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by

D. L. I. Kirkpatrick

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EXPERIMENTAL INVESTIGATION OF THE BREAKDOWN OF A VORTEX IN A TUBE

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D. L. I. Kirkpatrick

SUMMARY

The distribution of the total pressure and the angle of swirl across a vortex in a tube were measured using a pitot probe upstream of breakdown. The static pressure distribution along the length of the tube containing the breakdown was also measured. It was found that the total pressure fell sharply in the vortex core towards a very low value on the axis, and that the swirl-angle distribution was similar to that of an exponential vortex. The static pressure distribution along the wall of the tube was found to include a positive pressure gradient upstream and a negative pressure gradient downstream of the breakdown's position. When breakdown did not occur these pressure gradients were not present. From the total pressure and swirl-angle distributions across the vortex, the static and dynamic pressure distributions and the axial and circumferential velocity distributions were calculated. These results will be used as boundary conditions for numerical solution of the equations of motion of the vortex.

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ILLUSTRATIONS

1 INTRODUCTION

The development of high-speed aircraft with slender wings whose leading edges are highly swept-back has stimulated a large number of theoretical and experimental studies of the leading-edge vortices which are a characteristic feature of the flow round such wings. When slender wings are at high incidence, the cores of the leading-edge vortices above the wings undergo an abrupt change of structure at some point along their length. This change, which has been called vortex breakdown, gives rise to irregularities in the pitching moment characteristic. The phenomenon was first observed by Peckham[1,2], and also studied in greater detail by Lambourne and Bryer[3] and Werlé[4]. It is difficult to make a detailed study of vortex breakdown above a slender wing, because the breakdown occurs in the presence of continual feeding of vorticity to the vortex core. It was therefore decided to study first the similar phenomenon of vortex breakdown in a tube, to look for the characteristic features of such a breakdown, and to use the results to guide further analyses of the breakdown of leading-edge vortices.

Since vortex breakdown was first observed, various explanations of its nature have been proposed. Squire[5] has treated the breakdown as an instability phenomenon, triggered by the presence of standing waves in the flow field, and has presented a stability criterion based on the ratio of the maximum circumferential velocity to the axial velocity. Ludwieg[6], also considering breakdown to be the result of instability of the vortex core, has calculated a stability parameter dependent on the velocity profile in the core. Jones has criticised Squire's analysis, noting[7] that standing waves can exist even when the maximum circumferential to axial velocity ratio is small, and has suggested[8] that vortex breakdown is primarily dependent on the axial pressure gradient. Benjamin[9] considers that the breakdown marks, not the onset of instability, but a finite transition between two dynamically conjugate states of flow, and supports his argument by comparing vortex breakdown to a hydraulic jump.

Because of the difficulty of obtaining accurate quantitative measurements of conditions in the core of a vortex, especially close to the breakdown, without introducing an unacceptable amount of disturbance, experimental investigations of the vortex breakdown phenomenon have mostly been restricted to qualitative observation of the breakdown using flow visualization techniques. However, Harvey[10], who used smoke to study the structure of the breakdown, has estimated the swirl-angle distribution across a vortex just upstream of its breakdown from photographs of smoke traces.

The experiment described below was made to study the structure of a vortex in a tube not far upstream of its breakdown, and to find the static pressure distribution along the wall of the tube in the neighbourhood of the vortex breakdown. The results of the experiment will be used as a guide for further theoretical attempts to explain breakdown, and in particular to provide realistic boundary conditions for numerical solutions of the equations of motion.

2 APPARATUS AND EXPERIMENTAL TECHNIQUE

The apparatus used in this experiment was first used by Titchener[10], and has since been used and fully described by Harvey[11]. Air is drawn by a fan through a perspex tube 52 in. long and 3.5 in. in internal diameter. Swirl is imparted to the flow by a set of vanes mounted at its intake, as shown in Fig.1, this swirling flow being the vortex considered. By a suitable choice of fan speed and swirl-vane angle, vortex breakdown can be induced at any point on the axis of the tube. An initial survey of the vortex breakdown in the tube, using titanium tetrachloride smoke drawn into the tube (Fig.1) for flow visualization, revealed that the general features of the structure of the breakdown, i.e. the stagnation point on the vortex axis and the spherical region of swirling flow associated with it, were similar to those studied and photographed by Harvey. Subsequently the speed of the flow through the tube was set considerably higher than in Harvey's experiment so that the pitot pressure variations could be more easily measured. In consequence, the details of the flow in the breakdown region were not clearly visible, and the breakdown did not remain in the same position but oscillated unsteadily up and down the tube. To stabilize the breakdown's position, another perspex tube was placed inside the first. This second tube was 12 in. long, 3.5 in. in external diameter and its thickness was $\frac{1}{4}$ in. at the middle, tapering to zero over 4 in. at each end. After the second tube had been inserted, it was found that the breakdown occurred just upstream of the start of the expansion, and that the axial position of the breakdown was almost constant. The slight axial oscillations were estimated to be never greater than one inch in amplitude and were usually much smaller.

To find the total pressure and swirl angle distribution in the vortex upstream of its breakdown, pitot tubes made from hypodermic tubing of 1 mm and 0.5 mm outside diameter were inserted into the vortex about 8 in. upstream of the breakdown, and rotated about an axis perpendicular to the vortex axis as shown in Fig.2. Flow visualization tests showed that a pitot probe of outside diameter 0.0196 in. ($\frac{1}{2}$ mm) could be rotated with the tip as close as 0.1 in. from the vortex axis without any perceptible effect on it or on the breakdown downstream. When even the smallest probe was moved into the centre of the vortex, breakdown occurred at the probe and, when the probe was removed, the breakdown moved back downstream to its original position. The tip of the pitot probe was successively positioned at a number of points across the vortex using the traversing screws, and at each of these points the probe was set at a series of inclinations to the vortex axis. The pitot pressures measured at each inclination of the probe were plotted against the angle between the tip of the pitot probe and the vortex axis, and the local angle of swirl was found by averaging the angles at which the measured pitot pressure had a certain value, as shown in Fig.3. The local total pressure was then taken to be the pitot pressure measured when the probe was set at the local angle of swirl; it was assumed that the radial velocity at any point was negligible compared to the axial and circumferential velocities. The static pressure at the wall of the tube upstream and downstream of the vortex breakdown was measured by hypodermic tubes set in the wall of the perspex tube so that their tips were flush with its inside surface. The static pressure distribution was measured twice; once when vortex breakdown occurred in the tube and again after the angles of the swirl vanes had been slightly reduced, so that no breakdown occurred. All the pressure measurements were made using long tube Chattock manometers which can be read with an error of less than 0.001 in. of water. Throughout the experiment a fixed pitot probe remained always in the vortex downstream of breakdown to check that the performance of the fan did not vary excessively during the tests.

The method used in this experiment has certain inherent disadvantages. The tips of the pitot probes must be made carefully and must be regularly inspected for damage or distortion, otherwise the measurement of local swirl angle is unacceptably inaccurate. The pitot probes, which must be thin and consequently of small bore to minimise disturbance of the vortex, give pressure readings which change only slowly when the probes are moved. A considerable time is therefore required to take a complete set of pressure readings. Also, as it is essential that no part of a pitot probe should go through, or even near, the vortex axis, it is not possible, in one traverse, to measure the pitot pressures at points equidistant from, but on opposite sides of, the vortex axis. Despite these imperfections, which are reflected in the scatter of results, the results are sufficiently consistent for use in theoretical work. It is believed that the accuracy could be greatly increased if improved traversing apparatus and pitot probes were used.

3 DISCUSSION OF RESULTS

The measured values of the angle of swirl ϕ and the total pressure H were plotted against the parameter r/r_o, where r is the radial distance from the vortex axis and r_o is the local radius of the tube, in Figs.4 and 5 respectively. The total pressure was non-dimensionalized with respect to the difference between the static pressure p_o at the wall of the tube in the plane of the pitot traverse and the total pressure H_o a short distance from the wall of the tube where $\frac{dH}{dr}$ is negligible. The dynamic pressure $q_o = H_o - p_o$ thus found represented an equivalent air speed V_o of 85 ft/sec.

The results show that the distribution of the angle of swirl across the vortex is, in the inner part of the vortex, similar to that of an exponential vortex whose swirl angle is proportional to

$$\frac{1}{r}\left(1 - e^{-r^2}\right) .$$

In the outer part of the vortex the measured values of the swirl angle are appreciably higher than those of an exponential vortex. The maximum swirl angle measured was 49.5 degrees, located 0.38 in. ($r/r_o = 0.217$) from the vortex axis. Harvey's measurements were made at a much smaller value of Reynolds number and he found the maximum swirl angle to be 50.5 degrees, located 0.2 in. ($r/r_o = 0.331$) farther from the vortex axis. This indicates the expected increase in the relative importance of viscous forces when the Reynolds number is low.

The characteristic loss of total pressure in the centre of conical vortices above slender wings has been closely studied by Earnshaw[12]. Fig.5 shows that in the tube the total pressure of the swirling flow drops sharply when $r/r_o < 0.3$. As the pitot probe was not placed in the centre of the vortex to avoid disturbing it, the maximum total pressure drop was not measured, but can be estimated to be between 3 and 4 times the dynamic pressure q_o.

From the measured values of the local total pressure and angle of swirl, the local static pressure p, and hence the axial and circumferential velocities, were found as outlined below. When the radial velocity is assumed to be negligible, the equation of motion relating the radial pressure gradient to inertial forces reduces to the simple form

$$\frac{dp}{dr} = \frac{\rho V^2 \sin^2 \phi}{r} \quad .$$

Since

$$H = p + \tfrac{1}{2}\rho V^2$$

we may write

$$\frac{dp}{dr} = \frac{2 \sin^2 \phi}{r} (H - p) \quad .$$

This differential equation was solved using a "predictor-corrector" method. The distributions across the vortex of the local static and dynamic pressures, as well as the local circumferential and axial velocities, were found from the above equations and plotted in Figs.6, 7, 8 and 9 respectively. Though incomplete through the lack of results at or very close to the vortex axis, these graphs serve to show clearly the characteristic features of vortex flow. The static pressure drops as the vortex axis is approached, though the drop begins farther from the axis and is less steep than the total pressure drop, and the static pressure loss at the axis can be estimated to lie between 4 and 5 times the dynamic pressure q_o. The dynamic pressure rises to more than 2.5 q_o where $r/r_o = \frac{1}{4}$ but does not exceed this value closer to the vortex axis. In the outer part of the vortex the axial velocity remains constant and the circumferential velocity rises as the axis is approached. But in the core, where viscous forces exert a significant effect, the circumferential velocity drops to zero on the vortex axis, while the axial velocity increases sharply towards the centre of the vortex. It should be remembered that all the graphs found from the differential equation above depend on the measured total pressure and swirl angle distributions whose accuracy is difficult to assess.

The variation of the static pressure along the wall of the vortex tube, when vortex breakdown occurred, was plotted in Fig.10 along with a drawing to the same scale of a section of the wall of the tube. The juxtaposition of the drawing and the graph of the pressure variation helps to relate the pressure changes to the geometry of the tube and the position of the vortex breakdown. There are two significant features of the pressure variation curve, viz. the positive pressure gradient upstream of the vortex breakdown and the steeper, negative gradient downstream of it. When the angle of the swirl vanes was slightly reduced so that vortex breakdown did not occur in the tube, both these features disappeared. The static pressure distributions in the tube, with and without breakdown present, are shown in Fig.11, non-dimensionalized with respect to the pressure drop Δp induced in each case by the contraction. It is clear that the effect of breakdown extends some distance upstream of the associated stagnation point.

4 CONCLUDING REMARKS

The experimental results obtained are in broad agreement with those of earlier investigations. The total and static pressure distributions across the vortex reveal the expected presence of low total and static pressures at the vortex axis. The swirl angle rises to a maximum value of 49.5 degrees at the edge of the vortex core, and the shape of the swirl angle distribution is similar to that of an exponential vortex. The static pressure variation along the wall of the tube includes, if the vortex breaks down in the tube, a slight positive pressure gradient upstream of the breakdown and a negative gradient downstream. The results will be used as boundary conditions in a study of vortex structure by numerical solution of the equations of motion, using a method now being developed[13].

SYMBOLS

H	total pressure
p	static pressure
Δp	static pressure drop in the tube contraction
q	dynamic pressure
r	radial distance from the vortex axis
V	velocity
ρ	density
ϕ	$\tan^{-1}$ (circumferential velocity/axial velocity)

Subscripts

o	conditions at the edge of the vortex in the plane of the pitot traverse

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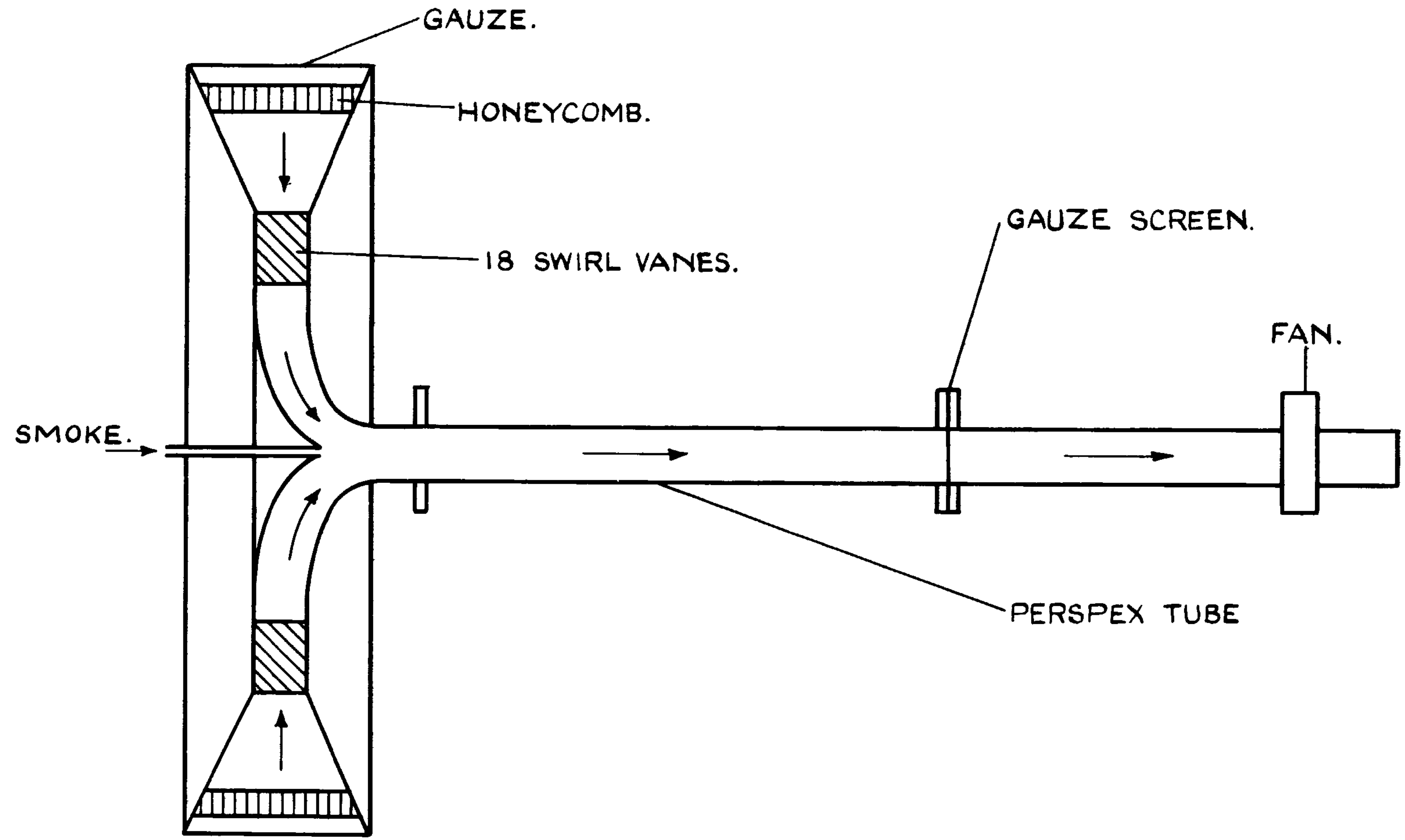

FIG. 1. THE VORTEX TUBE

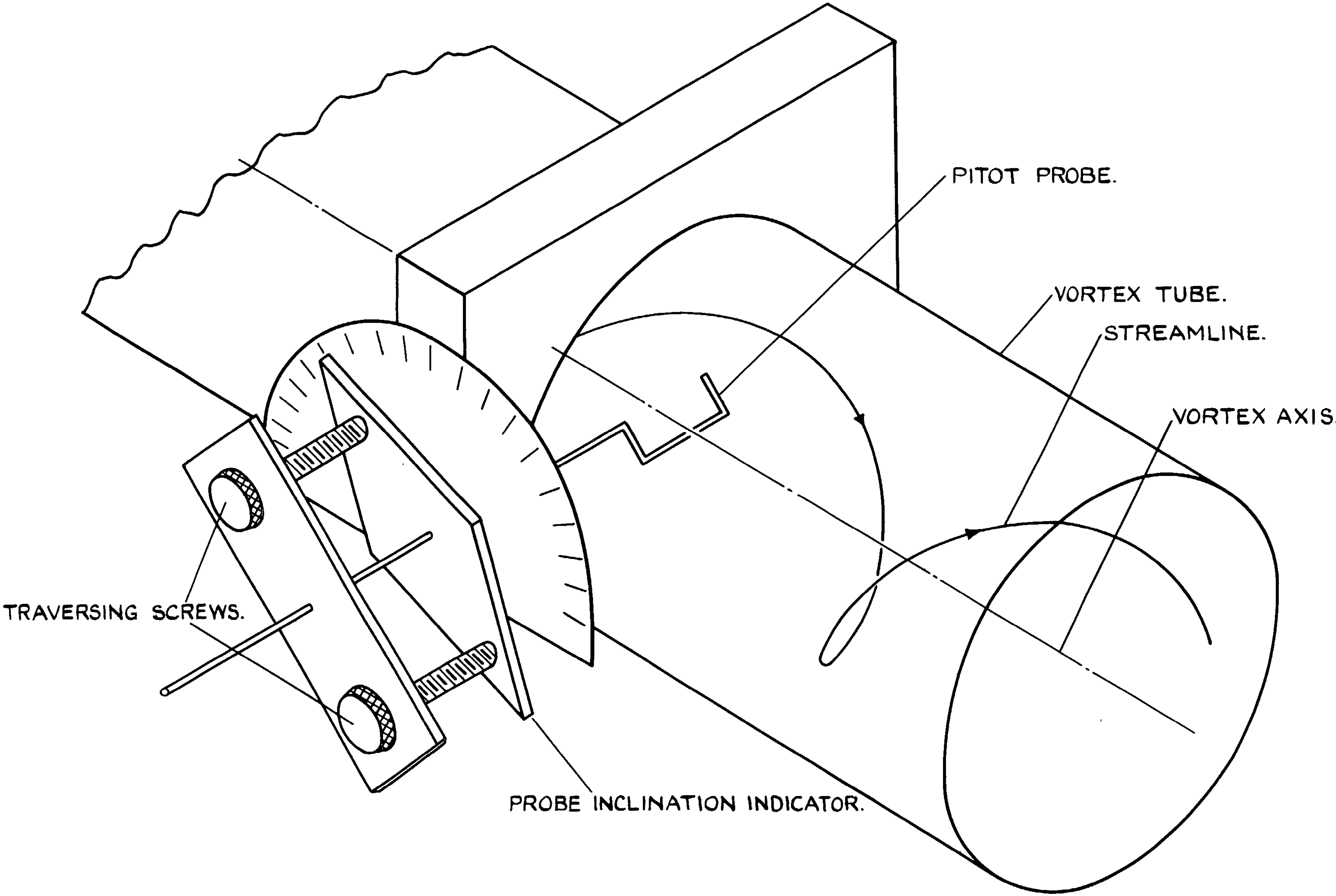

FIG. 2. PITOT PROBE.

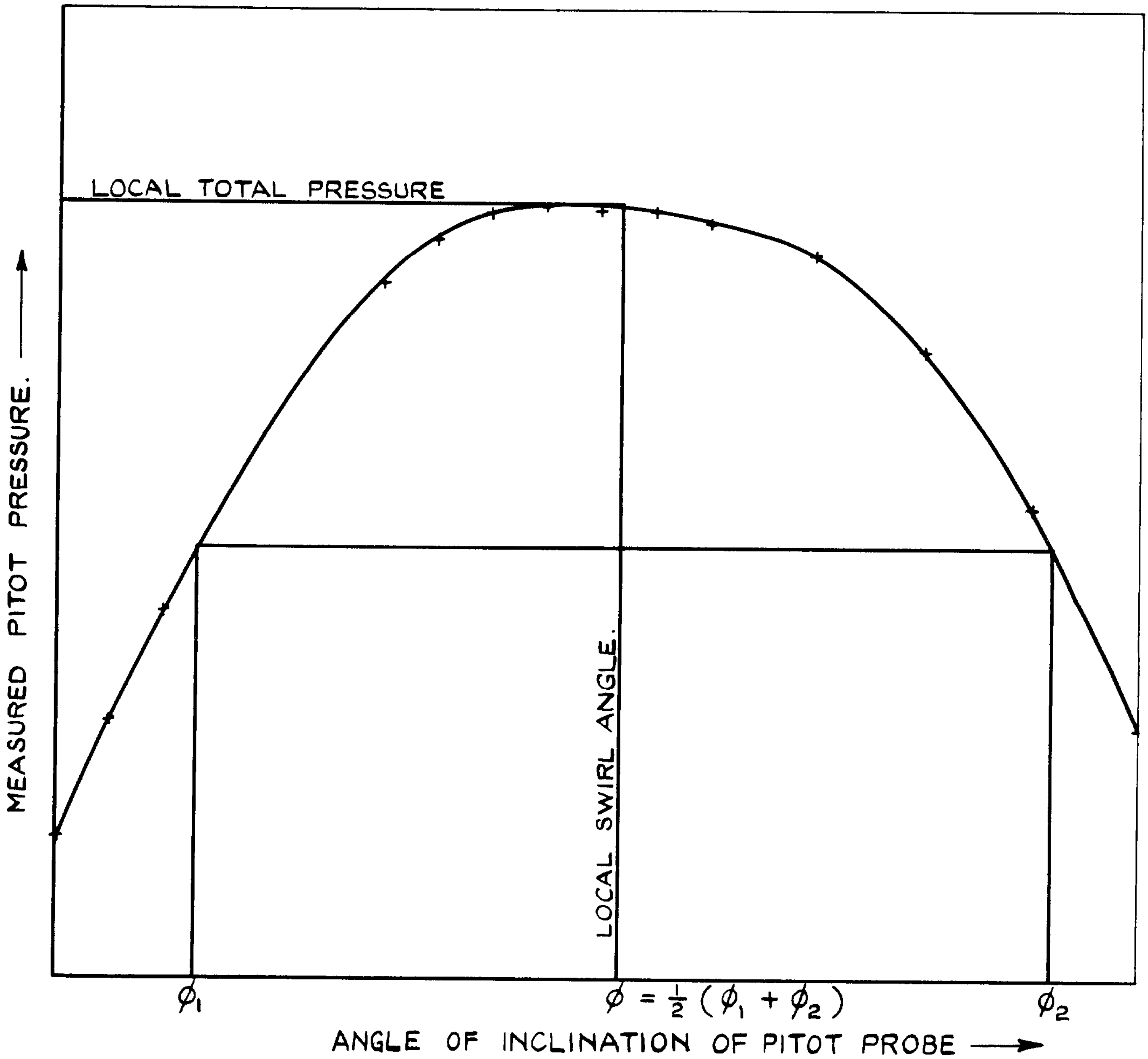

FIG. 3. METHOD OF FINDING LOCAL TOTAL PRESSURE AND SWIRL ANGLE (TYPICAL CURVE.)

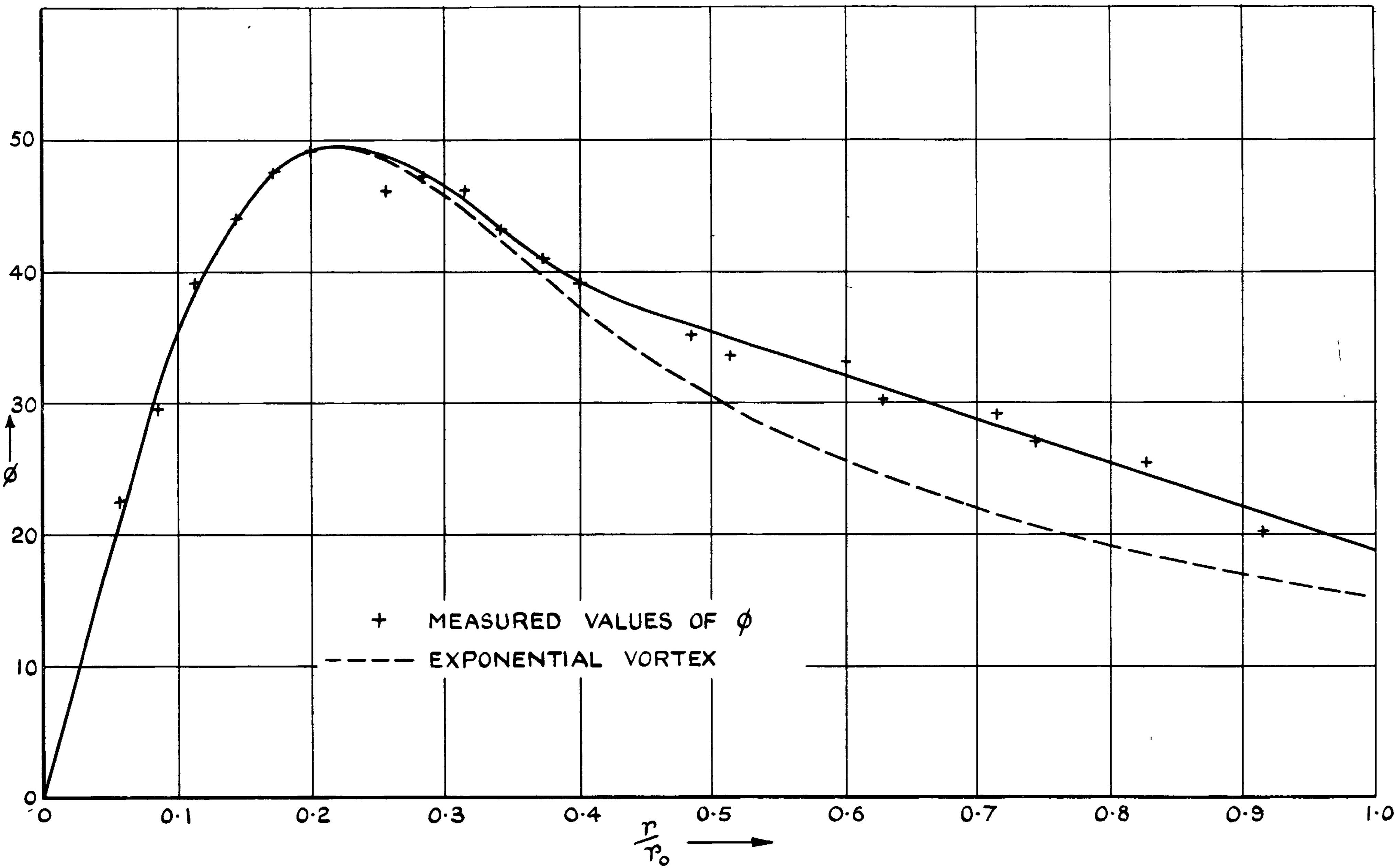

FIG. 4. DISTRIBUTION OF THE SWIRL ANGLE ACROSS THE VORTEX.

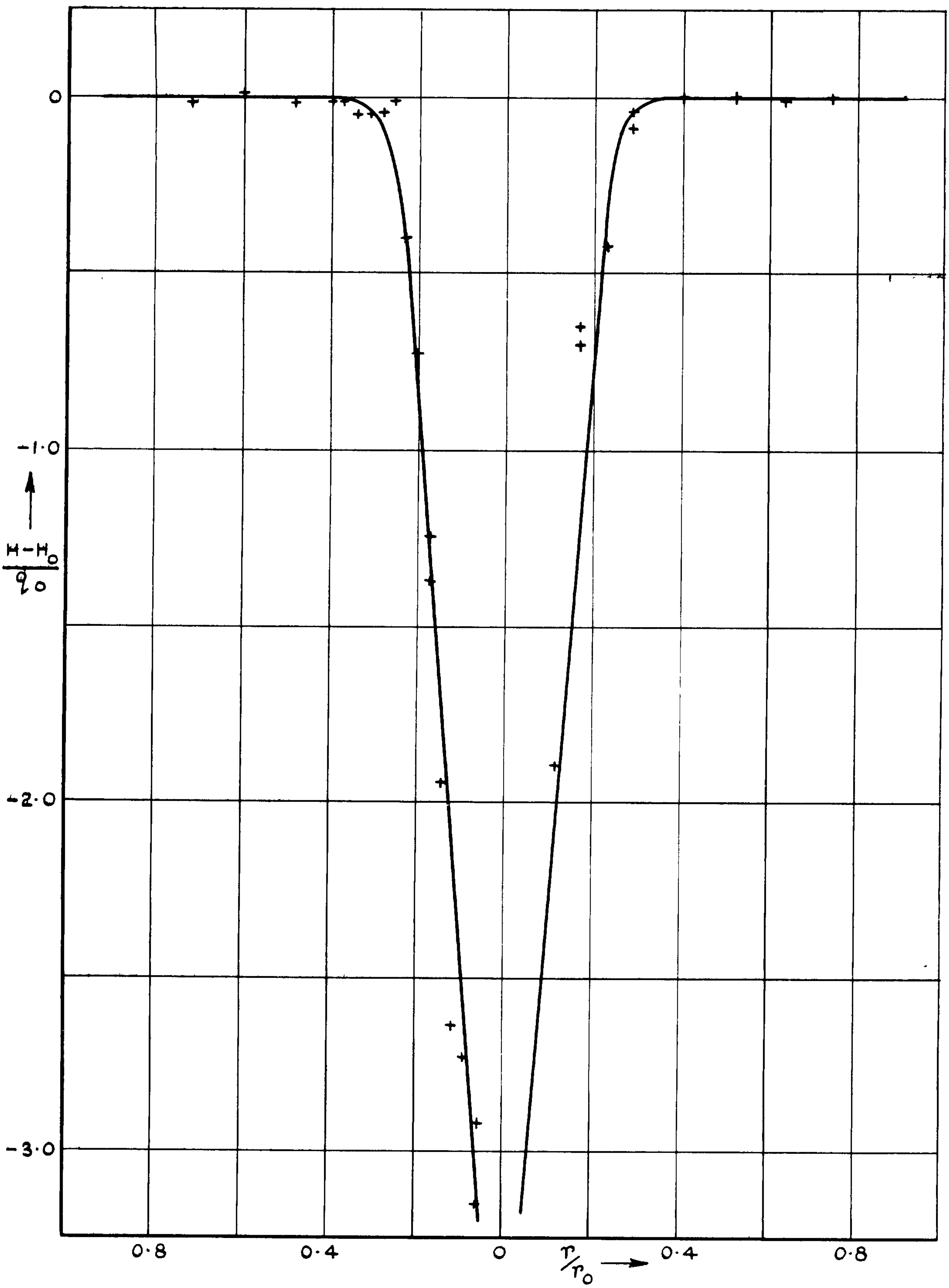

FIG. 5. DISTRIBUTION OF THE TOTAL PRESSURE ACROSS THE VORTEX.

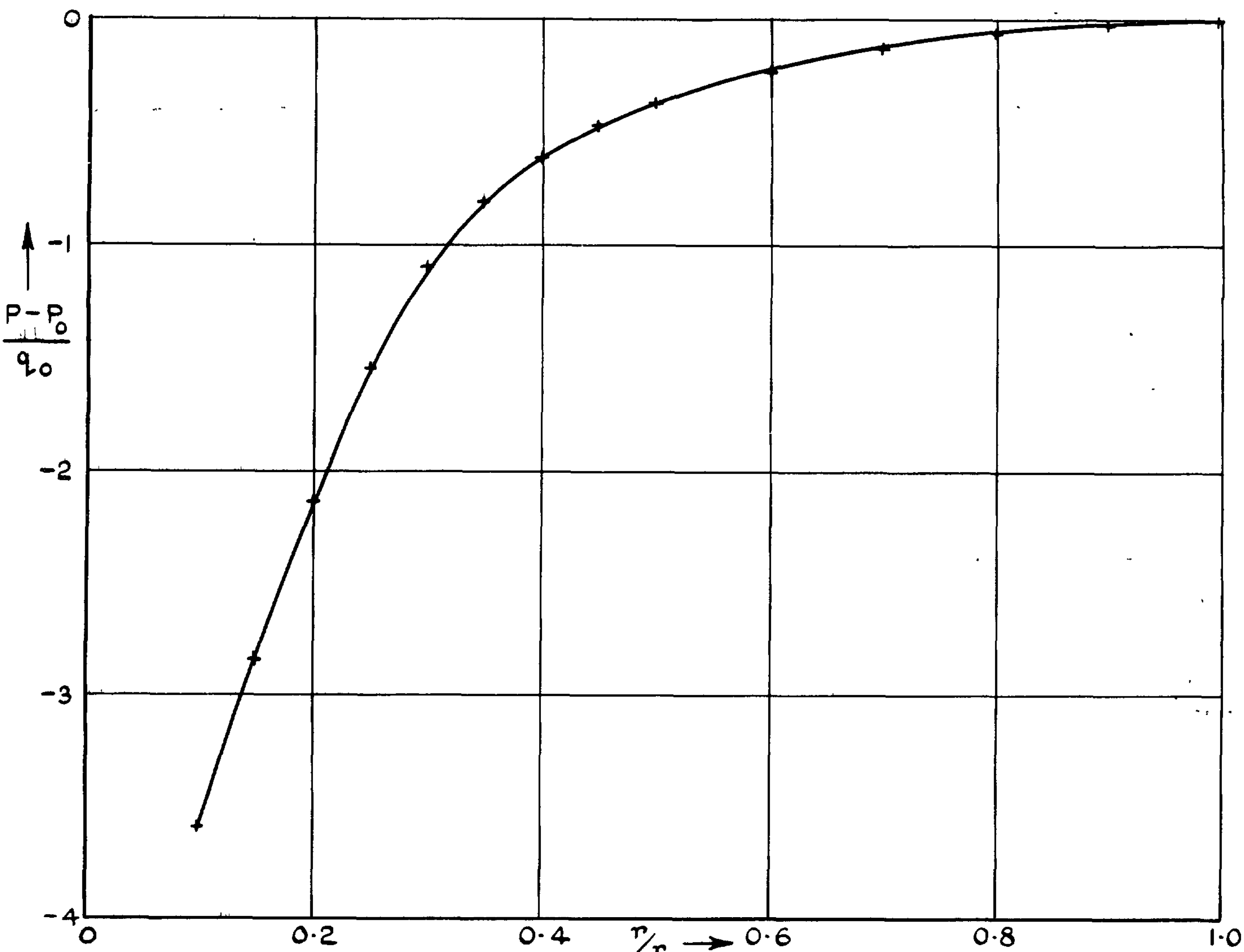

FIG. 6. STATIC PRESSURE DISTRIBUTION ACROSS THE VORTEX.

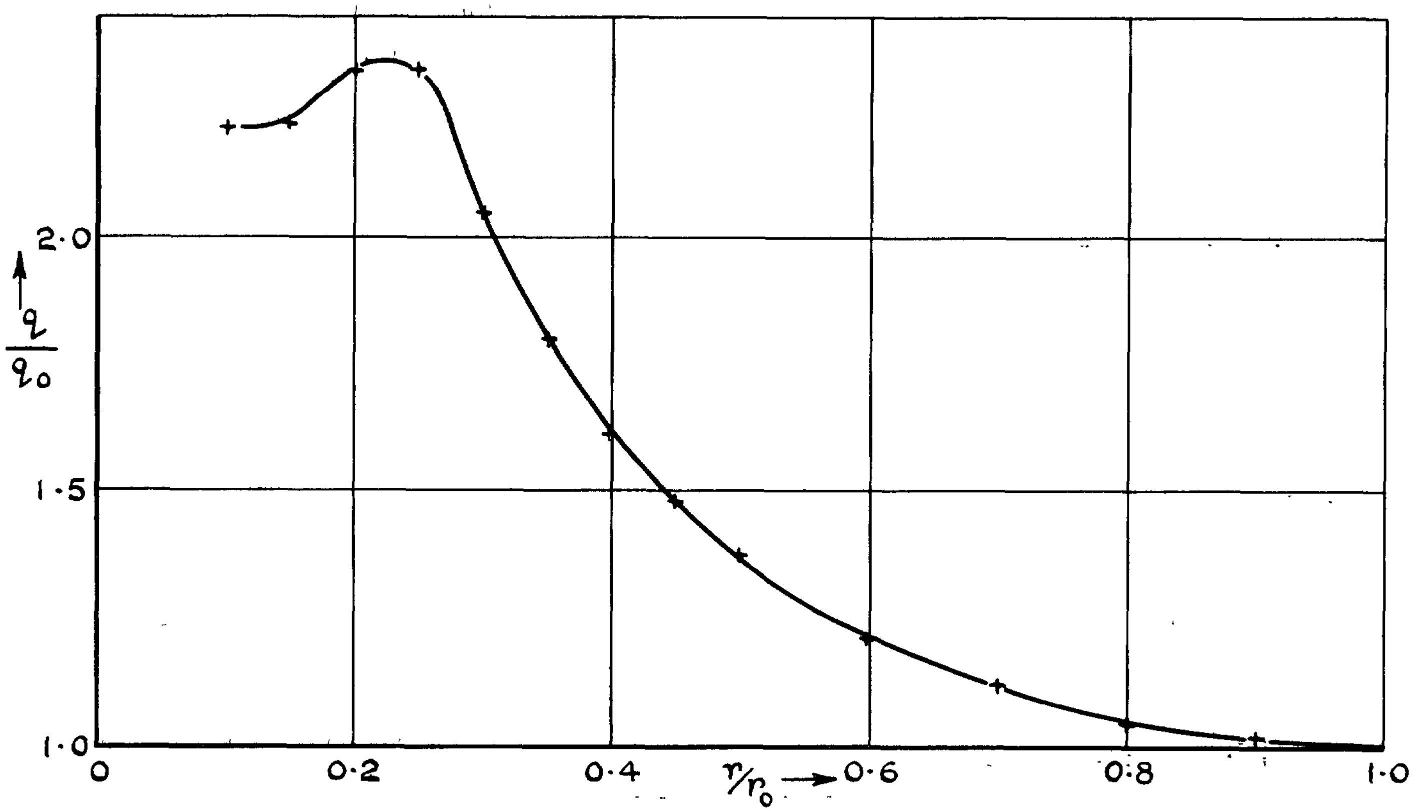

FIG. 7. DYNAMIC PRESSURE DISTRIBUTION ACROSS THE VORTEX.

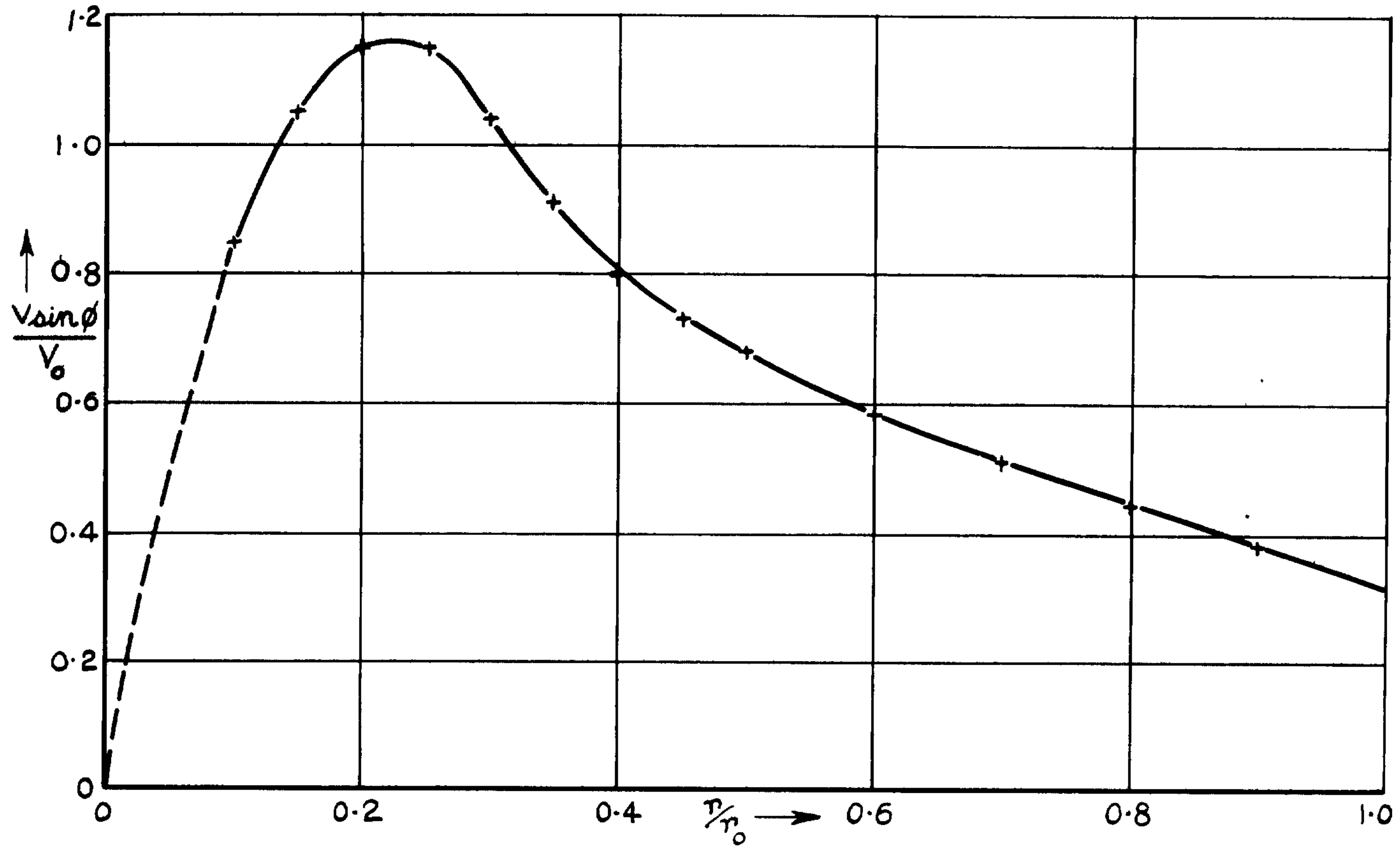

FIG. 8. CIRCUMFERENTIAL VELOCITY DISTRIBUTION ACROSS THE VORTEX.

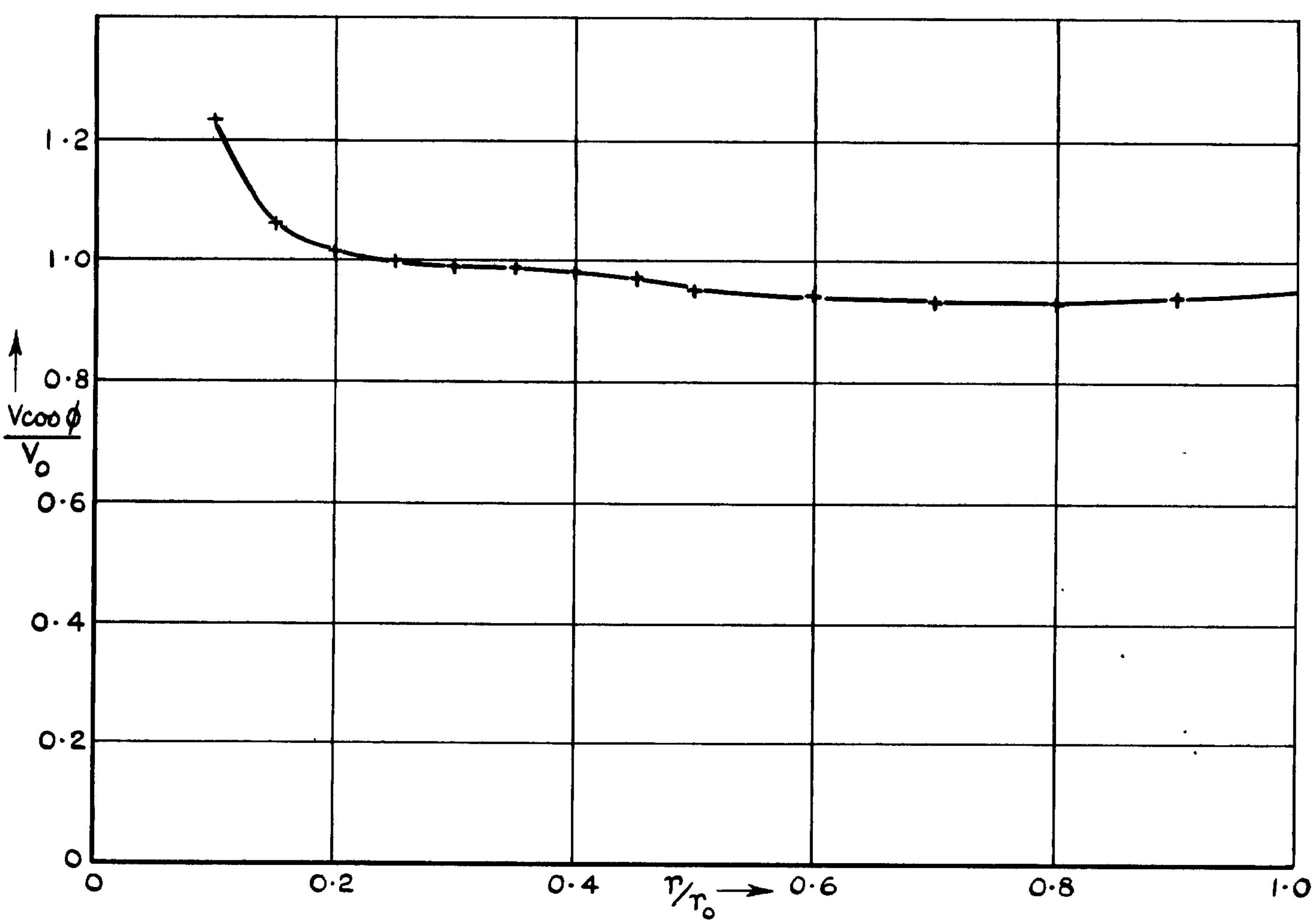

FIG. 9. AXIAL VELOCITY DISTRIBUTION ACROSS THE VORTEX.

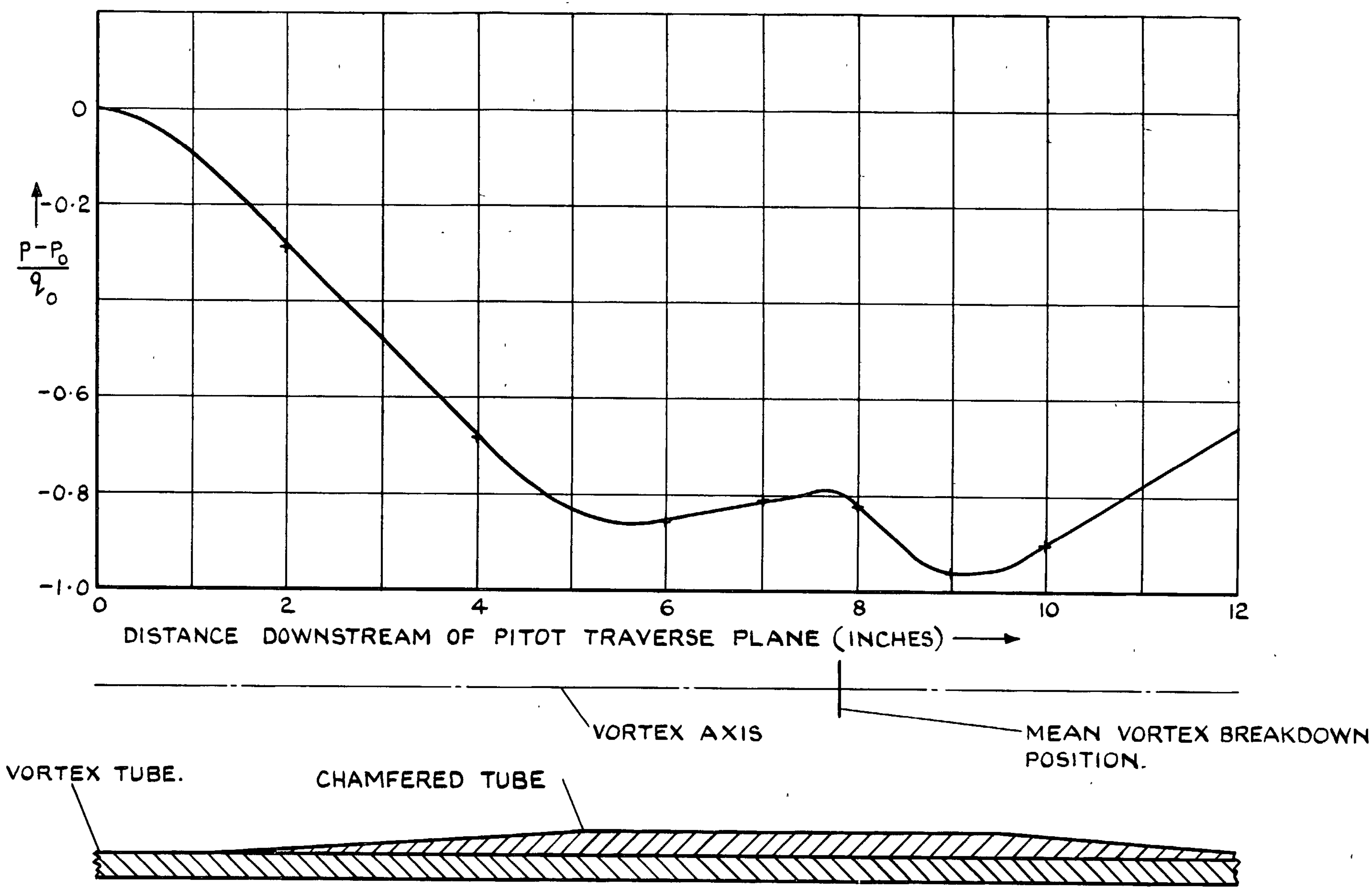

FIG. 10. STATIC PRESSURE VARIATION ALONG THE WALL OF THE VORTEX TUBE AND A DRAWING OF A SECTION OF THE WALL.

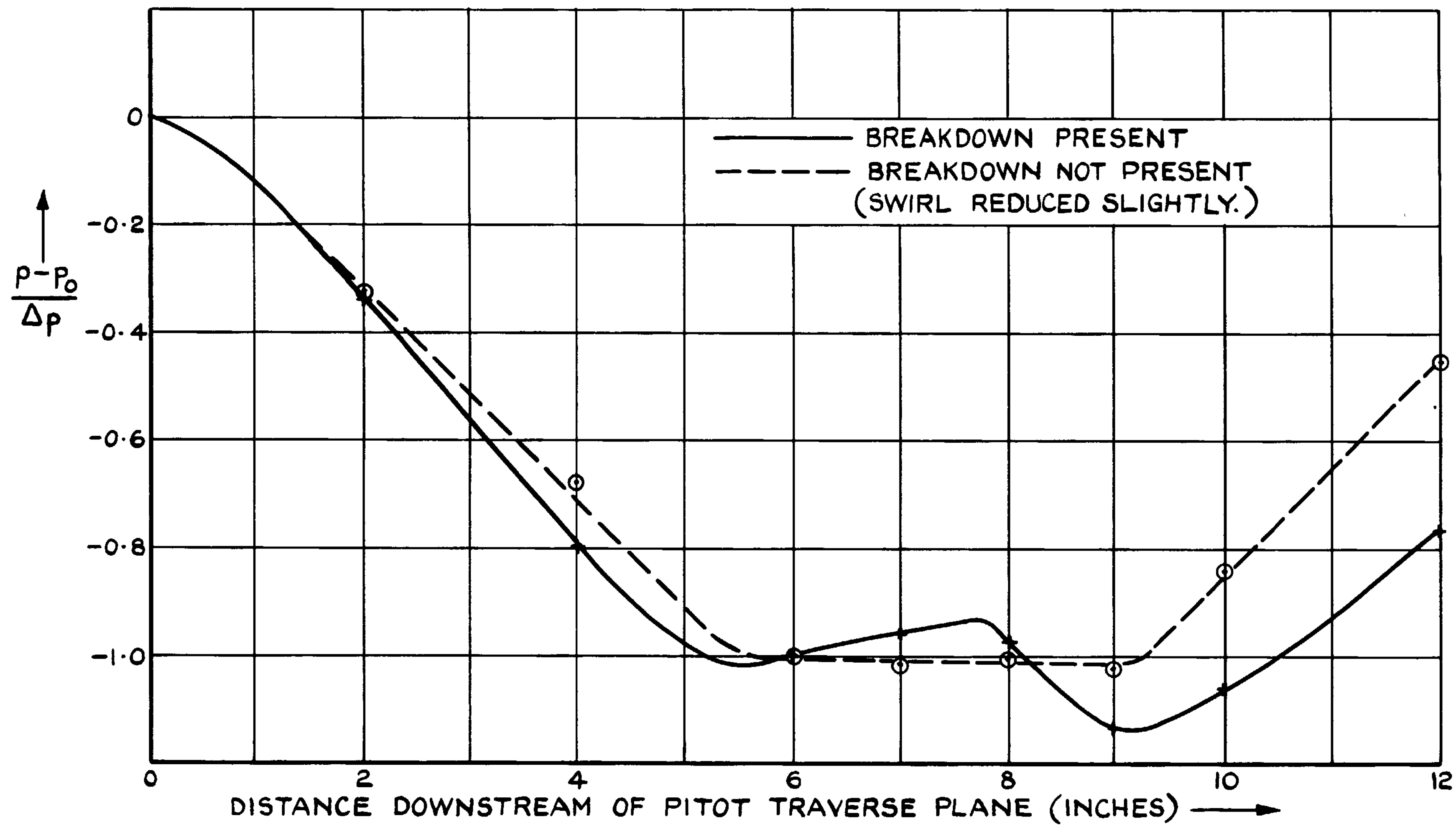

FIG. 11. STATIC PRESSURE VARIATION ALONG THE WALL OF THE VORTEX TUBE WITH AND WITHOUT VORTEX BREAKDOWN PRESENT.

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