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By

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A SHORT STATIC PROBE WITH GOOD INCIDENCE CHARACTERISTICS AT SUPERSONIC SPEED

I. S. DONALDSON* AND D. J. RICHARDSON+

SUMMARY

Tests carried out on a short static probe at supersonic speeds between Mach numbers of 1.1 and 2.5 are described. The probe consists of a 50° included angle cone-cylinder having sensing holes 0.88 calibres aft of the cone-cylinder junction.

The tests show that at zero incidence the probe measures a pressure (approximately independent of Mach number) of 0.793 times the local static pressure. They also show that, at up to 18° incidence in any pitch plane, the pressure measured is 0.763 ±0.03 times the local static pressure. For a limited Mach number range near a Mach number of 1.6, this accuracy can be maintained to incidences over 30°.

Of particular interest is the fact that relatively small internal differences between externally identical probes appear to have a significant effect on the incidence characteristics and in some respects can improve the performance.

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*Replaces A.R.C.29 558

INTRODUCTION

At supersonic speeds it is usual to measure static (or ambient) pressure by means of cylindrical probes of large fineness ratio (1). This type of probe is not satisfactory at low Mach numbers and is sensitive to incidence at all Mach numbers.

Attempts have been made to improve the Mach number performance of these probes by the use of special head shapes and sensing hole locations and to improve the incidence characteristics by locating sensing holes at particular roll angles (2),(3), (4). It is usual to locate two sensing holes symmetrically with respect to a particular pitch plane. Typical spacings are ± 35° but it is shown in 2, that the optimum spacing is a function of Mach number. Whilst this considerably improves the incidence characteristics in a particular pitch plane when the holes are on the windward side of the probe, out of this pitch plane performance deteriorates rapidly and the probes are not suitable for manoeuvring vehicles or for vehicles (such as cruciform missiles) in which the incidence plane may have any orientation with respect to vehicle axes.

There is still therefore a requirement for a probe which has a small sensitivity to incidence in any pitch-roll or pitch-yaw plane, even if only for a limited Mach number range. If such a probe were to have a small fineness ratio and hence be stiff, it would be an additional advantage.

Clippinger and Giese(5) have used the method of characteristics to study the zero incidence flow about cone-cylinders at supersonic speeds. Their results for a 50° included angle cone show that, fortuitously, at a point 0.88 calibres aft of the cone-cylinder junction the surface pressure is approximately independent of Mach number for Mach numbers between 1.4 and 5.0, at 0.8 times the true static pressure. The pressure distribution is shown diagrammatically in fig. 1. Hence, if a probe of this shape, with sensing holes 0.88 calibres aft of the cone-cylinder junction is used as a static or ambient pressure probe, its zero incidence characteristics at moderate supersonic speeds should be as good as those of the conventional slender probe. In addition it would be structurally stiffer and easier to manufacture.

In many cases, these alone would be sufficient incentive to use a short probe, but in addition, there is evidence to suggest(6) that, as the effects of cross-flow separation near the nose are small, such a probe might be relatively insensitive to incidence.

The possible advantages of such a probe were considered to be sufficient to warrant extensive wind tunnel testing and these tests are described below. Because of the use which was to be made of the probe, great care was taken in the experiments and tests were also made to indicate the significance of internal geometry of externally identical probes.

NOTATION

C	Van Dykes cone pressure correction factor.
M	Mach number.
p	pressure.
P	differential pressure $(p-p_r)$.
R	$p_2/p_{\infty 2}$.
θ	angle of incidence
Suffices	
∞	free stream conditions.
1	calibration cone results.
2	probe results.
r	reference pressure.

MODELS

The models used are shown in fig. 2. The two probe models were externally identical but model B was modified internally to suit the particular application for which the probes were required. Two 5° calibration cones are also shown. Probe models A and B had a constant diameter of 2 in. for some ten calibres aft of the sensing holes. A simple constant diameter support was also used for the cone models.

The surface finish on both probes and cones was better than 4 μin. and great care was taken to remove all internal and external burrs from the sensing holes.

Although referred to as models, the probes were in fact the size required for flight vehicles.

WIND TUNNEL

Tests were carried out in the A.R.A. 8 ft. x 9 ft. transonic tunnel at a Reynolds number of $3.6 \pm 0.1 \times 10^6$/ft, in the low supersonic region, and in the A.R.A. 27 in. x 30 in. supersonic tunnel for the Mach number range $1.4 \leq M \leq 2.5$ at a constant Reynolds number of 3.0×10^6/ft.

TEST METHOD

To carry out a calibration of the required accuracy, it was not considered sufficient (as is often done) to assume that the static pressure at a test point in the centre of the tunnel is the same as that at a reference point on the side wall. It was however assumed that the ratio of these pressures would remain the same when a particular tunnel condition was repeated. Prior to the probe calibration it was therefore necessary to relate these two pressures for a particular tunnel Mach number setting. The two 5° calibration cones were used for this purpose.

A cone was mounted in the tunnel with the sensing holes coincident with the location of the probe static holes (and also with the centre of rotation of the tunnel incidence gear). The tunnel was then run through the range conditions under which the probes were to be tested, the difference between cone pressure and reference pressure being measured on an oil manometer. The reference pressure was measured relative to atmosphere on a mercury manometer. At each test condition, cone incidences were varied slightly to ensure the correct zero incidence setting. The tests were then repeated using the second cone, only negligibly small random differences in results being recorded.

Probes A and B were then tested in the supersonic tunnel and cone B in the transonic tunnel. The conditions were:

Supersonic tunnel	$1.4 \leq M \leq 2.5$
Incidence (θ)	$-2^{\circ} \leq \theta \leq 42^{\circ}$
Transonic tunnel	$0 \leq M \leq 1.4$
Incidence	$-2^{\circ} \leq \theta \leq 20$

As the probes are only useful for Mach numbers above about 1.1; results for lower Mach numbers are not plotted.

RESULTS

It can be shown that

$$R = \frac{p_2}{p_{\infty 2}} = \frac{1}{C}\,\frac{1 + P_2/p_{r_2}}{1 + P_1/p_{r_1}}$$

where R is the ratio of pressure (p_2) measured by the probe to true static pressure ($p_{\infty 2}$) at the test point and P is the difference between model pressure (p) and reference pressure (p_r). Suffices 1 and 2 refer to the calibration cone and test probes respectively.

The factor C is obtained from Van Dykes second order theory(7) and is used to obtain true static pressure from the measured cone pressure, the actual cone angle first being corrected for laminar boundary layer displacement thickness.

For all practical purposes the boundary layer correction is independent of Mach number and the factor C is then a function of Mach number only and is indistinguishable from the exact solution for small cone angles.

Results of the tests are summarised in figure 3 which shows the zero incidence results for models A and B plotted as $\frac{p_{2_{\theta=0}}}{p_\infty}$ against Mach number and figures 4a and b which show the effect of incidence for the two models plotted as $(p_{2_{\theta=\theta}} - p_{2_{\theta=0}})/p_{\infty_2}$ against incidence, for various Mach numbers. Figures 5 and 6 are respectively a typical shadowgraph taken at a Mach number of 1.1 and a typical schlieren picture taken at a Mach number of 1.4.

DISCUSSION OF RESULTS

Zero Incidence

Perhaps the best measure of overall accuracy and repeatability of the tests can be obtained from fig. 3. At zero incidence internal geometry would not be expected to affect the pressure measured by externally identical probes, hence the difference between the results for probes A and B gives the desired measure. It can be seen that the maximum difference occurs at a Mach number of 1.4 and is slightly less than one per cent of the true static pressure. Whilst an error of ±0.5 per cent is better than would normally be expected from tests of this nature it is considerably worse than would be expected from an analysis of the likely error. No explanation for the difference can be offered.

The zero incidence tests also show some discrepancy between transonic and supersonic tunnel results at Mach numbers near 1.4. At a Mach number of 1.4, as the transonic tunnel was being run at the upper limit of its Mach number range, the discrepancy is perhaps what would be expected from tunnel to tunnel variations. The sharp dip in the zero incidence curve at a Mach number of 1.3 is however, not understood and has been ignored. Although photographs were not taken at this Mach number, a visual check was kept on the shadowgraph and there was no evidence of a change in character of the flow about the model. However, there is some evidence that tests on other models have given suspect results at this Mach number in this tunnel and the dip is considered to be due to tunnel flow variations rather than to flow caused by the model.

If the result at $M = 1.3$ is ignored, it can be seen that, assuming $p_2/p_{\infty_2} = 0.793$, the maximum error in p_{∞_2} will be approximately 1.2 per cent in the Mach number range $1.1 \leq M \leq 2.5$. This represents about 300 ft. in altitude at sea level and a negligible small error at 40,000 ft.

RESULTS AT INCIDENCE - PROBE B

The most complete set of results at incidence were obtained with probe B, which it was proposed to use on a flight vehicle. These results are shown in fig. 4b.

It is noticeable that (except at the lowest Mach numbers) the pressure first undergoes a negative excursion and then increases monatonically with incidence. The maximum negative excursion of approximately seven per cent of the static pressure, occurs at a Mach number of 1.6, the excursion becoming positive at relatively high, but progressively lower incidences with increasing Mach number.

The initial fall in pressure with increasing incidence arises because of the dominance of the relatively low pressure on the lee side of the probe, whilst the rise, with further increase in incidence appears to be associated with the compression waves from the cross-flow separation (6), and from the separation bubble at the cone-cylinder junction. Schlieren photographs show that two shocks occur on the lee side of the body,that from the separation bubble being just downstream of the cone-cylinder junction whilst that from the cross-flow separation is rather more than one calibre downstream of this point. With increasing incidence the shocks increase in strength and tend to merge in the vicinity of the sensing holes. The pressure rise across the shock waves progressively cancels out the effect of the relatively low pressure on the lee side of the body due to the cross flow and the mean pressure at the sensing holes rises.

It should be noted that there is again a difference in measurements made under nominally similar conditions at a Mach number of 1.4 in the two tunnels. No definite explanation is possible but it is probable that differences in tunnel turbulence levels cause differences in the separation bubble and cross-flow separation. A simple, but less attractive explanation is a negative error of about 0.01 in the zero incidence result which would completely match the zero incidence results and considerably improve the match at incidence. However, because of the magnitude of the error and because the sequence in the incidence programme was likely to expose such an error, it is considered very unlikely to be the correct explanation.

RESULTS AT INCIDENCE - PROBE A

Probe A was tested only in the supersonic tunnel. Qualitatively the results are similar to those taken from probe B with the significant differences that the negative excursion is considerably less than for probe B and that the positive excursion commences at a smaller (though still relatively large) angle of incidence. Spot checks showed that roll angle was not a significant variable. It is therefore considered that the differences can only be due to the differing internal geometries of the two probes. Whilst these differences are small, if as has been suggested, the incidence characteristics depend critically upon the separation phenomena on the lee side of the body, quite small changes in internal cross-flow may have a disproportionate effect upon the mean pressure measured.

Although the best zero incidence value of $p_2/p_{\infty 2}$ is 0.793 the range of usefulness of the probes can be greatly extended by assuming that the probes measure a different value of $p_2/p_{\infty 2}$. Thus, ? if it is assumed, say, that a B type probe measures 0.763 of the true static pressure, the static pressure derived from a probe measurement will be in error by a maximum of approximately three per cent for $1.1 \leq M \leq 2.5$ and for angles of incidence up to 18° in any pitch plane. For a small Mach number range near 1.6, the same accuracy may be obtained for incidences up to about 35°.

These results compare very favourably with those given in reference 2, where the incidence vector is limited to a single pitch plane or to only small angles of yaw. In the supersonic region the incidence characteristics of probes A and B are always as good as those of the probes described in reference 2 and extend to much higher incidences. However probes A and B cannot be used at subsonic Mach numbers.

Neither the effect of Reynolds number nor of after bodies was investigated in these tests. The probes used had several calibres of constant diameter cylinder downstream of the sensing holes. The effect of afterbody shape would need to be investigated in the context of a particular installation.

The effects of Reynolds number were not investigated because of shortage of tunnel time. The sensitivity to internal geometry would indicate that the flow is sensitive to small changes in flow and hence Reynolds number would be expected to be an important parameter, particularly in determining the incidence at which the effects of the cross-flow change sign.

CONCLUSIONS:

Wind tunnel tests at supersonic speeds on two, externally identical, 50° included angle cone-cylinder static probes are described. The pressure sensing holes were distributed uniformly about a section of the cylinder 0.88 calibres aft of the cone-cylinder junction.

The tests showed that in the Mach number range $1.1 \leq M \leq 2.5$

1. The pressure measured by the probe varied by approximately 1.2 per cent of the true static pressure from a mean value of 0.793 times the true static pressure.
2. If it is assumed that the probe measures 0.763 times the true static pressure, the error in static pressure derived from probe measurements will be less than 3 per cent for incidences up to 18° in any plane. For a restricted range of Mach numbers near 1.6 this can be extended to 35°.
3. Internal differences of externally identical probes can have a significant effect upon the incidence characteristics of the probes.

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FIGURE CAPTIONS:

Figure 1	-	Variation of pressure distribution with Mach number about a 50° included angle cone cylinder.
Figure 2	-	Model details.
Figure 3	-	Variation in sensed pressure with Mach number at zero incidence.
Figure 4a	-	Effect of incidence on sensed pressure - Probe A.

Figure 4b - Effect of incidence on sensed pressure - Probe B.

Figure 5 - Probe B - transonic tunnel $M = 1.1$ $\theta = 12^{\circ}$.

Figure 6 - Probe A - supersonic tunnel $M = 1.4$ $\theta = 16^{\circ}$.

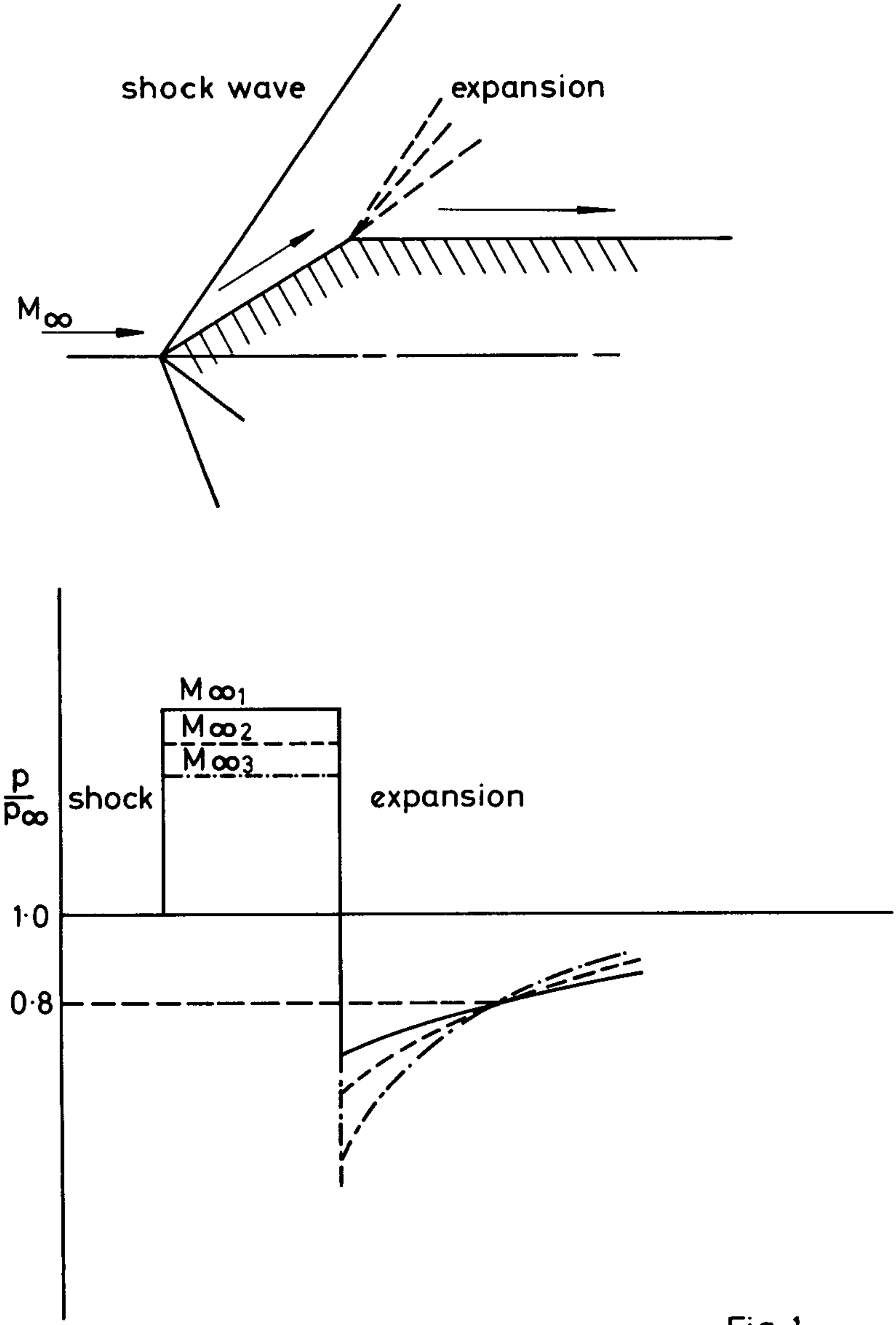
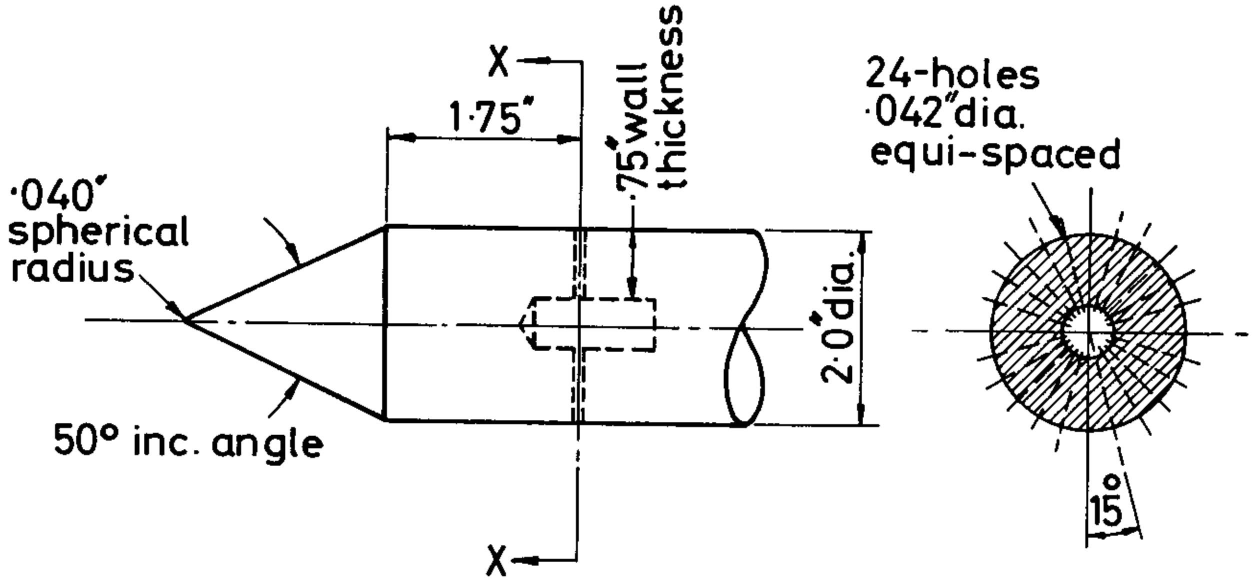
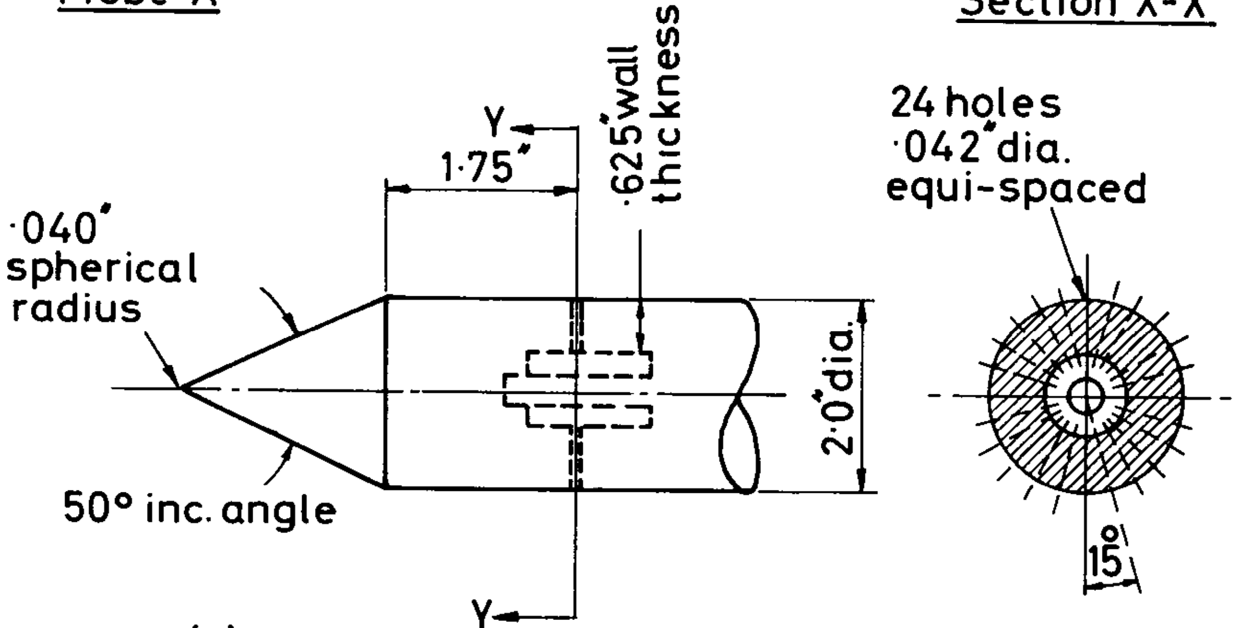

shock wave
expansion
M_∞
$M_{\infty 1}$
$M_{\infty 2}$
$M_{\infty 3}$
$\frac{p}{p_\infty}$
shock
expansion
1·0
0·8

Fig 1



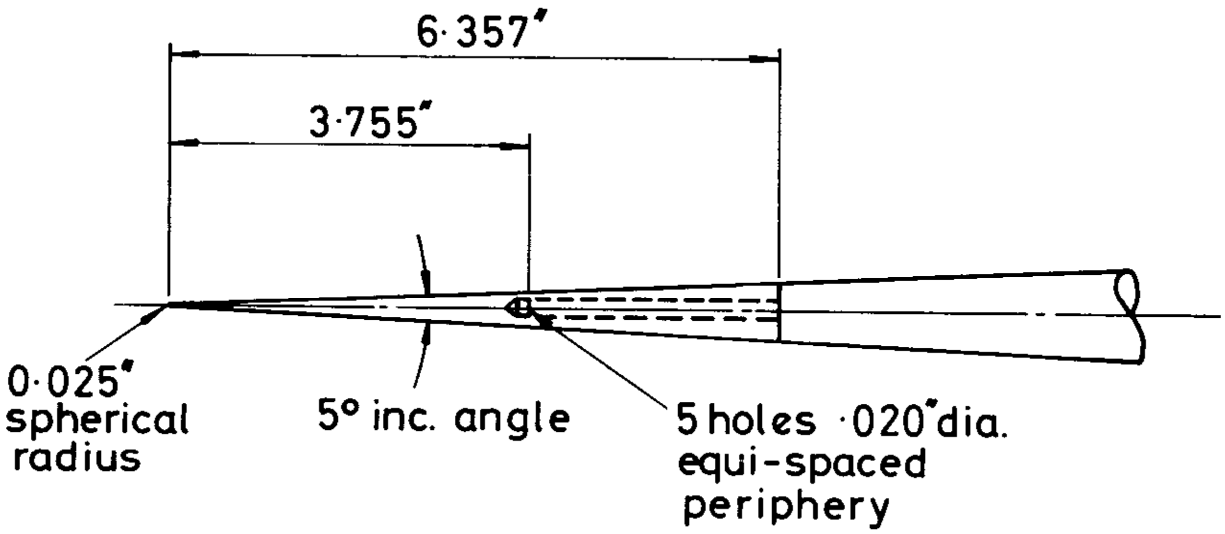
Probe 'A'

Section X-X



Probe 'B'

Section Y-Y



Calibration Cone

Fig. 2.

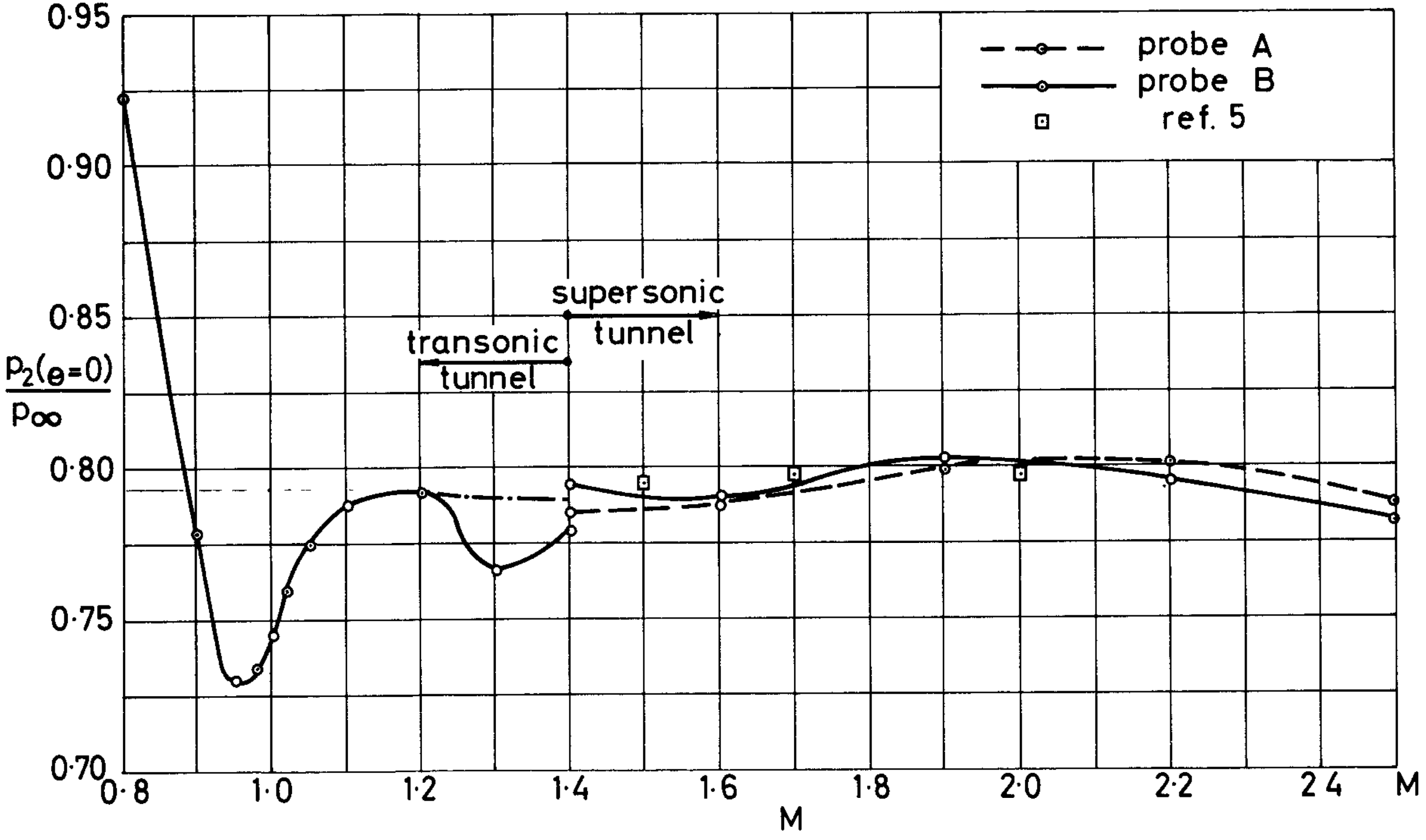
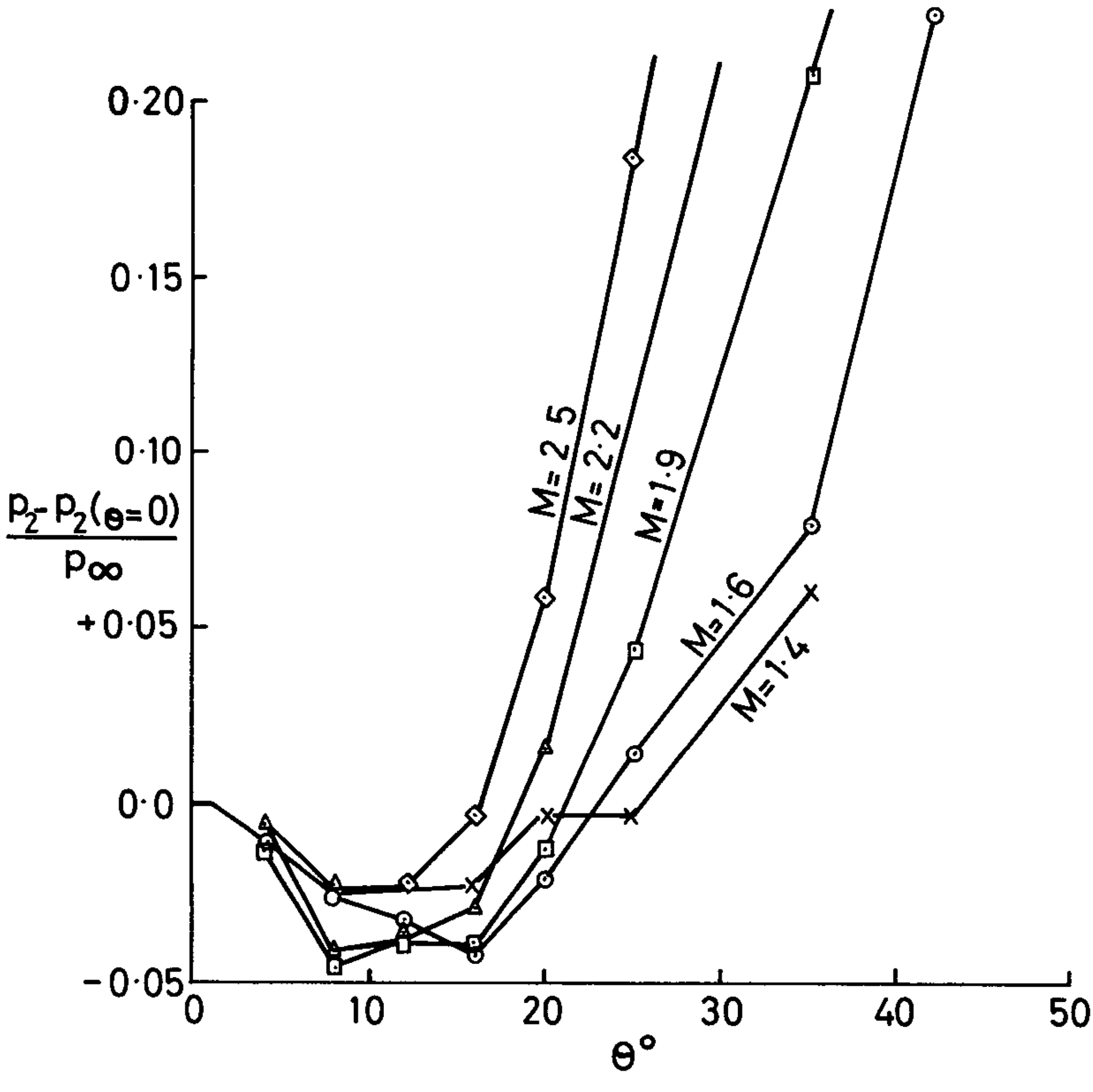

0·95
0·90
0·85
0·80
0·75
0·70
$\frac{p_2(\theta=0)}{p_\infty}$
probe A
probe B
ref. 5
supersonic tunnel
transonic tunnel
0·8
1·0
1·2
1·4
1·6
1·8
2·0
2·2
2 4
M
M

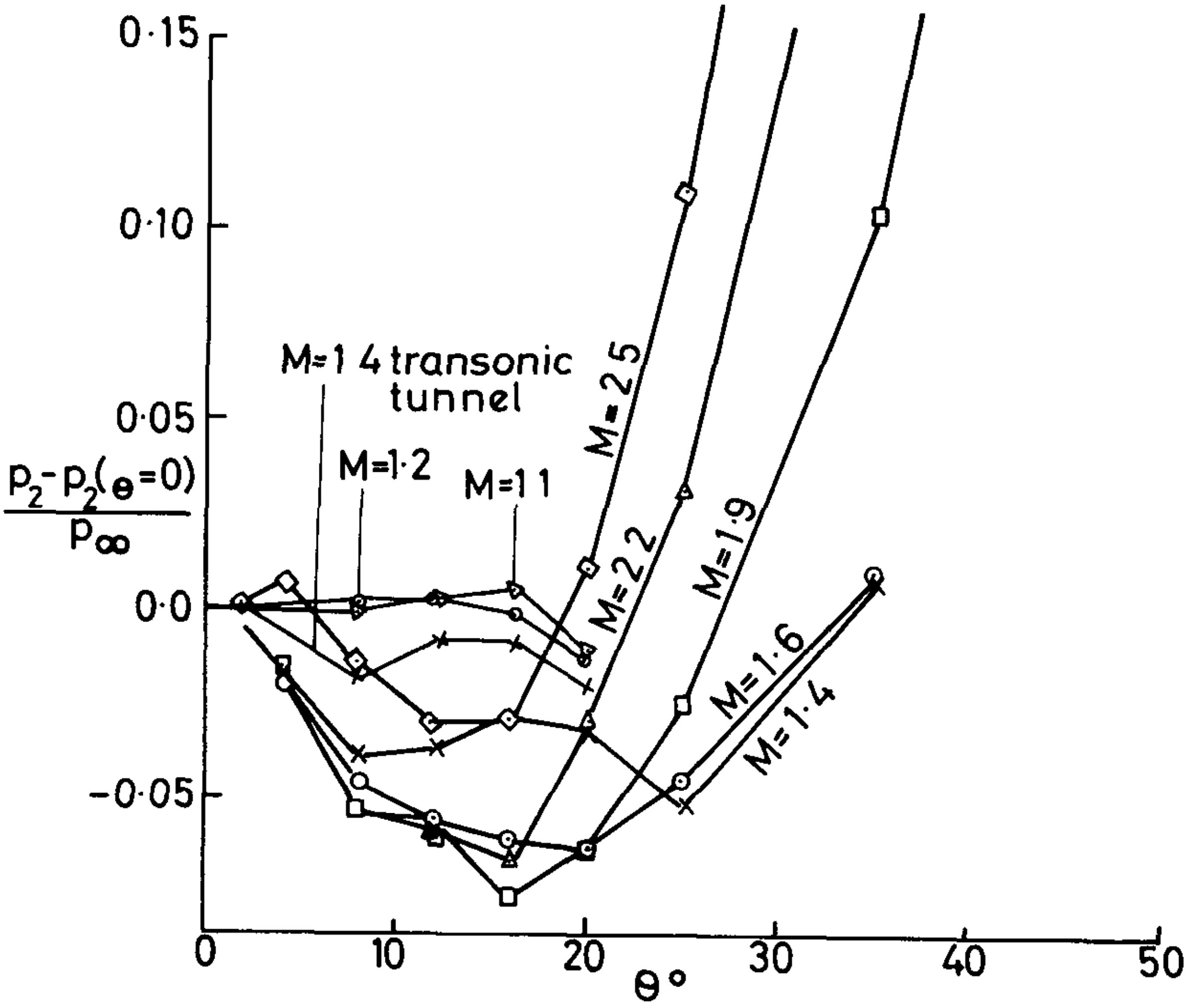
Fig. 3.

[illegible]



0·20
0·15
0·10
+0·05
0·0
−0·05
$\frac{p_2 - p_2(\theta=0)}{p_\infty}$
0
10
20
30
40
50
θ°
M= 2.5
M= 2·2
M=1·9
M=1·6
M=1·4
Probe A

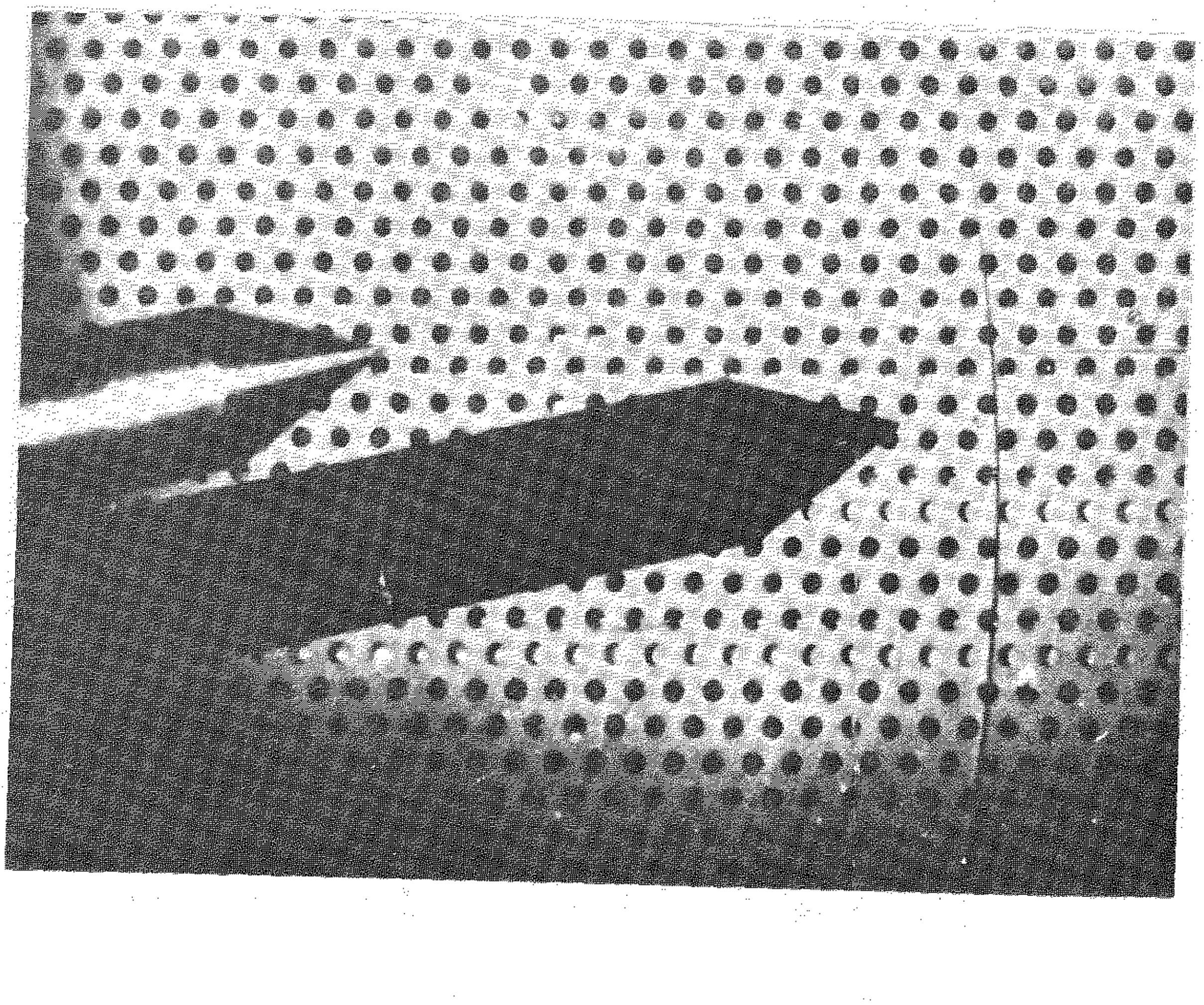
Fig. 4a.



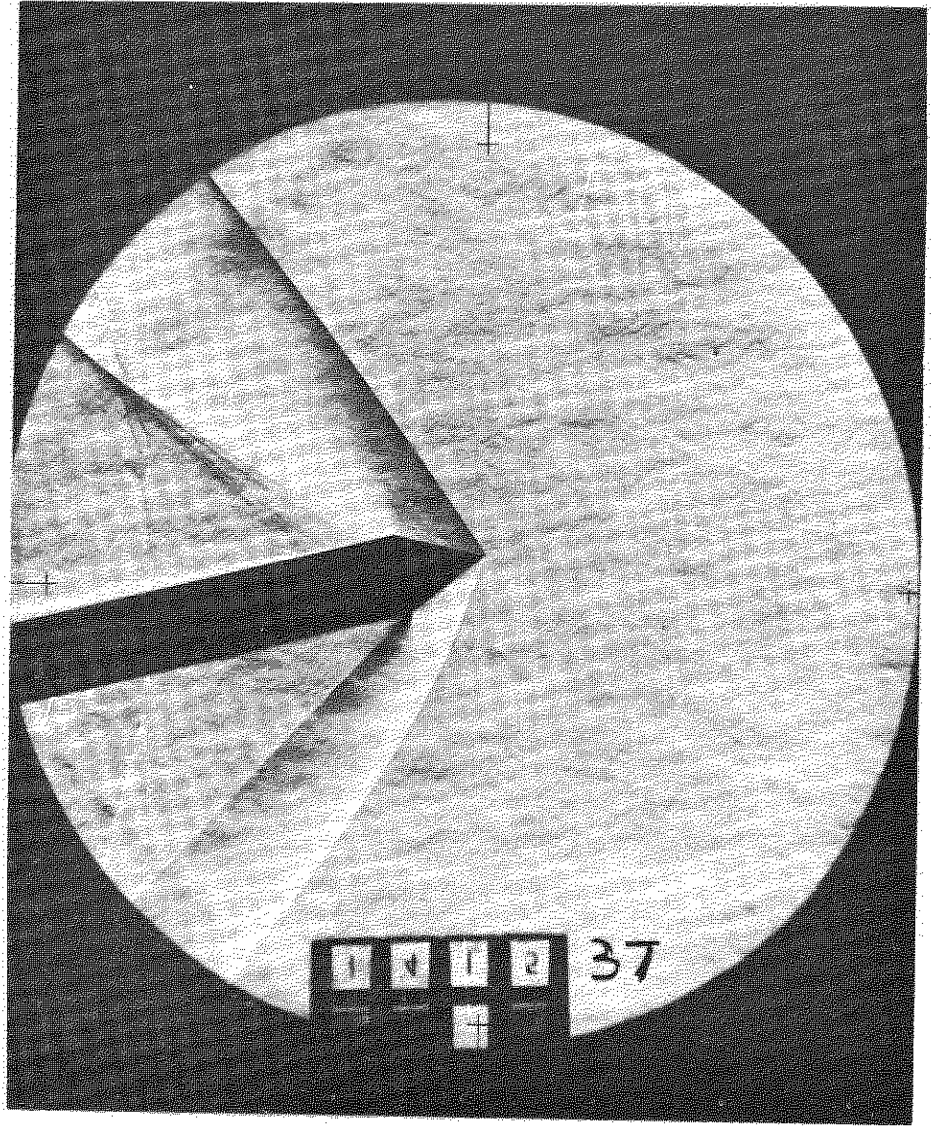
Probe B

Fig. 4 b.

FIG. 5



<u>FIG. 6</u>



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plane,/

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