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R. & M. No. 3037
(17,997)
A.R.C. Technical Report

MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

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LONDON: HER MAJESTY'S STATIONERY OFFICE
1958
PRICE 9s. 6*d*. NET

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*Reports and Memoranda No. 3037**

November, 1955

Summary.—Seven pressure probes have been tested in a uniform stream in order to ascertain the best types for measuring velocity and flow direction. Methods of calibration are discussed in section 3 together with the effects of wind speed, flow direction and turbulence on the calibration factors (section 4).

The performance of three of the probes in the turbulent boundary layer of a flat plate is analysed and their accuracies compared when they are used to estimate displacement and momentum thicknesses (section 6).

The Conrad probe is proved superior to other types for boundary-layer measurements. Further research on the lines indicated in section 7 is necessary before the best type of probe for use in regions of separated flow can be ascertained. The main features of the velocity-measuring probes are listed in Table 4.

For measuring static pressure in three-dimensional flow, a disc type of probe is described and shown to be insensitive to flow direction and scale effect (section 5).

1. *Introduction.*—In recent years, low-speed wind-tunnel research has been much concerned with swept-back wings and the behaviour of the flow past them. Although qualitative flow observations are fairly easily obtained, the detailed study of the three-dimensional–flow characteristics demands the precise measurement of flow parameters at many positions around the model. For this purpose it is necessary to consider means of improving flow-measuring instrumentation which should not only provide data of acceptable quality but be capable of rapid operation.

In general, there are two main types of flow in which measurements are likely to be required:

(*a*) The attached boundary layer where large changes in flow direction are confined to planes parallel to the wing surface, but where normal distance from the surface must be known to a high degree of accuracy.

(*b*) Regions of separated flow such as the wake or part-span vortices where large changes in flow direction may be encountered in any plane, but where measurements to a lesser degree of accuracy than for (*a*) are usually acceptable.

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Flow parameters in conditions similar to both (*a*) and (*b*) were obtained in the past by separate measurements of a number of flow quantities at one point, different instruments being used for each quantity. This method, apart from the excessive time required, proved inaccurate because of errors in the positioning of successive instruments. It became evident that a first step towards an improved technique was to find a single instrument which could be used to measure all the relevant quantities without the necessity of shutting down the tunnel to adjust or substitute probes. With this object, a number of instruments of the pressure-probe type have been tried. It was seen that for (*a*), the probe must be small, but the component of flow normal to the wing surface need not be measured. By contrast, for (*b*), with less likelihood of interference, a larger instrument can be tolerated but all the flow components are required. Therefore the probes fall into two main categories, those suitable for use in flow of type (*a*) and those for type (*b*).

At the National Physical Laboratory, measurements in a swept-wing boundary layer were first attempted by the Conrad yaw-meter method due to Brebner (1950) ; the results in this case were found to be unrepeatable owing to the inadequacy of the available traversing apparatus. An accurate apparatus (Ref. 2, 1953) was then constructed with which repeatable results were obtained, but some discrepancies remained and were attributed to the uncertain behaviour of the calibration factors. To discover the cause of the discrepancies, a series of tests were carried out in the N.P.L. Low-Turbulence Wind Tunnel where the performance of various probes was studied to determine the most satisfactory types for use in either boundary layers or regions of separated flow. The results of the investigation form the subject of this report.

2. *Details of Probes and Apparatus*.—2.1. *Choice and Construction of Probes*.—Eight types of pressure probe were tested. Drawings of these and their relevant dimensions are given in Figs. 1a to 1h. Their selection was governed partly by availability and ease of manufacture, but they form a representative group of the types used for wind-tunnel work in recent years. Spherical and hemispherical probes were intentionally omitted. Past experience has shown that probes of this type, small enough for most wind-tunnel work, are very difficult to make accurately ; even if this can be achieved, they are then liable to excessive lag in the transmission of pressure readings. Their properties have been discussed elsewhere by Winternitz[3] (1956).

The Conrad probe (Fig. 1a), evolved from a yaw meter design due to O. Conrad[4] (1950), consists of two nickel tubes soldered together side-by-side with their forward ends ground to form a point. Four of these probes were made in order to observe the effect of changing the external diameter of the tubes, the ratio of the internal to external diameters, and the apex angle between the forward faces.

The 3-tube and 5-tube probes (Figs. 1b and 1c) embody a central tube to which are attached side tubes with their forward ends chamfered in the same manner as the Conrad tubes.

The chisel, conical and pyramid probes, shown respectively in Figs. 1d, 1e and 1f, are all constructed in a similar manner from stainless-steel tubing. Individual tubes are selected to fit into an outer sheath, the interstices packed with copper wire and the whole soldered together. The forward end of the probe is then ground to its particular shape.

The axial probe, designed by Templin[5] (1954) at the National Aeronautical Establishment, Canada, has a solid tip (Fig. 1g) to which are connected three hypodermic tubes encased by a tapered shroud. The three pressure holes in the tip are drilled before final shaping.

Fig. 1h shows details of the disc-static probe which will be discussed later in section 5. It consists of a brass disc with its edge radiused and a small pressure hole drilled through its centre. An internal passage connects the central hole to a hypodermic tube fixed to the edge of the disc.

In the manufacture of all these probes, the internal diameter of the pressure tubes was increased from a position as close as possible to the measuring point. Thereby lag in the transmission of pressures was reduced to a minimum.

2.2. *Apparatus and Tests.*—All the probes were calibrated in the N.P.L. Low-Turbulence Wind Tunnel which had a 16-sided working-section with opposite faces 7 ft apart. The probes were mounted in turn on a traversing and yawing apparatus (Ref. 2) and provision was made for the accurate setting of pitch. Tests were carried out at wind speeds ranging between 50 ft/sec and 110 ft/sec. In some of the tests a steel-mesh screen was used to increase turbulence in the tunnel stream. The screen was $\frac{1}{8}$ in. thick with $\frac{3}{4}$ in. square holes separated by $\frac{1}{4}$ in. wide strips and was fixed normal to the flow at a position 6 ft upstream of the calibration position. Pressures were measured with a sloping-tube alcohol manometer which could be read to 0·01 in.; this gave an overall accuracy within approximately 1 per cent of the dynamic pressure in the worst case, this being the lowest wind speed of test.

In order to carry out boundary-layer measurements, a flat plate of 0·625 in. thickness, 4 ft span and 14 ft. chord was rigged horizontally in the working-section; incidence could be set to either 0 or +3 deg and surface pressure holes were disposed chordwise along its centre at intervals of 1 ft. To ensure a turbulent boundary layer, a trip wire was fixed to the surface at a short distance behind the faired leading edge. To increase the turbulence in certain tests, a spoiler of 1 in. square section was fitted to the surface immediately behind the trip wire. Before making measurements with the various probes, total-head and static-pressure traverses normal to the surface were carried out at selected positions along the centre-line of the flat plate. For these, a 0·048 in.-diameter total-head tube and a 0·063 in.-diameter static tube were used, both instruments having been carefully calibrated against an N.P.L. sub-standard pitot-static tube in the calibration position. It was considered that, in the absence of yaw and a change of pitch of less than 3 deg, the measurements so obtained were accurate to plus or minus $\frac{1}{2}$ per cent of the dynamic pressure at the edge of the boundary layer except in positions very close to the surface or when the spoiler was present.

3. *Principles of Calibration.*—In a steady stream, the magnitude and direction of the flow at any point may be defined by four independent parameters, the angle of pitch θ, the angle of yaw ψ, the total head H and the static pressure p. In order to calculate these from wind-tunnel observations, at least four quantities must be measured at the point and their relationship to the flow parameters ascertained by calibration of the measuring instrument. We now examine methods of calibrating the velocity measuring probes described in section 2.1.

3.1. 2-*Tube Method.*—For use in boundary layers where the velocity component normal to the surface may be ignored, we consider first the simple Conrad yaw meter (Fig. 1a). It is seen from Fig. 2a that, when the probe is yawed about the vertical axis through its apex, the difference in pressure in the two tubes $(p_1 - p_2)$ behaves linearly with ϕ, the angle between the longitudinal axis of the probe and the local flow direction for $|\phi| < 15$ deg. Moreover, as shown in Fig. 1 of Ref. 1, the values of $(p_1 - p_2)$ are substantially greater than those obtained with other types of yaw meter. Having recognized that a pressure probe could be fairly easily arranged to rotate about the vertical axis through its apex, Brebner has given in the Appendix to Ref. 1 a method of operation which may be simplified in the following way.

The probe is yawed until the pressures in the two tubes are equal, i.e., $p_1 = p_2 = p_0$, say. At this position $(\phi = 0)$, p_0 is noted together with the angle of yaw. The probe is then rotated to $\phi = \pm 10$ deg and the values of p_1 and p_2 recorded for both positions. Then, with the aid of the calibration factors K_1 and K_2:

$$\left.\begin{aligned} H &= p_0 + K_1 \Delta \\ p &= p_0 + K_2 \Delta \end{aligned}\right\} , \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

where

$$\Delta = \tfrac{1}{2}\{(p_1)_{+10} - (p_2)_{+10} - (p_1)_{-10} + (p_2)_{-10}\} .$$

The choice of $\phi = \pm 10$ deg is large enough to ensure 1 per cent accuracy in measuring ϕ , yet well within the range for linear Δ (Fig. 2a).

For all the probes illustrated in Figs. 1b to 1f, the behaviour of the side-tube pressures with yaw is similar to that of the Conrad probe, so that the method described above might be applied to any of them. For example, Fig. 2b shows the effect of yawing or pitching the symmetrical pyramid probe (Fig. 1f), whose upper and lower tubes could be used to indicate changes in pitch.

3.2. 3-*Tube Methods*.—The addition of a central tube to the Conrad probe to form the 3-tube probe (Fig. 1b), enables total head to be observed directly when the probe is rotated in the plane of the tubes until the side-tube pressures are equal ($p_1 = p_2 = p_0$). If p_3 is the pressure in the centre tube:

$$\left.\begin{aligned} H &= p_3 \\ p &= p_0 + K_3(p_3 - p_0) \end{aligned}\right\} , \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (2)$$

where K_3 is obtained from calibration.

Küchemann[6] (1955) describes a method due to Crabtree, who suggests that the 3-tube probe might be used without rotation. This method relies on three conditions being satisfied ; the difference between the pressures in both pairs of adjoining tubes must be linear and their sum in one pair must remain constant with respect to yaw. In practice, the first condition appears to be satisfied, but Fig. 3 shows that the sum of the presures in adjoining tubes is approximately constant only in limited ranges of yaw, 28 deg $< |\psi| < 47$ deg for this particular 3-tube probe. By increasing the apex angle of the probe to 146 deg these ranges could be brought together to give an approximately constant sum for $|\psi| < 15$ deg. This renders the method impracticable, since the sensitivity $(p_1 - p_2)/\phi$, which varies roughly as the cosine of half the apex angle, would be reduced by a factor of about one third.

3.3. 5-*Tube Methods*.—The methods mentioned so far in this section are intended primarily for conditions where the angle of pitch is negligible or its effect on the measured pressures is small within a limited range of θ . Where the flow is truly three-dimensional, it is necessary to measure a fourth quantity, either angle or pressure, to obtain all four flow parameters. Such measurements are usually required at positions far enough from the surface, to permit the use of a larger probe without introducing any serious interference effects.

The most direct method of measurement is to use a 5-tube probe (Fig. 1c), which can be aligned directly into wind so that the pressures in the four side tubes are equal ; the angles of pitch and yaw are indicated by the traversing apparatus, H is read from the centre tube and p can be obtained from equation (2) as for the 3-tube probe. Unfortunately, the mechanical problems involved in making the traversing apparatus are difficult to solve. It is therefore necessary to investigate other methods which require rotation of the probe about only one axis.

The following method has been examined. The 5-tube probe is yawed to obtain equal pressure readings in the side tubes, so that $p_1 = p_2 = p_0$. If p_3 and p_4 are the pressures in the upper and lower tubes and p_5 the centre-tube pressure:

$$\left.\begin{aligned} \theta &= C(p_4 - p_3)/(p_5 - p_0) \\ q &= H - p = K(p_5 - p_0) \\ H &= p_5 + F(\theta)\, q \end{aligned}\right\} , \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (3)$$

where C, K and $F(\theta)$ are obtained from calibration.

3.4. *Templin's Method.*—Another method, due to Templin[5], is to use a probe of the pattern shown in Fig. 1g. In this case, the probe is rotated about its longitudinal axis until the side-tube pressures are equal, when this pressure p_0 and the centre-tube pressure p_3 are recorded. Then the velocity vector lies in the plane containing the longitudinal axis and the normal to the plane through the side tubes. The probe is then rotated through 90 deg and the larger of the side-tube pressures p' is recorded; from this reading p', together with p_0 and p_3 from the previous position, the remaining flow parameters may be deduced from calibration curves. In the presence of scale effect at large flow angles, the method outlined above would require calibration charts. To facilitate the reduction of results when the angle Θ between the velocity vector and the axis of the probe does not exceed 15 deg, however, it is suggested here that calibration factors could be applied instead, the flow parameters being computed from the equations:

$$\left.\begin{aligned} \Theta &= C'(p' - p_0)/(p_3 - p_0) \\ q = H - p &= K'(p_3 - p_0) \\ H &= p_0 + F'q + G'(p' - p_0) \end{aligned}\right\}, \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (4)$$

where C', K', F', G' may depend on wind speed.

4. *Calibration Factors.*—The utility of any velocity measuring probe will depend ultimately on the manner in which the calibration factors vary with flow conditions. Changes in flow direction, Reynolds number, turbulence and velocity gradient are likely to have some effect. The uniform-stream calibration was intended to estimate the relative magnitude of the effects due to the first three of these variables. On the result of this, three of the probes were selected and the behaviour of their calibration factors was further examined in the presence of total-head gradient.

The apparatus used in the calibration tests has been described in section 2.2. Changes of flow direction were simulated by altering the attitude of the instruments in relation to the wind direction. Reynolds number was varied with wind speed and small-scale turbulence introduced by fitting the steel-mesh screen. To observe the effect of total-head gradient, measurements were made in the flat-plate boundary layer where turbulence could be further increased by attaching the spoiler. In no case was turbulence measured, but the perturbation of silk tufts held at the measuring positions showed that an appreciable increase resulted from either of the devices described.

4.1. 2-*Tube Method.*—*Uniform Stream.*—Results from the uniform-stream calibration of six types of probe to which the 2-tube method (section 3.1) could be applied are given in Figs. 4a, 4b, 5a, 5b, 6 and 7. As regards the various types of Conrad probe, it is seen in Fig. 4a and Fig. 6 that the effect of pitch on the sensitivity ratio $(p_1 - p_2)/q\phi$ for $|\theta| < 6$ deg is small in all cases and will scarcely affect the accuracy of measurement except when the sensitivity ratio itself is low. This is the case for the Conrad-(iii) probe, whose large apex angle reduces sensitivity by about 40 per cent. In Fig. 4b, scale effect is seen to be appreciable for the Conrad-(i) probe, but tends to disappear when the external diameter of the tubes is increased; scale effect does not appear to depend on the internal diameter, but reduction in the ratio d/D lowers the sensitivity. The introduction of small-scale turbulence by means of the screen (section 2.2) has no serious effect on the behaviour of the Conrad probes which are therefore likely to be suitable for boundary-layer exploration. For tests in boundary layers, the Conrad-(i) was selected as being conveniently small, and the Conrad-(iv) as being insensitive to scale effect; with these two probes, it was possible to study further the effect of varying the ratio d/D.

It is quite clear from Figs. 5a and 5b that of the five probes compared, all except the pyramid probe show a degree of sensitivity to pitch sufficient to preclude their use with the 2-tube method.

It follows that the chisel probe can be used only as a yaw meter. The conical probe can be used to measure flow direction, but, lacking a central tube, cannot at the same time provide sufficient data to estimate velocity. The pyramid probe, being reasonably insensitive to pitch, scale effect and small-scale turbulence, was selected as the third probe for boundary-layer tests.

A comparison of the Conrad-(i), Conrad-(iv) and pyramid probes in Fig. 6 shows them to be of practically uniform sensitivity. In Fig. 7, the calibration factor $K_1 = (H - p_0)/\Delta$, used to obtain total head, is plotted against θ for each of the three probes. In each case, K_1 appears to be independent of the flow conditions, provided that $|\theta| < 6$ deg. Constant values of the calibration factors defined in equation (1) are taken as follows:

Probe	K_1	K_2
Conrad-(i)	1·13	—
Conrad-(iv)	1·42	$-0{\cdot}93_5$
Pyramid	0·90	$-1{\cdot}53_5$

In the case of the Conrad-(i) probe, there is an appreciable scale effect, which can be represented by the formula:

$$- K_2 = 1{\cdot}03 - 0{\cdot}20 \log_{10} \frac{2{\cdot}16\Delta}{q_0}, \qquad \ldots \qquad (5)$$

where $q_0 = \frac{1}{2}\rho V^2$, when $V = 110$ ft/sec. In all cases the dynamic pressure is $q = (K_1 - K_2)\Delta$.

4.2. 2-*Tube Method.—Boundary Layers.*—The calibration factors, K_1, K_2 and $(K_1 - K_2)$ obtained from boundary-layer measurements with the Conrad-(i), Conrad-(iv) and pyramid probes are given in Figs. 8a, 8b and 8c respectively. For the Conrad probes corrections of $0{\cdot}18D$ have been applied to the vertical displacement, as suggested by Young and Maas[7] (1936) for total-head tubes. The calibration quantities, plotted against wind speed, include results from positions at the edge of the boundary layer, and at 0·5 and 0·2 of the boundary-layer thickness δ; a few results in the separated turbulent flow behind the spoiler (section 2.2) are also included. For each calibration factor a full-line curve indicates the values taken from the uniform-stream calibration.

For the Conrad-(i) and Conrad-(iv) probes, it is seen that the values of K_1 and K_2 from the uniform-stream calibration are in fair agreement with those estimated from measurements taken in the presence of a velocity gradient; of these two probes, the Conrad-(i) shows the least scatter. In the case of the pyramid probe, the boundary-layer values are somewhat lower than in the uniform stream, which suggests that free-stream values of K_1 and K_2 would tend to overestimate total head and underestimate static pressure when used for boundary layers. As may be expected, values of K_1 and K_2 at the edge of the boundary layer are generally close to the uniform-stream value, whilst for the larger probes at $0{\cdot}2\delta$ they are occasionally subject to interference effects. The effect of increasing the scale of turbulence is seen to be small.

4.3. 3-*Tube and* 5-*tube Methods.*—The 3-tube probe has been calibrated in a uniform stream on the basis of equation (2). From these measurements, the sensitivity ratio $(p_3 - p_0)/q$ has been plotted against velocity ($\theta = 0$) and against angle of pitch $\theta (V = 110$ ft/sec) in Fig. 9. Sensitivity and scale effect are compared with results from the Conrad-(i) and 5-tube probes; the effect of θ is compared with the 5-tube probe. The scale effect on $(p_3 - p_0)/q$ is seen to be similar to the effect on $(p_1 - p_2)/q\phi$ for the Conrad-(i) probe, but the 3-tube probe has only about three quarters of the sensitivity of the Conrad-(i) when $\phi = \pm 10$ deg. The lower sensitivity is quite offset by the rapidity of the 3-tube equi-balanced method; however, its extreme sensitivity to pitch renders it unsuitable for use in any but purely two-dimensional flow.

When upper and lower tubes are added to the 3-tube probe to form the 5-tube probe, the effect of pitch on $(p_5 - p_0)/q$ is small (Fig. 9), but the scale effect remains appreciable. This scale effect must be taken into account when calibrating for the 5-tube method using equations (3). The calibration factors from the uniform-stream calibration of the 5-tube probe are given in Fig. 10. With this method, it is seen that the accuracy of dynamic-pressure measurement diminishes rapidly for $|\theta| > 15$ deg, but the method could be used up to $|\theta| = 20$ deg if an accuracy of plus or minus 4 per cent is acceptable. It should be noted that this method can utilize the same type of traversing apparatus as the 2-tube method.

4.4. *Axial-Probe Methods.*—Uniform-stream calibration curves for the axial probe are shown in Fig. 11a where values from the Canadian tests (Ref. 5) are also plotted. The wind speed of the Canadian tests was 50 ft/sec. Calibration of the axial probe reveals a marked scale effect at the higher values of Θ and there is a discrepancy between the values of $(p_3 - p_0)/q$ obtained with the N.P.L. instrument and the values from Ref. 5. It is difficult to account for this discrepancy as the probe examined here is a fairly exact copy of the Canadian design; at the same time, the reasonably constant values of $(p_3 - p_0)/q$ for $\Theta < 15$ deg given by the N.P.L. instrument facilitate the application of calibration factors (equation (4)) for limited flow angles. The behaviour of such factors under various flow conditions is illustrated in Fig. 11b where a possible accuracy of plus or minus 2 per cent on velocity measurement is indicated for $|\Theta| < 15$ deg. If this is acceptable, equation (4) can be used with the values:

$$C' = 25 \cdot 3 \text{ deg}, \quad F' = 0 \cdot 55, \quad G' = 0 \cdot 07 \text{ and}$$

$$K' = 1 \cdot 69 - 0 \cdot 125 \log_{10} \frac{p_3 - p_0}{q_0}, \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (6)$$

where $q_0 = \frac{1}{2}\rho V^2$, when $V = 110$ ft/sec.

5. *Disc-Static Probe.*—Although not entirely relevant to this paper, the disc-static probe has been included as a type of static-pressure probe which is insensitive to changes of flow direction in one plane and is not subject to scale effect. The instrument, described in section 2.1 and illustrated in Fig. 1h, is shown to have the above properties in Fig. 12. Furthermore, if provision is made to rotate the disc about the vertical axis through its centre (Fig. 12), it can be used in three-dimensional flow where very large changes in flow direction occur. The probe was first calibrated in the N.P.L. 18-in. Octagonal Tunnel at wind speeds up to 70 ft/sec. It was observed to have negligible scale effect and a low degree of sensitivity to pitch. As shown in Fig. 12, the recorded pressure attained a well-defined maximum, as the disc was rotated in yaw to about minus or plus 4 deg from the 'into wind' position. Within these limits the recorded pressure remained practically constant; it is apparent that this property can be employed to align the disc approximately along the wind direction when this is unknown. Further tests in the Low-Turbulence Tunnel show that scale effect remains small between 50 and 110 ft/sec and that the reading is little affected by turbulence in the tunnel stream. The readings obtained with the present instrument require correction by about $0 \cdot 12$ of the dynamic pressure so that an approximate estimation of total head is necessary before the static pressure can be deduced to an accuracy of plus or minus 1 per cent of the dynamic pressure. By altering the edge shape or thickness ratio of the disc it would be possible to reduce this correction.

6. *Boundary-Layer Traverses.*—Measurements of boundary-layer velocity are most frequently undertaken in order to estimate the displacement thickness and momentum thickness:

$$\left.\begin{aligned} \delta_1 &= \int_0^\delta \left(1 - \frac{u}{U}\right) dz \\ \delta_2 &= \int_0^\delta \frac{u}{U}\left(1 - \frac{u}{U}\right) dz \end{aligned}\right\} . \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (7)$$

It is therefore of major interest to compare the performance of the Conrad-(i), Conrad-(iv) and pyramid probes when measurements with each are used to evaluate the above integrals. Results from nine different boundary-layer profiles on the flat plate have been taken. Initially, careful measurements were made with pitot and static tubes; the traverse positions and associated data are listed in Table 1. Two typical traverses are illustrated in Fig. 13a and Fig. 13b, where the total-head and static pressure deduced from measurements with the three probes are plotted together with curves obtained with the pitot and static tubes. The tendency for the pyramid probe to overestimate velocity is clearly shown. For the Conrad probes, no consistent effect appears to accompany a change in the ratio d/D. Tables 2 and 3 show respectively the values of δ_1 and δ_2 obtained with the pitot and static tubes together with available values from the three probes. To obtain these values rapidly from a minimum number of observations, use has been made of the formulae which are included under Table 3 and fully discussed in Ref. 8 (Garner. 1956). The use of these formulae is well justified by the comparison in Tables 2 and 3 of integrated values of δ_1 and δ_2 with those obtained with the formulae for each of the nine pitot and static traverses. Values computed by the two methods agree to within 1 per cent in nearly all cases. Figs. 14 and 15 are intended to illustrate the degree of correlation in δ_1 and δ_2 between results from the three probes and pitot and static measurements. The Conrad-(i) results are seen to be nearest to the line representing perfect correlation, although with this instrument, experimental scatter can be up to plus or minus 4 per cent. The general tendency of the pyramid probe to underestimate values of δ_1 and δ_2 is thought to be due partly to interference and partly to a change in K_1 and K_2 (section 4.2) associated with a total-head gradient.

The effect of flow conditions on the accuracy of velocity measurement does not alone dictate the type of probe best suited to boundary-layer exploration. Other factors, which may have no direct bearing on the overall accuracy but influence the choice of pressure probe, are ease of manufacture, size and rapidity of operation. Pressure probes comprising a simple arrangement of tubes are readily manufactured to a high degree of accuracy. The maximum size is usually limited by the minimum boundary-layer thickness to be encountered whereas the minimum size will depend both on the pressure-transmission lag and the accuracy attainable in manufacture. It has been seen here that no particular merit attaches to the use of tubing of ratio d/D less than $0 \cdot 60$, so that standard hypodermic tubing of this ratio can be used.

7. *Concluding Remarks.*—7.1. *Assessment of Probes.*—An assessment of the various pressure probes is given in Table 4, which lists their advantages and disadvantages when used to measure velocity and flow direction by the methods described in section 3. In summarizing the salient features of the probes and their methods of operation, consideration has been given to the overall requirements of pressure probes for wind-tunnel work:

(*a*) Small size with structural stiffness

(*b*) All measurements as nearly as possible at a point

(*c*) Rapid pressure response

(*d*) Calibration unaffected by flow conditions

(*e*) Simplicity of accurate construction

(*f*) All the required measurements from one instrument

(*g*) Rapid measurements at a number of points by remote control.

The last two properties are almost essential for detailed exploration of three-dimensional flows.

7.2. *Boundary-Layer Measurements.*—For velocity measurement in the attached three-dimensional boundary layer, the Conrad probe (Fig. 1a) is suitable and can be calibrated in the manner described in section 3.1.

From the free-stream calibration (Figs. 4b, 6 and 7) the Conrad-(iv) appears slightly superior to the Conrad-(i) mainly on account of smaller scale effect. Further calibration in the boundary layer (Figs. 8a and 8b) reveals this to be misleading, as variations in the calibration factors K_1 and K_2 under boundary-layer conditions suggest for velocity measurement an accuracy of plus or minus $2 \cdot 4$ per cent for the Conrad-(iv) and plus or minus $1 \cdot 6$ per cent for the Conrad-(i). The pyramid probe (Fig. 1f) does not measure velocities in boundary layers more accurately than plus or minus $3 \cdot 3$ per cent.

From boundary-layer traverses with the Conrad-(i), Conrad-(iv) and pyramid probes, the root-mean-square error in the estimation of displacement thickness δ_1 (Fig. 14) is respectively $3 \cdot 5$, 5 and 11 per cent, and for momentum thickness (Fig. 15) is 3, $4 \cdot 5$ and 9 per cent.

Besides showing more consistently accurate results, the Conrad-(i) probe is preferred to the Conrad-(iv) because the ratio $d/D = 0 \cdot 6$ allows for a smaller probe with less pressure transmission lag or danger of blockage due to dust particles.

The 3-tube, 5-tube, chisel, pyramid and conical probes are unlikely to be of use for measurements in three-dimensional boundary layers (sections 4.1, 4.2 and 4.3).

7.3. *Measurements in Detached Flow.*—It is premature to suggest that any pressure probe will give acceptable results under all possible conditions of detached flow. Generally, a sharp-edged instrument is preferred to a rounded one, boundary-layer transition at the nose being affected less by Reynolds number.

The 5-tube probe could be used equi-balanced, or with two calibration factors and one curve (Fig. 10), providing the angle of pitch is less than 15 deg.

Similarly, the axial probe could be used with calibration factors for values of the mean-flow angle Θ less than 15 deg (Fig. 11b). For $\Theta > 15$ deg, the calibration requires two charts and a single curve for p (Fig. 11a).

Where very large changes in flow direction occur, static pressure could be measured with a disc probe (section 5). Tests show the disc-static probe (Fig. 1h) to be essentially free from scale effect at wind speeds below 110 ft/sec.

7.4. *Future Work.*—It is probable that the best results in detached flow would be obtained using instruments of the 5-tube type with apparatus capable of aligning the probe to the local mean flow direction. An apparatus of this type due to Fail (Ref. 6) has been used at the Royal Aircraft Establishment; development of a remotely controlled apparatus is being undertaken at N.P.L.

In a programme of tests about to be started at N.P.L., it is proposed to examine the behaviour of Conrad probes in the boundary layer of a two-dimensional model aerofoil. The 5-tube and axial probes will be tested in the wake of the aerofoil with separated flow of high turbulence intensity and low mean velocity. Under these conditions it is known that different pressure probes give inconsistent measurements of mean flow. In the opinion of the authors, this may be due to the relative sensitivities of the probes to fluctuations in flow direction. It is hoped that from hot-wire turbulence measurements and a knowledge of the steady-flow characteristics of the probes it may be possible to ascertain to what extent they measure the true mean velocity.

8. *Acknowledgements.*—The authors wish to acknowledge the help of Miss S. M. Passmore, who carried out much of the computation, and Miss I. G. Davidson, who assisted Mr. Walshe with the experimental work. Mr. J. H. Warsap was responsible for the calibration of the disc-static probe.

NOTATION

D	External diameter of individual probe tube or of circular-section probe
d	Internal diameter of probe tube
H	Total head
K_1, K_2	Calibration factors (2-tube method)
p	Static pressure
p_0	Pressure in side tubes when probe is orientated until these give equal readings
p_n	Pressure in tube n of probe ($n = 1, 2, \ldots 5$)
p'	Pressure in side tube of axial probe (section 3.4)
q	Dynamic pressure ($= \frac{1}{2}\rho V^2$)
q_0	Reference value of q ($V = 110$ ft/sec)
$R_{\delta 2}$	Reynolds number of boundary layer ($= U\delta_2/\nu$)
U	Velocity at edge of boundary layer
u	Velocity at distance z from surface
V	Velocity
z	Normal distance from surface
Δ	Average pressure difference between side tubes {equation (1)}
δ	Thickness of boundary layer
δ_1	Displacement thickness
δ_2	Momentum thickness
Θ	Angle of flow relative to axial probe (section 3.4)
θ	Angle of pitch
ν	Kinematic viscosity
ρ	Density of fluid
ϕ	Angle of probe in yaw (relative to ψ)
ψ	Angle of flow in yaw

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TABLE 1

Boundary-Layer Data

Case	Incidence (deg)	Position (ft)	U (ft/sec)	δ (in.)	δ_1/δ_2	$R_{\delta 2} \times 10^{-3}$
1	0	2	113	0·53	$1{\cdot}38_5$	3·3
2	0	8	113	1·35	$1{\cdot}35_5$	8·0
3	0	12	115	2·00	1·35	11·5
4	0	12	67	1·90	1·37	7·2
5	0	12	54	2·30	1·33	6·3
6	3	4	116	1·00	$1{\cdot}36_5$	6·0
7	3	12	116	2·20	1·33	13·1
8	3	4	68	1·10	1·37	3·9
9	3	12	68	2·25	1·35	8·4

TABLE 2

Values of δ_1 (in.)

Probe	Pitot and Static		Conrad-(i)	Conrad-(iv)	Pyramid
Case	Integrated	Formula	Formula	Formula	Formula
1	0·0761	0·0754	0·0717	—	—
2	0·1837	0·1819	0·1839	—	0·1701
3	0·2587	0·2557	0·2414	0·2434	0·2260
4	0·2785	0·2763	0·2662	—	—
5	0·2937	0·2954	0·2806	0·2765	—
6	0·1345	0·1347	0·1355	0·1244	0·1171
7	0·2866	0·2860	0·2803	0·2776	—
8	0·1498	0·1490	0·1520	0·1448	0·1308
9	0·3167	0·3141	0·3236	0·3107	—

TABLE 3

Values of δ_2 (in.)

Probe	Pitot and Static		Conrad-(i)	Conrad-(iv)	Pyramid
Case	Integrated	Formula	Formula	Formula	Formula
1	0·0550	0·0543	0·0522	—	—
2	0·1357	0·1359	0·1373	—	0·1292
3	0·1915	0·1915	0·1810	0·1822	0·1724
4	0·2035	0·2044	0·1989	—	—
5	0·2206	0·2228	0·2116	0·2088	—
6	0·0985	0·0987	0·0995	0·0922	0·0880
7	0·2155	0·2154	0·2112	0·2092	—
8	0·1092	0·1086	0·1102	0·1059	0·0977
9	0·2348	0·2340	0·2414	0·2318	—

$$\left.\begin{aligned} \frac{\delta_1}{\delta} &= 0{\cdot}8769 - 0{\cdot}3370\left(\frac{u}{U}\right)_{0\cdot 1468\delta} - 0{\cdot}5289\left(\frac{u}{U}\right)_{0\cdot 6195\delta} \\ \frac{\delta_2}{\delta} &= 0{\cdot}8774_5 - 0{\cdot}3302\left(\frac{u}{U}\right)^2_{0\cdot 1468\delta} - 0{\cdot}5310\left(\frac{u}{U}\right)^2_{0\cdot 6195\delta} - \frac{\delta_1}{\delta} \end{aligned}\right\}$$

TABLE 4

Summary of Probe Characteristics

The following probes are assessed for boundary-layer work only requiring measurements of yaw and velocity.

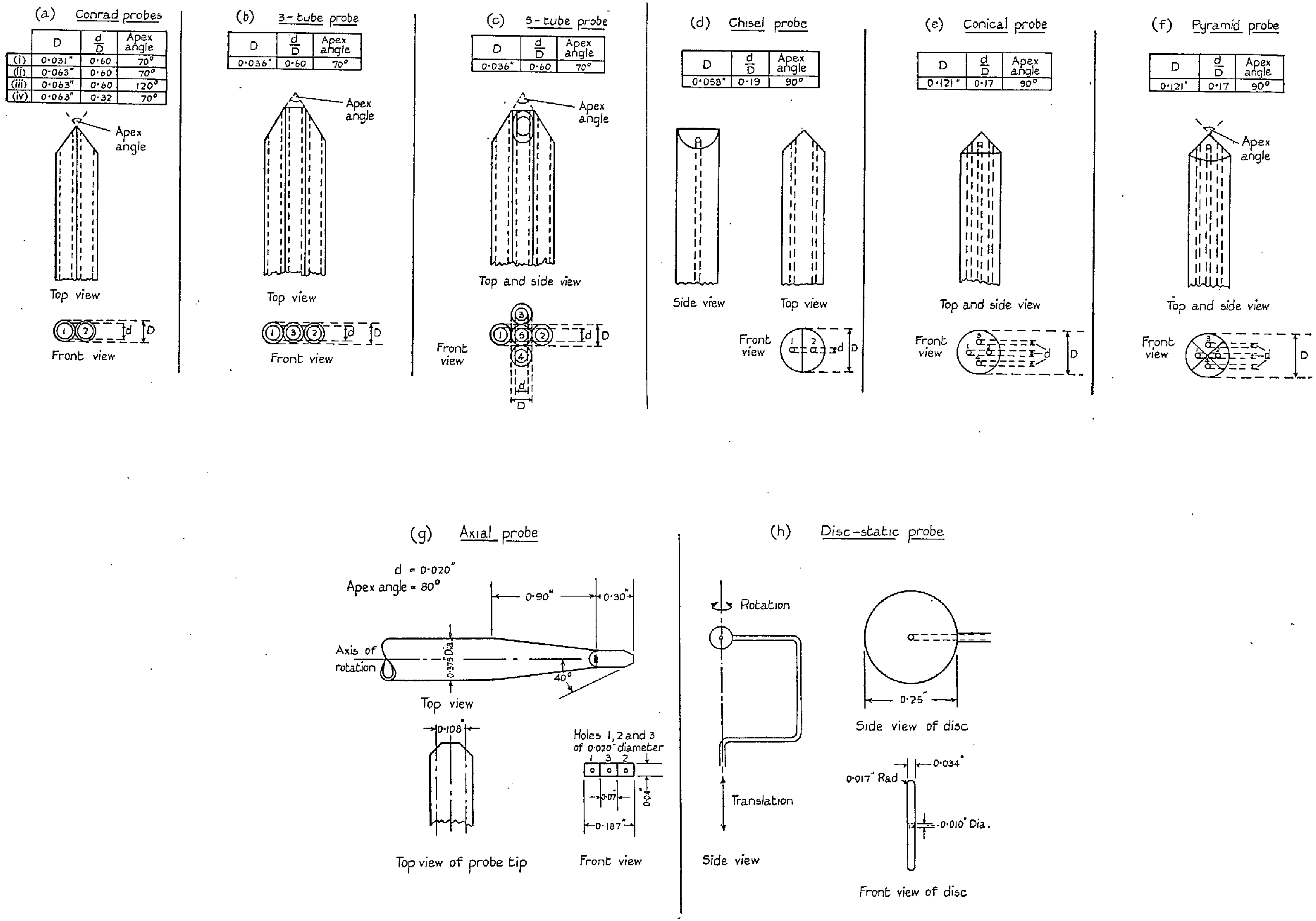
Probe	Fig. No.	Method	Advantages	Disadvantages
Conrad	1a	2-tube	Easily manufactured. Measurements nearly at a point. Practically insensitive to ± 6 deg of pitch	Requires accurate yawing apparatus
Conrad-(i)	1a	2-tube	Small (suitable for boundary-layer measurement). Most accurate	Scale effect must be taken into account
Conrad-(ii)	1a	2-tube	High sensitivity. No scale effect	Large for boundary-layer work
Conrad-(iii)	1a	2-tube	No special advantages	Low sensitivity. Appreciable scale effect
Conrad-(iv)	1a	2-tube	No scale effect	Large for boundary-layer work (if reduced, internal diameter too small)
3-tube	1b	equi-balanced	Direct reading of total head. Very rapid	Sensitive to pitch and scale effect
3-tube	1b	2-tube	Direct reading of total head	Sensitive to pitch and scale effect Requires accurate yawing apparatus
Chisel	1d	2-tube	No special advantages	Very sensitive to pitch. Unsuitable for 3-dimensional work. Slow response. Difficult to manufacture

TABLE 4—*continued*

Summary of Probe Characteristics

The following probes are somewhat large for boundary layers and are assessed for other three-dimensional work. In addition to yaw and velocity, the angle of pitch is obtainable with all these probes.

Probe	Fig. No.	Method	Advantages	Disadvantages
5-tube	1c	equi-balanced	Direct reading of total head. Rapid	Requires elaborate yawing and pitching apparatus. Appreciable scale effect
5-tube	1c	2-tube	High sensitivity	Sensitive to pitch and scale effect. Accurate yawing required
5-tube	1c	5-tube	Requires only to be yawed	Unsatisfactory for large pitch (> 20 deg)
Conical	1e	2-tube	No special advantages	Difficult to manufacture. Very sensitive to pitch
Pyramid	1f	2-tube	Insensitive to limited pitch. No scale effect	Difficult to manufacture
Axial	1g	Templin (section 3.4)	Requires rotation about probe axis only	Requires careful manufacture. Appreciable scale effect (requires calibration charts)
Axial	1g	Equation (4)	Requires rotation about probe axis only. Simple calibration	Scale effect. Flow angles limited to 15 deg



FIGS. 1a to 1h. Details of various probes.

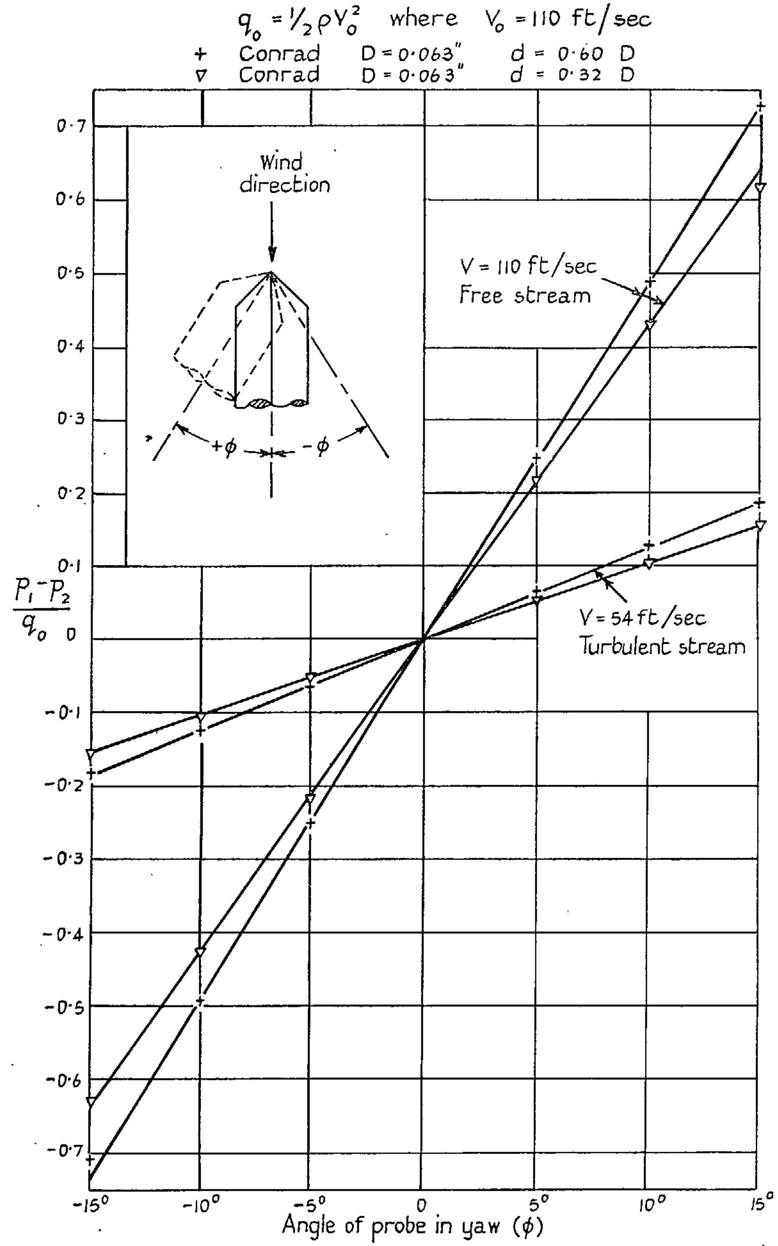


FIG. 2a. Effect of yawing. Conrad probes at zero pitch.

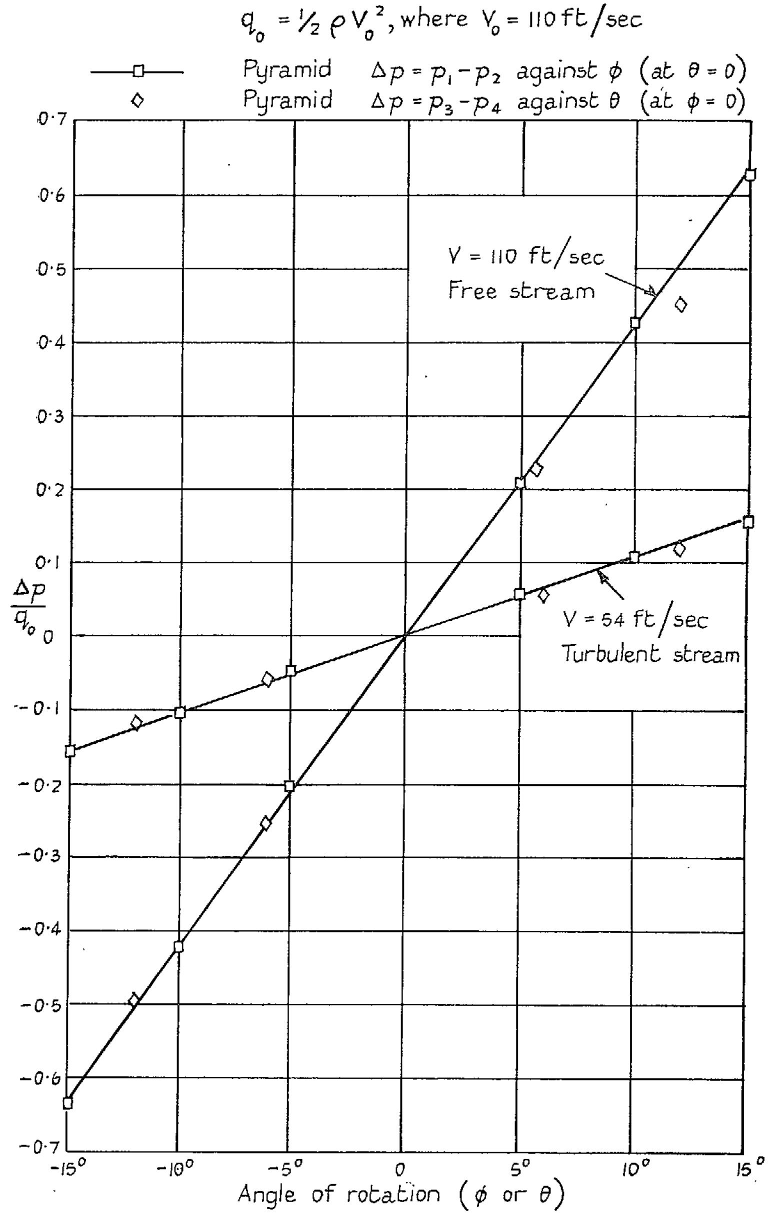


FIG. 2b. Effect of rotating Pyramid probe in yaw and pitch.

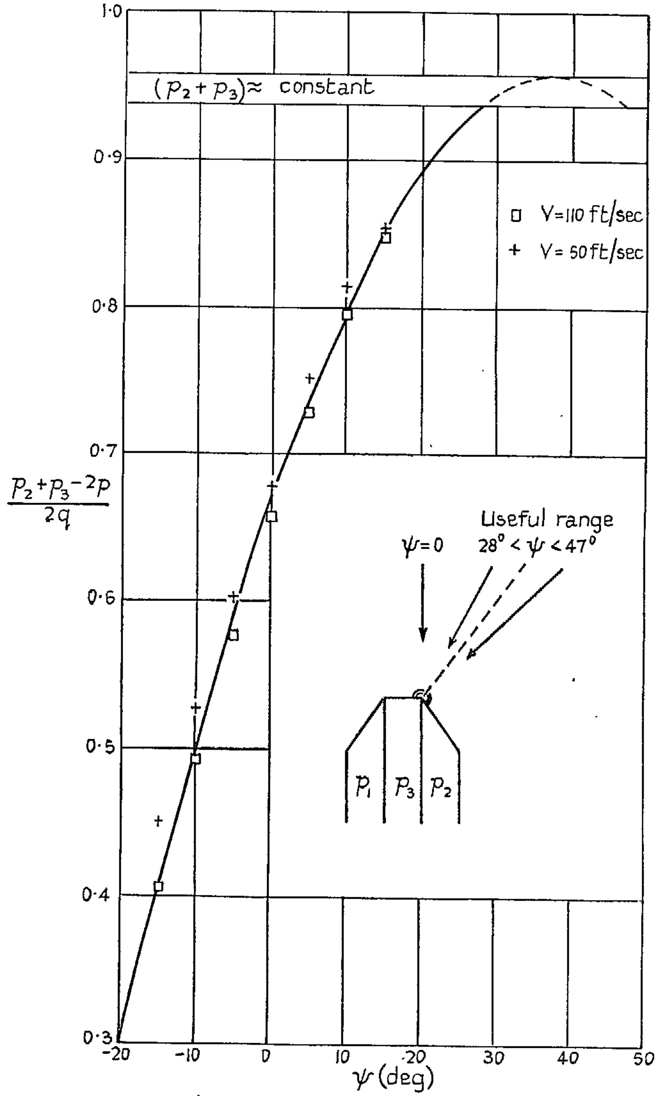


FIG. 3. Limitation of non-rotating 3-tube probe.

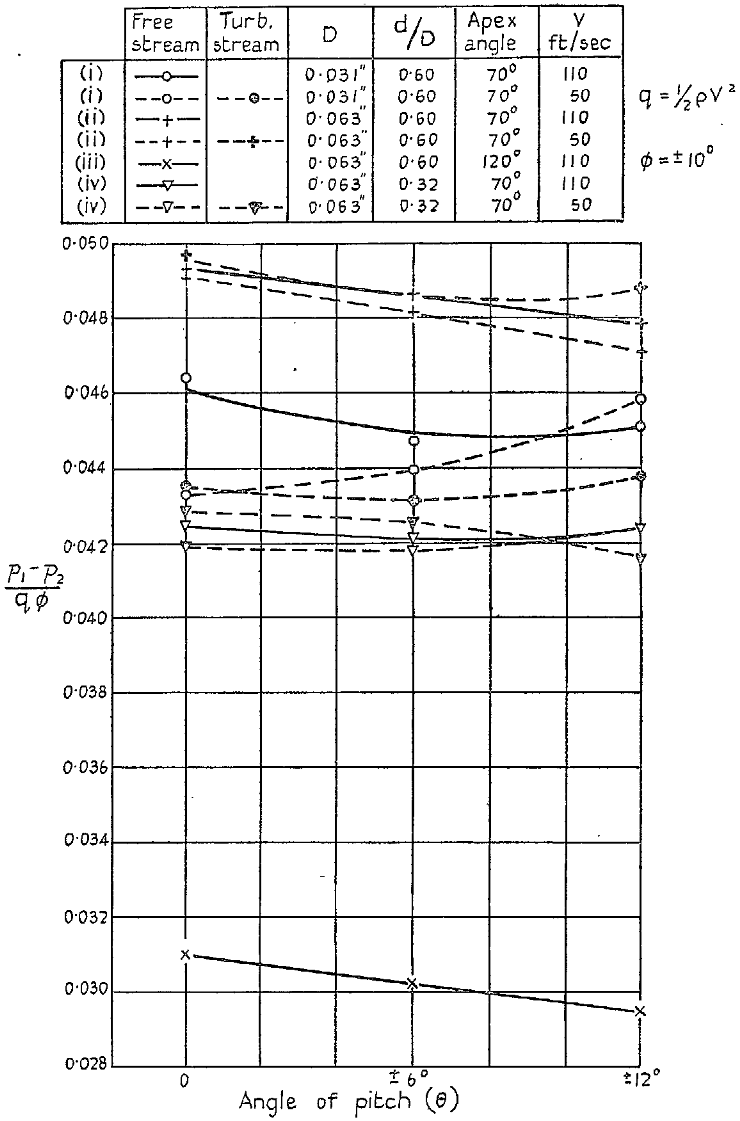


FIG. 4a. Sensitivity of Conrad probes in measuring velocity.—Effect of pitch.

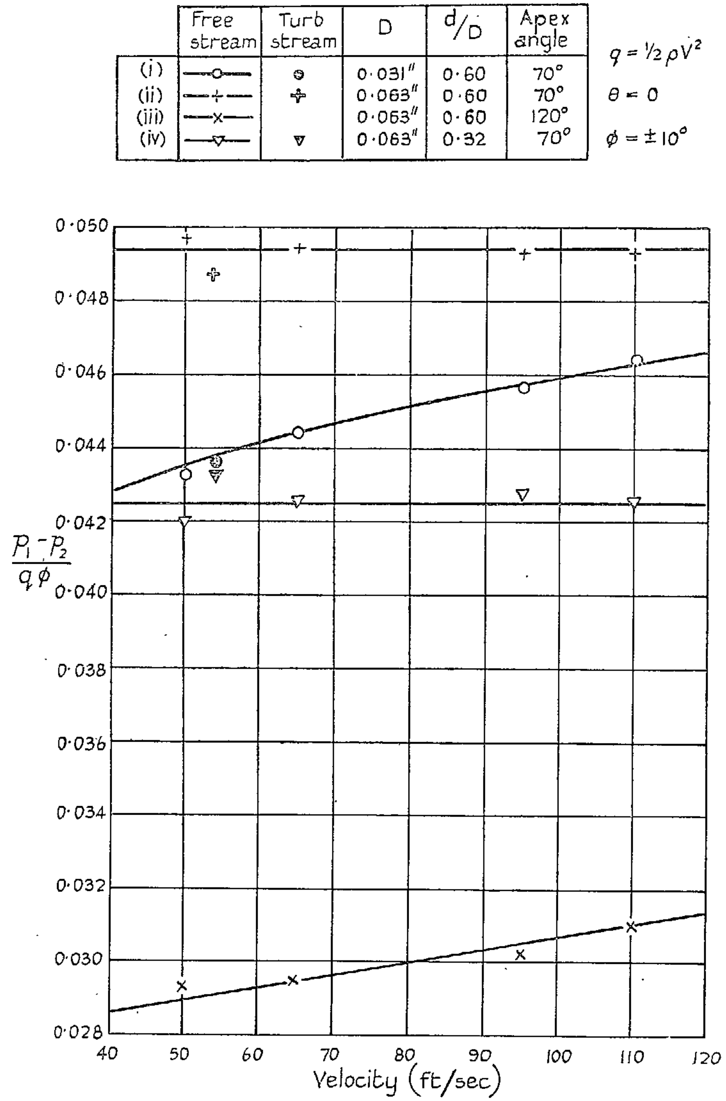


FIG. 4b. Sensitivity of Conrad probes in measuring velocity.—Effect of velocity.

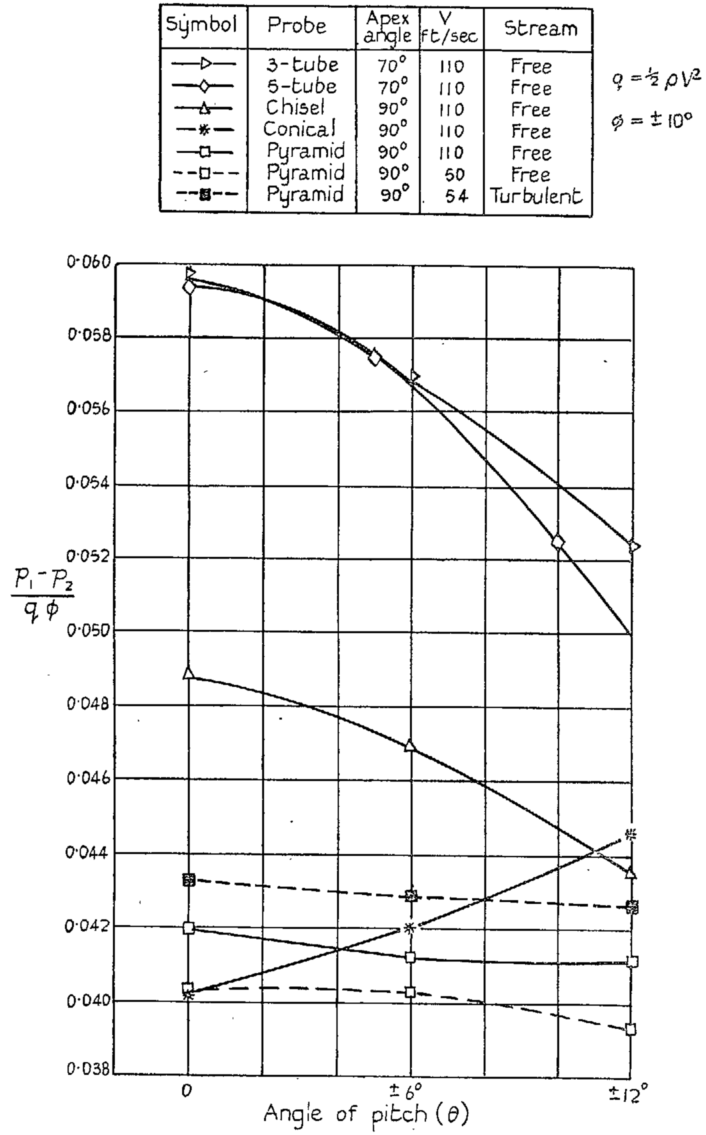


FIG. 5a. Sensitivity of various probes in measuring velocity.—Effect of pitch.

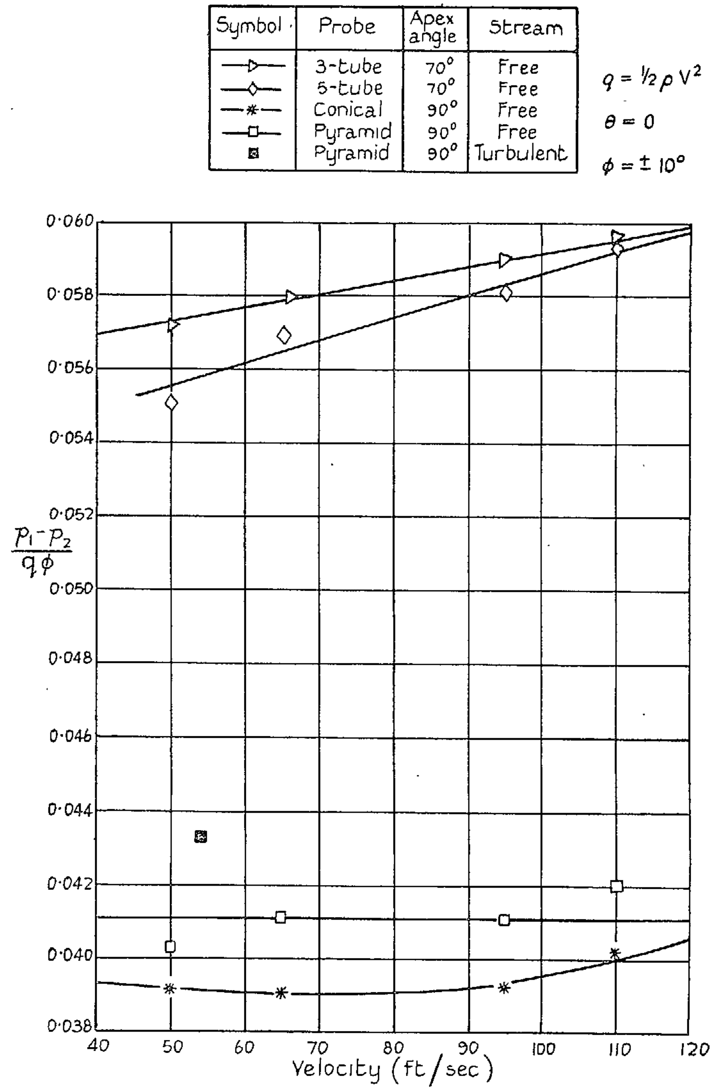


FIG. 5b.—Sensitivity of various probes in measuring velocity.—Effect of velocity.

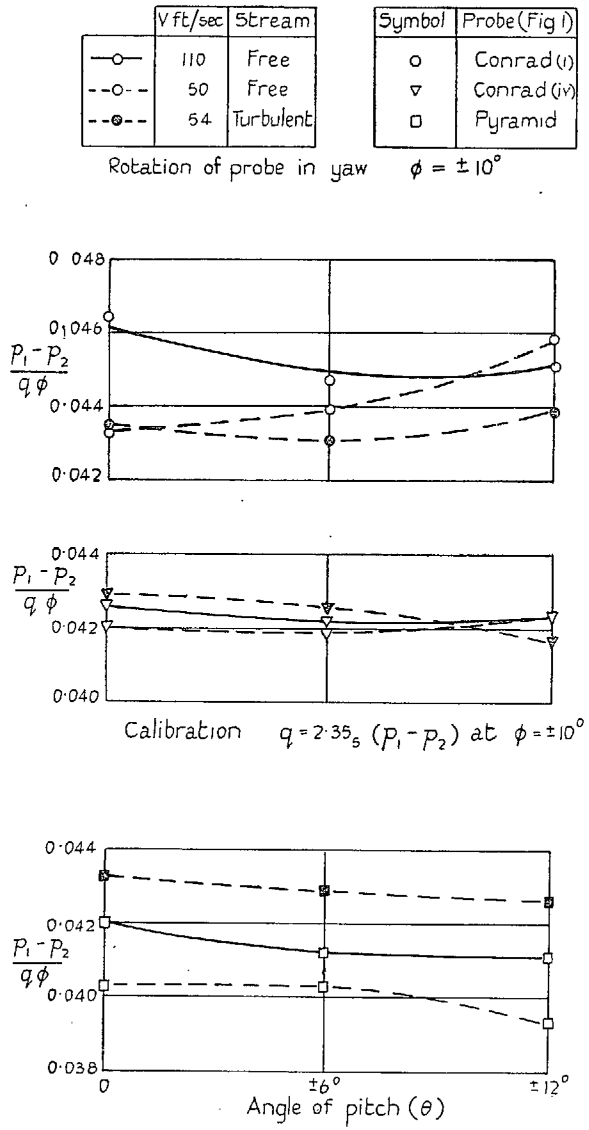


FIG. 6. Velocity-measuring probes of practically uniform sensitivity.

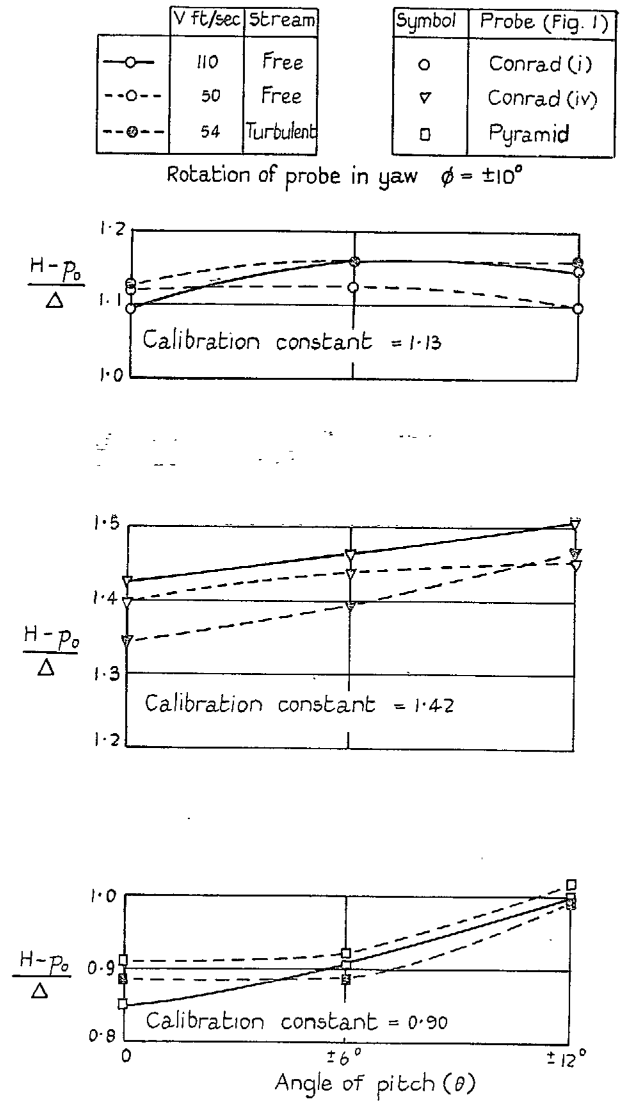


FIG. 7. Calibration constants for obtaining total head.

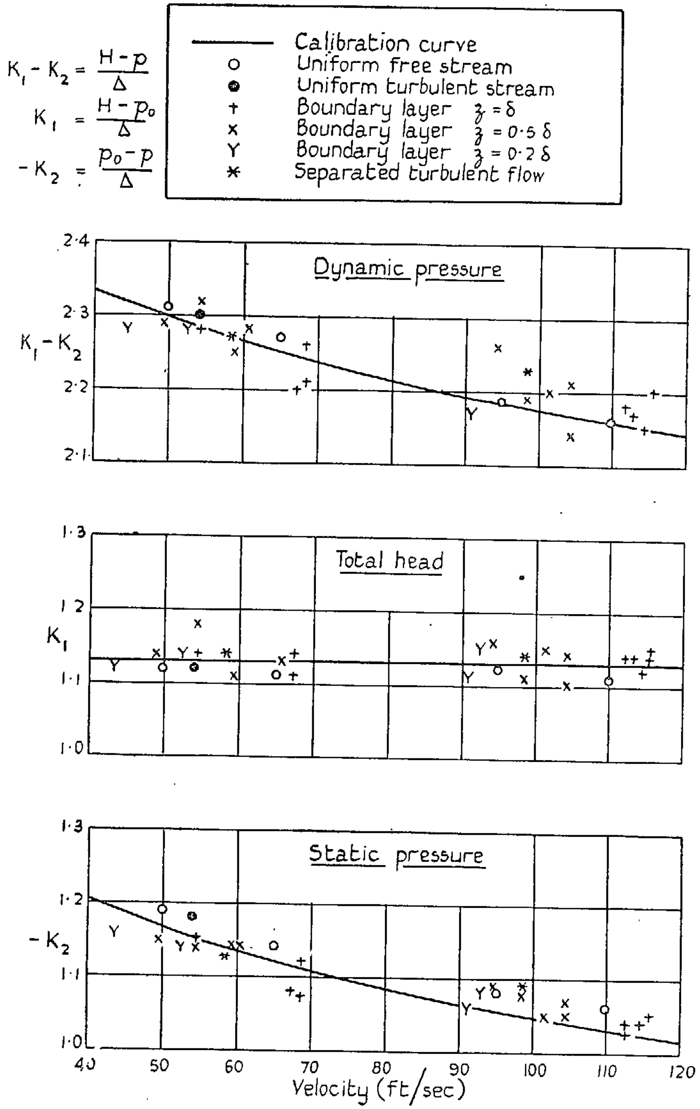


FIG. 8a. Dependence of calibration on flow conditions.—Conrad-(i) probe.

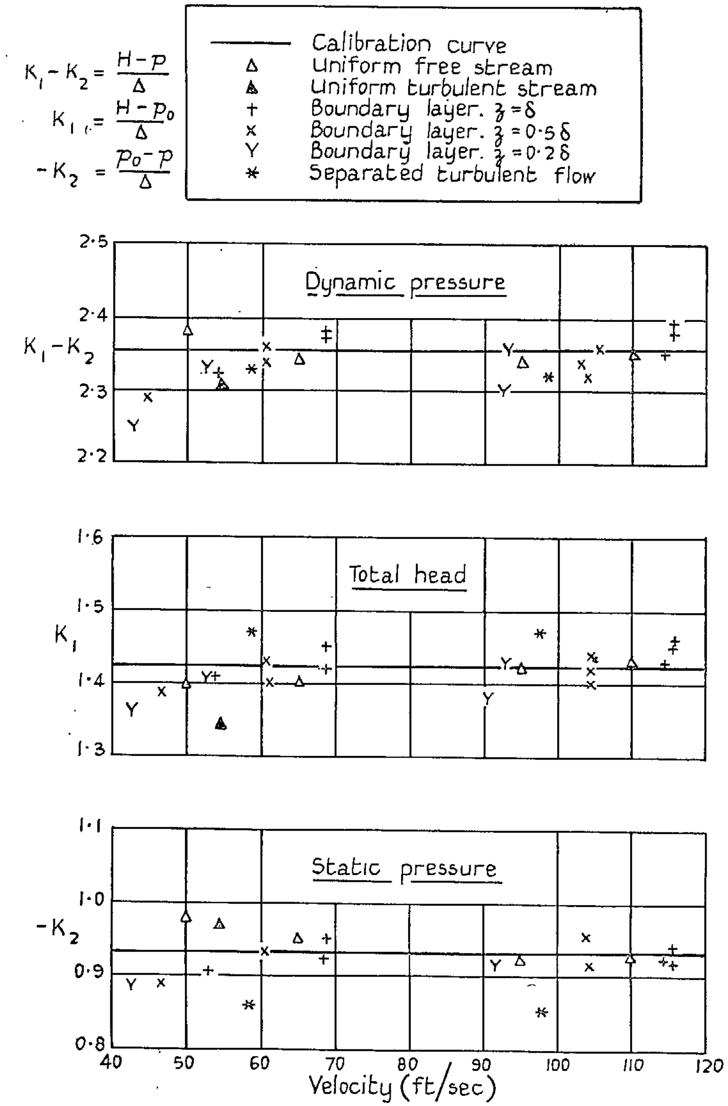


FIG. 8b. Dependence of calibration on flow conditions.—Conrad-(iv) probe.

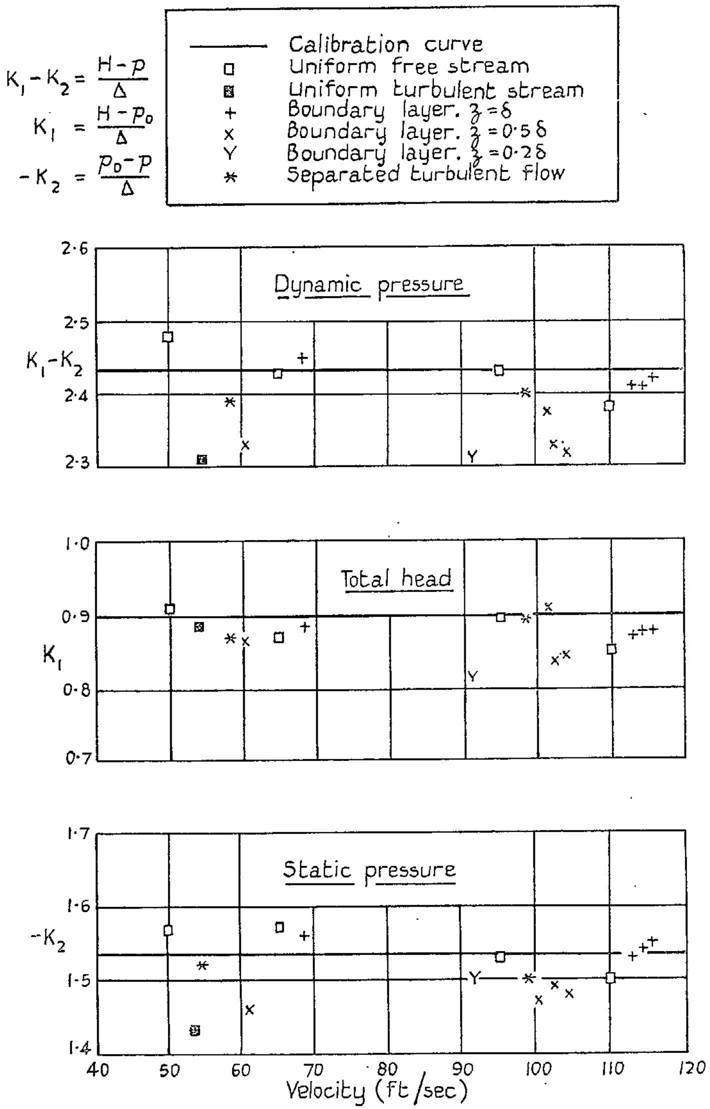


Fig. 8c. Dependence of calibration on flow conditions.—Pyramid probe.

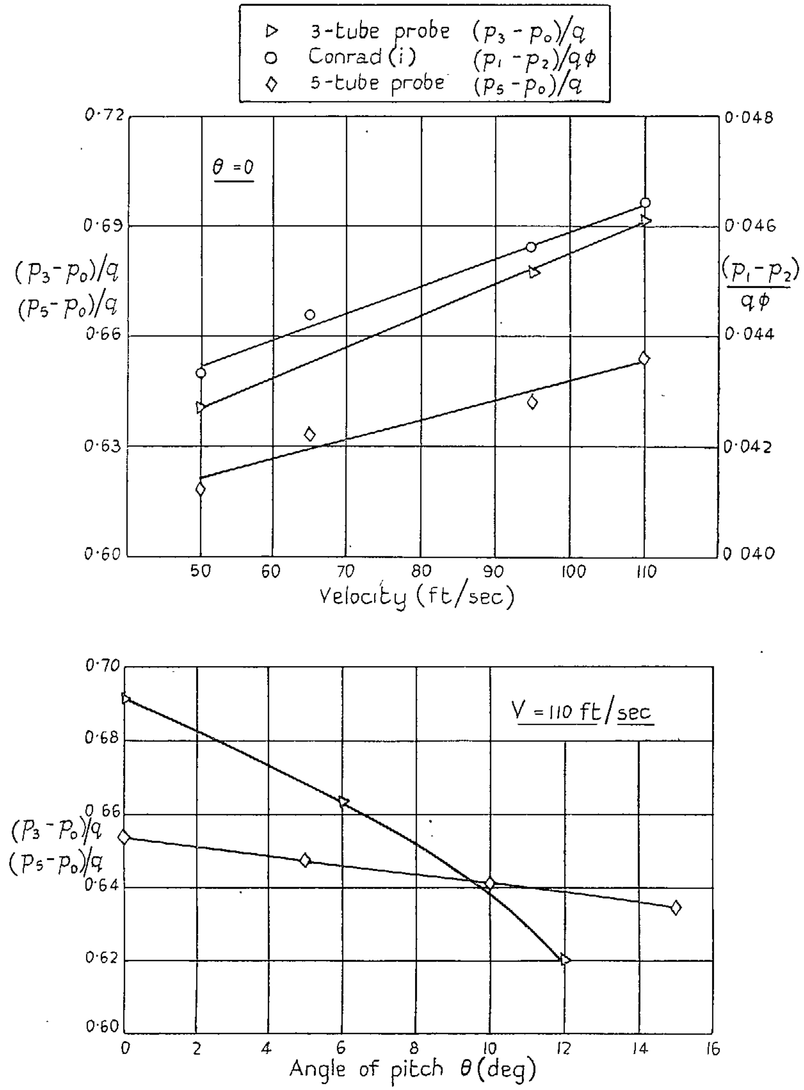


Fig. 9. Usefulness of equi-balanced 3-tube probe.

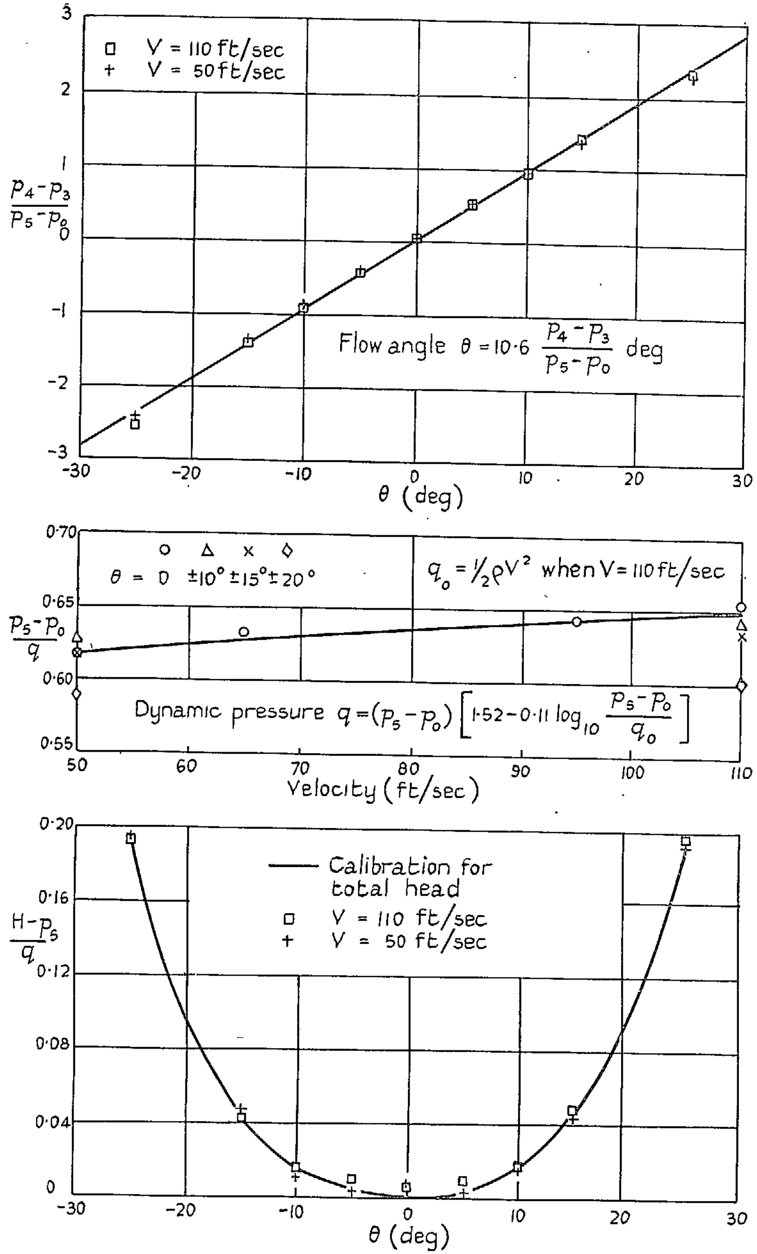


FIG. 10. Calibration of 5-tube probe for limited flow angles.

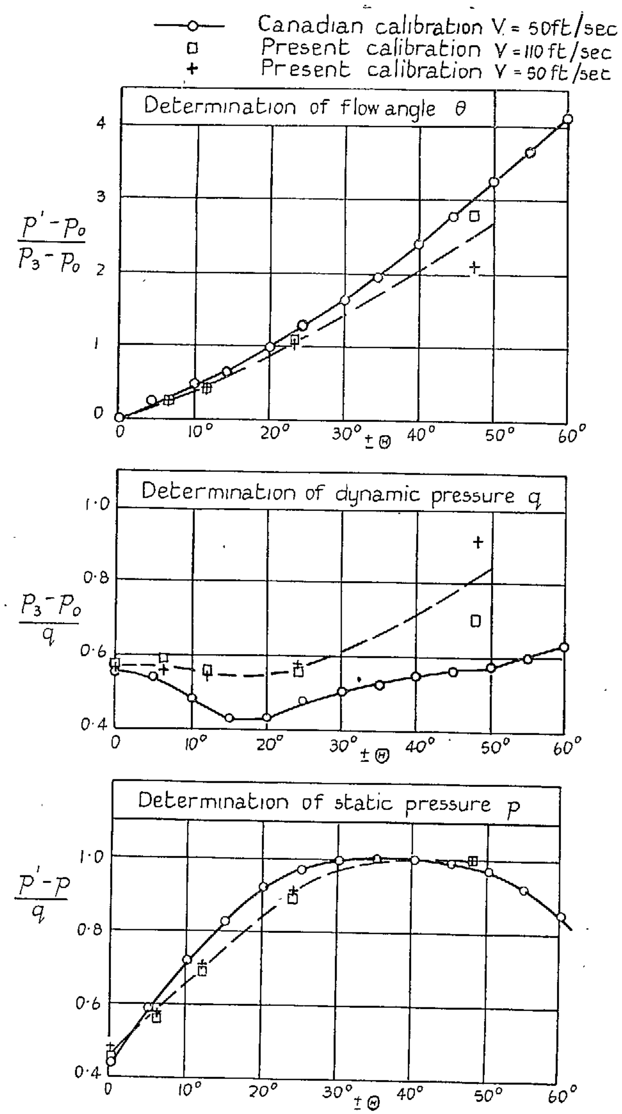


FIG. 11a. Calibration of axial probe.

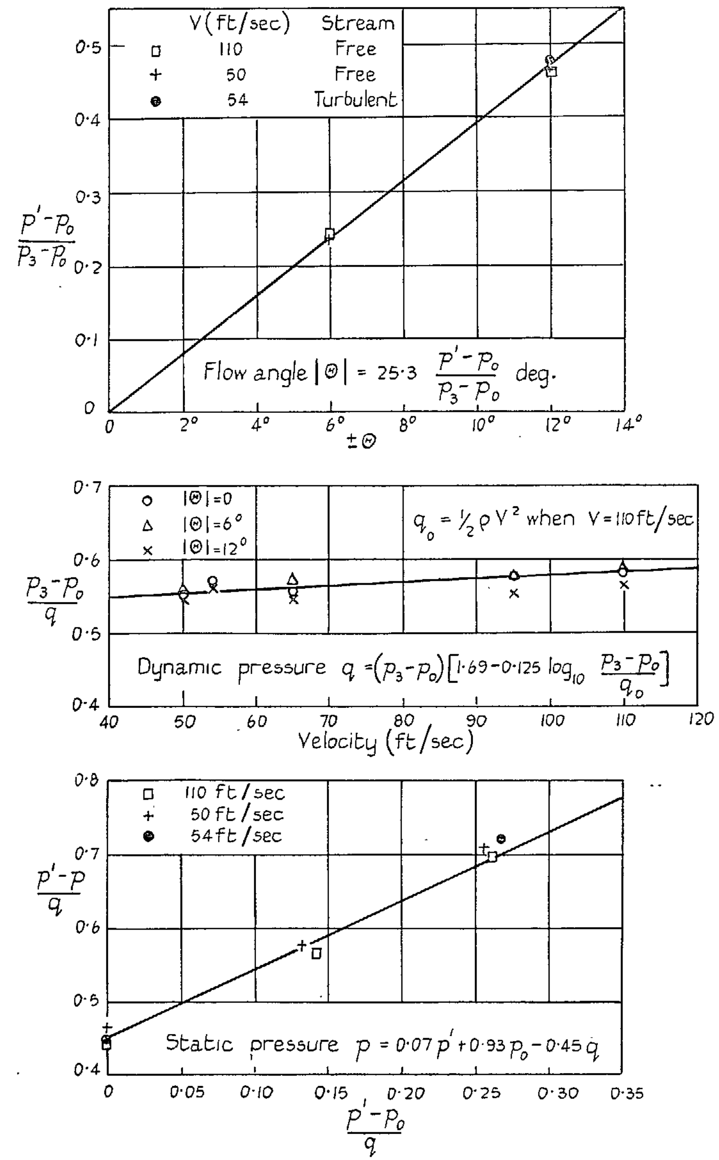


FIG. 11b. Calibration of axial probe for limited flow angles.

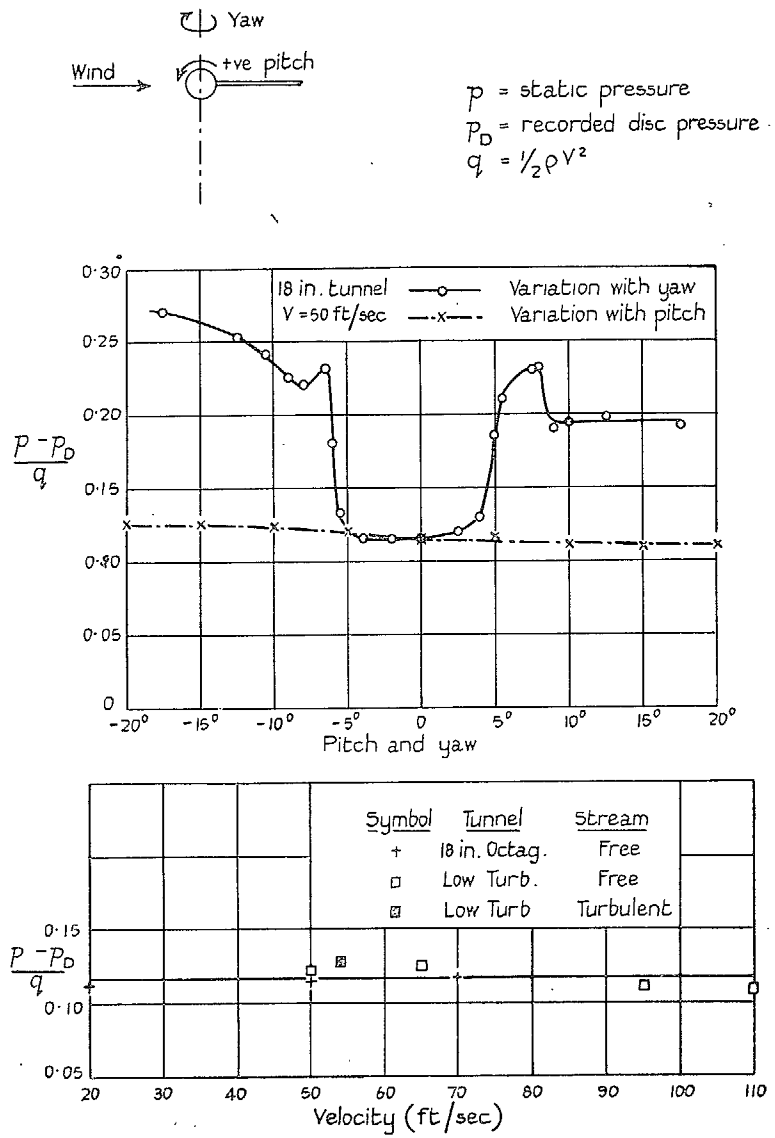


FIG. 12. Calibration of disc-static probe.

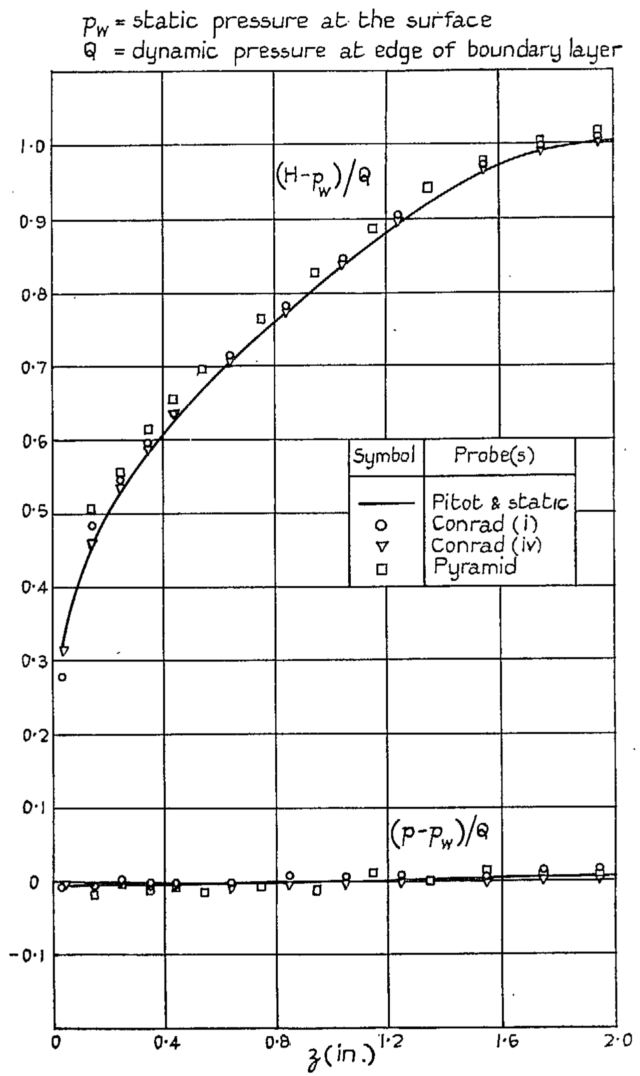


FIG. 13a. Boundary-layer traverse. Comparison of probes. $\delta = 2 \cdot 0$ in. $u = 110$ ft/sec.

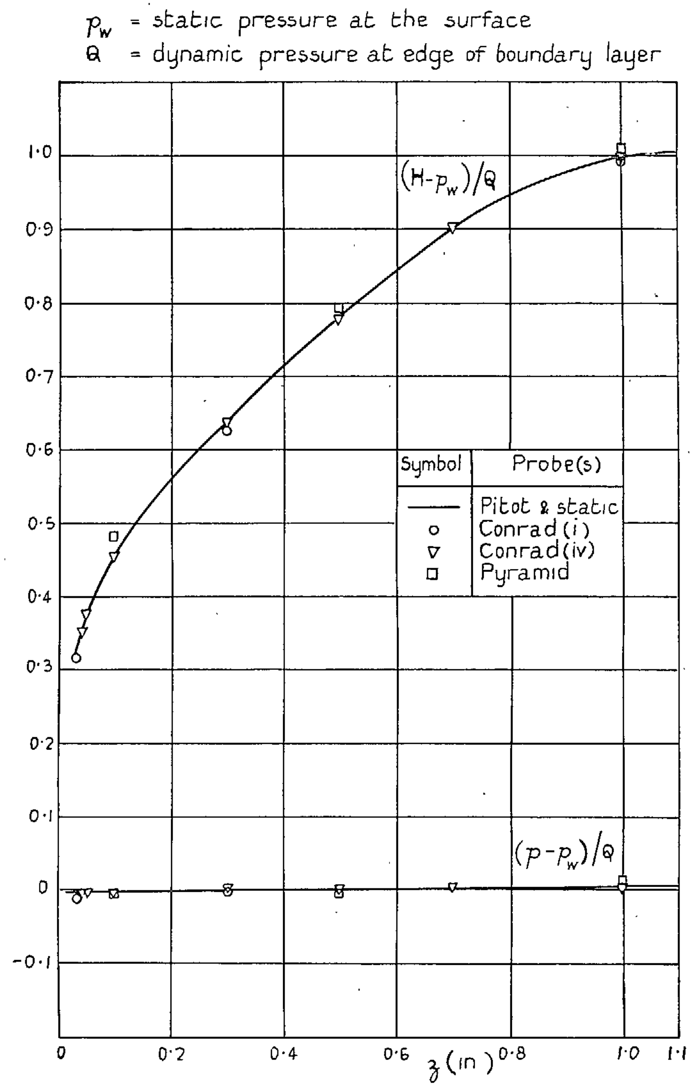


FIG. 13b. Boundary-layer traverse. Comparison of probes. $\delta = 1 \cdot 1$ in. $u = 65$ ft/sec.

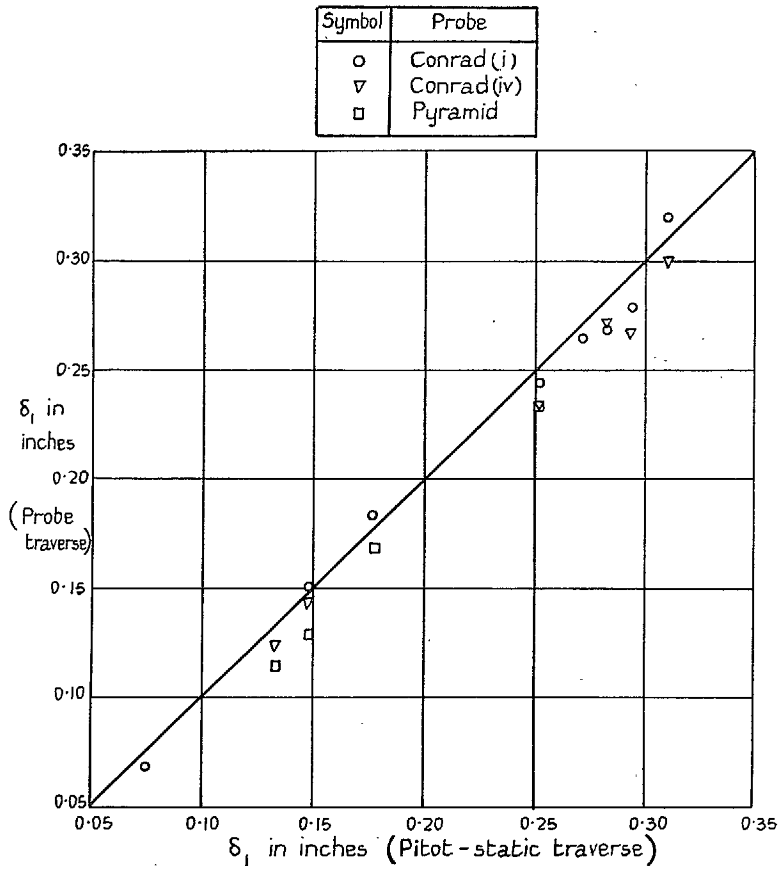


FIG. 14. Accuracy in estimation of displacement thickness.

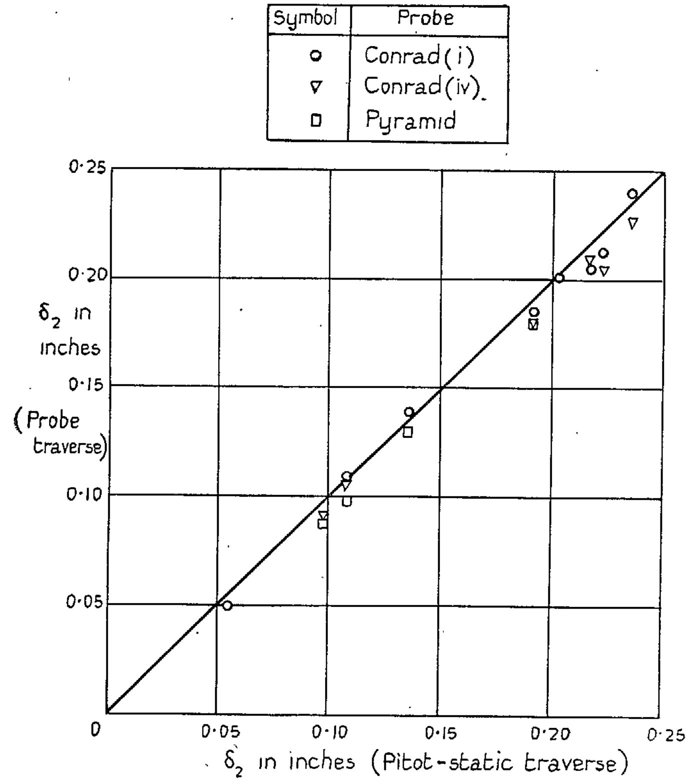


FIG. 15. Accuracy in estimation of momentum thickness.

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