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SUPERSONIC FLAT PLATE AT HIGH INCIDENCE

by

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SUMMARY

The numerical method of integral relations in both the one and two strip modes has been used to calculate the inviscid perfect gas flow field between a plane flat plate and its detached shock wave. Corresponding wind tunnel experiments are described and results compared with the theory.

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INTRODUCTION

An attempt is being made to define gas conditions at the forward edge of a supersonic surface, fig.1. The plate is taken to have a flat leading edge which stands normal to the free stream. The solution for the flow field behind the detached shock provides a set of initial conditions with which to explore the nature of the subsequent viscous interaction near the leading edge of the plate. The fact that the solution for the flow field between shock and flat leading edge is also that on a thin flat plate normal to the free stream, and is therefore relevant to the re-entry problem of long slender delta lifting surfaces, is noted (1).

So far as is known there are no published experimental data for a plane supersonic flat blunt face, although results are available for the flat faced cylinder or disc in both symmetric (2) and asymmetric attitudes (3).

The numerical method of integral relations has been found to give very good results both on rounded nose shapes and for attached flows (5,8,10). The method has been developed to solve the flow field on the front face of a disc (4,5), and flat plate (4,5,6) both normal to the stream and at arbitrary incidence.

We now wish to explore the validity of the solution for the flat face at supersonic Mach numbers.

EXPLORATION OF VALIDITY OF ONE STRIP SOLUTION

In order to provide a basis for comparison with the theory, experiments have been run at M1.8, Imperial College, London (7) and M3.0, University of New South Wales. The one strip solution has been extended to the limits of its range of Mach number, fig.2, and incidence, fig.3, using an IBM 360-50 computer.

The conditions of model size required for the achievement of truly plane flow information at M3.0 required a separate investigation. The largest possible model is desired within the limit of blockage. Given the small available cross section 102 mm x 140 mm (4 in x 5½ in), the largest full span plane model size which would permit stable running was found to be 13 mm (½ in) deep. Because larger models were required for subsequent experiments, the use of end plates was proposed and their influence on shock standoff distance studied, fig.5. The limiting conditions of no end plates and of infinitely long end plates, corresponding roughly to the wind tunnel side walls for a full span model, are also shown for a range of model aspect ratios (span/depth). It is clear that aspect ratios should be at least 10, if no end plates are to be used, and also that it is preferable to test models which do not span the tunnel, unless the aspect ratio is very large.

Tests to determine shock shape have been run on models varying in depth from 1.6 mm (1/16 in) to 9.5 mm (3/8 in), having aspect ratios exceeding 10 and a range of lengths from 0 to 8 times model depth. Normal shock standoff distance in all cases was found to be 0.70 ± 0.05, based on model depth. Arbitrary scaling of the model depth to include the width across the corner separation bubble does reduce this to 0.6, which however is still well above the prediction of one strip theory, fig.3. The superior agreement for the axisymmetric case is noted parenthetically.

The question therefore arises as to whether the higher order two strip solution is demanded for plane flow. This requires iteration on the initial unknown value of velocity at the midpoint of the stagnation streamline. The closing condition chosen was that used in (8) for sharp edged caps, namely, simultaneous zero values for numerator and denominator of surface velocity gradient (saddle singularity in velocity) at the sharp corner edge, which is also taken to be the sonic point on the body. About 10 iterations each of 1 minute computing time were required. However, no improvement in agreement with experiment was obtained, fig.4, and in addition the predicted sonic line shape is unexpectedly close to the side boundary of the front shock layer, compare (2).

This raises doubt about the correctness of the selected closing conditions. Alternatives such as a tangent wedge at the corner (compare Sinnott, tangent cone (9)), which, although no less arbitrary has the virtue of approximating the viscous boundary at the corner, can be imagined. One such technique which was tried, was to satisfy the saddle singularity on the centre strip boundary rather than atthe sharp corner. This entailed transfer of coordinates from body-oriented to corner-oriented, or polar, coordinates, at the corner itself following (8). However, the solution was found to be no different from that already obtained.

SHOCK GENERATED VORTICITY LAYER

Quite apart from the observed separation bubble on the corner leeside, and its relation to free stream conditions ($M = 3.05$, $Re = 4.10^4$ per mm), and to the front face laminar boundary layer (unit displacement thickness 1.2×10^{-7} mm/mm) a vortical flow generated by shock curvature exists in the inviscid flow region itself. An inversion layer of vorticity, with maximum entropy streamline lifted off the surface of the face, will be created at asymmetric attitudes, fig.1, but so far as is known its size has not been previously measured. The one strip theory above does not reveal its presence. The two strip theory has not been attempted because it would require iteration on two unknowns. The analysis of Swigart and Muggia for nose shapes supporting parabolic shocks predicts a very small separation of stagnation and maximum entropy streamlines (10).

An experiment was therefore designed to identify the "entropy layer" on the flat face, fig.6. The model was 19 mm (3/4 in) square with end plates profiled to the known shock shape and standoff, fig.5, and set at an incidence of 75° in M3.0 flow (Re 4×10^4/mm). Traverses in both angle and position of the handmade miniature pitot probes (0.13 mm x 0.89 mm) at two stations on the front face near the corner of the model determined the position of the maximum entropy streamline, (11). Combining this result with shock shape, it was possible to fix 3 points on the streamline, and to locate the stagnation streamline at the shock, fig.7.

CONCLUSIONS

1. New experimental results at M3.0 for plane flat faces at high incidence are presented. New techniques for ensuring two dimensionality of the flow were developed. These are especially appropriate to small testing facilities.

2. The numerical method of integral relations which has been so successful on other shapes, including the axisymmetric flat faced body, does not accurately predict experimental shock standoff at M3.0 on plane flat face, even after making allowance for viscous separation bubble size.

ACKNOWLEDGMENT

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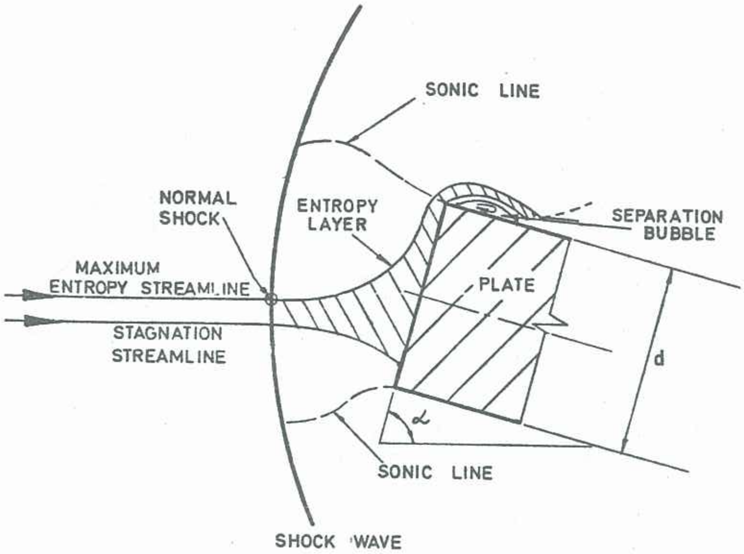


FIG.1 FLAT PLATE AT HIGH INCIDENCE IN SUPERSONIC FLOW

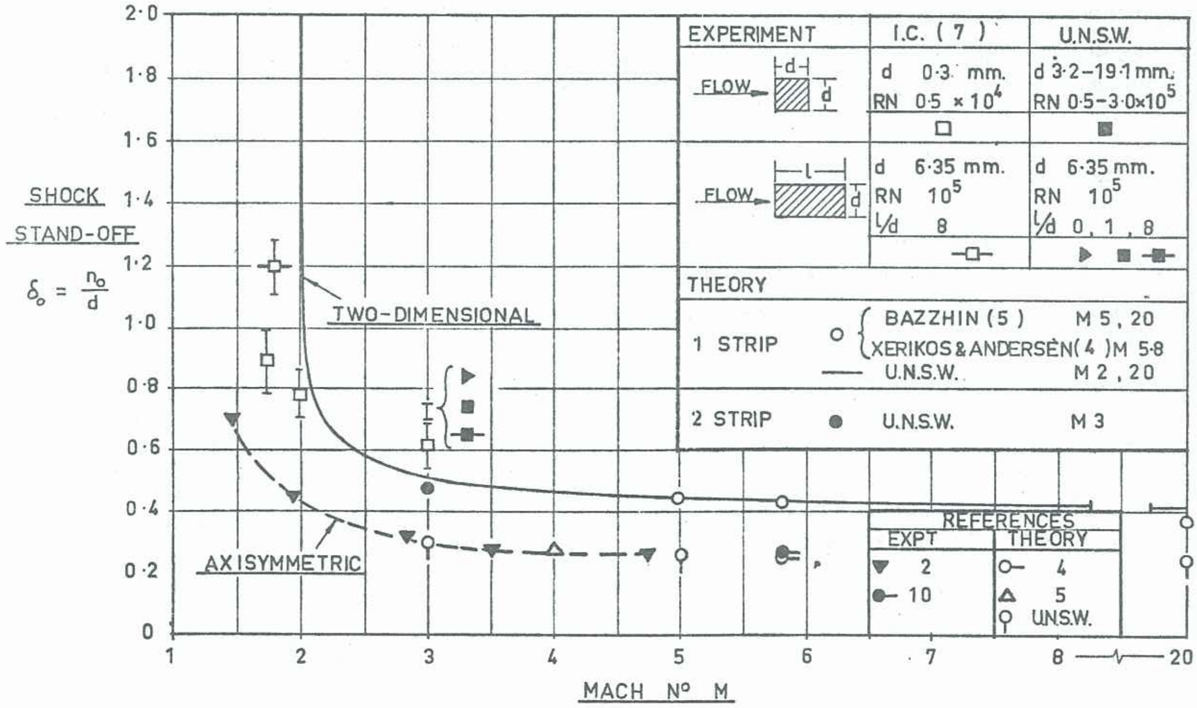
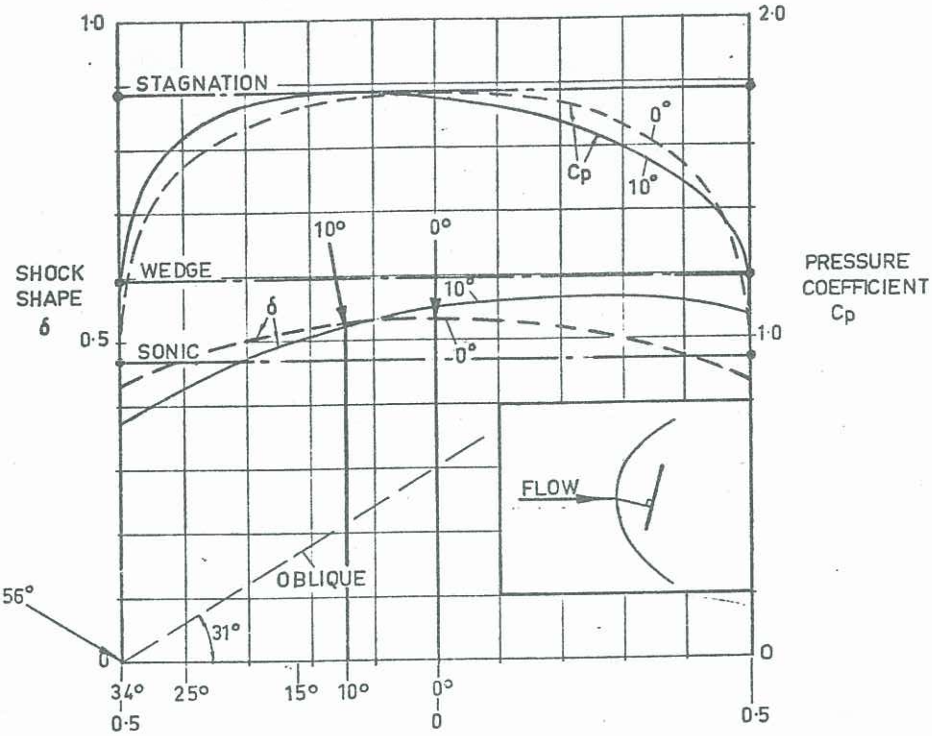


FIG. 2 SHOCK STAND OFF FOR FLAT PLATE NORMAL TO A SUPERSONIC AIRSTREAM



FLAT PLATE AT HIGH INCIDENCE

M.I.R. SOLUTION 1 STRIP

MACH 3·0 $\gamma = 1{\cdot}4$ PERFECT GAS

BOUNDARIES OF ONE STRIP SOLUTIONS

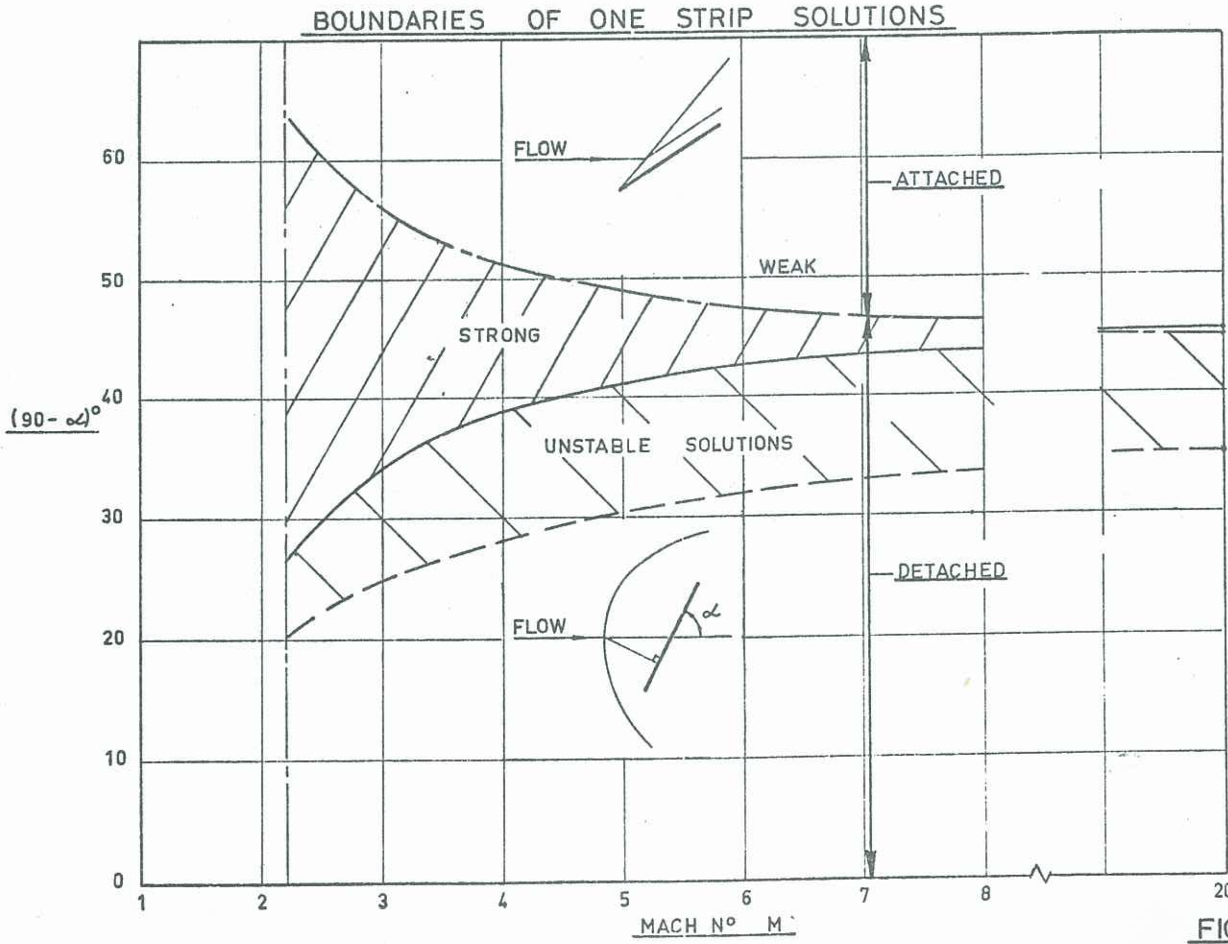


FIG.3

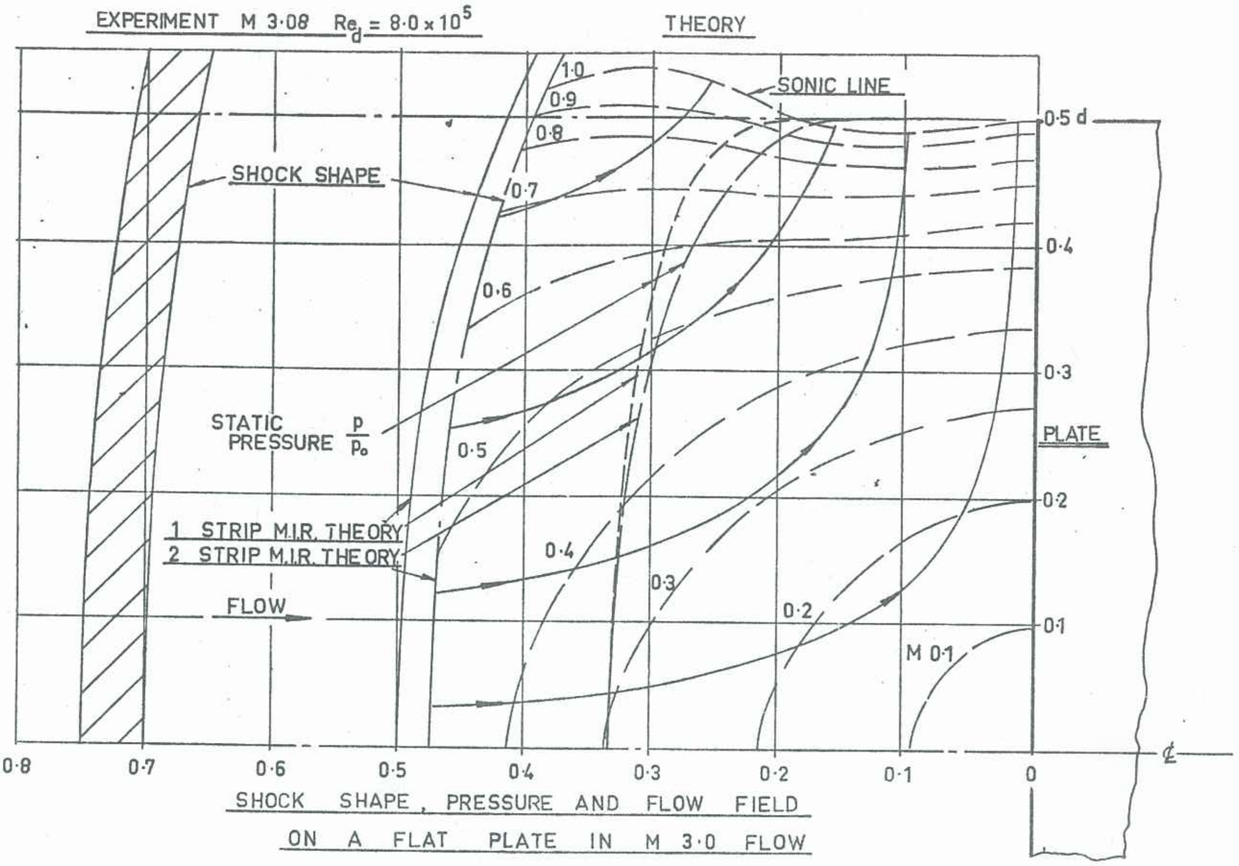

EXPERIMENT M 3·08 Re_d = 8·0 × 10^5
THEORY
SONIC LINE
SHOCK SHAPE
STATIC PRESSURE p/p₀
1 STRIP M.I.R. THEORY
2 STRIP M.I.R. THEORY
FLOW
PLATE
M 0·1
SHOCK SHAPE, PRESSURE AND FLOW FIELD
ON A FLAT PLATE IN M 3·0 FLOW

FIG. 4

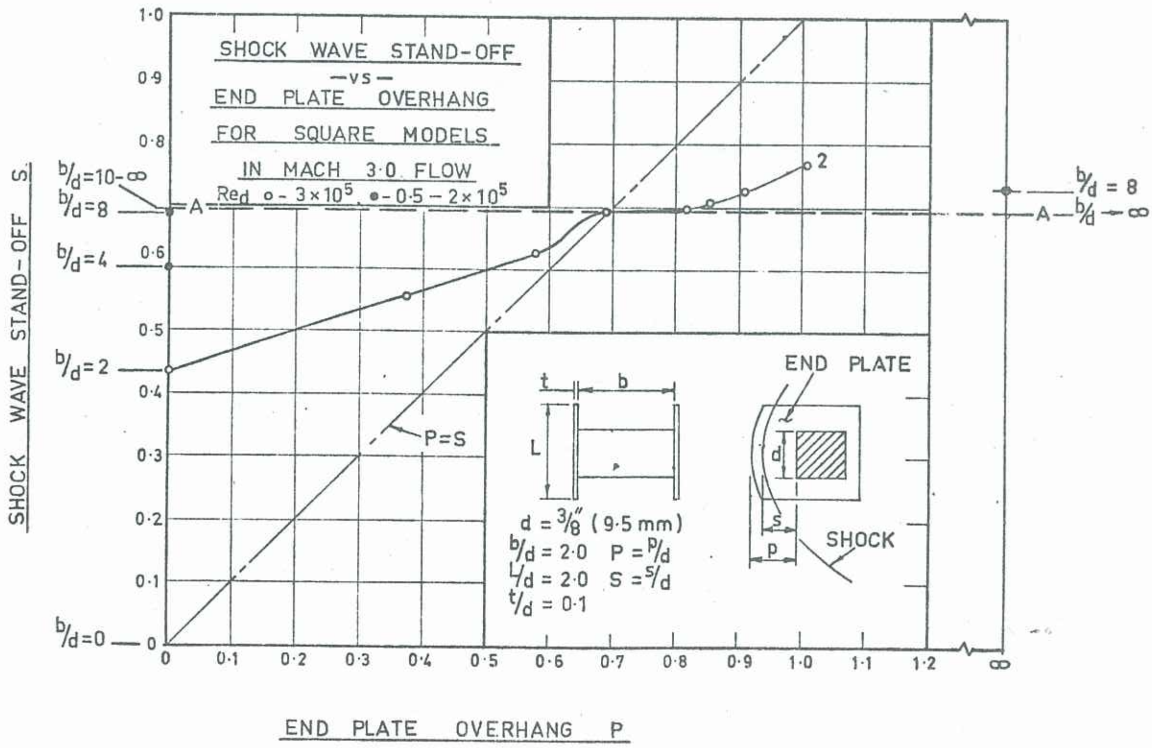

SHOCK WAVE STAND-OFF
—vs—
END PLATE OVERHANG
FOR SQUARE MODELS
IN MACH 3·0 FLOW
Re_d o - 3×10^5, • - 0·5 - 2×10^5
SHOCK WAVE STAND-OFF S
END PLATE OVERHANG P
P=S
END PLATE
SHOCK
d = 3/8" (9·5 mm)
b/d = 2·0 P = p/d
L/d = 2·0 S = s/d
t/d = 0·1

FIG. 5

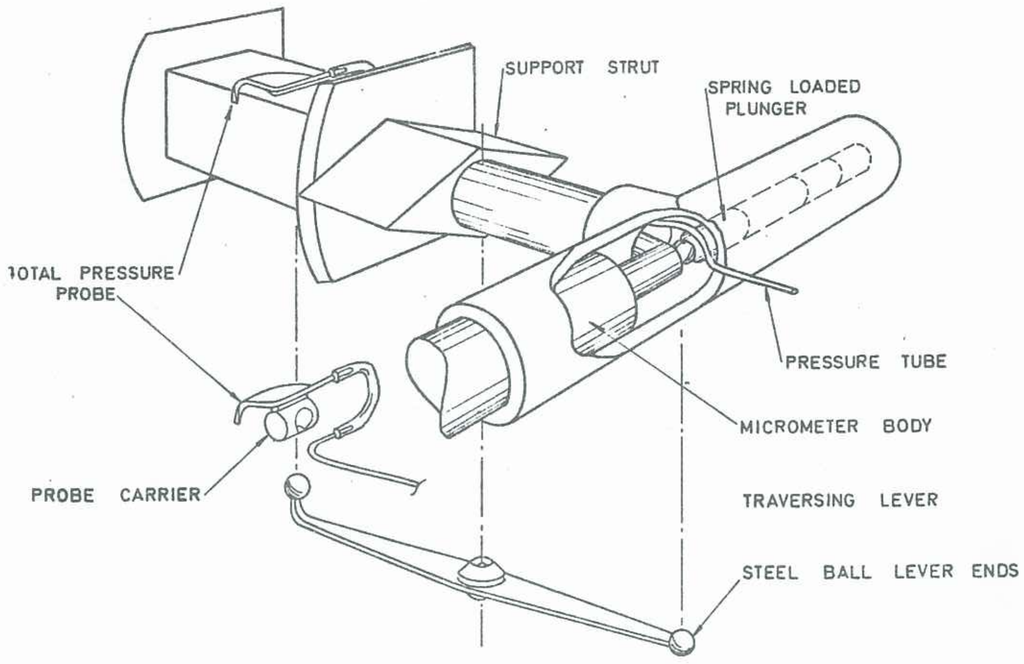
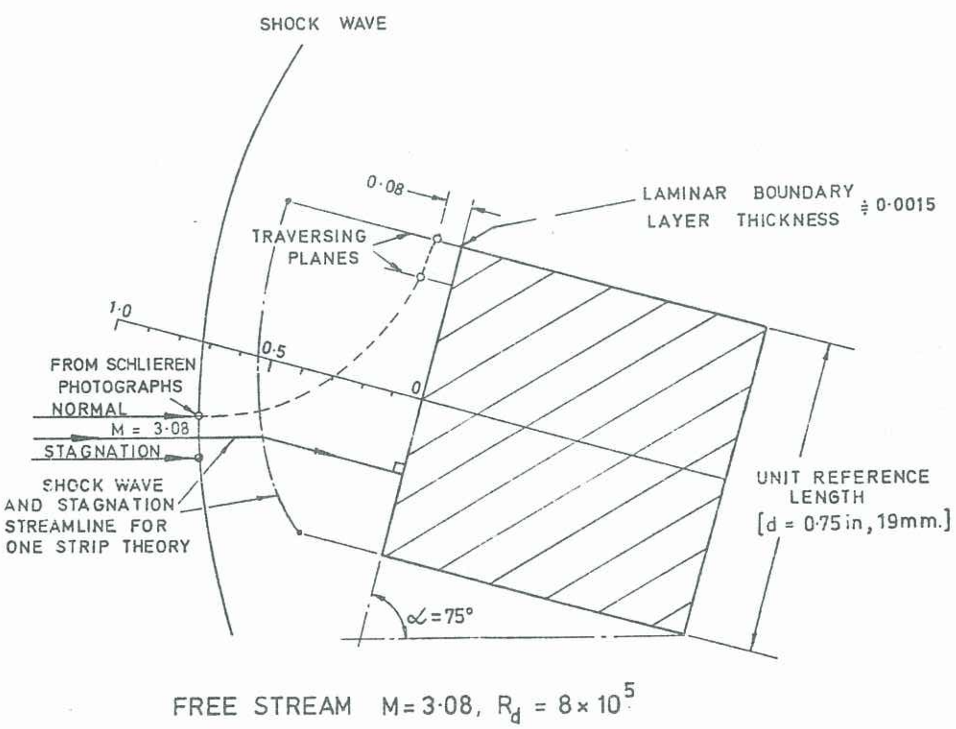


FIG. 6 TOTAL PRESSURE PROBE MODEL



FREE STREAM $M = 3{\cdot}08$, $R_d = 8 \times 10^5$

FIG. 7 IDENTIFICATION OF ENTROPY LAYER ON FLAT PLATE