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SURFACE PRESSURE MEASUREMENTS ON A SERIES OF TWO-DIMENSIONAL YAWMETER BODIES

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16. Abstract

It is shown that certain two-dimensional bodies exist having a sensitivity of surface pressure to flow direction which is much higher than for currently used two dimensional yawmeters. A body having a simple cross sectional shape was selected for experimental evaluation at low Mach number, but at a typical Reynolds number for such instruments. Employed as a yawmeter this body would have a sensitivity 3-1/2 times that of the best known alternate. Its performance would be exploited most suitably in the form of a two dimensional nulling yawmeter.

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SUMMARY

It is shown that certain two-dimensional bodies exist having a sensitivity of surface pressure to flow direction which is much higher than for currently used two-dimensional yawmeters. A body having a simple cross sectional shape was selected for experimental evaluation at low Mach number but at a typical Reynolds number for such instruments. Employed as a yawmeter this body would have a sensitivity 3-1/2 times that of the best known alternate. Its performance would be exploited most suitably in the form of a two-dimensional nulling yawmeter.

1. Introduction.

This report concentrates on yawmeters which exploit the changes of surface pressure occurring with change of angle of attack on two-dimensional bodies. The usual body shapes employed[1] have circular or wedge-shaped cross sections. Two pressure orifices placed symmetrically in the body lead to a pressure difference transducer, the output of which is used as an indication of the misalignment of the flow with the plane of symmetry of the instrument. A nulling yawmeter is rotated about an axis parallel to the axis of the cylinder until the pressure difference is zero, the flow direction then being indicated by its attitude. In both cases the resolution of the instrument in terms of flow angle is inversely proportional to its sensitivity; a highly sensitive instrument will be able to resolve small changes in flow direction. Sensitivity is defined as the change of difference in pressure between the two orifices as a fraction of free stream dynamic pressure, per degree change of flow direction. The circular and wedge-sectioned yawmeters are referenced as having sensitivities[1] of 0.080 and 0.053 per degree respectively.

That two-dimensional bodies exist which can develop much higher sensitivities can easily be demonstrated. An uncambered airfoil is one such body, and the NACA 0012-64 is typical. The difference in pressure between the upper and lower surfaces of this airfoil at a suitably chosen chordwise station changes very rapidly with angle of attack below stall. The difference between upper and lower surface pressure coefficients, at 5% chord, is shown for this airfoil measured at a very low Reynolds number on Fig. 1. On this Figure ΔCp is upper surface minus lower surface pressure coefficients. At zero angle of attack the slope of the curve is 0.322 per degree. An instrument having the same cross section would develop the same sensitivity, which is four times that given by the circular cylinder and more than three times that of the most sensitive[1] yawmeter. Thinner sectioned airfoils might be expected to provide higher sensitivities.

There are several ways in which the notion of the airfoil sectioned yawmeter might be put into practice. On figure 2 is shown one possible arrangement. Two pressure tubes, with orifices pierced from the wing surface, are shown touching and located at 5% chord. A compact instrument is a normal requirement, and considerations of orifice size, instrument response rate, strength etc. would dictate the minimum tube diameter D and hence the size of the instrument. However, the design shown on figure 2 can be seen to be large: the maximum depth is nearly twice the depth of the pair of tubes (the smallest yawmeters have a depth equal to that of a pair of pressure tubes) while the excessive length would normally be regarded as undesirable. Furthermore, it might be difficult to manufacture with the required accuracy a small instrument having such a complex shape.

To be of general use an instrument must maintain its performance over the wide ranges of Mach and Reynolds numbers brought about by changes in its environment. The range of Mach number experienced in wind tunnel testing is of course very wide, extending upwards from near zero and very commonly exceeding 3. Likewise the values of unit Reynolds number experienced in practical testing could range from about 5.2×10^5 per meter (1.6×10^5 per foot) to 5.2×10^8 per meter (1.6×10^8 per foot). Both ranges are very wide, and an ideal instrument would be one having a performance which was only a weak function of these two parameters.

Pressure tubes of order one millimeter in diameter are commonly used in small instruments. In a yawmeter this would yield a depth of 2 mm and a range of Reynolds number (based on this dimension) that could be encountered by the yawmeter in wind tunnel testing extending from about 10^3 to 10^6.

It is appropriate at this stage to review the requirements of a two-dimensional yawmeter. Very briefly these seem to be:

(a) high sensitivity to flow direction

(b) small size

(c) small effects of Mach and Reynolds numbers

(d) simplicity of shape

An instrument has been developed which satisfies at least some of these requirements, and is based on a body having the leading edge shape shown on figure 3. One attraction of this shape is that it can be formed conveniently from two stacked tubes.

Leading to the choice of this geometry was the report[2] of a large change in pressure between symmetrically disposed points on the surface of a cylinder having such a leading edge, with change of angle of attack from zero to 5° in subcritical flow. The difference in pressure coefficient changed by about 3, giving an average sensitivity of about 0.6 per degree over this range of angle. The body was basically square in cross section, with the four corners radiused to approximately D/2, and is here referred to as body type A.

This body geometry was first investigated in a low-speed atmospheric wind-tunnel at the University of Southampton and is reported, but gave a disappointing performance. However, alternative and satisfactory bodies based on the same leading edge shape were found. These are type B and the performance over a range of Reynolds number is given, together with a proposed design of yawmeter based on the body shape.

2. Body type A.

Reynolds number R_{2D} is based on the depth of the body 2D, D being the diameter of tubes which it is anticipated would form part of the leading edge and dictate the depth. A pressure distribution taken at NASA Langley Research Center[2] in low speed flow at $R_{2D} = 303{,}000$, reproduced on figure 4, led to this investigation. At stations $x/P = \pm 0.155$ (x, the distance around the cylinder from its center leading edge, is defined on figure 4, and P is the total perimeter) there are seen to be large changes of pressure coefficient with change of angle of attack α from 0 to 5°. The changes of pressure coefficient are indicated by arrows A. An interesting feature of the pressure distribution at $\alpha = 5^{\circ}$ is that the highest negative pressure coefficient occurs on the under-surface.

A similar but smaller model was constructed for wind tunnel testing having essentially the same cross sectional shape. This model had a depth 2D of 15.93 mm (0.627 inches) and spanned the center of a 30.48 cm (12 inch) square test section of the low-speed tunnel at Southampton. Test data from this model at a Reynolds number of 29,300 are also shown on figure 4. It is seen that the suction peaks are much lower, and that the changes of pressure coefficient at stations $x/P = \pm 0.155$ were more modest such that the change of pressure coefficient difference between 0° and 5° angle of attack now amounted to about unity. This is in sharp contrast with the value of about 3 obtained at the higher Reynolds number.

The sensitivity indicated by the low Reynolds number data of about 0.2 per degree is still more than twice that of a conventional yawmeter, and that fact taken on its own might encourage exploitation of the body shape. However, the shape is quite unsuitable for use as the basis of a yawmeter. because the changes of surface pressure coefficient proved to be highly non-linear functions of angle of attack in the range $\pm 5^{\circ}$. The pressure coefficient is shown for one appropriate point on the perimeter as a function of angle of attack on figure 5. It is seen that pressure is almost invariant with α over a considerable range, and that a sudden change in C_p occurs at this station at about $\alpha = -5^{\circ}$. Appreciable hysteresis was also evident as indicated by the arrows on this figure. Clearly the body shape is unsuitable for use as a yawmeter.

3. Body type B.

This is shown in cross section on figure 6. It is seen to be rectangular in cross section (body type A was square), and has its leading corners radiused but its trailing corners sharp (all corners of body type A were radiused). Seventeen pressure orifices, shown numbered on figure 6, were distributed around the leading edge. Eight body lengths ℓ were tested as detailed on the figure, giving length to depth ratios L from unity to 3.4. The tests were carried out with the body spanning the 30.48 cm (12 inch) test section of a low speed atmospheric wind tunnel.

The available range of airspeeds gave a range of Reynolds number R_{2D} from about 12,000 to about 35,000. These values lie inside the extremes mentioned in the Introduction. An angle of attack mechanism allowed full 360° rotation, with an angular resolution of $\pm 0.1^{\circ}$ in the α range $\pm 10^{\circ}$.

Two typical pressure distributions are shown on figure 7, taken at zero and 5° angles of attack on a body having L = 2.2. All data is uncorrected for blockage. Note that orifice number 9 is on the leading edge center line, in the plane of symmetry. For use as a yawmeter the orifices would be paired symmetrically about number 9, for example 8 with 10, or 1 with 17. The changes in the difference in pressure coefficient between a pair, with change of angle of attack, is the sensitivity available from that pair. Among the orifices which can be paired, 5 with 13 give the highest sensitivity. The pressure changes are indicated on figure 7 by arrows. The total change in C_p over 5° is seen to be about 0.91, or an average sensitivity of 0.18 per degree over this 5° range. In fact, the sensitivity given by this orifice pair at zero angle of attack is higher than this, as shown by the plot of pressure difference coefficient ΔC_p as a function of a small angle of attack range centered on zero shown in figure 8. ΔC_p is defined as C_p at orifice 5 minus C_p at orifice 13. The sensitivity is 0.342 per degree at that particular

Reynolds number. Measurements at the extreme available values of Reynolds number on the same body gave similar sensitivities. The data is shown on figure 9.

The variation of ΔC_p for the same body and orifice pair over the complete range of angle of attack is shown on figure 10. The high level of sensitivity at zero α is apparent from the steepness of the curve in that region. The important information from this figure is that no ambiguity of indicated flow direction can occur. Only at one angle of attack where ΔC_p is zero is the slope of the curve strongly negative.

The effect of change of body length at constant Reynolds number is shown on figure 11. Sensitivity is seen to be only weakly dependent on L in the range 1.4 to 3.4. Tests on the shortest body, L = 1, indicated a sensitivity near zero. That data point is not shown.

The curve on figure 11 indicates that a body having a length to depth ratio L of about 1.8 would combine the highest sensitivity with a compact geometry. A sensitivity of about 0.34 per degree would be expected at that value of Reynolds number. Indicated also on the figure is the band of sensitivities quoted for a wide range of yawmeters in reference 1. A yawmeter based on body type B, with L = 1.8, will give a sensitivity more than 3-1/2 times that of the best referenced yawmeter.

The cross section of a practical design of yawmeter based on body B with L = 1.8, is shown in figure 12. With tubes of diameter 1 mm the cross section of the yawmeter would have the compact dimensions of depth 2 mm, length 3.6 mm. The outline of the yawmeter is superimposed on figure 2 to allow a comparison of the relative sizes of two yawmeters having roughly equal sensitivities and employing equal diameter pressure tubes.

While two-dimensional yawmeters have many applications, of more general use would be an axi-symmetric shape, because of the possibility of the instrument providing flow angles in two planes, and because of the lower level of flow interference. This work indicates that axi-symmetric yawmeter body shapes could possibly be developed, perhaps with leading edge shapes similar to that of body B, giving higher sensitivities than normal.

4. Conclusions.

1. Two-dimensional yawmeter bodies are available which can develop much higher values of sensitivity than hitherto exploited.

2. A yawmeter body has been developed having a compact, simple, basically rectangular cross section which at representative Reynolds number develops a sensitivity more than 3-1/2 times that of the most sensitive alternate.

3. The two-dimensional body shape requires evaluation over a wider range of Reynolds number, and also over a range of Mach number.

4. Effort should be applied to the development of an axi-symmetric yawmeter body shape having a high sensitivity.

5. References.

1. Bryer, D. W., Pankhurst, R. C. Pressure probe methods for determining wind speed and flow direction, H.M.S.O., 1971.
2. Polhamus, E. C., Geller, E. W., Grunwald, K. J. Pressure and force characteristics of noncircular cylinders as affected by Reynolds number with a method included for determining the potential flow about arbitrary shapes. NASA TR R-46, 1959.

SYMBOLS.

C_p	Pressure coefficient
D	Tube outside diameter
L	Body length-to-depth ratio, $\ell/2D$
ℓ	Body length
M	Mach number
P	Perimeter length
R_c	Reynolds number based on chord length
R_{2D}	Reynolds number based on body depth
x	Distance around perimeter from the leading edge center
α	Angle of attack
ΔC_p	Difference in pressure coefficient between two orifices

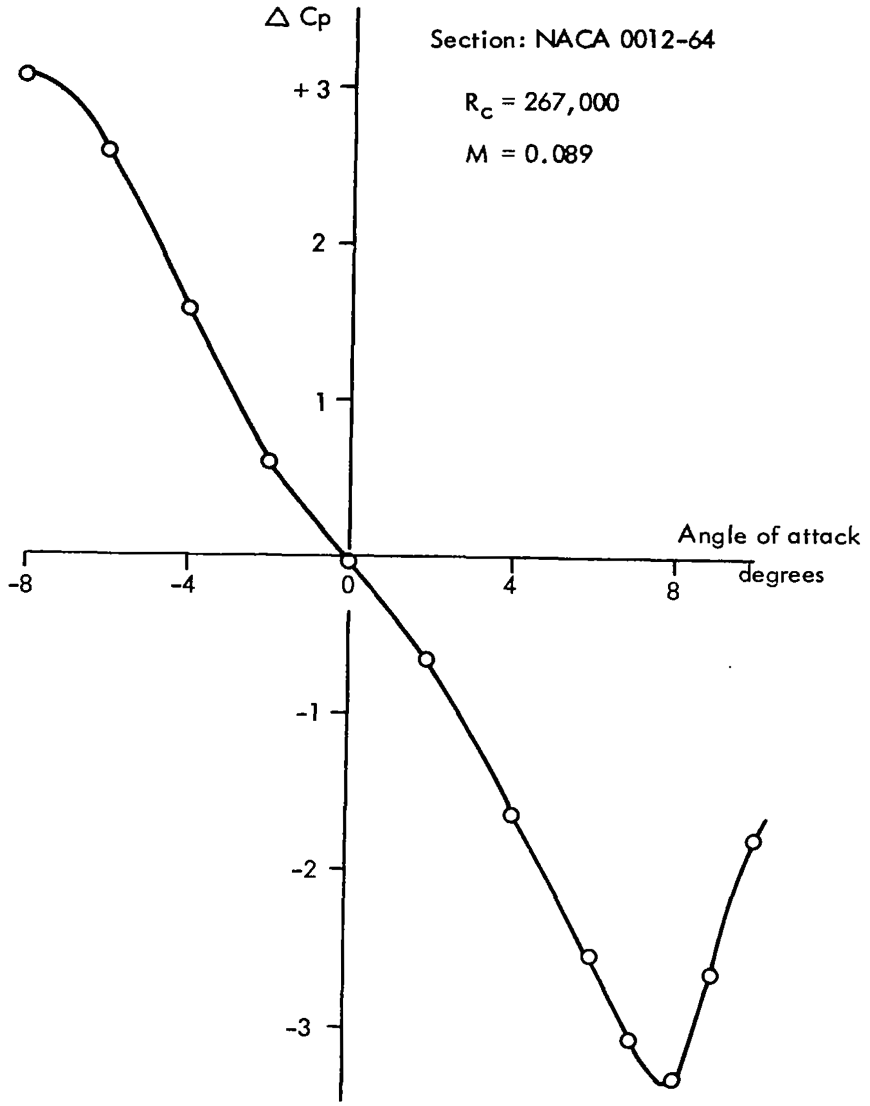


FIG. 1. VARIATION OF PRESSURE COEFFICIENT DIFFERENCE ΔC_p WITH ANGLE OF ATTACK, ON A TYPICAL TWO - DIMENSIONAL AIRFOIL SECTION AT 5% CHORD.

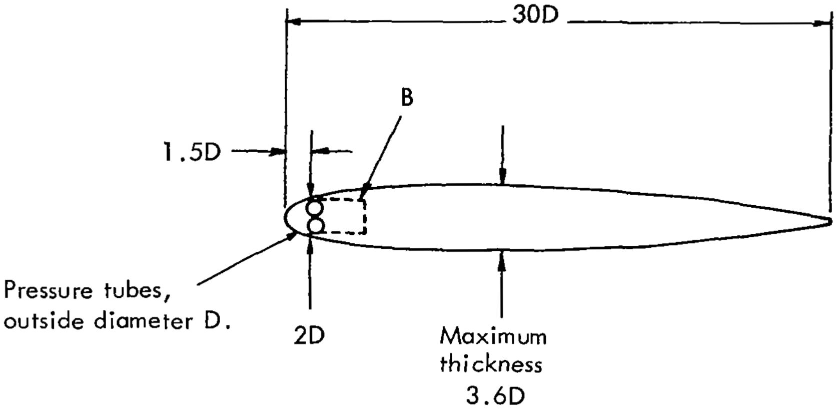


FIG. 2. THE ADAPTATION OF AN UNCAMBERED AIRFOIL AS A TWO DIMENSIONAL YAWMETER.

(THE OUTLINE OF BODY TYPE B, DESCRIBED LATER IN THIS REPORT IS SHOWN FOR COMPARISON).

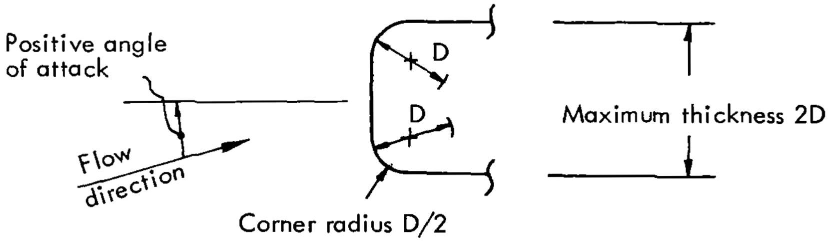


FIG. 3. A CROSS SECTION THROUGH THE LEADING EDGE SHAPE COMMON TO A SERIES OF CYLINDRICAL YAWMETER BODIES.

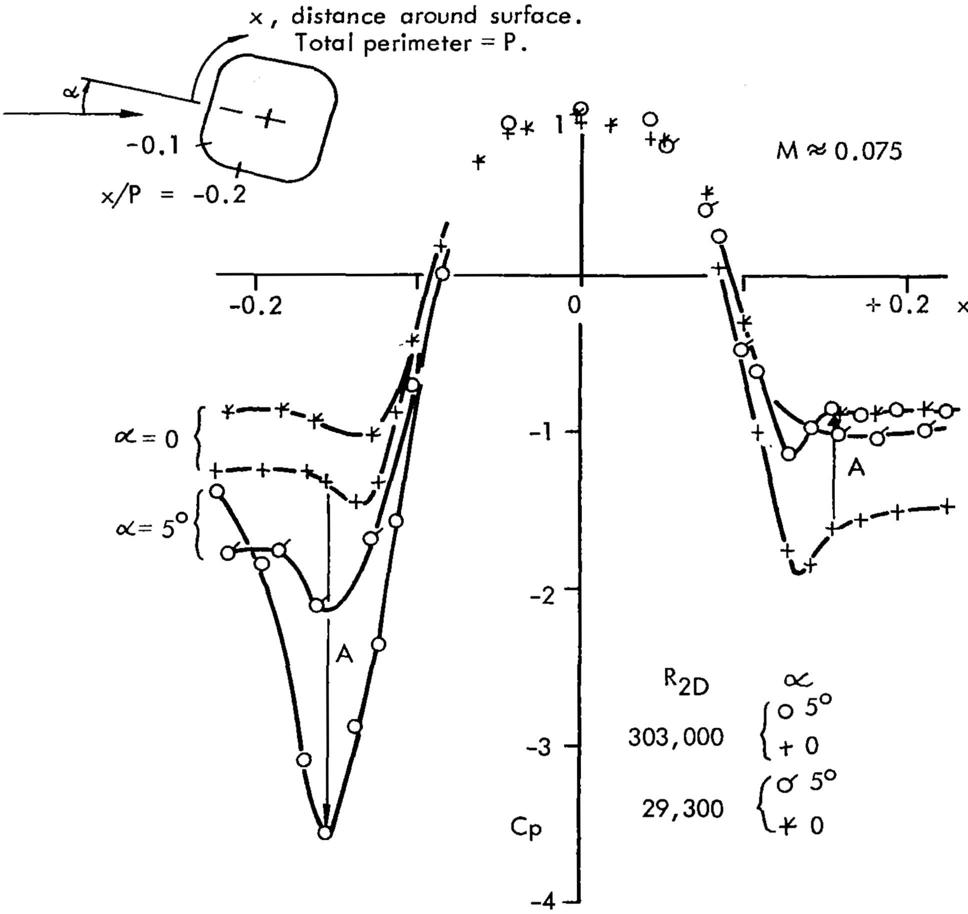


FIG. 4. THE INFLUENCE OF REYNOLDS NUMBER, AT 0 AND 5° ANGLE OF ATTACK, ON THE PRESSURE DISTRIBUTION AROUND THE LEADING SURFACE OF A CYLINDRICAL BODY, TYPE A.

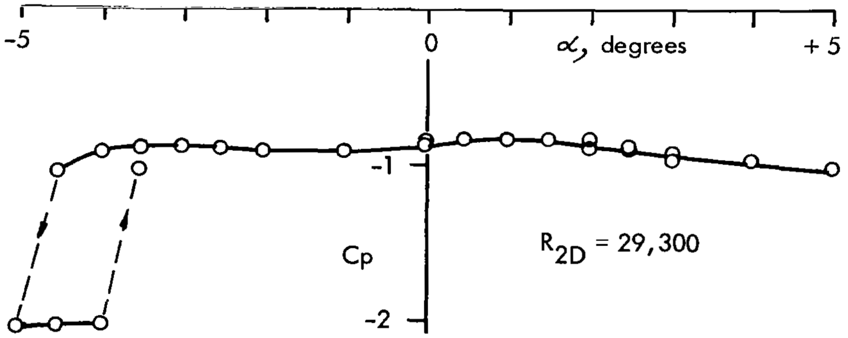
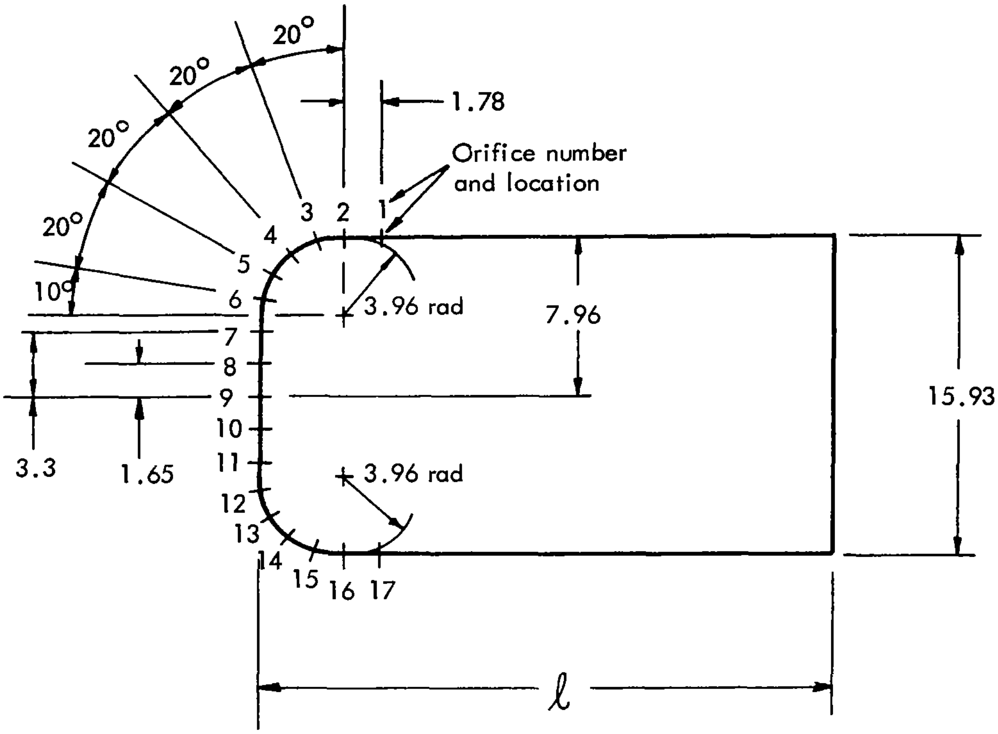


FIG. 5. VARIATION OF PRESSURE COEFFICIENT WITH ANGLE OF ATTACK, AT STATION x/P = 0.16 ON BODY TYPE A.



Dimensions in mm.

Body length ℓ	15.93	22.3	25.49	28.67	31.86	35.05	41.42	54.16
$L = \ell / 15.93$	1	1.4	1.6	1.8	2	2.2	2.6	3.4

FIG. 6. NOMINAL DIMENSIONS OF THE CROSS SECTION OF THE TWO-DIMENSIONAL YAWMETER BODIES, TYPE B.

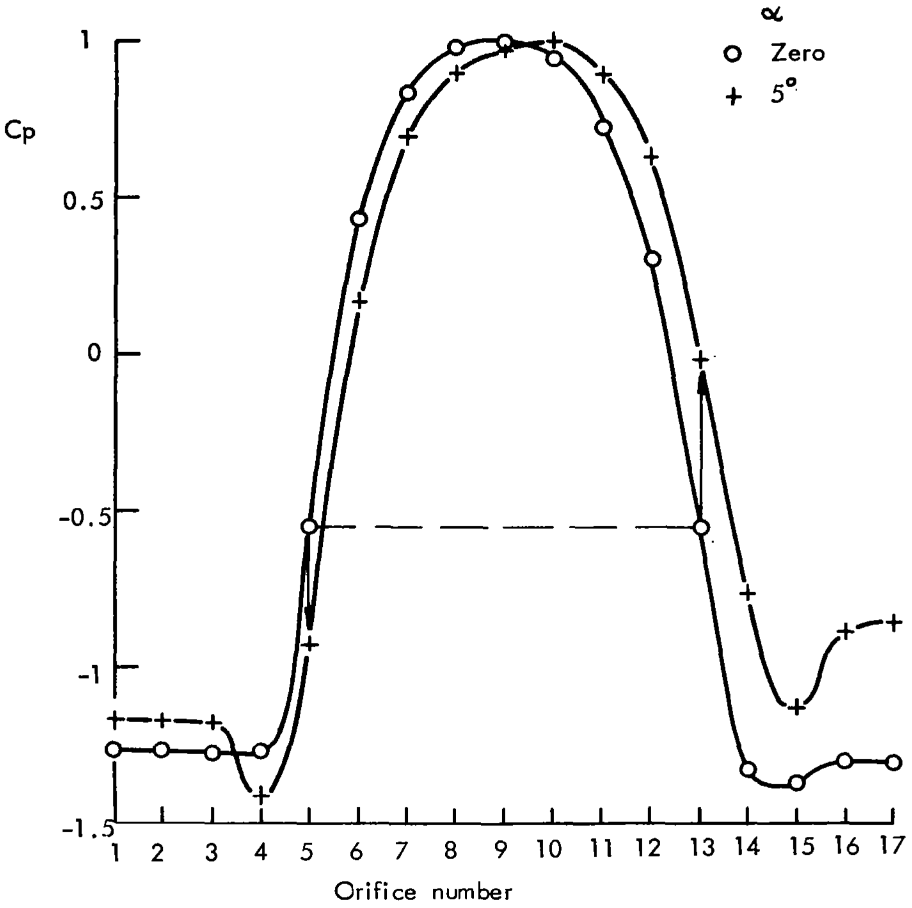


FIG. 7. VARIATION OF PRESSURE COEFFICIENT AROUND THE LEADING EDGE OF A TYPICAL YAWMETER BODY (TYPE B, L = 2.2) AT TWO ANGLES OF ATTACK.

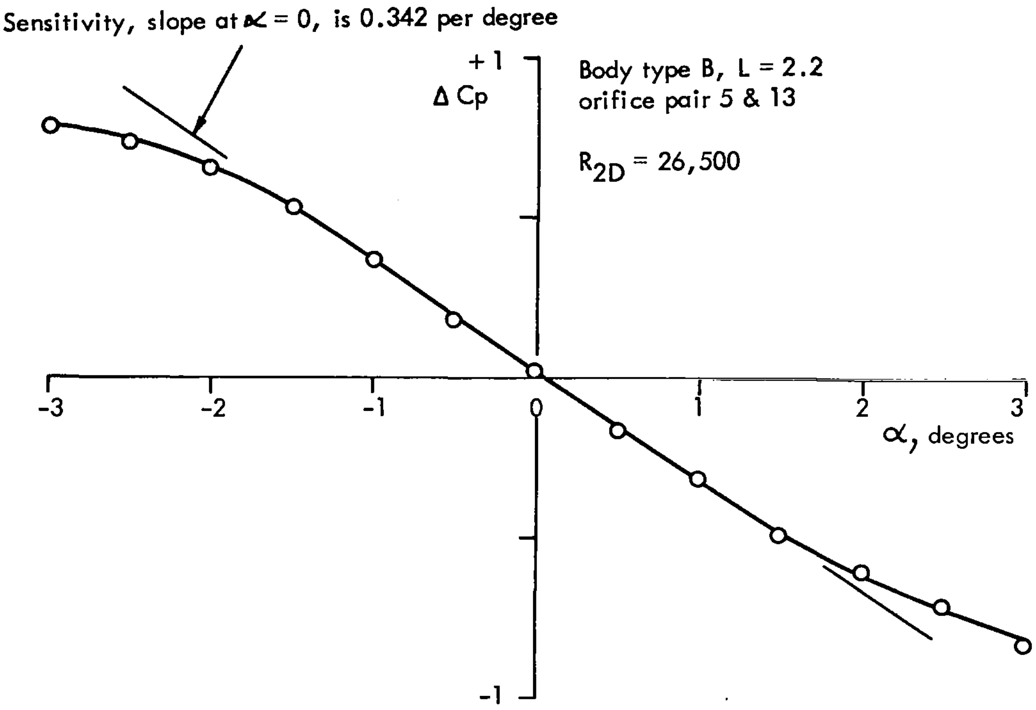


FIG. 8. SENSITIVITY TO ANGLE OF ATTACK OF THE DIFFERENCE IN PRESSURE COEFFICIENT BETWEEN TWO SYMMETRICALLY LOCATED ORIFICES.

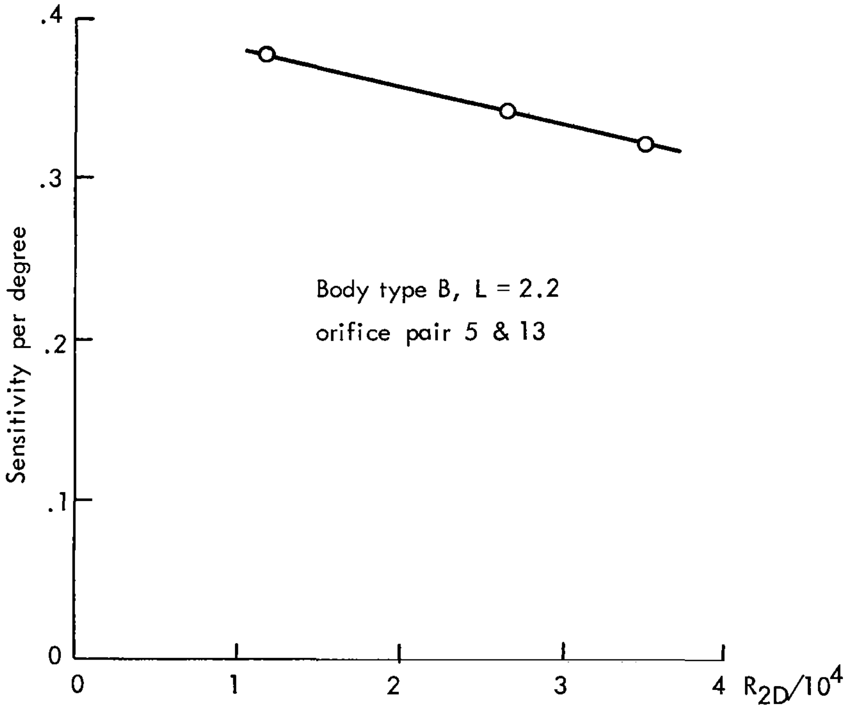


FIG. 9. INFLUENCE OF REYNOLDS NUMBER ON SENSITIVITY.

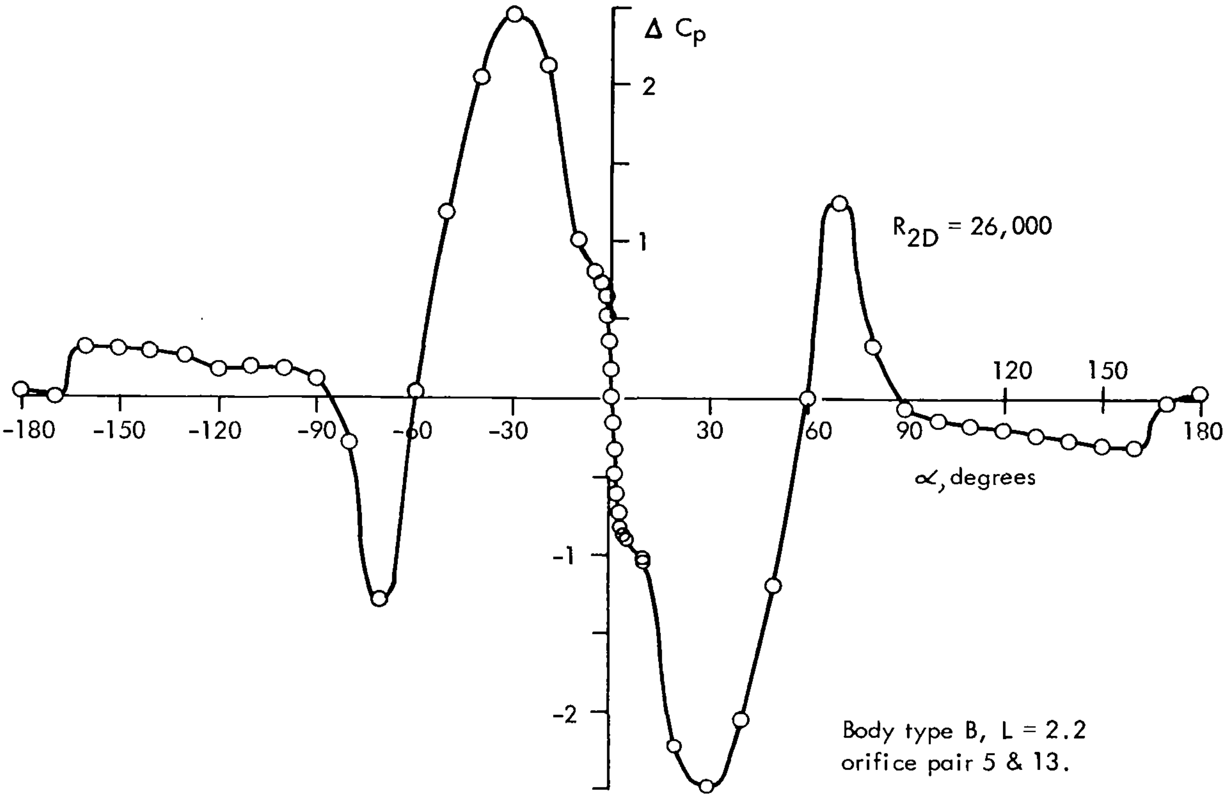


FIG. 10. VARIATION OF PRESSURE DIFFERENCE COEFFICIENT OVER THE COMPLETE RANGE OF ANGLE OF ATTACK, FOR ONE YAWMETER BODY AND THE PAIR OF ORIFICES GIVING MAXIMUM SENSITIVITY AT ZERO ANGLE OF ATTACK.

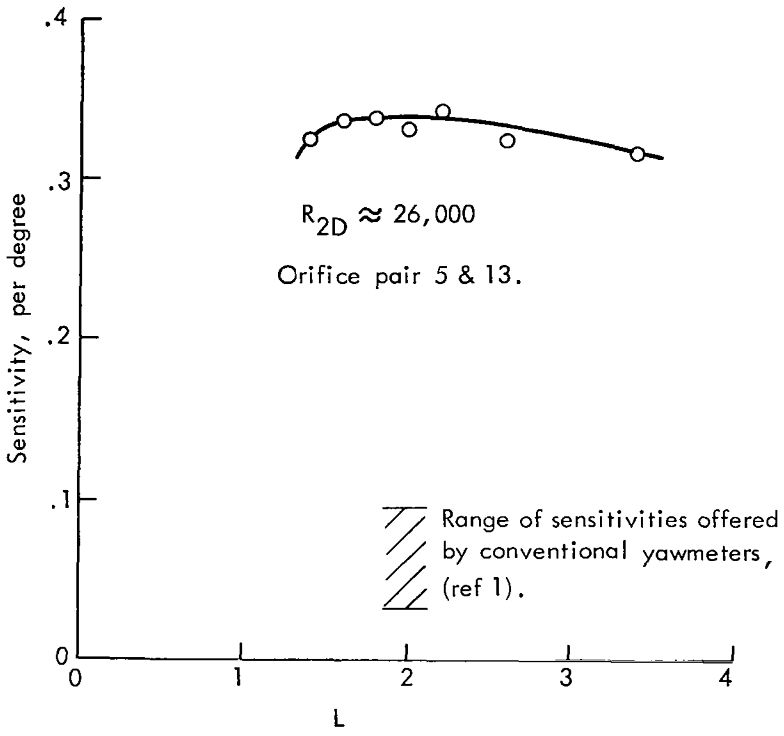


FIG. 11. INFLUENCE OF GEOMETRY ON SENSITIVITY, YAWMETER BODY TYPE B.

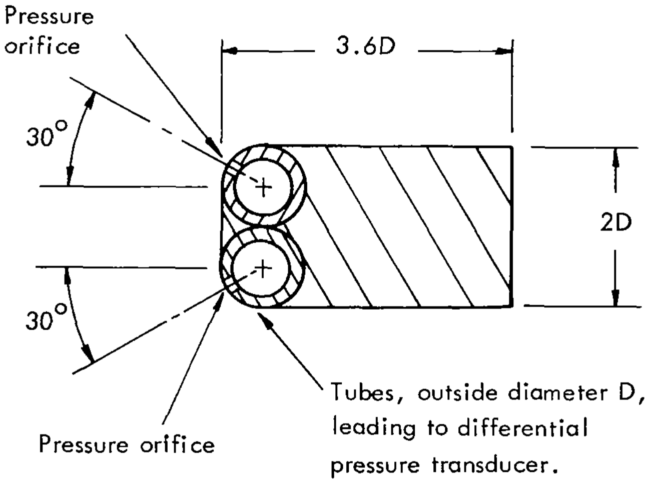


FIG. 12. THE CROSS SECTION OF A PROPOSED DESIGN OF SENSITIVE TWO DIMENSIONAL NULLING YAWMETER.

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