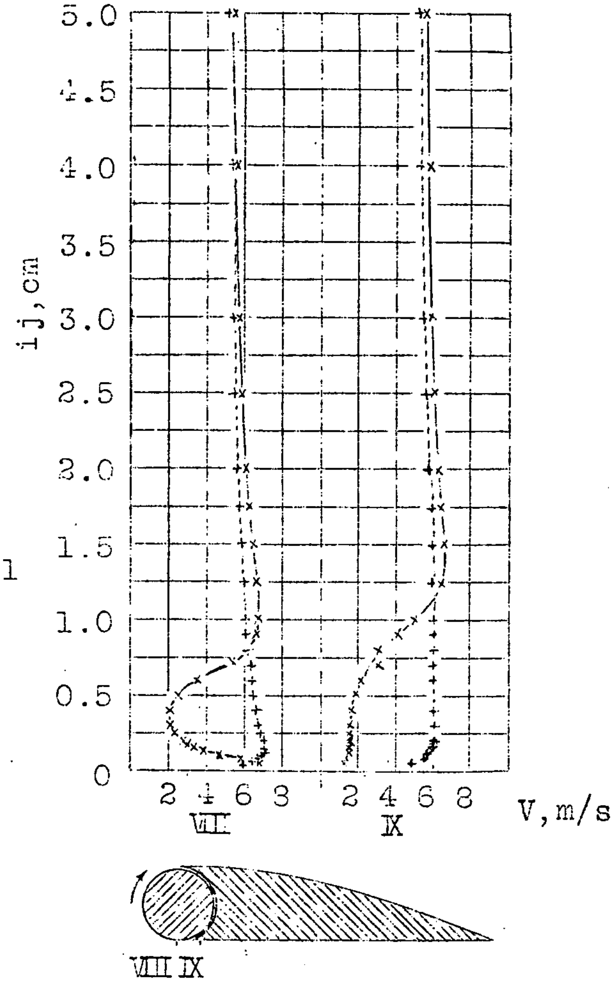


Fig.7 Comparison of the velocity distribution on the surface of the model with cylinder at rest(B) and that with cylinder at rest and gap closed(C).

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

Fig.8 Comparison of the velocity distribution on the surface of the model with cylinder rotating (A) and with cylinder at rest (B)



1-16, Measuring points.
The numbers indicate the distances, in cm, from the trailing edge
—+—, Model with cylinder rotating
—×—, Model with cylinder at rest
—o—, Model with cylinder at rest and gap closed (C)

Fig.9 Pressure distribution.
P/P_0, measured pressure divided by dynamic pressure.