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Experiments at M 1.8 on Bodies of Revolution having Ogival Heads

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27th January, 1953

SUMMARY

Measurements have been made in the N.P.L. 9 × 3 in. High-speed Wind Tunnel of the pressure distributions at a Mach number of 1.8 on three bodies of revolution with ogival heads of different shapes at zero incidence. Comparison between the experimental pressures and those obtained theoretically showed good agreement.

1. Introduction

In a recent paper[1] several methods have been suggested for calculating the pressure distribution on ogival heads at zero incidence at supersonic speeds. These methods, whilst giving results in reasonable agreement with those obtained by second-order theory afford a considerable saving in the time spent in numerical calculation. In order to provide a better comparison it was decided to test three such heads in the N.P.L. 9 × 3 in. High-speed Wind Tunnel and to compare the experimental values for the pressure distributions so obtained with the theoretical distributions obtained by the methods of Ref.1. This report describes the work done and the results obtained.

2. The Models, Apparatus and Techniques Used

The details of the ogival heads are set out in Table I:-

Table I

Ogive	Generating Curve	Fineness Ratio	Nose Semi-angle
I	$y = \frac{1}{14}\{4 - (x-2)^2\}$ where $0 \leqslant x \leqslant 2$	3.5	15.95°
II	$y = 1.036[0.1889\,X^5 - 0.5634\,X^4 + 0.7560\,X^3 - 0.4670\,X^2 - 0.02504\,X + 0.3963\,\{1 - (1-X)^{3/2}\}]$ where $X = 0.9\,x/L$ and $0 \leqslant x \leqslant 2$	3.5	14.9°
III	$y = 0.0620\,x + 0.0403\,\log_e(1 + 8x)$ where $0 \leqslant x \leqslant 2.5$	4.5	21.0°

y in. is the radial distance from the axis
x in. is the axial distance from the nose
L in. is the axial length of the ogival head.

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The models were made from brass with a maximum diameter of approximately 9/16 in. and had a parallel portion downstream of the ogival head. They were supported at zero incidence on a sting in the 9 × 3 in. High-speed Wind Tunnel[2] which was fitted with wooden liners to give a Mach number of 1.8. Each model had a hollow interior divided into two compartments; the pressure in each compartment was taken to a manometer by hypodermic and plastic tubing carried along the sting mounting and passing through one of the tunnel side walls at the downstream end of the working section. Pressure holes 0.025 in. diameter were drilled normal to the surface to connect the inner compartments with the surface (Fig.1). The surface holes were filled with plasticine and only one hole in each compartment was open at any one time.

Photographs of the flow round the models (Fig.2) were taken by using an electric spark and a Toepler Schlieren system with two 9 in. diameter circular mirrors of 9 ft focal length.

The first results obtained showed a marked scatter in the pressure distribution along the axis of the models. It was then found that considerable variation in the static pressure at any particular hole could be obtained by rotating the model about its axis. As the pressure on the surface of a cone could readily be determined theoretically it was decided to pressure plot a cone which had approximately the same length and maximum diameter as the ogives. The variation in the pressure coefficient* at the several 0.010 in. diameter holes on the surface of the cone (nose semi-angle $6\frac{1}{2}^\circ$) is shown in Fig.3 for four rotational positions. It will be seen that there is considerable scatter of the experimental points both along the length of the cone and at any one hole. Fig.3 also shows the theoretical value of the pressure coefficient for a $6\frac{1}{2}^\circ$ cone at $M = 1.80$ as given by the method of Taylor and Maccoll[3].

Since the correction to the pressure at the surface of the cone due to the growth of the boundary layer is small, the variation observed can only be accounted for by non-uniformity of the flow in the tunnel. Now as the static pressure on the cone and on the ogives is always little different from the free-stream static pressure, small changes in the value of the free-stream static pressure can produce comparatively large percentage changes in the value of the pressure coefficient, C_p, since

$$C_p = \frac{p - p_0}{\frac{1}{2}\rho V^2}$$

where p is the static pressure at the surface of the ogive and p_0, ρ, V are the values of the static pressure, density and velocity in the free stream.

To try to eliminate the scatter of the experimental values of the pressure coefficient on the ogives it was decided to produce an "effective free-stream static pressure" by calculating[3] the value of the free-stream Mach number which would give the observed pressure at any pressure hole on the cone. Thus a variation of free-stream static pressure with axial distance from the tip of the cone was built up for each rotational position (Fig.4).

The ogives were then retested with their noses at the same position as that of the cone, the pressures being observed for each of the same four rotational positions that were used when pressure plotting the cone. From these observations the values of the pressure coefficient were calculated using the values of the free-stream static pressure given in Fig.4.

3. Results and Comparison with Theory

The experimental pressure distributions, obtained as described above, are shown in Figs. 6-8. Despite the correction for the non-uniformity of flow in the tunnel the measured pressure coefficients still show some scatter. This is particularly marked for the measurements taken at the four rotational positions of

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*In calculating these values a free-stream Mach number of 1.80 has been assumed.

the model. However the scatter is well within that to be expected from a non-uniformity of the flow of ± 1% in Mach number.

Also shown in Figs. 6-8 are theoretical pressure distributions calculated by the "Ogive of Curvature Method"[1] using Ref.4. Briefly, the method[1] rests on the assumption that the ratio of static to stagnation pressure at a point P (see Fig.5) on an arbitrary convex body of revolution at zero incidence in a supersonic free stream of Mach number M, is the same as that at P on the ogive of curvature* at P at the same free-stream Mach number. Since the pressures on the ogive of curvature can readily be determined by the method of Ref.4, the pressures on any convex ogival head can be calculated. The only information that is required about the geometry of the head is the distribution along the head of θ, the angle of inclination to the axis of the meridian curve of the head, and of χ, the nose semi-angle of the ogive of curvature (Fig.5). The assumption on which the ogive of curvature method rests, was discovered empirically while making step-by-step calculations based on the less arbitrary assumption[1] that on a head of convex profile, the flow along the profile from point P to the adjacent point Q (Fig.5) expands as if the head were replaced between P and Q by its ogive of curvature at P. It was then found[1] that the two assumptions described above gave essentially the same results and that pressure distributions thus calculated agreed in a number of representative cases with accurate pressure distributions calculated by the second order theory of van Dyke[5].

Bearing in mind the imperfections of the flow in the tunnel working section, the comparison of the experimental results with the theory is satisfactory.

The agreement is best in the case of Ogive I (Fig.6), where the discrepancy between the mean experimental and the theoretical pressure coefficients is no more than about 6% of the pressure coefficient at the nose.

On Ogive II (Fig.7) the experimental scatter is rather large, but the mean experimental pressure distribution reproduces well the shape of the theoretical pressure distribution; here again the discrepancies between the theory and experiment are of the order of 6% of C_p at the nose. The pressures registered by the last pressure hole on the head ($x/L = 0.95$) show some evidence of the upstream influence, via the boundary layer, of the Prandtl-Meyer expansion round the 3.6° angle of the head-body junction.

The case of Ogive III represents a very severe test of the theory since this ogive has:

(i) a large nose angle (42°)

(ii) a very large curvature at the nose followed by a rapid change of curvature, and

(iii) a small curvature over the rear half of the head,

and all these factors tend to decrease the accuracy of the theory. As will be seen from Fig.8, the theory appears to predict successfully the rapid expansion over the first 10% of head length; over the next 40% the pressure coefficient is underestimated by some 5% of its nose value. Particularly gratifying is the reasonable agreement over the rear 40% of the head length, since owing to a small curvature there the data of Ref.4 had to be extrapolated when calculating the theoretical pressure distribution, and the applicability of the theory was in some doubt.

So far the present results have been compared only with the ogive of curvature method using Ref.4. Four other methods have been suggested[1]; of these the step-by-step method, which has already been referred to above, gives results practically identical with those of the ogive of curvature method. Of the

remaining/

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*The ogive of curvature is the ogive generated by the revolution about the axis of the arc APQ (Fig.5) of the circle of curvature at P.

remaining three, two are essentially variants of the latter method - in one, the generalized pressure distributions on circular arc ogives obtained by the method of characteristics[6] are used instead of Ref.4; the other involves some further approximations and gives C_p in a closed form in terms of θ and χ and hence of y, dy/dx and d^2y/dx^2 (Fig.5); both are rather less accurate than the ogive of curvature method using Ref.4. The fifth method (called the "log $p \sim \theta$ law") is based on another fact discovered empirically, viz., that on convex ogival heads

$$\log \frac{p}{p_N} \propto (\theta_s - \theta)$$

where p_N is the static pressure on the ogive just downstream of the nose and θ_s is the nose semi-angle. On ogives whose curvature does not vary widely (such as Ogives I and II) this relation gives results in excellent agreement with those of the ogive of curvature method using Ref.4, and of the step-by-step method, but it is less accurate on heads with large variations of curvature (such as Ogive III).

The ogive of curvature method, using Ref.4, has been chosen for comparison with the present experimental results since it is believed to offer the best combination of accuracy with speed and ease of computing for a wide variety of head shapes. However it is hoped to publish shortly an addendum to Ref.1, giving a detailed comparison of all five methods with the present experimental results.

4. Drag

The drag coefficient for an ogival head may be expressed as

$$C_D = 8 \int_0^{\frac{1}{2}} \{C_p(y/t)\}\, d(y/t) .$$

The theoretical and experimental values of C_D have been obtained from the curves given in Figs. 6-8 and they are given in Table II. Also shown in Table II are the values of C_D for the ogives expressed as a fraction of the value of C_D for the inscribed cone.

Table II

	Ogive I		Ogive II		Ogive III	
	C_D	$C_D/C_{D_{I.C.}}$	C_D	$C_D/C_{D_{I.C.}}$	C_D	$C_D/C_{D_{I.C.}}$
Theoretical	0.0828	1.075	0.0600	0.779	0.0356	0.659
Experimental	0.0836	1.086	0.0668	0.868	0.0428	0.792

The theory appears to give values for the drags of the ogives that are lower than those determined experimentally. However it will be seen that a reduction in drag from that of the inscribed cone of at least 20% is realized for Ogive III. The rather large discrepancy between the two values for this ogive is due to the difference in the pressure coefficient being always in the same sense and hence its cumulative effect on integration being large.

5. Conclusions

Measurements of the pressure distributions at a Mach number of 1.8 have been made on three non-lifting bodies of revolution having ogival heads and the results have been compared with theoretical pressure distributions obtained by one of the five methods suggested recently[1].

In spite of some experimental scatter, good agreement with the theory was obtained in all three cases. The theory predicts correctly the shape of the pressure distribution curves, whilst the discrepancies between the theoretical and the mean measured pressure coefficients amount in each case to no more than about ±6% of the pressure coefficient just downstream of the nose of the ogive. The drag coefficients given by the theory appear in all three cases to be too low.

Further verification of the theory at lower (1.5 or 1.6) and higher (2 - 4) Mach numbers is required.

References

No.	Author(s)	Title, etc.
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4	H. K. Zienkiewicz	A method for calculating pressure distributions on circular arc ogives at zero incidence at supersonic speeds, using the Prandtl-Meyer flow relations. (English Electric Co. Ltd., Navigational Project Division, Luton. Report No. L.A.t.024). C.P.114. January, 1952.
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		also available as
		A study of second-order supersonic flow theory. (N.A.C.A. TN 2200).
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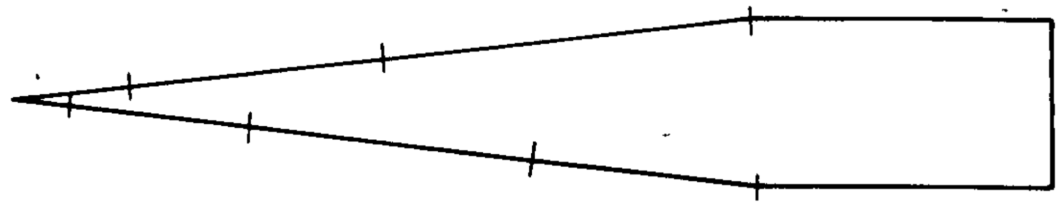
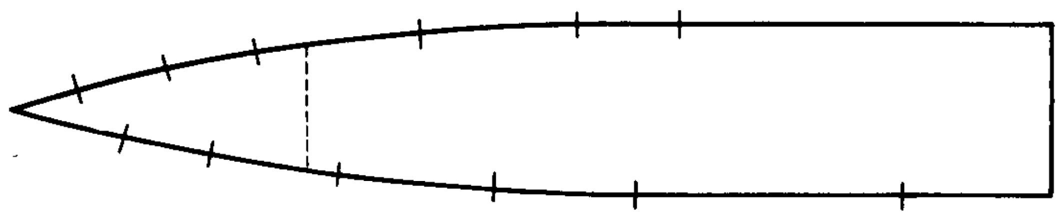
FIG. 1

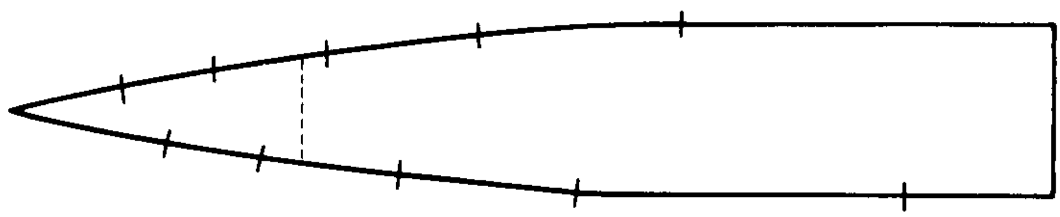
Pressure hole positions shown thus
Position of wall between compartments shown thus



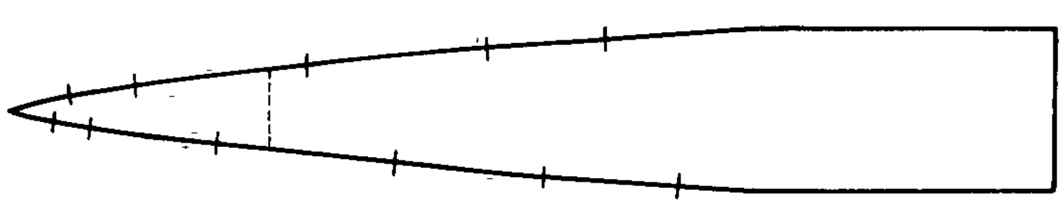
(a) 6½° Semi - angle cone



(b) Ogive I



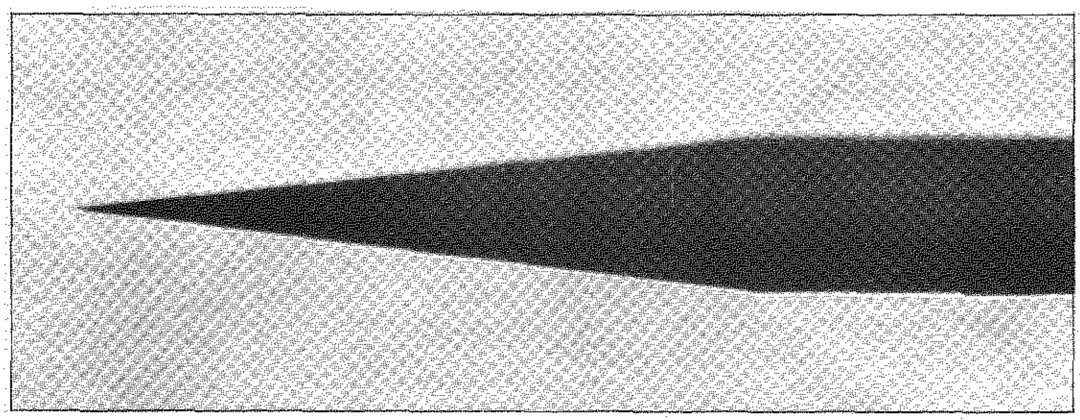
(c) Ogive II



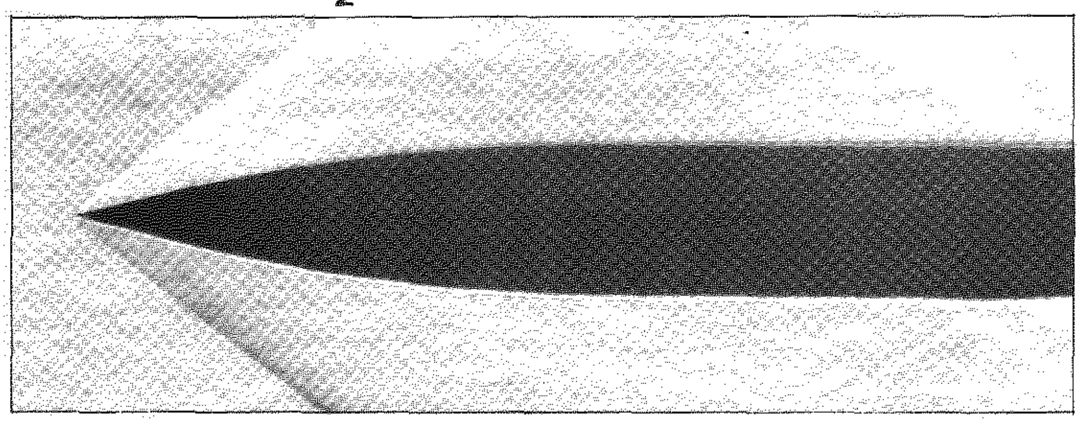
(d) Ogive III

The profiles of the models used showing the positions of the pressure holes

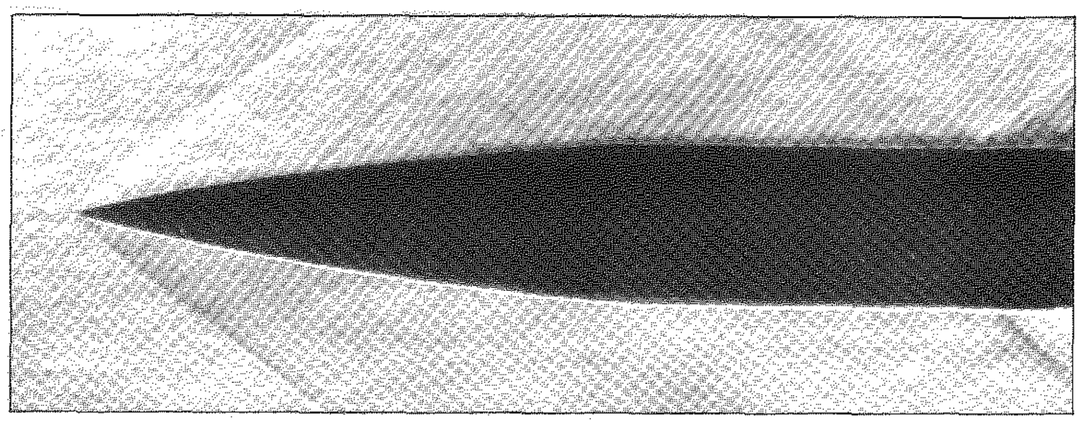
FIG. 2.



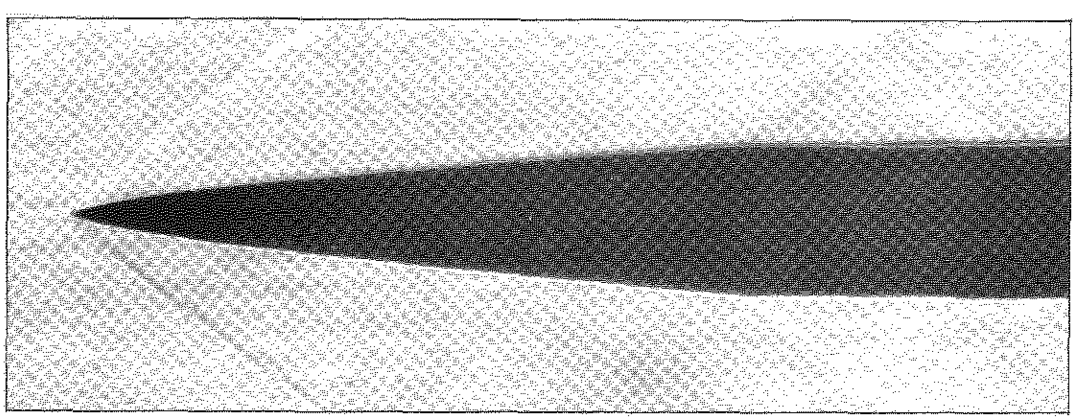
$6\frac{1}{2}^{\circ}$ SEMI ANGLE CONE



OGIVE I



OGIVE II



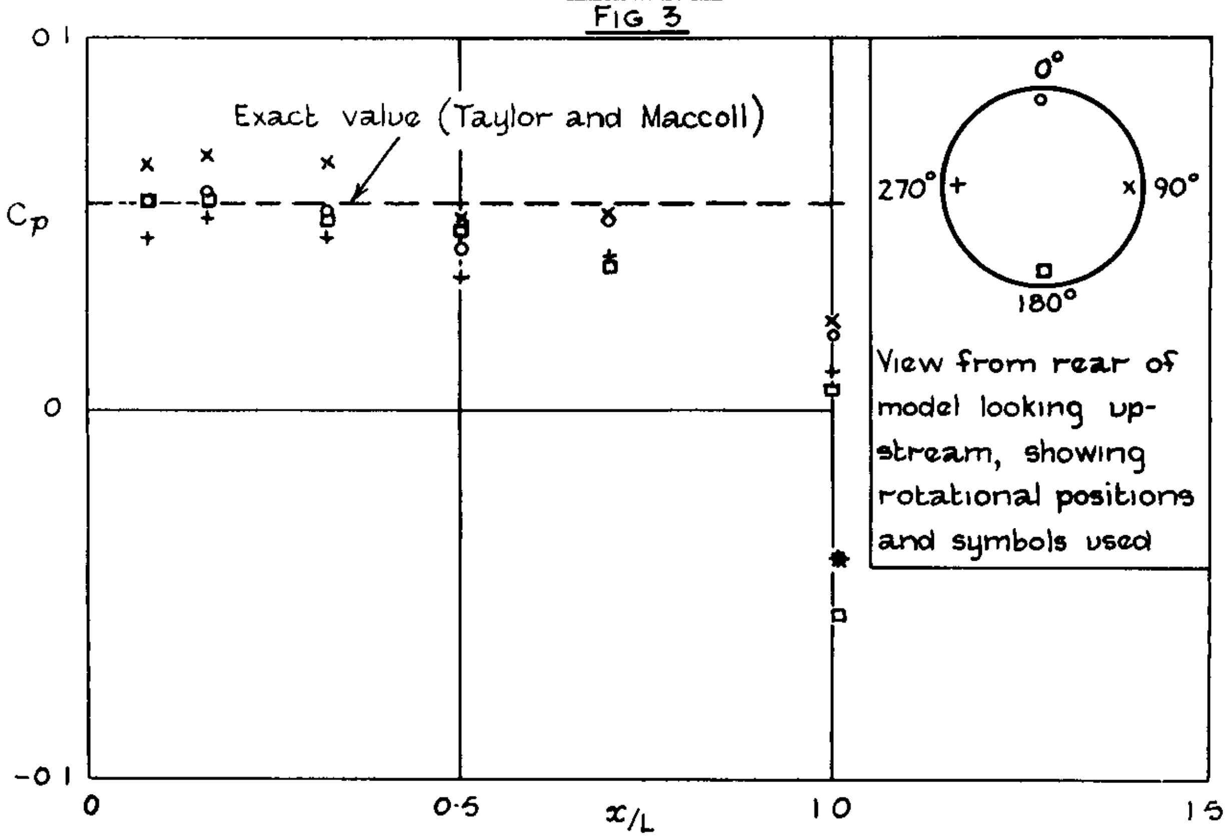
OGIVE III

FIG. 2.

SCHLIEREN PHOTOGRAPHS OF THE FLOW ROUND THE MODELS.

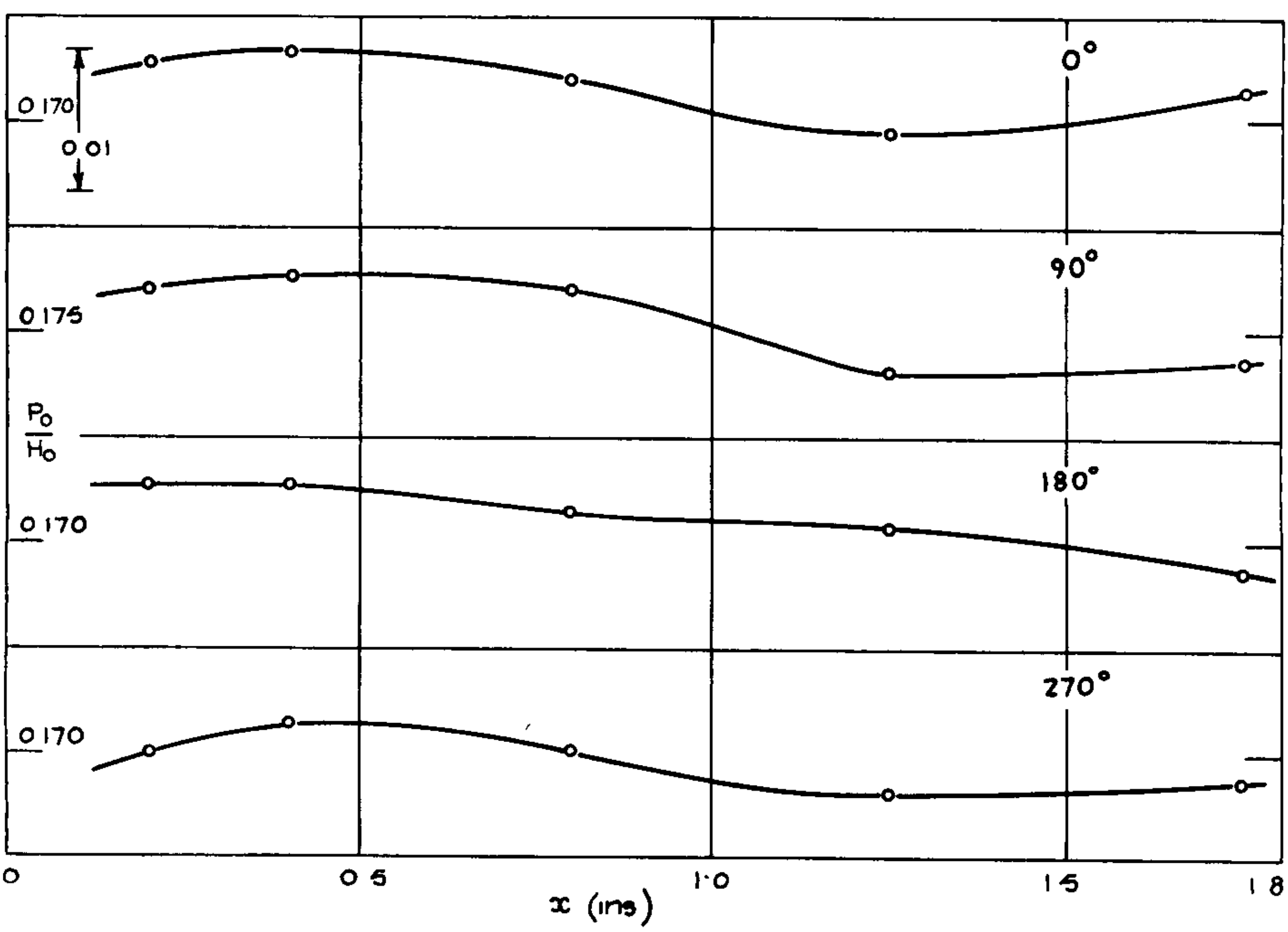
FIGS 3&4

FIG 3



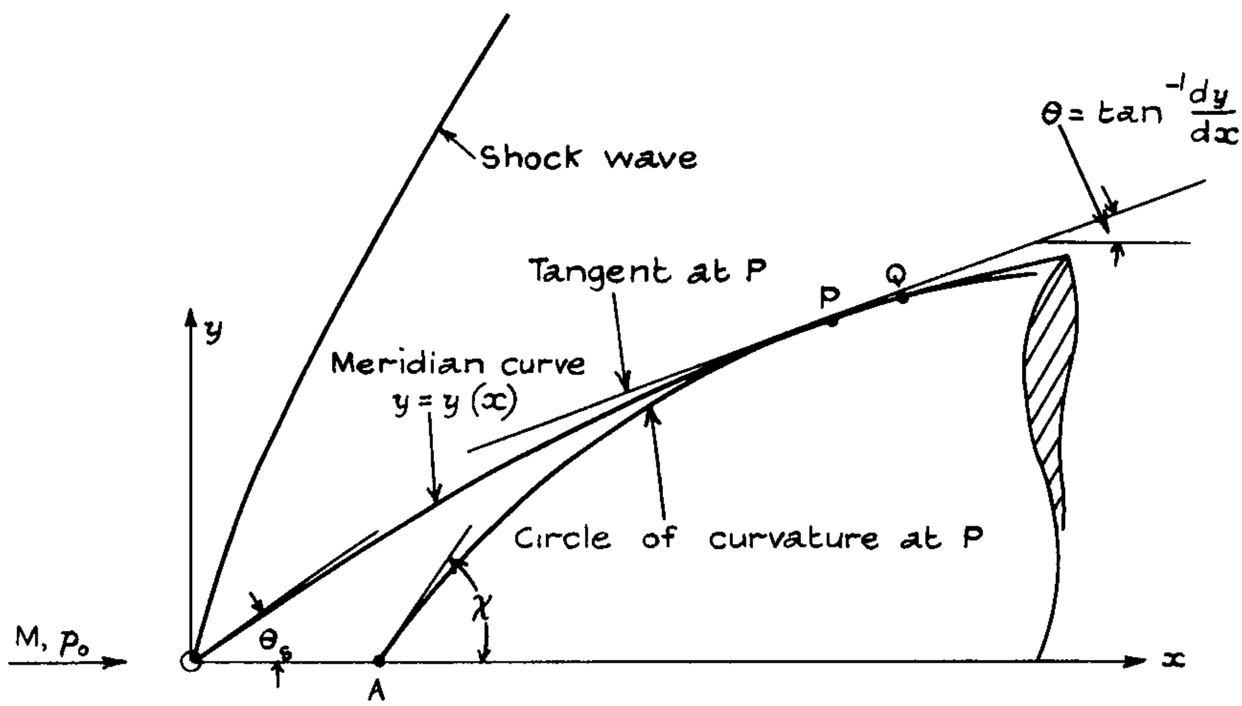
Pressure Distribution on the 6½° Cone

FIG 4



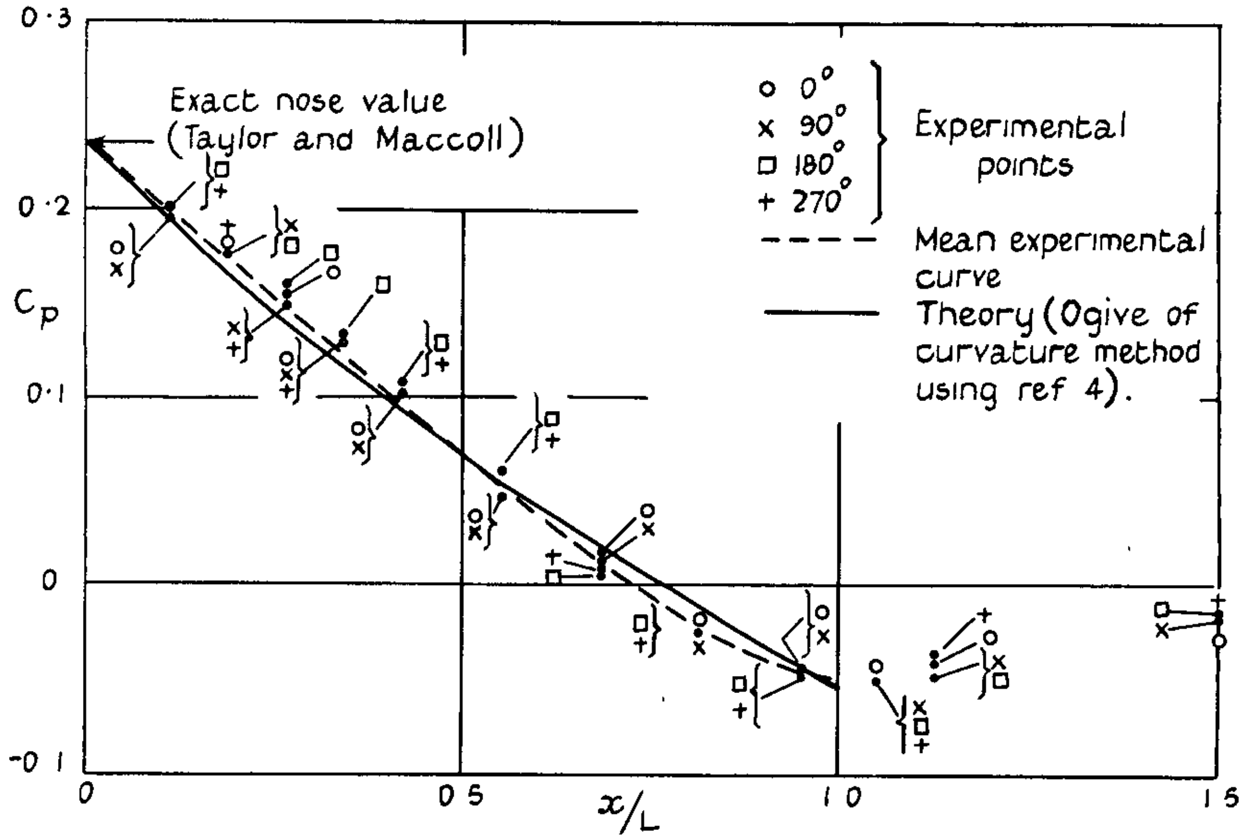
Variation of the Free Stream Static Pressure Deduced from the Variation of the Local Static Pressure at the Surface of the Cone

FIG 5



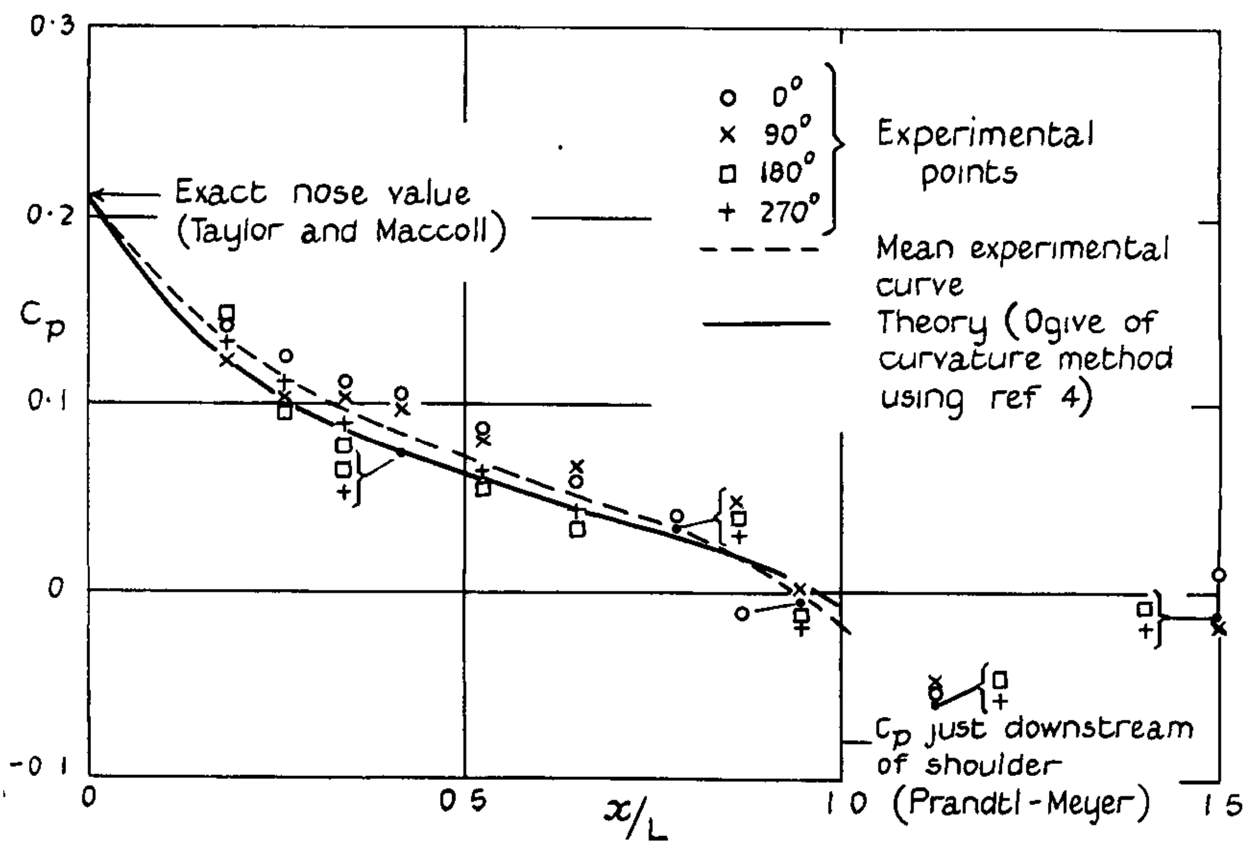
Notation Used in the Ogive of Curvature Method [1]

FIG 6.



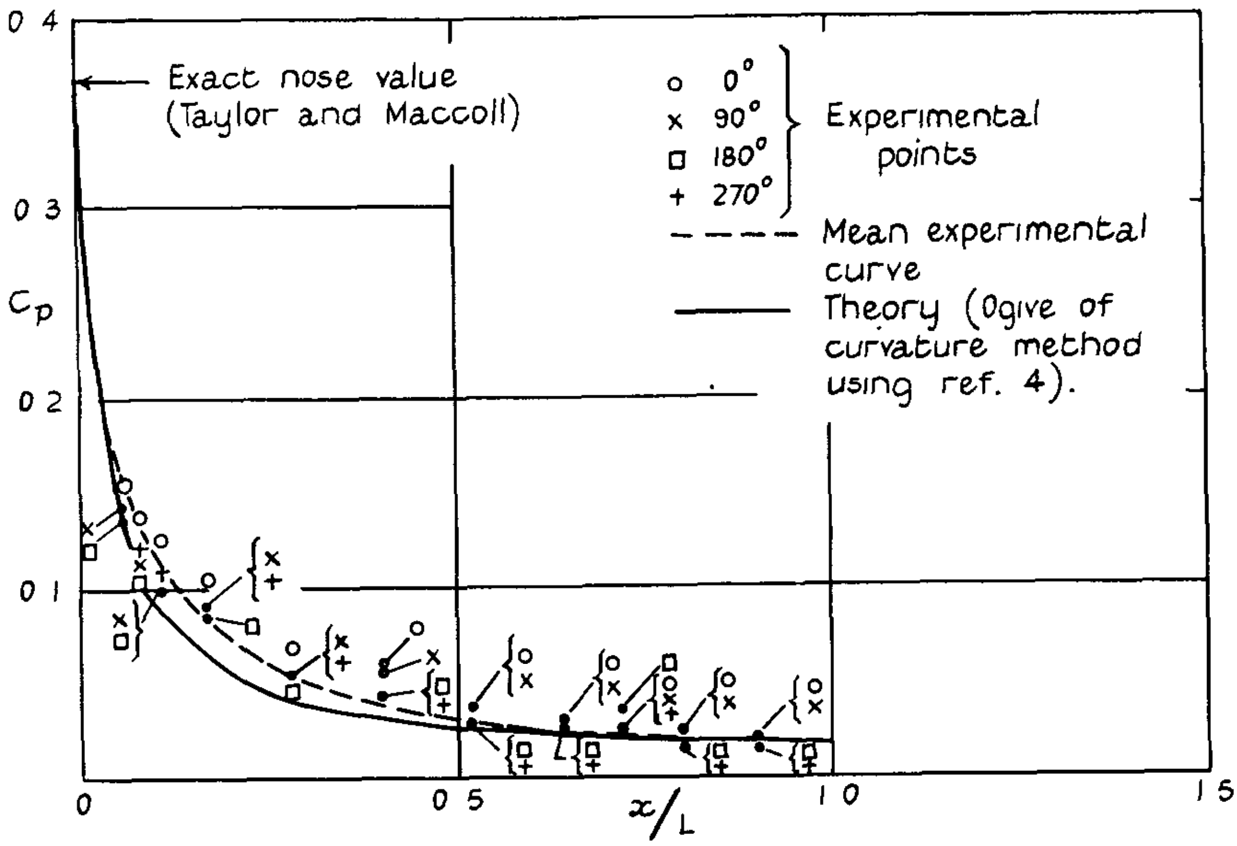
Pressure distribution on the Ogive I

FIG 7.



Pressure distribution on the Ogive II

FIG 8



Pressure distribution on the Ogive III.

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