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The Displacement Effect of Pitot Tubes in Narrow Wakes at Subsonic and Supersonic Speeds

-by-

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SUMMARY

The apparent displacement of the effective centre of a circular pitot tube from its geometric centre when placed in narrow wakes has been measured at sub- and supersonic speeds. Similar effects were found at all speeds. If the tube diameter was small compared with the wake width, the displacement was towards the region of higher velocity, and was proportional to the tube outside diameter. For larger tubes the displacement was reduced, and was reversed in direction when the tube diameter exceeded about three times the wake width.

MEP

16. 1mm. tube behind $\frac{1}{2}$in. chord wing at M = 3.19 (0.5mm offset)
17. 6.4mm ' ' ' ' ' ' ' (0.2mm offset)
18. 6.4mm ' ' ' ' ' ' ' (0.5mm offset)

2. List of Symbols

a	radius of cylinder (see Appendix)
D	outside diameter of pitot tube
d	inside diameter of pitot tube
H_p	pitot pressure (measured) in wake
H_o	reference pitot pressure (measured) outside wake
M	Mach number
p_s	stagnation pressure ahead of pitot tube shock wave
p_o	calculated freestream stagnation pressure downstream of trailing edge shock wave
r,θ	cylindrical polar coordinates
s	transverse gradient of total head ratio $\frac{\partial H/H_o}{\partial y}$
u_o	freestream velocity along cylinder axis (see Appendix)
w	apparent wake width
w_o	undisturbed wake width
W_o	maximum undisturbed wake width
(x,y)	rectangular cartesian coordinates
δ	displacement of stagnation streamline
ζ	vorticity

3. Introduction

It has been shown by Young and Maas (1) that at low subsonic speeds the effective centre of a pitot tube in a transverse gradient of total head is displaced from the geometric centre of the tube towards the region of higher velocity. Their results showed that over a fairly wide range of conditions this displacement was approximately equal to 0.18D, where D is the outside diameter of the pitot tube. It follows that the displacement effect is small if the pitot tube diameter is small compared with the width of the region of varying total head. In general, therefore, in experiments in wakes or boundary layers at subsonic speeds it is usual to select a pitot tube diameter small compared with the wake width or boundary layer thickness.

At supersonic speeds, however, it may often be desirable to use a pitot tube whose size is large compared with the dimensions of the wake or boundary layer which it is traversing. This may be due either to the small size of model being used, or in intermittent wind tunnels where the long time lag associated with a small tube must be avoided. It is therefore important to know the magnitude, if any, of the pitot tube displacement effect in flows at supersonic speeds. Measurements with pitot tubes in the wake of an aerofoil at a Mach number of 1.96 have been reported by Johannesen and Mair (2). These tests were conducted in the wake of a 0.75in. span single wedge aerofoil, 2.5in. downstream of the trailing edge. The outside diameter of the tubes used varied from 0.036in. to 0.720in., but no displacement effect as found by Young and Maas could be detected.

The experiments described in this report were intended to investigate the displacement effect over a wide range of Mach numbers and tube diameters. For completeness, some tests having similar ratios of pitot tube diameter to wake width were also carried out at a low subsonic speed. These latter tests extended the range of the Young and Maas tests to the case where the pitot tube diameter was of the same order as the wake width.

The experimental results at supersonic speeds were obtained between 1953-1955 by Brown A.C. and Olds W. (M = 1.75), Keates R.E. and Socha W. (M = 2.36), Hastings R.C. and Searle G.A.C. (M = 3.19), as a part fulfilment of the requirements for the Diploma of the College of Aeronautics.

4. Description of tests and apparatus

(i) Supersonic

These tests were conducted in the College of Aeronautics $2\frac{1}{2}$in. x $2\frac{1}{2}$in. supersonic intermittent wind tunnel at Mach numbers of 1.75, 2.36 and 3.19. In normal operation, air flows from a dry air bag at atmospheric pressure through the working section of the tunnel into vacuum tanks which are exhausted by continuous pumping. The normal available running time varies from about 30 secs. to 90 secs. according to the Mach number. The stagnation pressure of the tunnel was approximately equal to atmospheric pressure, the small difference being measured by a Chattock gauge. The free-stream Mach number was found by measuring the static pressure on the surface of a calibrating cone placed in the working section.

The dimensions of the pitot tubes tested at each Mach number are given in table I. The tubes were first tested in the empty working section to check that they all gave the same reading. A two-dimensional symmetrical double wedge aerofoil of $\frac{1}{2}$in. chord and thickness chord ratio ten per cent was then fitted in the tunnel, and traverses were made through its wake, 1/4in. behind the trailing edge. The traverses were made in a direction perpendicular to the plane of the wing, by mounting each pitot tube on a sliding support moved by a micrometer screw. A static pressure tube was also traversed behind the wing at the same position. At $M = 3.19$, a similar wing of 1.75in. chord was also used, in order to obtain a wider wake.

The pitot pressures were measured on a vertical mercury manometer, to an accuracy of about 0.01in. of mercury. Corresponding readings of static pressure were taken from tappings in the top liner of the working section. A number of Schlieren photographs were taken at each Mach number, and some of these at $M = 3.19$ are shown in figs. 15 - 18.

(ii) Low speed

Two sets of low speed tests were made, the first being at a wind speed of 59 f.p.s., using the pitot tubes whose dimensions are given in table II. Traverses were made in the wake of a 2in. chord symmetrical 10 per cent thick aerofoil, with the pitot mouth 1in. from the trailing edge. The total head pressure was measured on an inclined tube manometer, and the traverses were repeated several times in one direction only, to avoid errors due to backlash in the lead screw of the traversing gear. In these tests all the pitot tubes except that of 32mm. diameter were very small compared with the wake width.

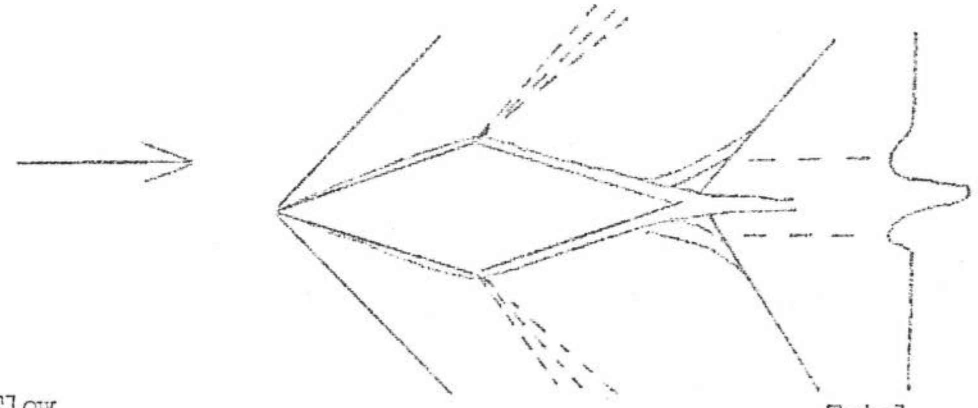
The second set of tests was made using very narrow wakes, given by 1/16in. and 1/32in. thick flat plates of 1in. chord at zero incidence. The wind speed was 50 f.p.s. and pitot tubes 2, 3, 4 and 9 (table II) were used.

5. Results

(i) Supersonic

At each Mach number, static tube traverses were made across the working section in the wake of the aerofoil, and the static pressure was found to be constant within about ± 2 per cent. The pitot tubes were then tested in the empty working section, and found to give similar readings of total head, indicating that no errors due to viscous effects were present. This might be expected, as Sherman (3) gives Re = 200 as the Reynolds number below which viscous effects on pitot tubes are important. In all these tests, the Reynolds number, based on conditions in front of the pitot tube shock wave, was greater than 1000 per mm. The readings of total head obtained from the pitot tube traverses were expressed as a fraction H_p/p_o, where H_p is the total head reading, and p_o is the calculated stagnation pressure behind the trailing edge shock wave in an inviscid flow. Typical total head profiles across the wake at M = 3.19 are shown in fig. 1. It will be seen that the apparent wake width at any given value of H_p/p_o increases as the tube diameter is increased. Thus the effect of pitot size in this case is to displace the effective centre of the tube towards the region of lower velocity - an effect opposite to that found by Young and Maas at subsonic speeds.

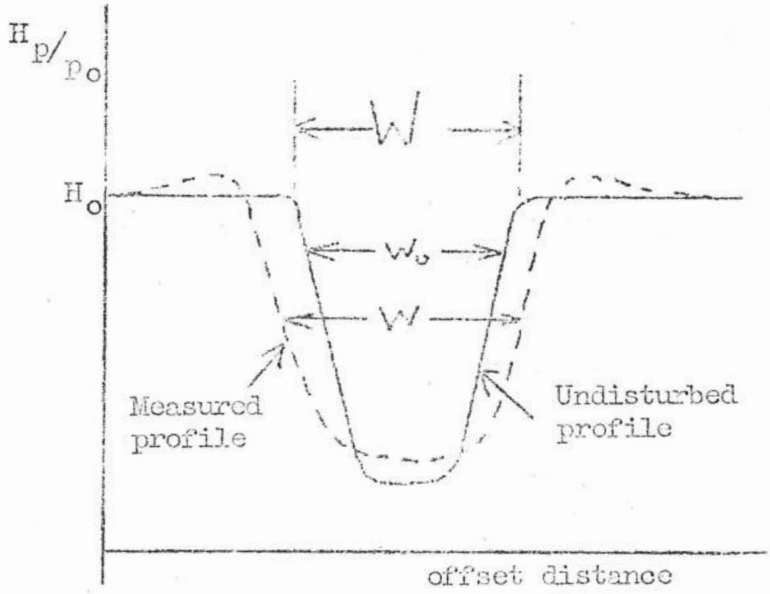
It may be noted that the total head readings rise to maximum values immediately outside the wake boundaries.



As will be seen from the diagram above, this rise in total head occurs in the region behind the fan-shaped compression waves near the trailing edge. Since it is probable that the total head loss across this compression fan is slightly less than that across the single oblique shock wave further out, this would explain the higher measured total head reading. This effect was not observed in the case of the larger wing, where boundary layer separation, induced by the upstream influence of the pitot tubes, occurred at about 60 per cent chord.

The results of the traverses behind the 1.75in. chord wing at $M = 3.19$ are shown in fig. 2. It will be seen that the displacement effect is in the opposite direction from that found when using the smaller wing.

In figs. 5 to 8, the apparent wake width w, at various values of H_o/p_o, is plotted against the external diameter of the pitot tubes the internal diameter being constant. The undisturbed wake width, w_o, at each value of total head, is given by extrapolating these curves back to zero diameter, and the displacement of the effective tube centre from its geometric centre, δ, is equal to $\frac{1}{2}(w - w_o)$. On each of these graphs is also shown the estimated undisturbed maximum wake width, W_o. This is taken as the maximum width of the linear portion of the profile given by the smallest tube used. It may not be an accurate estimate of the interference free maximum wake width but is useful as a reference length in analysing the results.



The variation of displacement with internal diameter was not investigated as such. In the results obtained for tubes of constant ratio d/D of internal to external diameter, most of the displacement was accounted for by the variation of external diameter, and the effect of internal diameter for values of this ratio less than 0.5 was found to be negligible. For $\frac{d}{D} > 0.5$, a slightly smaller displacement was found.

(ii) Low speed

All the readings were expressed as ratios of indicated total head to free stream total head, and typical profiles with different wakes are given in figs. 3 and 4. Plots of the apparent wake width against diameter are shown in figs. 9 and 10, together with an approximate value for the undisturbed maximum wake width W_o (see definition above). The effect of varying the internal diameter, with constant outside diameter, is shown in fig. 12, where wake widths obtained in the first set of experiments with pitot tubes of 32mm. outside diameter and inside diameters of 1.7mm. to 20mm. are shown. It will be seen that as in the supersonic case, the internal diameter has negligible effect for $0.1 < d/D < 0.5$. For values of d/D greater than 0.5, the displacement effect was slightly reduced. For very small inside diameters, the displacement effect was slightly increased.

6. Discussion

(i) Nature of the flow pattern

To clarify the physical picture, let us consider a pitot tube placed in an inviscid shear flow, such that the change in velocity across its diameter is small compared with the mean stream velocity. The vorticity present in the free-stream will give rise to a curvature of the streamlines in the vicinity of the tube and in particular to the stagnation

streamline which intersects the mouth of the tube. This stagnation streamline, therefore, does not come from a position far upstream coaxial with the pitot tube, but from a position displaced towards the region of higher velocity.

Since no flow is possible down the pitot tube a free streamline will exist across the mouth of the tube. This must be approximately a line (or surface, in the three-dimensional case) of constant pressure and velocity: the pressure is equal to the total head of the stagnation streamline, and the velocity is zero. Thus the flow past the pitot tube will be similar to that past a solid body of the same outside dimensions. The inside diameter therefore should have little effect on the external flow.

When the pitot tube spans the centre of a wake, and is acted upon by regions of opposite vorticity, the problem is obviously more complicated. An attempt was made to obtain a two-dimensional picture of such a flow in a smoke tunnel, but any measureable displacement of the stagnation streamline was masked by the rapid spreading of the flow near the tube mouth.

(ii) Direction of Displacement

The low speed experiments of Young and Maas, and also the earlier low speed tests made at Cranfield, showed that the displacement effect was torwards the region of higher velocity, and equal in practically all cases to 0.18 D. It appeared to be independent of total head and velocity gradient. On the other hand almost all the supersonic tests showed a displacement in the opposite direction, which varied considerably with total head and Mach number. * (Except for the larger wing at M = 3.19, only one wake was used at each Mach number).

/It was ...

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* Since on theoretical grounds the displacement effect is a function of the sign of the vorticity ahead of the pitot tube it was suggested that the negative displacement effect at supersonic speeds might be associated with a change in sign of the vorticity of the flow in crossing the bow shock wave of the pitot tube. In fact it is found that for a plane shock wave, upstream of which the supersonic flow is of constant vorticity and static temperature, a reversal in sign of the vorticity downstream of the shock wave occurs for Mach numbers between 1 and 2. In cases where the total energy, rather than the static temperature, is constant upstream of the shock wave, the vorticity is reduced in sign at all supersonic Mach numbers This might therefore explain the change in direction of the displacement in the supersonic experiments. However, there is no evidence as to whether either the temperature or total energy is constant across the flow, and it is difficult to establish whether this reversal in vorticity would take place across the curved bow wave. In any case, as the later experiments showed, a reversal of displacement can also occur at subsonic speeds.

It was noted, however, that the earlier low speed tests were all made using tubes of smaller diameter than the maximum wake width, whereas the supersonic tests giving a reversed displacement used very narrow wakes, and the tube diameters were then at least twice the wake width. The only large supersonic wake used, that from the 1.3/4in. wing at M = 3.19, gave a displacement in the same direction as the earlier low speed tests. It may be noted that boundary layer separation occurred on the larger wing at M = 3.19. No displacement effect was apparent in the relatively flat central region of the wake but a positive effect was found in the regions of shear flow. (We shall call this direction positive). Some further experiments were made at low speeds using very narrow wakes and large tubes, and a negative displacement was found. The direction of displacement appears therefore to be controlled, in our experiments, not by the stream Mach number, but by the size of tube relative to the wake width. In fig. 13, the value of δ/D given by experiment is plotted as a function of D/W_o, where W_o is the undisturbed maximum wake width. A logarithmic scale has been used for D/W_o, as these values vary from about 0.01 (Young and Maas 0.014in. tube) to 10 (Cranfield 6.4mm tube). It will be seen that both the subsonic and supersonic results, together with those of Young and Maas, lie roughly on a straight line. Tubes for which the value of D/W_o is greater than about 2 give a negative displacement effect. In the case of Johannesen and Mair, it was formerly assumed that no displacement was shown by their results. However, for their tubes B and C, D/W_o is of the order of 1 or 2, so we should expect the displacement to be very small. Plotting the wake widths as in fig. 11, we see that the mean displacement for tube D is about 0.06D, and for this tube $D/W_o = 3.6$. This result therefore agrees qualitatively with ours, although the total head profile given by tube D is considerably distorted. The other large tube, F, which has a very small internal diameter, gives a negligible displacement. This may be due to the small internal diameter causing an increased positive displacement as found in our experiments, and so reducing the negative displacement which would otherwise have been obtained for this tube.

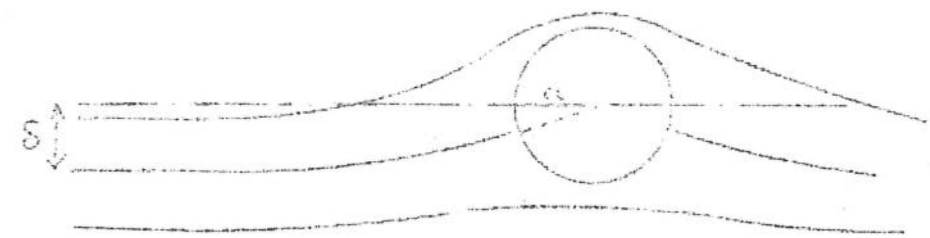
As mentioned in the previous section, it was not possible to obtain a satisfactory flow pattern in the smoke tunnel for the case of a very wide pitot tube. It is evident, however, that as the tube size increases, the upstream effect of the tube on the wake development will become greater, and there will be considerable distortion of the wake profile and external flow streamlines. An increase of the actual wake width will of course have a similar effect on the total head readings as a negative displacement effect. The real displacement effect, which is always positive, will be masked by the growth of the wake, and it is perhaps surprising that such little distortion of the true wake profile occurs when a tube of fairly large diameter is used.

(iii) Magnitude of the Displacement Effect

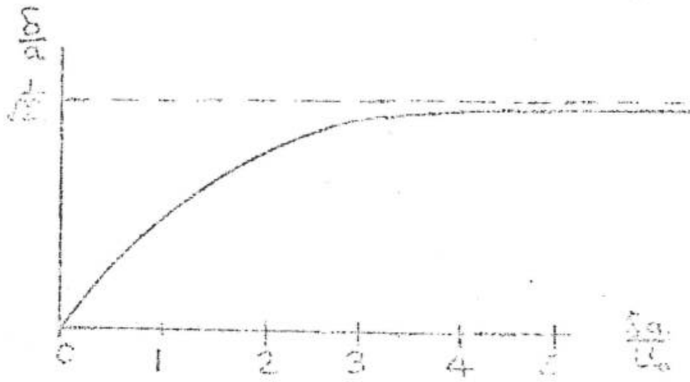
Having discussed qualitatively the effect of tube size, we can consider in more detail the behaviour of the displacement δ when the tube is much smaller than the wake width. Under these conditions the tube may be considered as in a unidirectional constant shear flow. The experimental results then show δ/D to be equal to 0.18D under a wide range of conditions. (Only one such result was obtained in the supersonic tests, however, owing to the small size of wake possible in the tunnel). As pointed out in ref. 1, δ/D should be some function of $D/u_o \zeta$, where ζ and u_o are the vorticity and mean velocity of the flow near the tube mouth. The results therefore imply that $F\left[D/u_o\zeta\right]$ is equal to 0.18 for all positive values of $D/u_o\zeta$, and -0.18 for all negative values, with a discontinuity as $D/u_o\zeta$ passes through zero. Physically, this is difficult to accept, and it is more likely that the function decreases rapidly for values close to zero, as would occur at the centre of a wake or with a very small tube. (The displacement given by the 1mm. tube in the low speed tests does, in fact appear to be much less than 0.18D).

The flow around a three dimensional body in shear flow, such as a pitot tube, has not been treated theoretically, but some light may be shed on the problem by considering the case of a two dimensional cylinder (see Appendix). The displacement of the stagnation streamline from the body axis far upstream is found to be $\frac{\delta}{a} = \frac{u_o}{\zeta a}\left[1 \pm \sqrt{1 + \frac{\zeta^2 a^2}{2\,u_o^2}}\right]$

(using the present sign convention)



where a is the radius of the cylinder. The form of this function is as shown.*



It will be seen that as $\frac{\zeta a}{u_o}$ becomes large compared to unity, $\frac{\delta}{a}$ tends towards a constant value of $\frac{1}{\sqrt{2}}$. Presumably, therefore, the displacement effect on the pitot tube will behave in roughly the same manner when $\zeta D/u_o$ becomes large with respect to a certain value. This value must be considerably less than 0.1, however, for the experimental results show that $\frac{\delta}{D}$ remains constant for values of $\frac{\zeta D}{u_o}$ down to 0.1. To examine experimentally the behaviour of $\frac{\delta}{D}$ in the region where $\frac{\zeta D}{u_o} < 0.1$, a series of extremely small pitot tubes in a wide wake would be needed.

Coming now to the case where the tube spans the wake, and the displacement is reversed, the flow is clearly too complex to find a theoretical relation for δ. Examination of figs. 5 to 11 shows that δ increases rapidly with tube

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* A more general result for two-dimensional cylinders of elliptical cross-section has been given by Mitchell and Murray (4).

diameter, and appears to be almost proportional to $\frac{H_p}{H_o}$, where H_o is the pitot reading outside the wake. It also increases with increasing velocity gradient (although the variation of the latter was small in the supersonic experiments). By plotting values of

$\log \frac{\delta}{H_p/H_o . s}$ (where s is the total head ratio gradient $\frac{\partial H_p/H_o}{\partial y}$) against log D (fig. 14), it is found that the displacement varies approximately as D^2, which gives the dimensionally correct formula $\delta = k \frac{H}{H_o} . s D^2$. The present results give values for k of 0.012 to 0.023 for the supersonic tests, and about 0.033 for the low speed test. The widest tube used in Johannesen and Mair's experiments gives a value of 0.035. Thus the order of magnitude of the displacement effect due to distortion of the wake by a very wide tube may be taken as very approximately $0.02\ H/H_o\ s\ D^2$.

This is only applicable where the tube is at least twice the wake width, whereas the relation $\delta = 0.18D$ seems to apply only for tube diameters less than one third of the wake width. In the intermediate region, the true displacement effect is clearly modified by the effects of distortion of the wake. Although no simple relation can be suggested for the value of δ in this region, some idea of the magnitude of the effect may be obtained from fig. 14. It will be noted that when D/W_o is approximately 2, the resultant displacement is practically zero.

(iv) Accuracy of the total head readings

In the shear region of the wake profiles, any inaccuracy of total head reading has been taken as part of the displacement effect. Thus, if a correction for the displacement is applied to the tube position, the reading of the tube will be the correct total head at the new position.

Near the wake centre, where the total head gradient falls to zero, there should be no error in the total head readings provided viscous effects are negligible. This appears to be substantiated by experiment, since the variations in total head reading at the wake centre are less than 2 per cent for tubes smaller than the wake width. In the case of the wider tubes, the spreading of the wake will of course alter the true total head at its centre.

For the widest tubes used, the total head at the wake centre appears to be almost doubled due to the presence of the tube.

Acknowledgements

The authors are indebted to Professor A.D. Young, now Professor of Aeronautics, Queen Mary College, for initiating this investigation, and to Dr. D.W. Holder, Aerodynamics Division, National Physical Laboratory, who supplied most of the pitot tubes used.

7. Conclusions

Experiments have been performed to measure the displacement of the effective centre of a pitot tube from its geometric centre when placed in wakes behind various thin two-dimensional wings. The measurements were made at low subsonic speeds and also at supersonic Mach numbers of 1.75, 2.45 and 3.19, using pitot tubes whose diameters varied from 0.5mm. to 31mm. The following conclusions were reached.

(i) When the pitot tube is in a wake whose width is at least three times the tube diameter D, or in a unidirectional velocity gradient, the displacement is towards the region of higher velocity, and is equal to 0.18D. Theoretical considerations, however, indicate that the displacement decreases from this value when the total head gradient or tube diameter become very small.

(ii) If the maximum wake width W_o is less than the tube diameter, the apparent displacement effect decreases to zero, and then becomes negative (i.e. in the direction of decreasing velocity) as the ratio D/W_o increases.

(iii) For values of D/W_o greater than about 3, the resulting displacement in the direction of decreasing velocity is approximately proportional to D^2, H/H_o (the ratio of total head measured at a point in the wake to that outside the wake), and s (the transverse gradient of H/H_o across the tube face).

(iv) The displacement is practically independent of internal tube diameter, d, provided this is less than half the external diameter. For values of the ratio d/D greater than this, the displacement is slightly reduced.

(v) No appreciable errors due to tube size were apparent in the pitot readings at the centre and outer edges of the wake (i.e. where the total head gradient was zero). However, when the wake itself was distorted by a very large tube, an increased total head reading was obtained at the centre.

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APPENDIX

The displacement effect for a two-dimensional circular cylinder in a shear flow

Consider a two-dimensional shear flow with constant vorticity ζ past a circular cylinder of radius a. The equation for the stream function, ψ, is

$$\nabla^2 \psi = - \zeta \qquad \ldots\ldots\ldots\ldots(1)$$

with the velocity components u and v given by

$$u = \frac{\partial \psi}{\partial y} , \quad v = - \frac{\partial \psi}{\partial x}$$

and
$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} .$$

If the axis of the cylinder is taken as the origin of the rectangular cartesian coordinates (x,y) and polar coordinates (r,θ) and u_o is the freestream velocity at $y = 0$ $(x = \pm \infty)$ then it can be shown that the solution to equation (1), satisfying the boundary conditions in the freestream and on the cylinder, is

$$\psi = - \frac{1}{4} \zeta r^2 + u_o \left(r - \frac{a^2}{r}\right) \sin \theta + \frac{\zeta}{4} \left(r^2 - \frac{a^4}{r^2}\right) \cos 2\theta \qquad \ldots\ldots\ldots\ldots(2)$$

and in the freestream $(r \to \infty)$

$$\psi = - \frac{\zeta}{2} y^2 + u_o y \qquad \ldots\ldots\ldots\ldots(3)$$

The stream function ψ_s for the stagnation streamline, and its coordinates, are found from equation (2) when $r = a$ giving

$$\psi_s(r',\theta') = - \frac{\zeta a^2}{4} = - \frac{\zeta}{4} r'^2 + \left(r' - \frac{a^2}{r'}\right) u_o \sin \theta + \frac{\zeta}{4} \left(r'^2 - \frac{a^4}{r'^2}\right) \cos 2\theta'$$

and since $r' \sin \theta' = y'$

$$\frac{\zeta}{2}\left(\frac{a^2}{r'^2} + 1\right) y'^2 - u_o y' - \frac{\zeta a^2}{4} = 0 \quad \text{.........(4)}$$

The stagnation streamline meets the cylinder at the point $P(a,\theta_s)$. From equation (4)

$$\sin \theta_s = \frac{u_o}{2\zeta a}\left[+ 1 \pm \sqrt{1 + \frac{\zeta^2 a^2}{u_o^2}} \right] \quad \text{............(5)}$$

For values of $\frac{\zeta a}{u_o} < \frac{4}{3}$ equation (5) gives one front and one rear stagnation point. For values of $\frac{\zeta a}{u_o} \geqslant \frac{4}{3}$ there are two front and two rear stagnation points. As $\frac{\zeta a}{u_o} \to \infty$ $(u_o \to 0)$ the stagnation points are at $(30^o, 150^o$ and $-30^o, 210^o)$. The displacement (δ) of the stagnation streamline far upstream from the cylinder axis is from equation (4), since $r' = \infty$, $\delta = - y'$,

$$\frac{\delta}{a} = -\frac{u_o}{\zeta a}\left(1 \pm \sqrt{1 + \frac{\zeta^2 a^2}{2u_o^2}}\right)$$

For values of $\frac{\zeta a}{u_o} \ll 1$ $\frac{\delta}{a} \approx - \frac{\zeta a}{4u_o}$ but for larger values of $\frac{\zeta a}{u_o}$ $\frac{\delta}{a}$ becomes more independent of $\frac{\zeta a}{u_o}$, and approaches the limiting values of $\frac{1}{\sqrt{2}}$.

TABLE I

Tubes used in Supersonic Tests

Tube	Outside Diam. D (m.m.)	Inside Diam. d (m.m.)	d/D
1	0.50	0.25	0.50
2	1.01	0.50	0.49
3	2.00	1.40	0.70
4	2.39	2.00	0.84
5	3.18	0.50	0.16
6	6.38	0.50	0.08

TABLE II

Tubes used in low speed tests

Tube	Outside Diam. D (m.m.)	Inside Diam. d (m.m.)	d/D
1	1.0	0.50	0.50
2	3.18	0.50	0.16
3	4.76	0.50	0.10
4	6.35	0.50	0.78
5	31.00	0.50	0.016
6	31.00	3.18	0.102
7	31.00	4.76	0.153
8	31.00	6.35	0.205
9	31.00	19.00	0.615

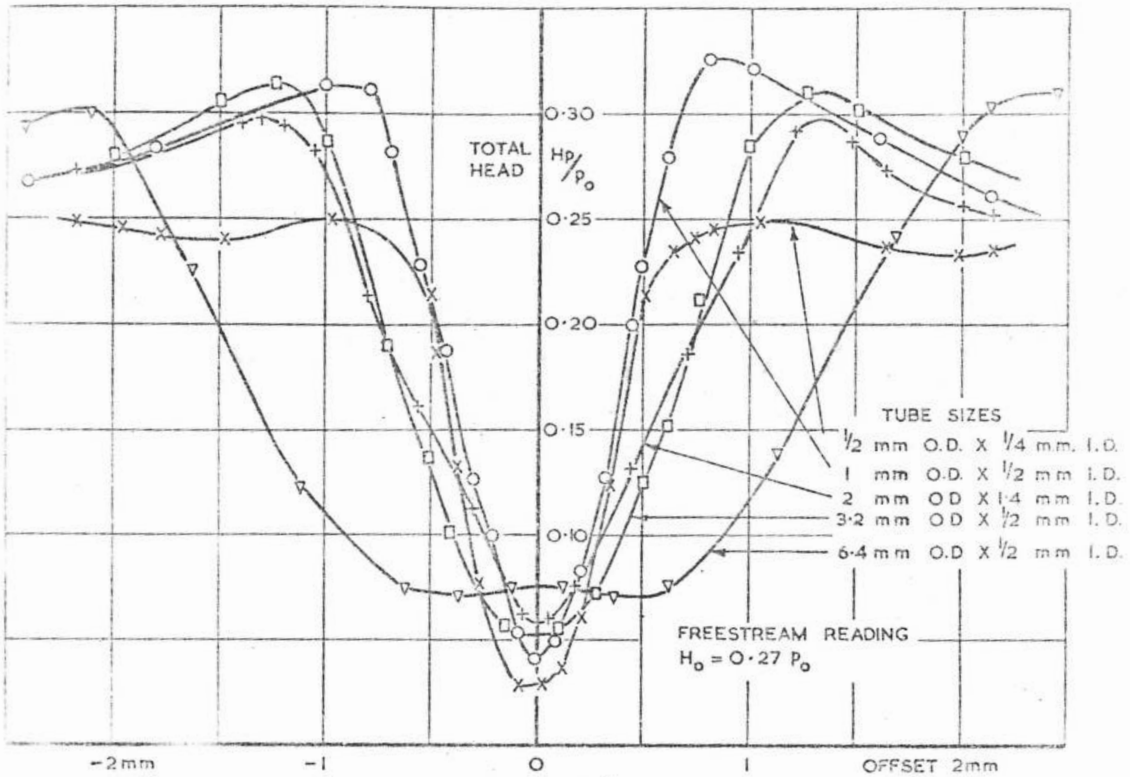


FIG. 1 WAKE TRAVERSES BEHIND 1/2" CHORD WING AT M 3·19

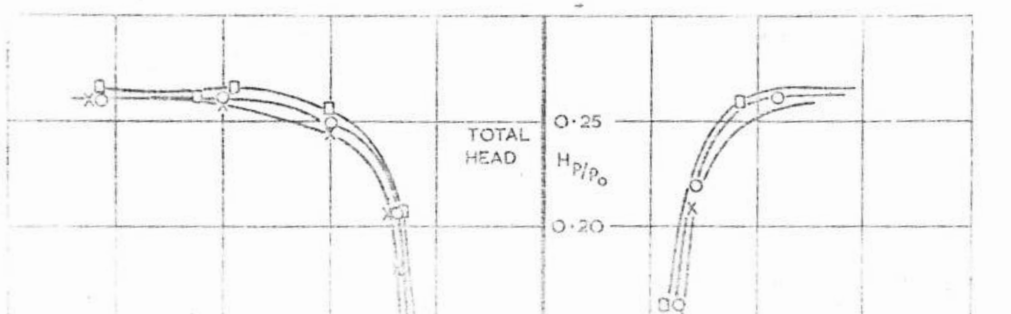


FIG. 2. WAKE TRAVERSES BEHIND 1·75" CHORD WING AT M=3·19

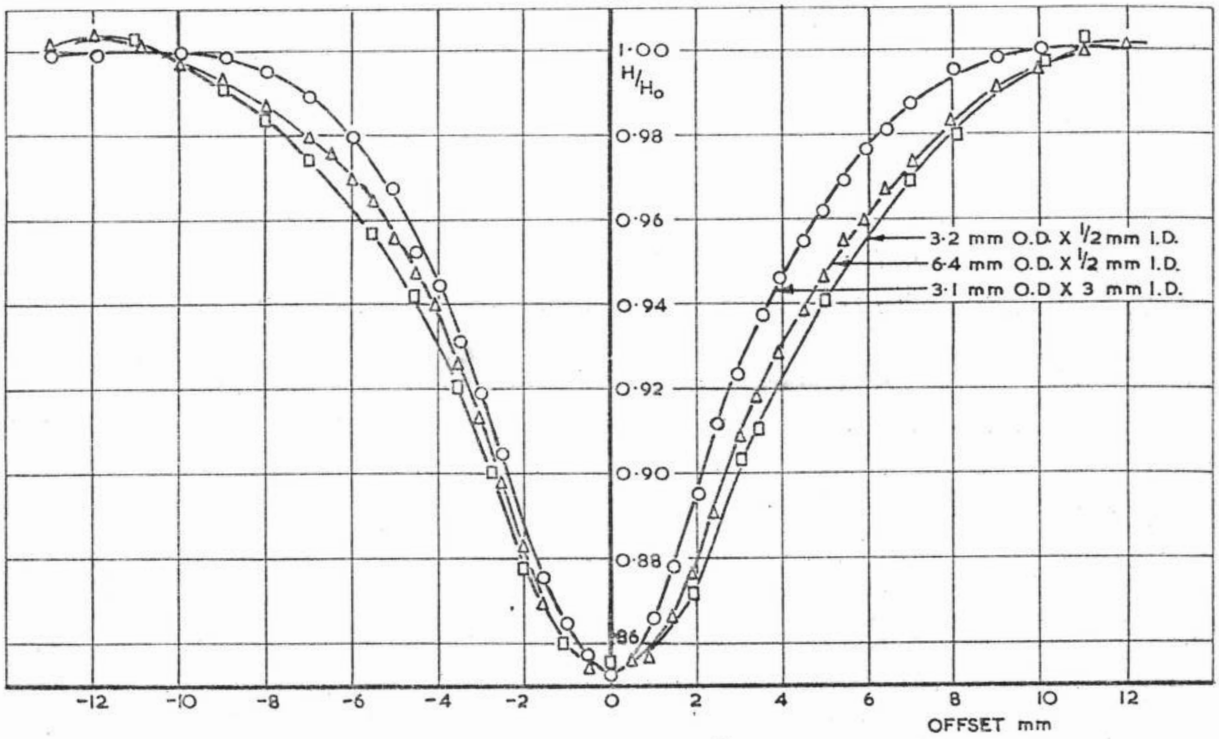


FIG. 3. WAKE TRAVERSES BEHIND 2" CHORD WING AT 59 F/S

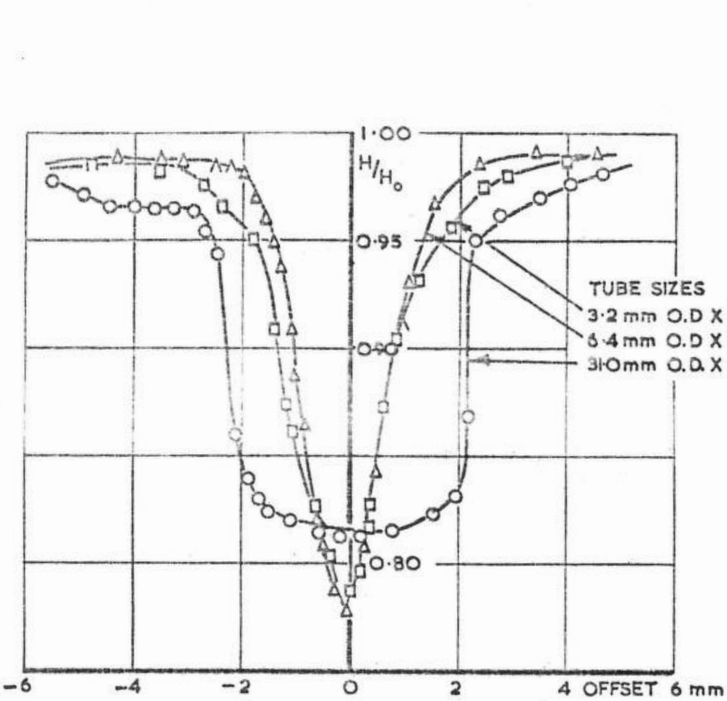


FIG. 4. WAKE TRAVERSES BEHIND 1" X 1/32 FLAT PLATE AT 50 F/S.

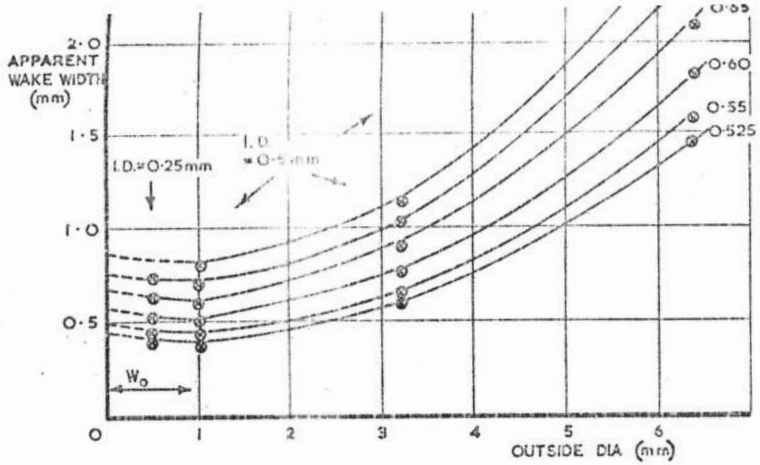


FIG. 5. VARIATION OF APPARENT WAKE WIDTH WITH OUTSIDE DIA OF TUBE (1/2" CHORD WING AT M = 1·75)

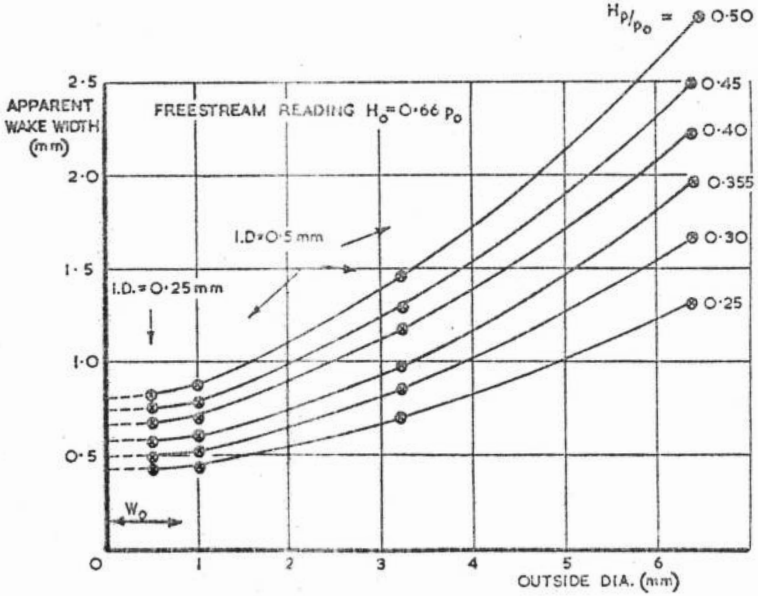


FIG. 6. VARIATION OF APPARENT WAKE WIDTH WITH EXTERNAL DIA OF OF TUBE (1/2" CHORD WING AT M=2·36)

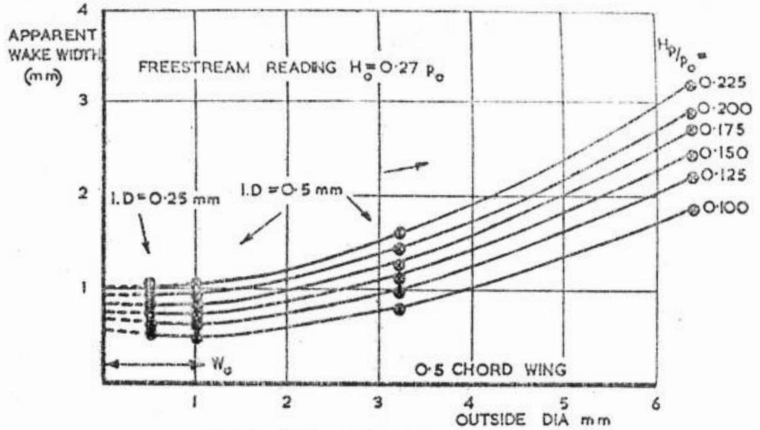


FIG. 7. VARIATION OF APPARENT WAKE WIDTH WITH OUTSIDE DIA. OF TUBE (1/2" CHORD WING AT M=3·19)

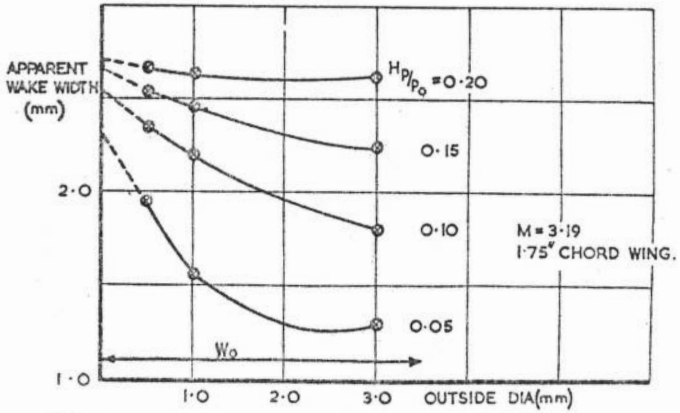


FIG 8 VARIATION OF APPARENT WAKE WIDTH WITH OUTSIDE DIA. OF TUBE (1 3/4" CHORD WING AT M=3·19)

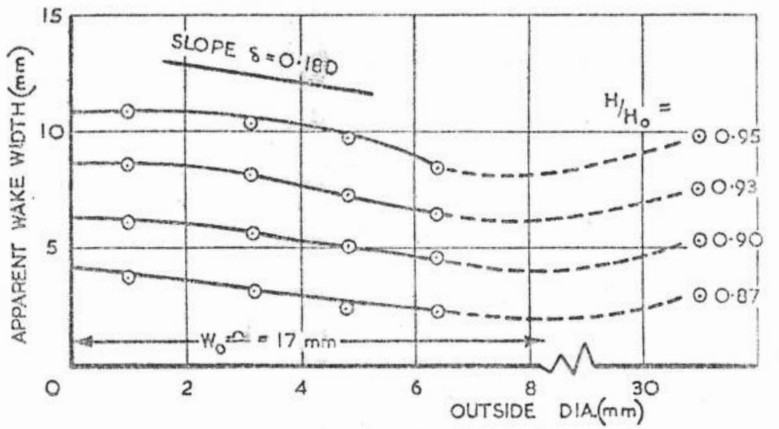


FIG. 9. VARIATION OF APPARENT WAKE WIDTH WITH OUTSIDE DIA. OF TUBE (2" CHORD WING AT 59F/S)

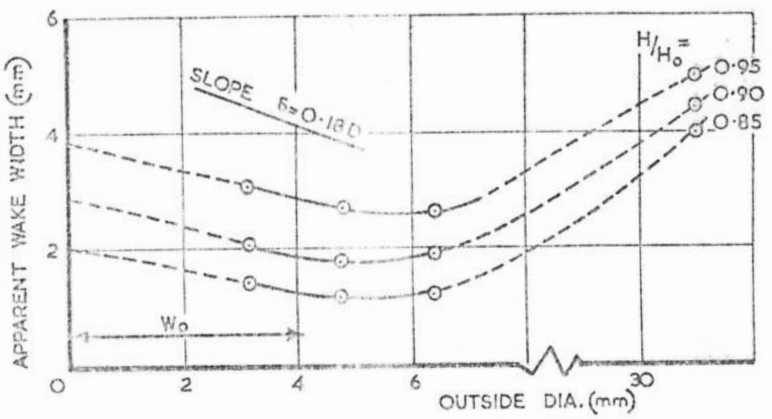


FIG. 10. VARIATION OF APPARENT WAKE WIDTH WITH OUTSIDE DIA. OF TUBE (1" CHORD FLAT PLATE AT 50F/S)

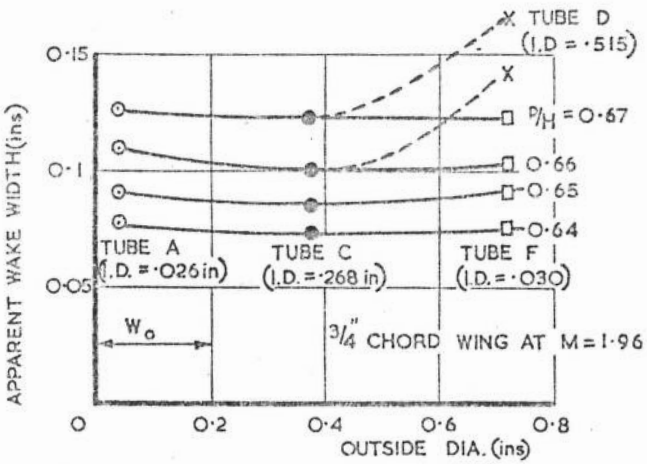


FIG. 11. VARIATION OF APPARENT WAKE WIDTH WITH OUTSIDE DIA. OF TUBE (JOHANNESEN & MAIR)

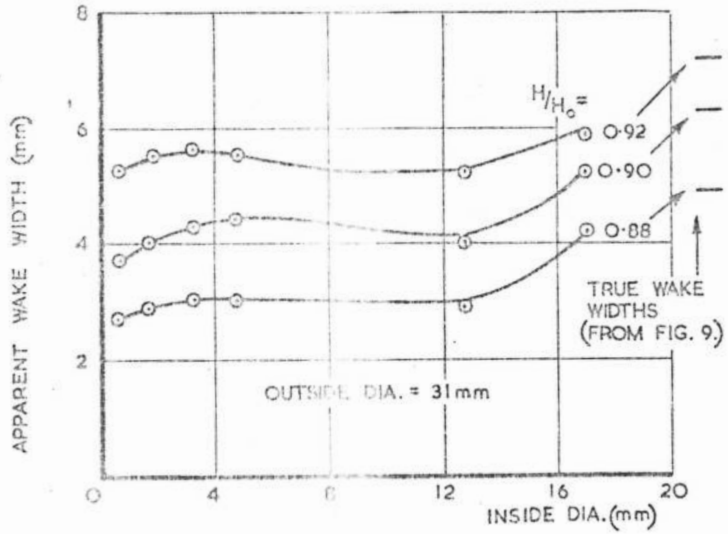


FIG. 12 VARIATION OF APPARENT WAKE WIDTH WITH INSIDE DIA. OF TUBE (2" CHORD WING AT 59F/S)

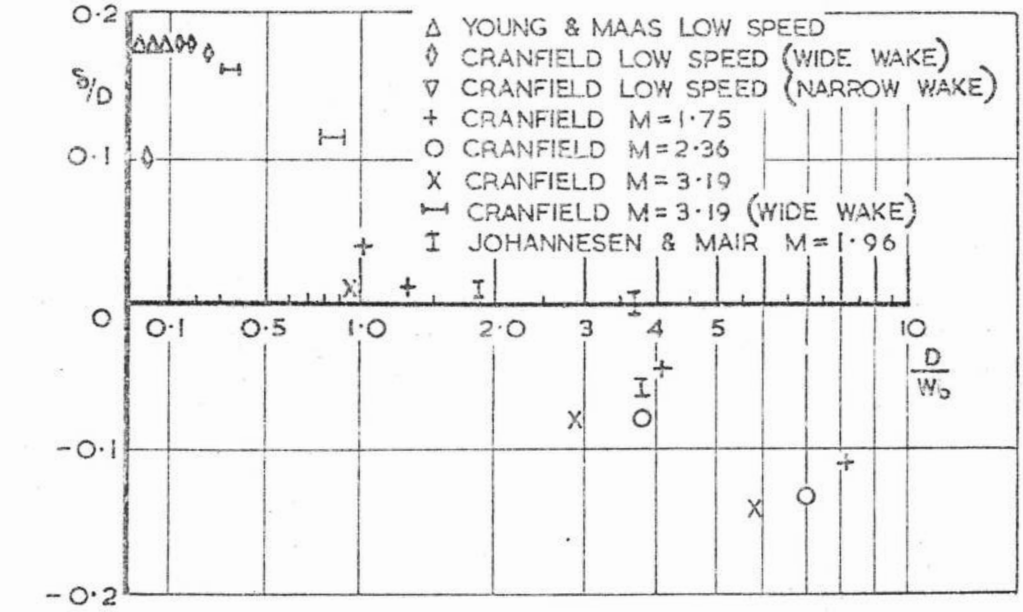


FIG. 13. VARIATION OF DISPLACEMENT WITH RATIO OF TUBE DIAMETER TO WAKE WIDTH

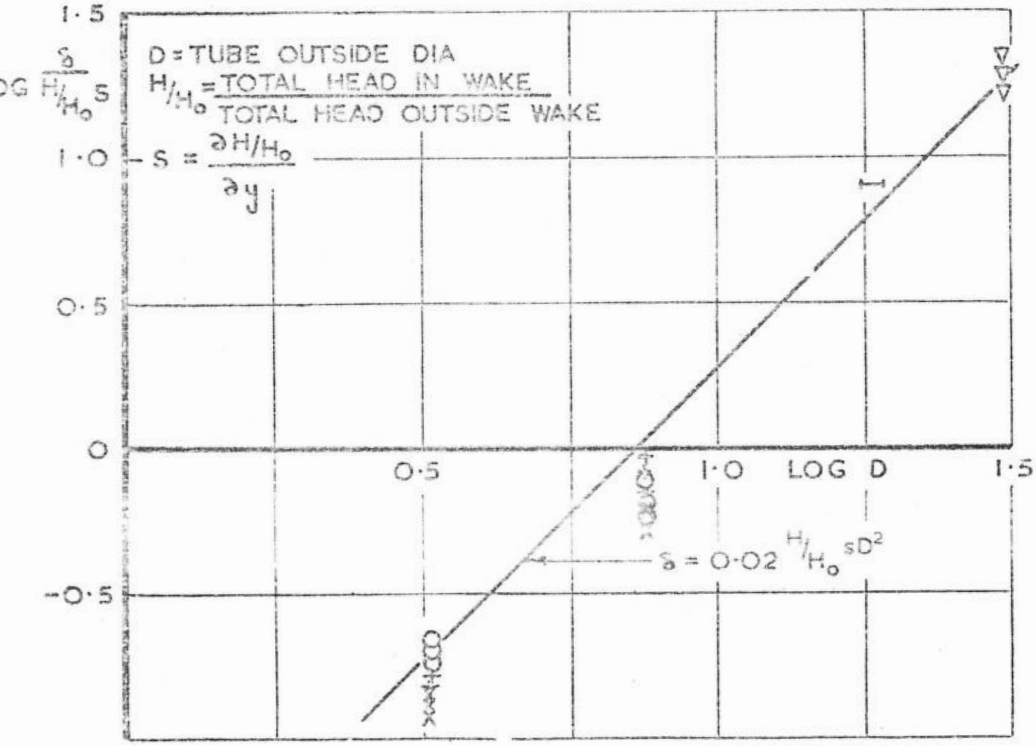


FIG. 14. VARIATION OF DISPLACEMENT FOR VERY LARGE DIAMETER TUBES

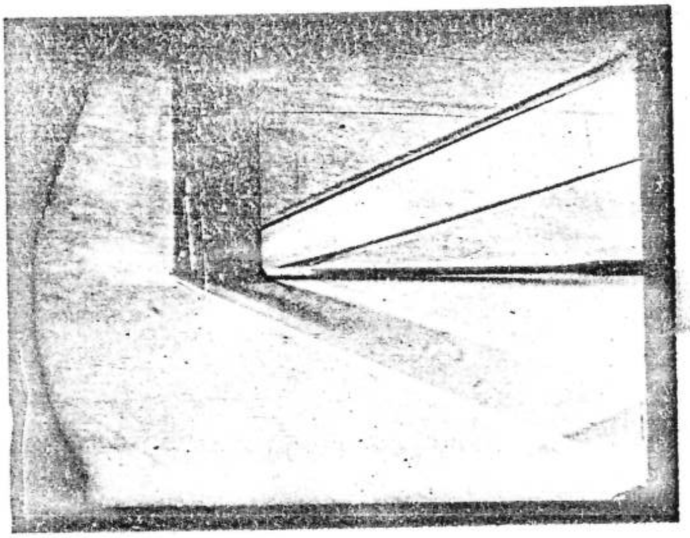


FIG. 15. 1mm TUBE BEHIND $\frac{1}{2}$" CHORD WING AT M= 3. 19(2mm OFFSET).

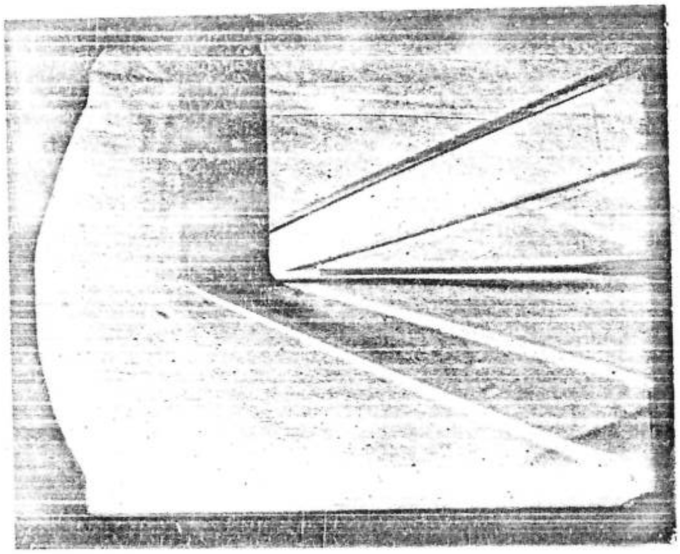
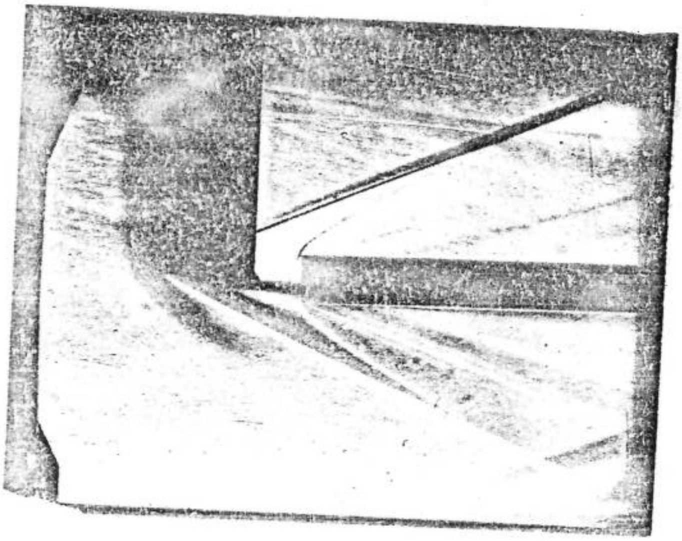
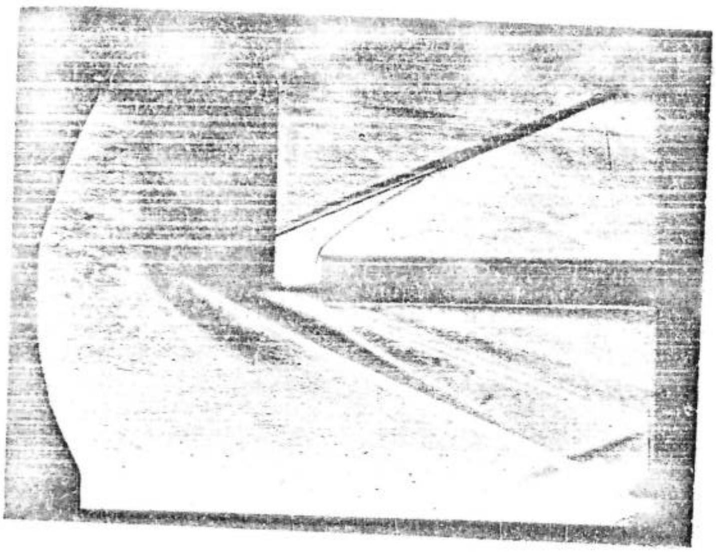


FIG. 16. 1mm TUBE BEHIND $\frac{1}{2}$" CHORD WING AT M=3. 19(0. 5 mm OFFSET).



IG. 17. 6.4mm TUBE BEHIND $\frac{1}{2}$" CHORD WING AT M = 3.19 (0.2mm OFFSET).



18. 6.4mm TUBE BEHIND $\frac{1}{2}$" CHORD WING AT M = 3.19 (0.5mm OFFSET).