The behaviour of a Pitot tube in transverse shear

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SUMMARY

This paper presents an experimental investigation of the displacement of the total-head profile in a shear flow from its true position when it is measured with a flat-ended round Pitot tube. The experiments showed that at least two forms of displacement may exist depending on the flow conditions.

In a wake the displacement of the effective centre of pressure towards the higher velocity was found to obey the law deduced theoretically by Hall (1956), provided that changes in flow direction were not large. In the presence of large eddies the behaviour of the Pitot is further modified by its characteristics in yaw. This introduces a total-head error reducing the observed total head.

In a turbulent boundary layer the experiments showed that the displacements were an order of magnitude smaller than in a wake and could be regarded as negligible for a round Pitot, even when it was touching the wall.

An empirical method for correcting the observations made with a round Pitot which is of the same width as the wake is given in an appendix.

1. INTRODUCTION

In the experimental studies of boundary layers and wakes, the velocity profile is generally established by a Pitot traverse. The displacement of the effective centre of pressure recorded by a total-head Pitot tube in a wake has been studied experimentally by Young & Maas (1936) and theoretically by Hall (1956). A more exact theoretical study has just been published by Lighthill (1957) and his results substantiate Hall's simplified theory.

Young & Maas studied the wake close behind a symmetrical aerofoil, and found a displacement towards the region of higher velocity that could be expressed as a constant fraction of the Pitot diameter and was independent of the velocity gradient. However, as Young & Maas pointed out, this implies a sharp discontinuity in the displacement correction as the velocity gradient approaches zero, which is not physically plausible. Their observations indicate a velocity correction at the centre of the wake, but they did not discuss this in their paper.

Halls' theoretical investigation was based on the consideration of the vorticity field alone and neglected viscosity. He pointed out that in front of a three-dimensional object in uniform shear the vortex tube must be stretched, giving a local increase in vorticity. This gives a larger displacement of the stagnation streamline than pure two-dimensional flow alone. He then calculated the displacement of the stagnation streamline for a sphere in uniform shear, and showed it was a function of the velocity gradient as well as the mean velocity and the diameter of the Pitot. This avoids the discontinuity described in the previous paragraph.

This paper first describes an experimental investigation of the validity of Hall's assumptions, to resolve the discrepancy with the results of Young & Maas. Further experiments are described which were undertaken to establish the form of corrections which apply to other examples of shear flow. The experiments indicated that the different conditions existing in other forms of shear flow introduce different corrections. Examples of shear flow where conditions may differ significantly include (*a*) flow in a wake after large eddies have decayed; (*b*) flow in a wake just downstream of the trailing edge; (*c*) flow in a turbulent boundary layer; (*d*) flow in a laminar boundary layer; (*e*) flow where compressibility is important; (*f*) pulsating flow.

These experiments were confined to the first three of the above examples. Hall's work is confined to the first shear flow example, which is discussed in §2 of this paper. The results of Young & Maas may be classed with example (*b*), which is discussed in §3. Flow of the type in example (*c*) is discussed in §4.

Other experimental work on displacement corrections has been published. Livesey (1956) has studied the corrections for cylindrical Pitots, and also gives some results for flat-ended Pitots of the conventional pattern. All his results were obtained in a turbulent boundary layer after it had been thickened by a wire cloth screen. Mawson & Lilley (1956) include results for high speed flow, and also include some observations for low speed flow which may be classed with examples (*a*) or (*b*). They were, however, primarily concerned with corrections for total-head tubes larger than the wake. Macmillan (1957) gives careful measurements which may be classed with example (*c*) both for a pipe and a flat plate. The effect of flow pulsations on total-head tube readings has been investigated by several authors, although very few observations have been recorded.

2. Total head measurements in a wake

Hall (1956) has shown that, when the vorticity field alone is considered, the displacement δ of the stagnation streamline from its position at infinity for a sphere in uniform shear can be expressed by

$$\delta/D = 0{\cdot}6200K - 0{\cdot}5786K^3 + O(K^5), \qquad (1)$$

where D is the sphere diameter, and K represents the maximum difference between the velocities at the edges of the sphere divided by twice the mean velocity. (Lighthill's (1957) asymptotically exact theory for flows with small shear (i.e. small K) gives $\delta/D = 0{\cdot}45K - CK^3$, where C is probably greater than 1·35. In his paper, K is expressed as Aa/u.) Hall suggested that a conventional flat-ended round Pitot tube may be represented by a sphere of slightly larger diameter.

It still remains to test Hall's two assumptions, namely that the viscosity may be neglected, and that a round Pitot of slightly smaller diameter may replace the sphere. To this end, traverses were made through a wake by a series of flat-ended round Pitots of graded size but constant shape, the ratio of bore to outer diameter being 0·6. Other experiments were made to investigate the effect of changing this ratio.

The traverses were carried out behind two models in a N.P.L. wind tunnel of 3 ft. × 2 ft. working section, the maximum available wind speed being 70 ft./sec. One of these was a two-dimensional symmetrical aerofoil of 10 in. chord and 5% thick. To permit the use of larger tubes an axi-symmetric double ogive (cigar-shaped), of 40 in. chord and 7 in. maximum diameter, was also employed. This form was chosen for the larger model to minimize the effects of tunnel interference. It was considered that at radii large compared with the Pitot diameter the flow could be considered for practical purposes two-dimensional. For checking Hall's assumptions, the traverses were carried out several wake widths downstream to allow for the decay of the large eddies produced by oscillation of the rear stagnation point, particularly in two-dimensional flow. Most of the measurements were made at a fixed wind speed, though check traverses made at other speeds gave similar results.

The undisturbed velocity head p_0 was measured with a standard round-nosed N.P.L. Pitot-static combination, of 0·5 in. outside diameter, placed well clear of the wake and just downstream of the trailing edge. The reading p of the total-head tube under test was compared with that from the standard total-head tube tapping, the difference $(p_0 - p)$ being observed. Care was taken to ensure this difference was exactly zero when the tube under test was outside the wake. This provided a check on the uniformity of the flow in the tunnel, and of the absence of leaks. The tunnel was an open N.P.L. type, and it was found that any leaks into the tunnel disturbed the flow there considerably.

The measurements were made in regions of appreciable turbulence, and therefore the pressure differences observed within the wake were fluctuating. To investigate a Pitot's behaviour it was essential to establish that the mean observed pressure was unaffected by changes in the dynamic behaviour of the manometer system due to changes of Pitot bore. It would have been ideal if the manometer system always recorded the true mean Pitot pressure, but it was not possible to establish that it did so in turbulent flow. Experiments did show, however, that variation of the manometer system response by throttling the leads produced no change in the recorded mean pressure in turbulent flow. This indicated that for the purpose of comparison of Pitot performance, variation of the dynamic behaviour of the manometer could be neglected.

Small temperature variations also limit the minimum Pitot bore which may be used satisfactorily with a given manometer system in unsteady conditions. It only requires a temperature change of 0·01° C to produce pressure variations of 0·015 in. of water in a constant volume system at atmospheric pressure. When the Pitot bore was 0·018 in., the manometer system would respond to a small disturbance of approximately ¼ second period. When the bore was reduced to 0·005 in., however, the period rose to 40 seconds, which was considered too long.

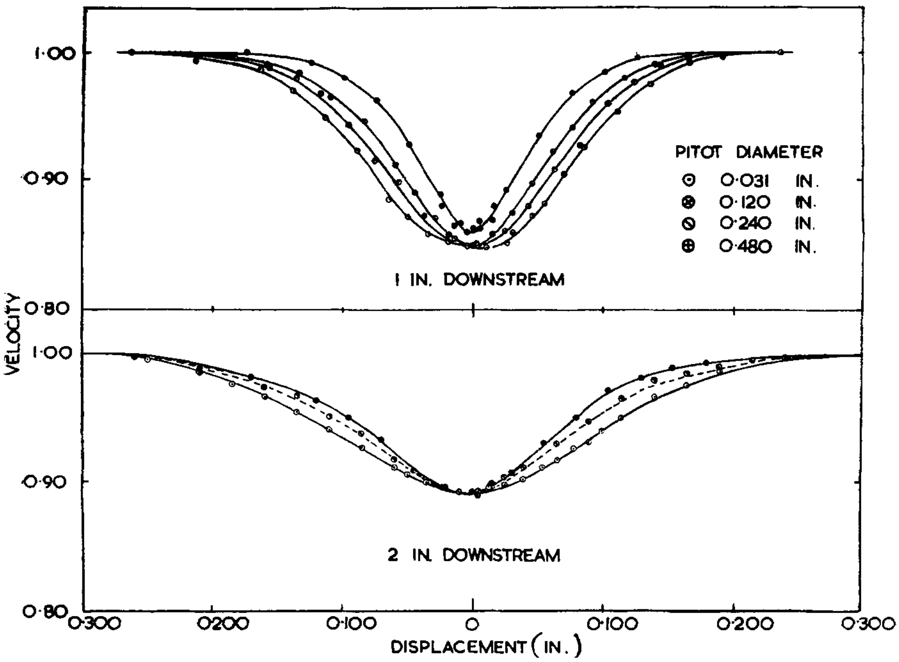

Figure 1. Wake velocity profiles observed by geometrically similar Pitots behind the aerofoil model.

The manometer was a simple vertical U-tube made of 3 mm precision bore glass tubing. A small quantity of detergent was added to the manometer water to minimize the effect of surface tension variations. The level was read with a travelling microscope fitted with a graticule to facilitate observation of fluctuating readings. Careful calibration showed that readings consistent to 0·001 in. of water were possible, though the precision could be increased by using a higher power microscope. When the amplitude of the fluctuations exceeded 0·010 in. of water, spot readings were taken every five seconds for half a minute and averaged to give the mean pressure.

Typical results are shown in figures 1 to 3, where the dimensionless wake velocity $(p/p_0)^{1/2}$ is plotted against transverse displacement y. From graphs of this type it was not possible to obtain the displacement correction and the corresponding value of K until the undisturbed profile was known. This was obtained by extrapolation from the profile measured with the

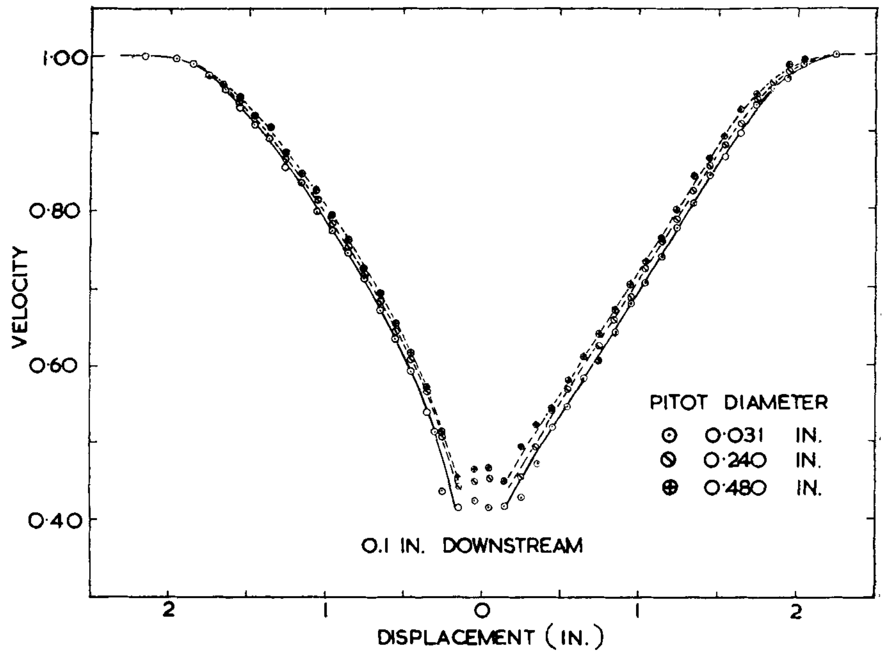

Figure 2. Wake velocity profiles observed by geometrically similar Pitots near the trailing edge of the axi-symmetric model.

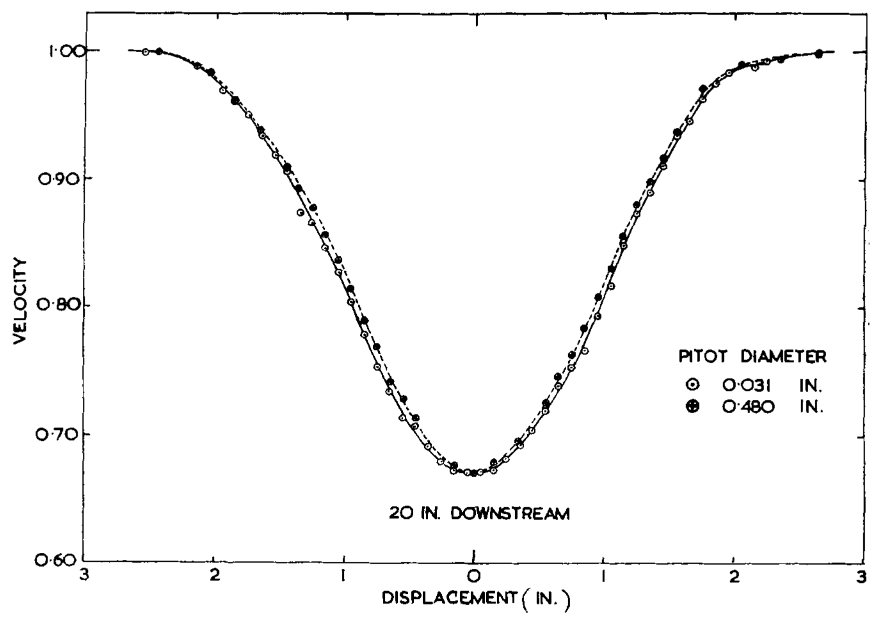

Figure 3. Wake velocity profiles observed several wake widths downstream of axi-symmetric model.

smallest tube. When K was small, the corrections for the smallest Pitot were negligible (less than 0·001 in. which was the limit of accuracy for measurements of y) compared with those for the largest tube, which were of the order of 0·05 in. Once the correction for low K was established, it was used to obtain the undisturbed velocity profile by extrapolation from that measured by the smallest Pitot. This prejudiced the accuracy of the results at high K values ($K > 0{\cdot}2$, say), but it was also difficult to obtain constant velocity gradients of sufficient width for measurements in this region.

The displacements observed have been plotted against the corresponding values of K in figure 4. This only includes those observations where the velocity gradient across the face of the tube was practically uniform. It can be seen from figure 4, particularly where $K < 0{\cdot}2$ and the accuracy is reasonably good, that the results show reasonable agreement with Hall's

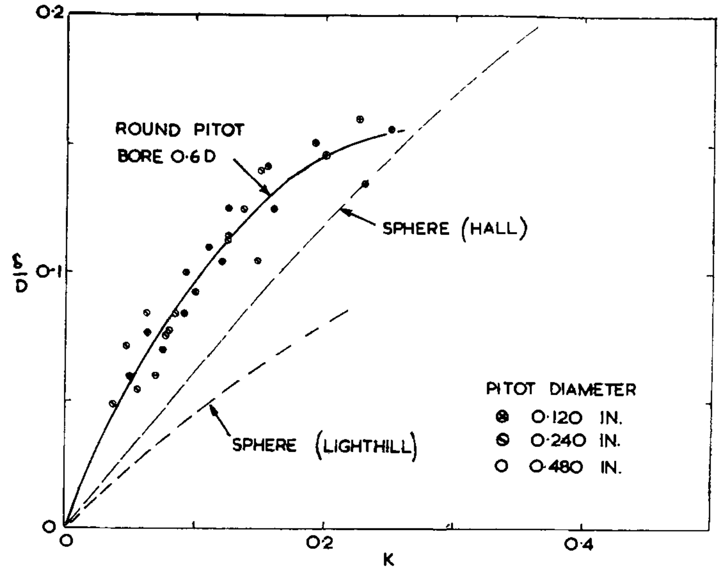

Figure 4. Pitot displacement corrections in two-dimensional uniform shear.

theoretical expression. The initial slope indicates a larger correction for a Pitot than for a sphere of the same diameter as Hall suggests. Lighthill (1957) has shown that the coefficient of $-K^3$ in Hall's expression (1) is much too small, which is in agreement with the results for flat-ended Pitots in figure 4. If Lighthill's expression is multiplied by two it fits these results.

Hall's theory applies to the displacement of the stagnation streamline in uniform shear flow. It might seem reasonable to suppose that an asymmetrical pressure distribution exists over the face of the tube corresponding to the incident flow. It is desirable therefore to check whether variations of the ratio of bore to diameter will alter the observed pressure. To this end a set of Pitots of constant diameter but varying bore were tested, the results being shown in the upper part of figure 5. It can be seen that no significant difference was observed even though the ratio of bore to diameter was varied from 0·075 to 0·800. The observed pressure was, however, found to vary when the measurements were repeated close behind the trailing edge, as is demonstrated later in this paper.

In many instances (e.g. in supersonic flow) it is not possible to employ a Pitot small compared with the width of the wake. Results for traverses made with large Pitots, the largest spanning the wake, are included in figures 1 and 2. The observed displacements are less than those obtained by applying Hall's theory using the slope of the undisturbed profile at the centre of the Pitot. This is to be expected since Hall's theory applies to uniform shear and here both the sign and magnitude of the vorticity changes continuously across the face of the tube.

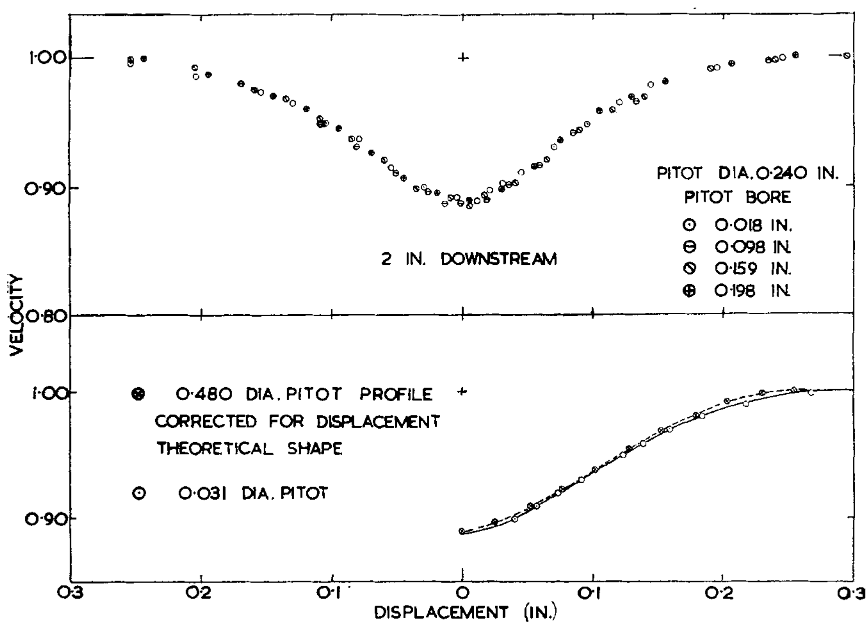

Figure 5. Effect of changing Pitot bore on observed wake velocity profile. The lower curve gives the corrected wake velocity profile.

It is, however, possible to obtain an approximate correction from a traverse with a large tube. The results in the lower part of figure 1 show that the corrections are zero at the centre of the wake. If the velocity in this position is taken as the minimum velocity, and if the maximum velocity is taken as unity, K being determined from these values, the corrections obtained are $\delta = 0{\cdot}031$ ($K = 0{\cdot}058$) compared with 0·033 observed with the large tube at the mean velocity. This correction is a little smaller than that observed, but not seriously so. It is well known that the shape of the velocity distribution in the wake obeys a universal law (Goldstein 1938, p. 581). If the velocity at the centre of the wake is known, and the width of the wake is also known at the mean wake velocity, it is possible to establish the whole profile. The details of the process are given in the appendix to this paper, and the corrected profiles so obtained for the big Pitot are plotted in the lower part of figure 5. It can be seen that this empirical process can yield satisfactory results under favourable conditions.

3. Wake total-head measurements close to the trailing edge

The results obtained when traverses were made close to the trailing edge differed from those already described. It was found that the profiles did not coincide at the centre of the wake, where the displacement correction should be zero as in figure 1. This implies a total-head correction also exists, as was indicated by the results obtained by Young & Maas (1936). The results obtained just behind the symmetrical aerofoil were all similar to those plotted in figure 6. It can be seen here that the displacement is proportional to the Pitot diameter, although it differs on each side of the wake.

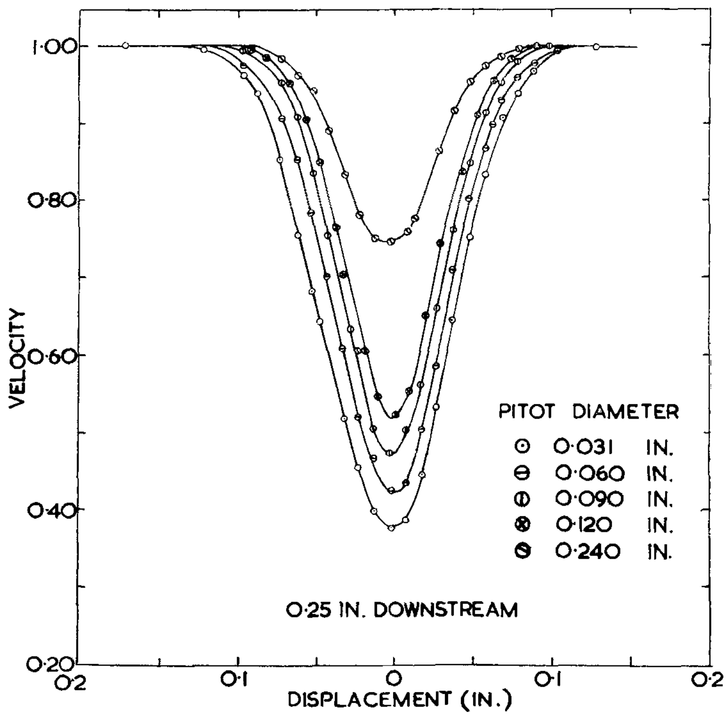

Figure 6. Wake velocity profiles recorded by geometrically similar Pitots near the trailing edge of aerofoil model.

Young & Maas obtained the correction by plotting the observed wake width at a given velocity versus the Pitot diameter. They obtained points lying approximately on straight lines of constant slope, the correction being equal to half this slope. Using their technique a displacement correction equal to 0·24D was obtained for the results in figure 6. However, traverses 3/16 in. closer to the trailing edge yielded a correction equal to 0·28D, while traverses an equal distance downstream gave a correction of 0·16D when reduced by the same method.

The matter can be carried further. The momentum thickness calculated for each profile measured behind the aerofoil has been plotted against distance downstream from the trailing edge in figure 7. It can be seen that there is a tendency for the observed momentum thickness to rise sharply as the trailing edge is approached. If the correction were simply one of displacement towards the higher velocity one would expect the curve to drop as the trailing edge is approached, not rise. The effect could be explained by the existence of a velocity-head correction close to the trailing edge. A reason for its existence is not hard to find.

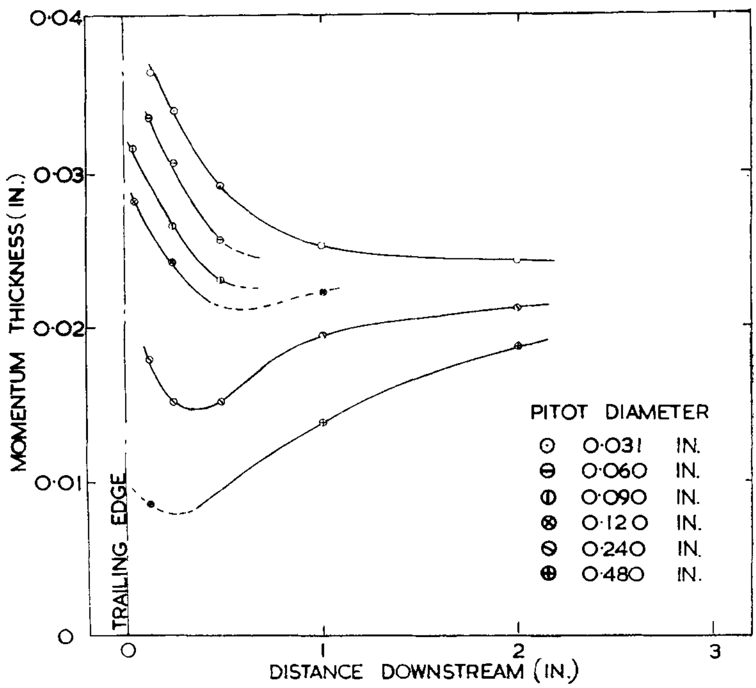

Figure 7. Momentum thickness calculated from uncorrected velocity profiles observed by geometrically similar Pitots in the aerofoil wake.

It is well known that a Pitot tube is very sensitive to yaw of more than a few degrees (Todd 1949). Not only is the mean direction of the flow inclined inwards near the trailing edges, but the flow direction oscillates rapidly about the trailing edge. This will produce large rapid variations in incident flow direction, and due to its directional characteristics the Pitot will record a pressure lower than the mean total head. Further downstream the fluctuations in the incident flow direction will be much smaller, and the Pitot will then record the mean total head.

It can be seen from figure 6 that this error in the total-head reading increases as the size of the Pitot is reduced. One would expect a Pitot close to the trailing edge would modify the flow there. The undisturbed flow is two-dimensional, but when a Pitot is introduced, the flow in its neighbourhood must be considered three-dimensional. In addition, the presence of a rigid body will introduce extra shear stresses if the flow direction departs from that of the body. This would modify the fluctuations in flow direction in the vicinity of the Pitot. The stabilizing of the flow would increase with the size of tube, with a corresponding reduction in the velocity-head error. The observations indicate that the reduction in the velocity-head error is roughly proportional to the diameter of the tube.

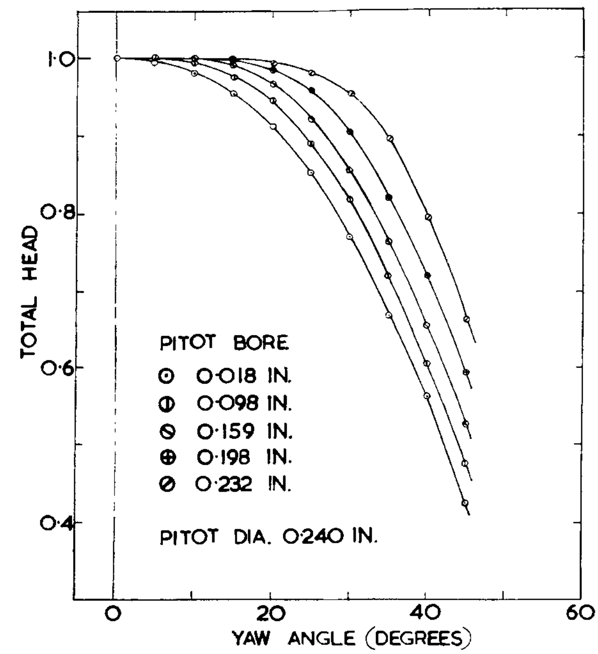

Figure 8. The effect of changing the bore of a yawed Pitot on its total head response.

This explanation of the results requires further confirmation. To this end, use may be made of the behaviour of yawed Pitot tubes. A series of Pitots of constant diameter but varying bore were tested in an empty tunnel at various angles of yaw. The results obtained are plotted in figure 8, which shows observed total head plotted against yaw angle. It can be seen that changes in bore produced substantial changes in total-head error. This seems reasonable as the forward stagnation point must be close to the leading corner of the Pitot and a pronounced pressure gradient must exist across the tapped face. Changes in bore will thus vary the observed pressure at any given yaw angle as the results indicate.

It has been shown earlier in figure 5 (upper part) that a series of Pitots of constant outside diameter but varying bore have the same displacement correction in a stream of uniform vorticity. Furthermore, it seems reasonable to assume that their influence on the flow around them must be the same. The results of traverses made by a series of such Pitots are plotted in figure 9. In this case any difference between the profiles should be due to changes of total-head error of the form indicated in figure 8. The results indicate that substantial total-head errors do exist particularly at the centre and edges of the wake where the largest fluctuations are known to occur.

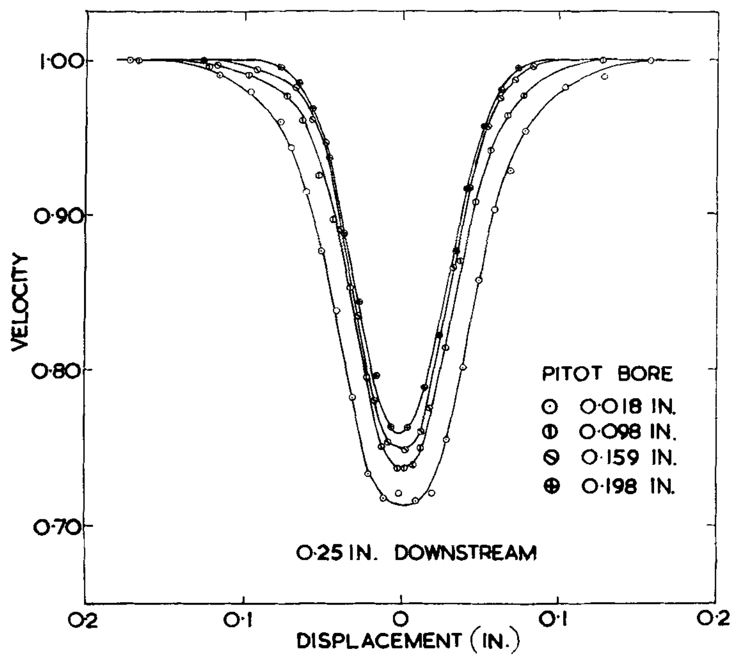

Figure 9. Wake velocity profiles displaying total head errors due to yaw.

A further experiment was performed to ensure the results in figure 9 were independent of the manometer system response. The 0·098 in. bore Pitot was fitted with a drilled plug to reduce its bore to 0·018 in. Traverses with the plug flush with the Pitot face reproduced the results obtained with the normal 0·018 in. Pitot, as would be expected. When the plug was pushed back, however, the behaviour approached that of an unplugged Pitot. The results are plotted in figure 10 and agree with those in figure 9. When the plug was displaced more than 0·050 in. the Pitot behaved as if it was unplugged. The dynamic response of the manometer system must have remained unchanged during these tests, demonstrating that the results in figure 9 were independent of the response.

It should be possible to obtain a profile corrected for velocity-head error corresponding to the results in figure 9, which are mean values. The results in figure 8 show how the correction varies with incident flow angle, but it would be necessary to determine the distribution of incident flow angles with time before a mean correction could be calculated. An empirical correction can be estimated if it is assumed that the velocity-head error approaches zero as the Pitot wall thickness does so. This is true for small angles as shown in figure 8.

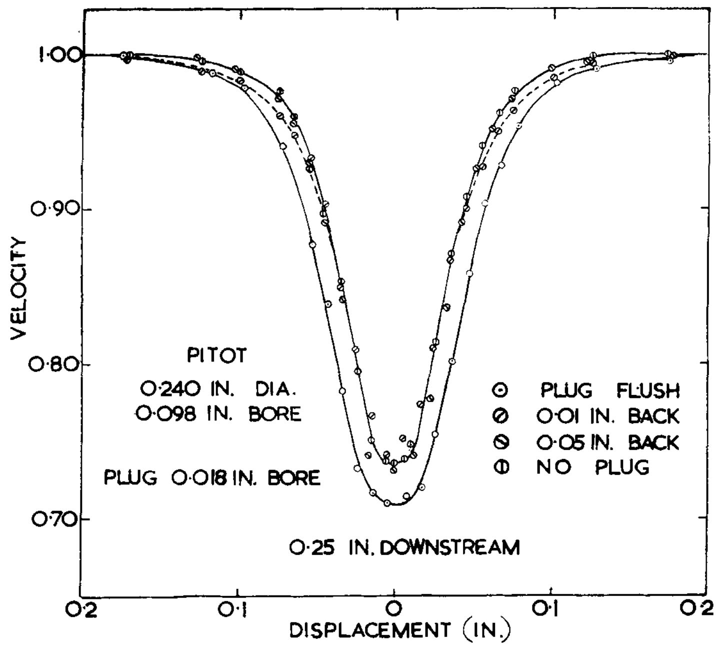

Figure 10. Wake velocity profiles observed with a manometer system of constant response obtained by fitting a sliding plug in the Pitot bore.

If this is done for the results in figure 9, the profile is very nearly that shown recorded with the largest bore Pitot, there being small corrections at the centre and edges of the wake. The profile so obtained must now be corrected for displacement error, and as the Pitot is large compared with the wake width the method outlined in the appendix is employed.

The profile finally corrected gives a momentum thickness of 0·025 in. (instead of the uncorrected value of 0·015 in.), which compares favourably with the values 0·025 in. and 0·0245 in. observed further down the wake using the smaller Pitot of 0·031 in. diameter.

The existence of a velocity-head error accounts for the discrepancy between Hall's results and those of Young & Maas. The presence of velocity-head corrections at the centre and edges of the wake, where the velocity gradient is small, explains why Young & Maas obtained large displacement corrections in this region.

4. Traverses in a turbulent boundary layer along a flat plate

In boundary layer flow it seems reasonable to expect that the results described above will be considerably modified by the presence of the wall. This will tend to reduce the displacement of the stagnation streamline as it will modify the flow around the Pitot. For the same reason one would expect that the random changes in flow direction will be much smaller. To illustrate this one may consider the extreme case of a Pitot in contact with a wall.

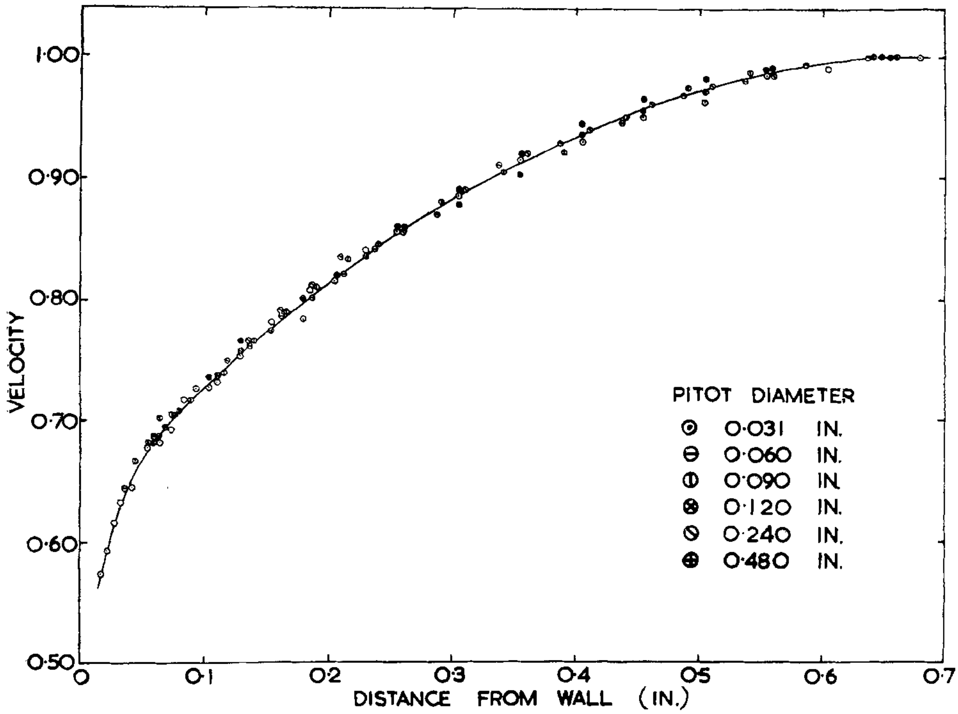

Figure 11. Comparison of the measurement of a turbulent boundary layer velocity profile by a series of geometrically similar Pitots.

Traverses made through the boundary layer near the trailing edge of a flat plate of 3 ft. chord at zero incidence confirmed the above suggestions. The results are plotted in figure 11, where it can be seen that no appreciable displacement or velocity-head error was observed, although the diameter of the largest Pitot was 16 times that of the smallest. This result was unexpected as it is reasonable to suppose some displacement would exist. A small displacement, 0·02 of the Pitot diameter, was recorded by the largest Pitot tube.

There is some evidence (Preston 1954) that corrections exist close to the wall for flat Pitots in a boundary layer. The results in figure 11 indicate that the correction for a round Pitot is negligible in this region, even when the

Pitot is touching the wall. Working with round Pitots, Macmillan (1957) observed displacements of the order of $0{\cdot}15D$ in a pipe, and of the same order in the boundary layer on a flat plate. His results also implied a total-head correction close to the wall which was expressed as a negative displacement. The absence of such corrections in the present results may be due to the higher response rate of the manometer system used.

Livesey (1956) obtained corrections for a flat-ended Pitot in a boundary layer that had been thickened considerably by a wire cloth screen. It is possible that the flow conditions in this case were more nearly those obtaining in a wake than those in a boundary layer. Livesey also reported that the corrections for a conical Pitot with a sharp lip were negligible indicating, that his other corrections were probably of the total-head type and not displacement corrections as he suggests. Assuming this is so the results in figure 4 can be applied to his measurements with the sharp-lipped Pitots. For his largest (0·7 in. diameter) Pitot at the centre of the velocity profile, we get $K = 0{\cdot}2$ giving a displacement of the order $0{\cdot}03D$ which is less than the scatter of the observations.

The results of both Livesey and Macmillan indicate that both types of corrections may be observed in a turbulent boundary layer. The conditions under which these corrections will occur have not been established.

5. Conclusions

The results indicate that the displacement of the effective centre of pressure recorded by a total-head tube in a wake obeys a relationship of the form put forward by Hall (1956) and by Lighthill (1957). This is expressed by equation (1), for a sphere in uniform shearing flow, and by the curve in figure 4 for a flat-ended round Pitot of conventional form.

When the Pitot is large compared with the dimensions of the wake, the displacement is reduced and may be determined approximately by the process outlined in the appendix.

In the region close behind a trailing edge, a velocity-head error also exists due to the characteristics of a yawed Pitot. Since this error is a function of the dynamic characteristics of the flow, it cannot be specified in terms of the Pitot geometry and the velocity gradient alone. It is possible to obtain a reasonably accurate corrected profile empirically, although the process is tedious. The results suggest that, for accurate drag measurements, it is best to make wake traverses well downstream of the trailing edge, and an advantage to use a Pitot with a sharp lip.

For a flat-ended round Pitot of conventional form and with bore 0·6 times the outer diameter, no corrections were observed in a turbulent boundary layer, even when the Pitot was touching the wall.

The majority of the experimental work was carried out in the Mechanical Engineering Department of the University of Adelaide.

Appendix

The estimation of displacement corrections for a Pitot large compared with the width of the wake

Schlichting (1930) has established that the velocity profile in a wake obeys the relation

$$\frac{U_0 - U}{U_0 - U_m} = \left[1 - \left(\frac{y}{y_0}\right)^{3/2}\right]^2, \tag{A 1}$$

where the notation is illustrated in figure 12.

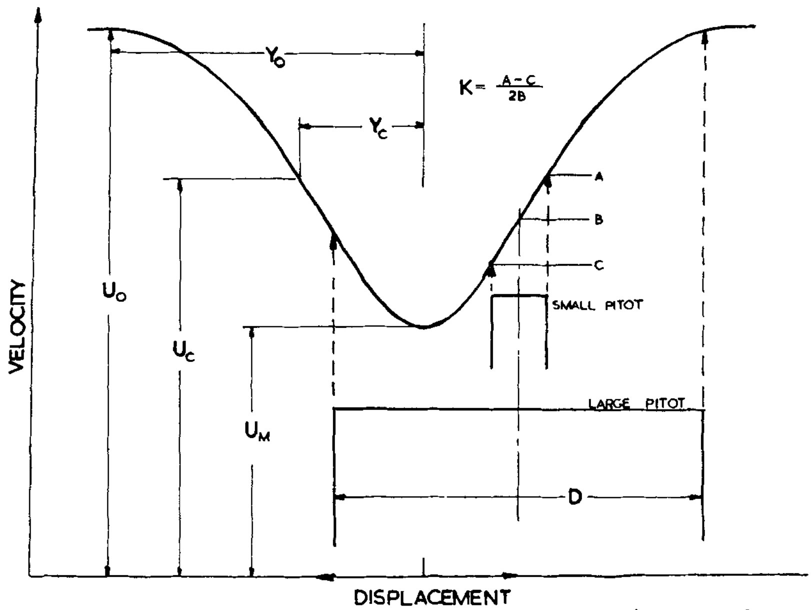

Figure 12. Illustration of notation used for displacement corrections to wake velocity profiles.

The value of U_m is given by the Pitot traverse regardless of the Pitot size, and y_0 can be found from (A 1) given the value of y corresponding to a known value of U. The most convenient for this purpose is y_c, corresponding to the mean wake velocity $U_c = \frac{1}{2}(U_0 + U_m)$, and (A 1) shows that $y_0 = 0{\cdot}441 y_c$.

The value of y_c must first be corrected for displacement. If the tube is small, the corrections can be determined from figure 4 using the appropriate value of K. When the Pitot diameter is of the same order of magnitude as the wake width, it has been shown experimentally that

$$K = \frac{U_0 - U_m}{2U_c}.$$

The corresponding value of δ/D may be read from figure 4.

Once y_0 is known, the whole profile may be calculated from (A 1). This profile will be in error near the edge of the wake, but it can be seen from the lower part of figure 5 that otherwise the agreement is good. It is not suggested that this empirical procedure may be applied to a case where the Pitot diameter is very much larger than the wake width. Such a condition is unlikely to arise in practice; but, if so, it is not difficult to establish a suitable correction experimentally.

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