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** Now at the Indian Institute of Technology, Bombay

SUMMARY

The report describes work carried out in a supersonic wind tunnel at a Mach number of 1.93 on the interaction produced by wedges of 8°, 12° and 16° angle. The wedges could be raised from the tunnel floor through distances comparable with the boundary layer thickness, and suction was applied at the resulting slot.

The pressure distributions and boundary layer traverses show how the suction reduces and eventually eliminates the separation region, causing the flow to approach that of ideal fluid theory. Estimates of optimum suction quantity and bleed height are obtained.

1. Introduction

One of the basic problems in the study of supersonic flow concerns the effects of interaction of shock waves with boundary layers. Shock induced separation can occur on many components of an aircraft. Whether it is detrimental to the aerodynamic efficiency of the system depends mainly on the resulting pressure distribution, but the effects can be quite large.

Simplified models of interaction have been investigated by many experimenters, usually in two-dimensional supersonic flow. Topics of greatest attention have been:

(a) the interaction between a boundary layer developed on a flat plate and an incident shock produced by a wedge, held in the main stream above the plate (Fig. 1a);[1,2,4,5,7]

(b) the interaction between a boundary layer approaching a corner and the shockwave produced by an abrupt change of slope of a surface behind the corner (Fig. 1b);[3,4,6,7]

(c) the interaction between a boundary layer produced on a flat plate, and a step on the plate (Fig. 1c).[5,6]

When the boundary layer separation occurs either with the incident shock model in front of a compression corner, or in front of a step, it is virtually independent of the agency provoking separation. Thus, for instance, for given upstream conditions the longitudinal surface pressure distribution at the wall near separation will be the same whether separation is provoked by an incident shock or by a compression corner. The reason for this is as follows. Near separation there are adverse pressure gradients, which thicken the stream tubes of low velocity inside the boundary layer. This thickening of the inner part of the boundary layer deflects the external flow from its original direction parallel to the wall and generates a band of compression waves. This compression and the thickening of the inner viscous sub-layer of the boundary layer must adjust themselves to be in equilibrium. This equilibrium process will be insensitive to downstream conditions provided that for some distance downstream of separation there are no disturbances imposed on the boundary layer. This is usually termed a 'free interaction'. The simplest type of free interaction flow is two-dimensional with the separation line straight and perpendicular to the direction of the flow.

1.2 Outline of the present investigation

The present investigation is relevant to the compression process in a supersonic air intake. To achieve high pressure recovery in these air intakes boundary layer separation must be avoided. The low energy air may be removed by suction. However, too much boundary layer suction will result in high drag and insufficient suction may not prevent boundary layer separation in the inlet. Although a considerable body of experimental data exists for estimating the pressure ratio required to separate the boundary layer, these results do not include the influence of suction in delaying or preventing boundary layer separation.

In the present investigation the effects of suction on the interaction between a turbulent boundary layer and shock wave has been studied. A compression corner was created by mounting a wedge on a flat surface. Part of the boundary layer approaching the corner was removed by suction through a discrete bleed located at the corner (see Fig. 2).

This two-dimensional bleed was achieved by lifting the wedge clear of the flat plate. A suction slot was thus created between the plane surface of the flat plate and the undersurface of the wedge.

Two bleed heights of 0.05" and 0.10" were used. These were about twice and four times the momentum thickness of the approaching boundary layer. The boundary layer air which entered the slot was removed, the amount of suction being controlled independently of the bleed height 'h'.

To vary the strength of shock wave at the compression corner, three wedges (of the same height) have been used. The angles of the wedges were 8°, 12° and 16°. They are typical in the sense that they give (a) no separation, (b) moderate separation and (c) large separation of the approaching turbulent boundary layer.

The experiments were conducted at a Mach number of 1.93 and a Reynolds number based on the distance x (distance measured from throat of the nozzle to the corner) of 6.4×10^6. The measurements consisted of:

(a) centre line pitot traverses on the inclined surface of the compression corner as well as upstream of the corner;

(b) static pressure plot along the centre line upstream and downstream of the corner;

(c) schlieren photographs using a spark-source for flow visualization;

(d) surface oil patterns to study the separation and to check the validity of the two-dimensional flow.

In addition to a general study of the effects of suction on the nature of interaction at a concave corner, an attempt has been made to determine the amount of suction necessary to prevent separation of the turbulent boundary layer.

2. Apparatus and Test Methods

2.1 Wind tunnel

The experiments were conducted in a 4" x 4" intermittent supersonic wind tunnel of the 'suck-down' type so that the stagnation pressure and temperature were atmospheric. The nozzle of the tunnel is shaped on one side only and for the present investigation the Mach number was 1.93. This gave the tunnel a running time of about 30 seconds.

Incorporated in the design of the tunnel is a parallel section 30" long behind the normal working section and of the same cross-section. A full description of the tunnel and the driving unit is given in reference 8.

2.2 Flat plate

The floor of the parallel section was used as the basic flat plate for the wedge. It was a 3/16" thick steel plate with 0.0165" dia. static pressure orifices spaced 0.20" apart.

Considerable care had to be taken to seal and smooth the joints between the nozzle assembly section and the parallel section. Schlieren pictures were taken to ascertain that there were no strong spurious shock waves generated by disturbances at the sealings.

Despite these precautions, however, the pressure distributions on the faces of the wedges show considerable disturbances which become evident only when the flow is attached. These disturbances result from waves originating at the join in the top wall of the tunnel.

2.3 Wedge models

Detail dimensions and angles of the wedges are shown in Table I. The wedges span the tunnel leaving a small clearance of about 0.0025" on the two sides for ease of mounting. They are made of steel, hardened, ground and polished. Static pressure orifices have been provided along the centre line of all the wedges.

2.4 Boundary layer traverse gear

The boundary layer traverse gear and the device for lifting the wedge up through the boundary layer is shown in Fig. 2.

The two rods A and B which carry the wedge are attached to a moveable platform. A worm box C (25:1 reduction ratio) mounted on this platform enables the platform to move up or down along the fixed screw E. Similarly, the probe holder screw F (40 T.P.I.) is driven through another worm box D (25:1 reduction ratio) mounted on the same platform. The two worm boxes are driven by reversible motors through flexible shafting. It was thus possible to move both wedge and pitot probe independently of one another. The longitudinal position of the pitot probe was controlled by a screw clamp on the probe holder.

The speed of the motor driving the pitot probe was controllable so that a complete boundary layer traverse could be obtained in a single run of the tunnel.

To cover the required traverse stations on the plate as well as on the wedge surface, pitot probes of different lengths were used. They were made of 0.0165" dia. hypodermic tubing, flattened at the tip to give an orifice height of about 0.01". The probe was connected to a transducer by a small length of heavy, plastic tubing.

2.5 The boundary layer suction system

The boundary layer air which is ducted beneath the wedge first enters a reservoir. It is then led through two 1" diameter pipes which joined to a single 3" diameter pipe, which in turn is connected to the main vacuum pump. Pressure tappings had been provided in the reservoir and the 3" pipe to obtain the pressure distribution in the ducting system. A valve in the 3" bleed pipe enabled the mass flow removed to be controlled independently of the slot height.

During the suction experiments, a full span packing piece held firmly between the wedge undersurface and the floor isolated the suction chamber from the flow outside. Different packing pieces were used for different slot heights.

3. Results and Discussion

3.1 Pressure distributions: effect of suction

Figs. 3a to d show the effects of varying the suction rate on the pressure distribution along the top of the wedge and along the tunnel floor just ahead of the wedge tip. In each case $^{P}/P_{\infty}$ is plotted against position along the tunnel, and the broken lines represent the distribution obtained with the wedge on the floor (h = 0) with no suction.

The shape of the broken line is similar to that obtained by other workers. The effect of raising the wedge from the floor, with no suction, is to push the upstream part of the interaction further forward and to create a discontinuity between the pressures on the floor and those on the wedge.

If we then apply suction, the effect is to pull the upstream part of the interaction back towards the wedge tip. In the process, the size of the dead air region is rapidly reduced, while the pressure along the wedge surface rises. Thus the curves showing the pressure on the wedge are in the opposite vertical order from those for the plate ahead of the wedge. Suction reduces the pressures ahead of the wedge but increases the pressure on its upper surface.

For the 16° wedge with no suction, the pressures are well below the theoretical value right along the wedge. This suggests that the separation region extends along the wedge at least to the shoulder. As suction is applied the general pressure level on the wedge rises but, in addition, the shape of the curves change, with a dip appearing at about 0.6 in. from the tip. This is particularly noticeable with the 0.1" bleed height.

This dip is believed to arise from a weak wave system originating at the join in the top wall of the tunnel. We should expect that a wave system of this kind would affect the pressure distribution only if the boundary layer is attached. The appearance of this dip thus probably provides an indication that the boundary layer has attached.

With the 12° wedge the same effects appear. With the 0.05" bleed height, however, only a little suction is required to bring the pressures at the rear of the wedge very near to their limiting value.

3.2 Suction quantity required

It is not easy to determine from the pressure distributions, precisely when the separation region disappears. This is perhaps not very important, since the curves clearly show how the flow pattern approaches the theoretical inviscid flow as suction is applied.

To get a measure of the required suction quantity, the pressure ratio at the first pressure hole in the wedge is plotted against the non-dimensional flow rate $\frac{Q}{\rho_1 U_1 \theta}$ (Fig. 4).

The figure shows that the pressure ratio increases approximately linearly with suction quantity. With the 16° wedge at 0.05" the highest obtainable suction rate was still insufficient to raise the pressure ratio to the inviscid flow value. For the 16° wedge at 0.1" and for the 12° wedge at both heights, the inviscid flow pressure was reached, at least approximately, at the highest suction rates. In view of the stray disturbances mentioned above little significance can be attached to slight differences from the theoretical value.

The suction rate at which the curves, extrapolated when necessary, reach the ideal pressure is well defined, and may be taken as a useful measure of the desirable mass flow for a given value of h. It should, however, be borne in mind that the optimum may in practice be lower, since the suction itself will involve some drag penalty.

Table II shows the desirable suction rates defined in this way, together with the thickness of boundary layer removed.

The data available are insufficient to determine with any certainty an optimum value for the bleed height. If this is too small it may not be possible to remove enough air, or alternatively an excessive pressure drop will be required with a high penalty in suction drag. On the other hand an excessive bleed height will make it necessary to remove too much air to preserve the geometry of the flow. Intuition suggests that the thickness of the original boundary layer to be removed should be somewhat less than the bleed height. This would cause the dividing streamline to curve away from the surface resulting in some rise in pressure ahead of the wedge, but not enough to cause separation. The deflection of the stream at the tip of the wedge would then be less than the wedge angle and the strength of the oblique shock consequently reduced.

Examination of Fig. 4 leads to the conclusion that the bleed height of 0.05" was just less than adequate for the 12° wedge (since the theoretical pressure was not reached) and that the 0.10" height was rather more than adequate for the 16° wedge (since the theoretical pressure was exceeded). In Fig. 5 the thickness of the original boundary layer removed at the "desirable suction rate" defined previously is plotted against bleed height for each wedge angle. The points are joined arbitrarily by straight lines. The above conclusions are then seen to be compatible with the notion that the bleed height should be approximately four thirds of the thickness of boundary layer to be removed. On this basis optimum values of suction quantity and bleed height for the two wedge angles are as follow:-

Wedge Angle	$\frac{h}{\theta}$	$\frac{Q}{\rho_1 U_1 \theta}$
12°	2.36	0.87
16°	3.75	1.50

However, it must be admitted that the above values depend considerably upon speculation and that further experiments are required.

3.3 Boundary layer traverses

Boundary layer profiles on the upper surface of the wedge were measured with zero suction and zero bleed height (that is, with the wedge on the floor) and at a single high suction rate at each of the bleed heights 0.05" and 0.1". The results are thus somewhat sparse and also show some features whose explanation is not clear. They are, therefore, only presented in order to give general support for the results already given.

Fig. 6a shows that the boundary layer on the tunnel floor, with the wedge removed, is reasonably close to a 1/7th power law profile. Fig. 6b shows the corresponding displacement and Mach number profiles, which have been used to determine the momentum thickness (0.0242"). Thicknesses of the boundary layer removed, Table II, were obtained from Fig. 6c which shows the mass flow in the boundary layer.

Fig. 7a shows Mach number profiles at two positions on the surface of the 12° wedge, for bleed heights zero, 0.05" and 0.1".

Near the wedge tip with no suction the boundary layer is clearly separated. The suction rate of $\frac{Q}{\rho_1 U_1 \theta} = 0.94$ with h = 0.05 appears to be just sufficient to prevent separation, while at h = 0.1" the suction rate of $\frac{Q}{\rho_1 U_1 \theta} = 1.38$ is more than sufficient.

The curves for the station 0.8 in. from the wedge tip show no separation even with no suction. They do, however, show the effect of suction in reducing the boundary layer thickness. Profiles at the 1.4 in. station were also measured. These were very similar to those at 0.8 in., and are, therefore, not shown.

These results agree reasonably well with the pressure distributions, though the apparent closeness to separation of the profile near the wedge tip at h = 0.05" and $\frac{Q}{\rho_1 U_1 \theta} = 0.94$ is somewhat surprising.

Fig. 7b gives the corresponding profiles for the 16° wedge, and these show effects very similar to those described above. The curves are as expected except for the profile at the 1.2" station, with no suction. The pressure distribution might suggest that the separation region extends back to this point, since the pressure is still considerably lower than the inviscid value. The profile, however, shows no separation and in fact it appears to be further from a separation profile than is the one with suction at h = 0.05". The explanation is not clear.

3.4 8° wedge results

Some results, including pressure distributions and boundary layer profiles, were obtained with an 8° wedge. It appeared, however, that even with no suction, there was little, if any, separation of the boundary layer. The pressure rise was only slightly increased by suction. The boundary layer profile near the wedge tip, with no suction, suggested that the boundary layer was close to separation but still not separated.

It appears, therefore, that for this wedge angle and pressure rise (pressure ratio 1.53) suction would not be required in practice.

3.5 Three-dimensional effects

A few results were obtained using an oil film to show the surface flow. While the results are not very clear, they do show vortices in the side wall corners behind the shock.

It appears reasonable to assume that so far as any upstream effects are concerned, three-dimensional effects will disappear as the upstream influence is reduced by suction. It is thus unlikely that the suction rate measurements will be seriously affected. The three-dimensional effects may, however, form an interesting subject for further investigation.

4. Conclusions

The flow with the wedge on the tunnel floor was very similar to that observed by earlier workers.

When the wedge was raised from the floor the upstream influence increased and a discontinuity appeared between the pressures ahead of the wedge and the pressures on its surface.

Suction reduced the upstream influence and at the same time increased the pressures on the wedge. The separation region disappeared and the flow approximates to that of ideal fluid theory.

The changes mentioned proceeded linearly with suction rate until the thoeretical pressure rise was obtained. The suction rate required varied from $\frac{Q}{\rho_1 U_1 \theta}$ = 0.81 (for the 12° wedge at 0.05") to $\frac{Q}{\rho_1 U_1 \theta}$ = 1.54 (for the 16° wedge at 0.1").

The best bleed height is not very clearly determined, but the results suggest that it may be about four thirds of the thickness of boundary layer which it is required to remove. If this is correct, the bleed height required is 2.36 times the momentum thickness for a wedge angle of 12°, and 3.75 times this thickness for the wedge angle of 16°.

The boundary layer profiles generally confirm the results obtained from the pressure distributions, though several features remain unexplained.

While three-dimensional effects are present in the flow it is likely that they will be reduced by suction and that their presence will not greatly affect the conclusions reached.

Further work is clearly required to determine with more certainty an optimum bleed height, to study losses in the shock, boundary layer and slot, and to study the three-dimensional effects.

Acknowledgments

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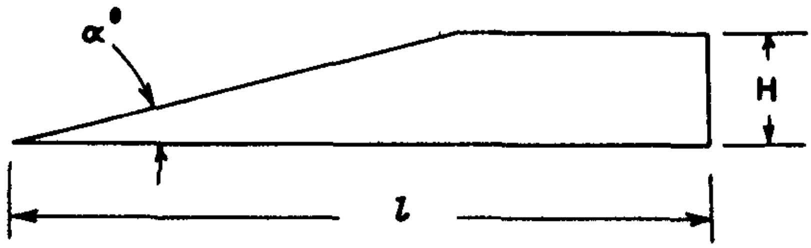
TABLE I



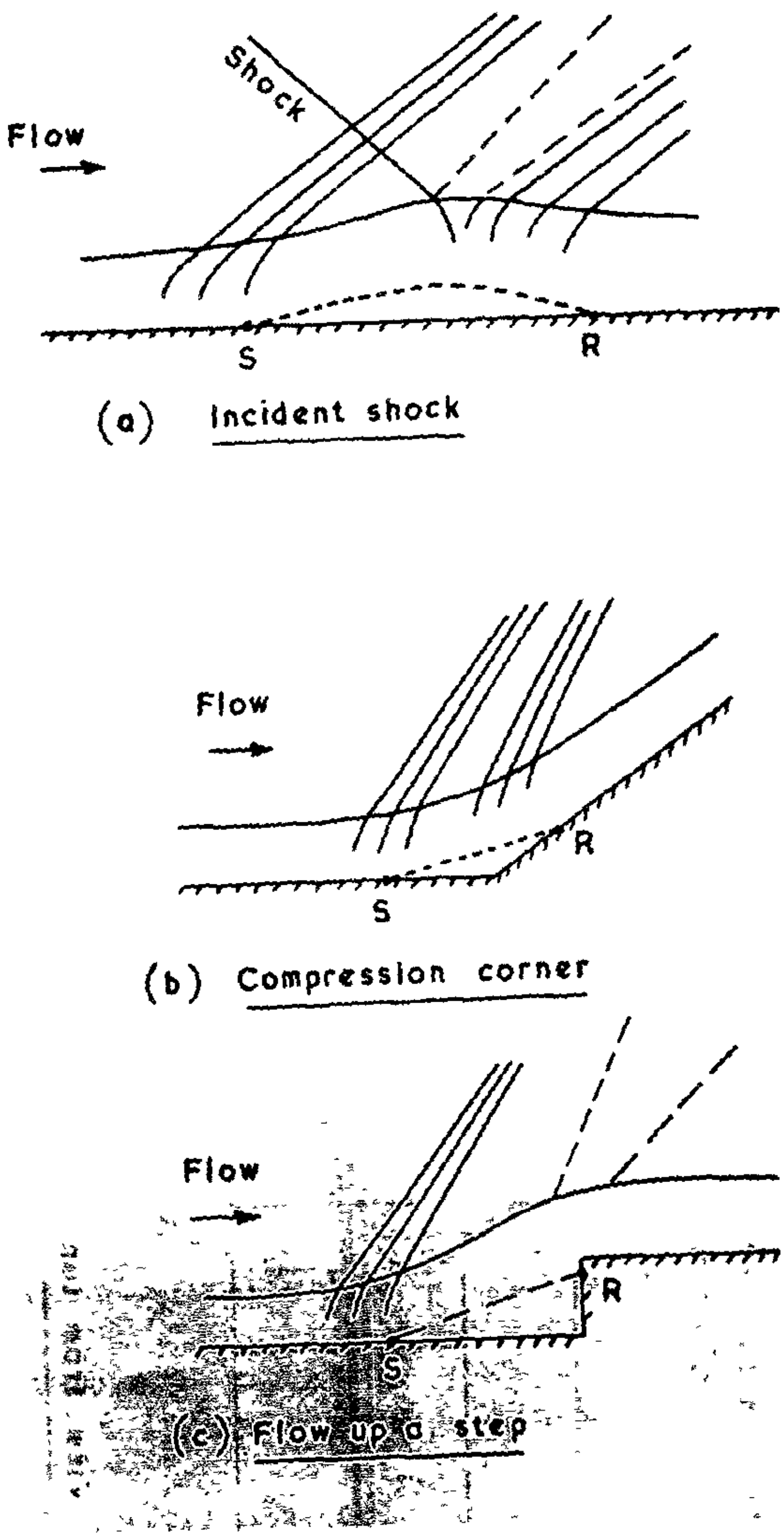
Model	Angle $\alpha°$	Height H"	Length l"
A	8	3/8	3
B	12	3/8	2 3/4
C	16	3/8	2 3/4

Model dimensions.

TABLE II

Wedge Angle	Ideal Pressure Ratio P/P_∞	Bleed Height h(in.)	Ideal Suction Rate $\frac{Q}{\rho_1 U_1 \theta}$	Boundary Layer Thickness Removed (in.)
8°	1.53	0	0	0
12°	1.87	(0.05	0.81	0.040
		(0.10	1.33	0.062
16°	2.28	(0.05	1.33	0.062
		(0.10	1.54	0.070

FIG 1



Typical interactions

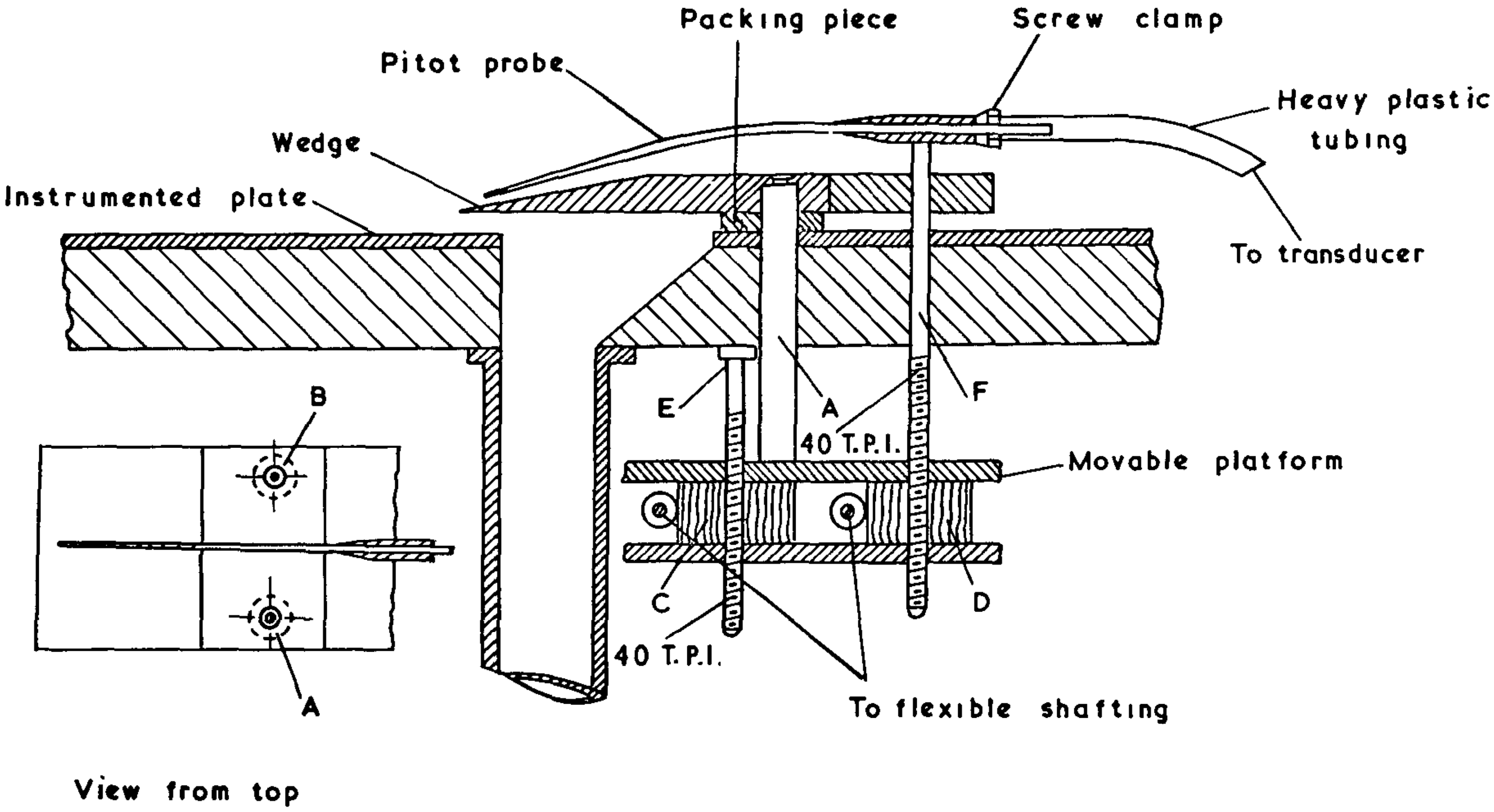


FIG. 2

Boundary layer traverse gear

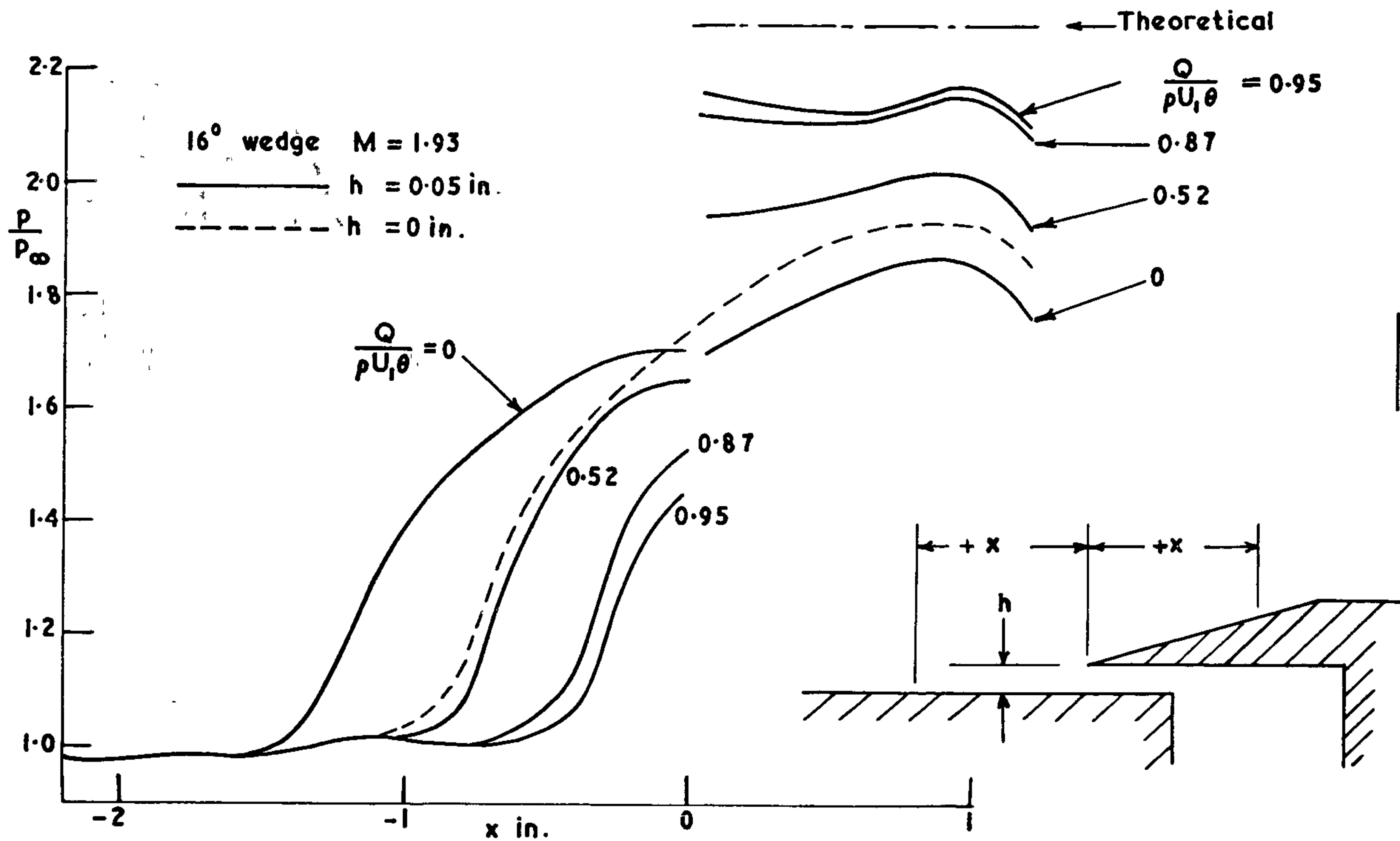
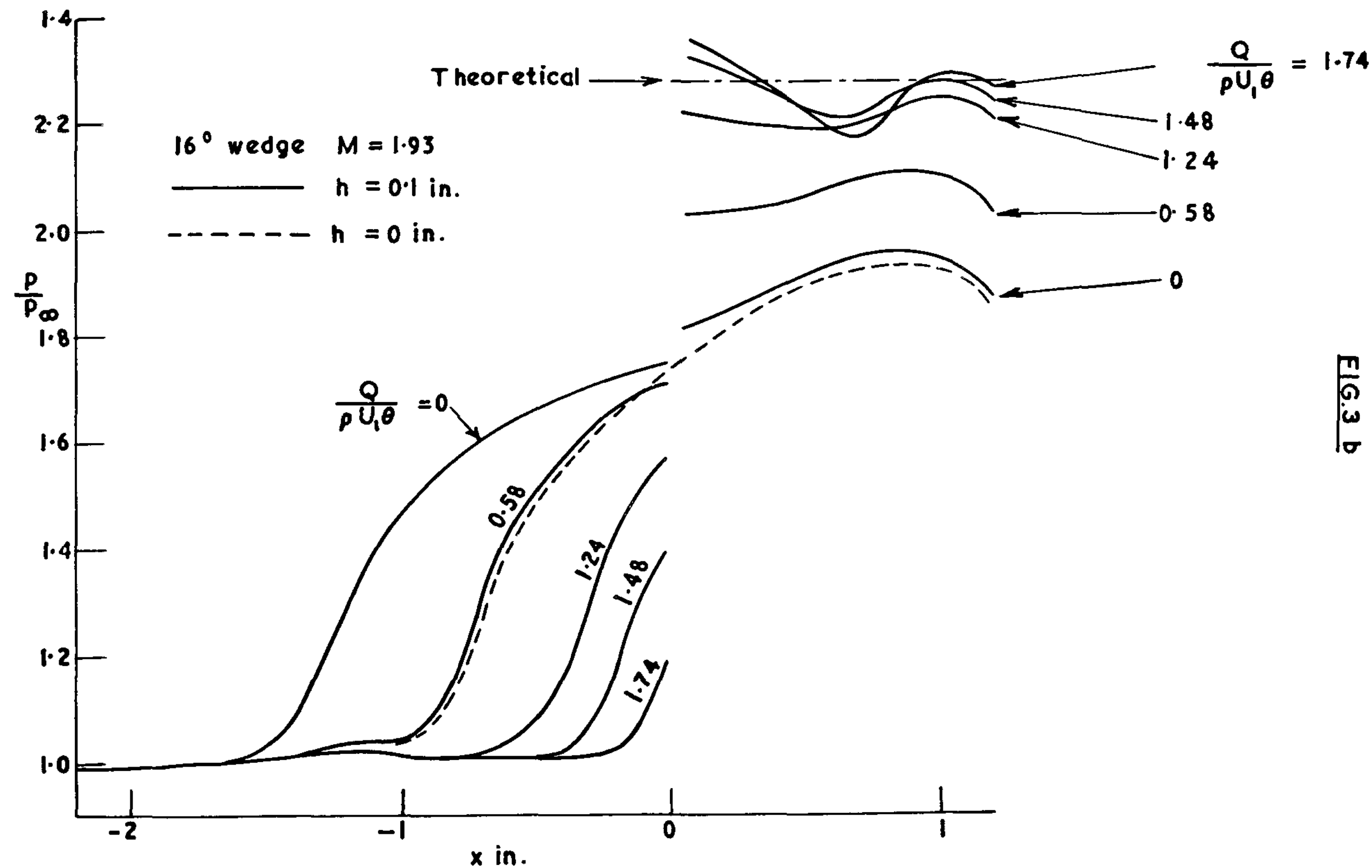


FIG. 3a

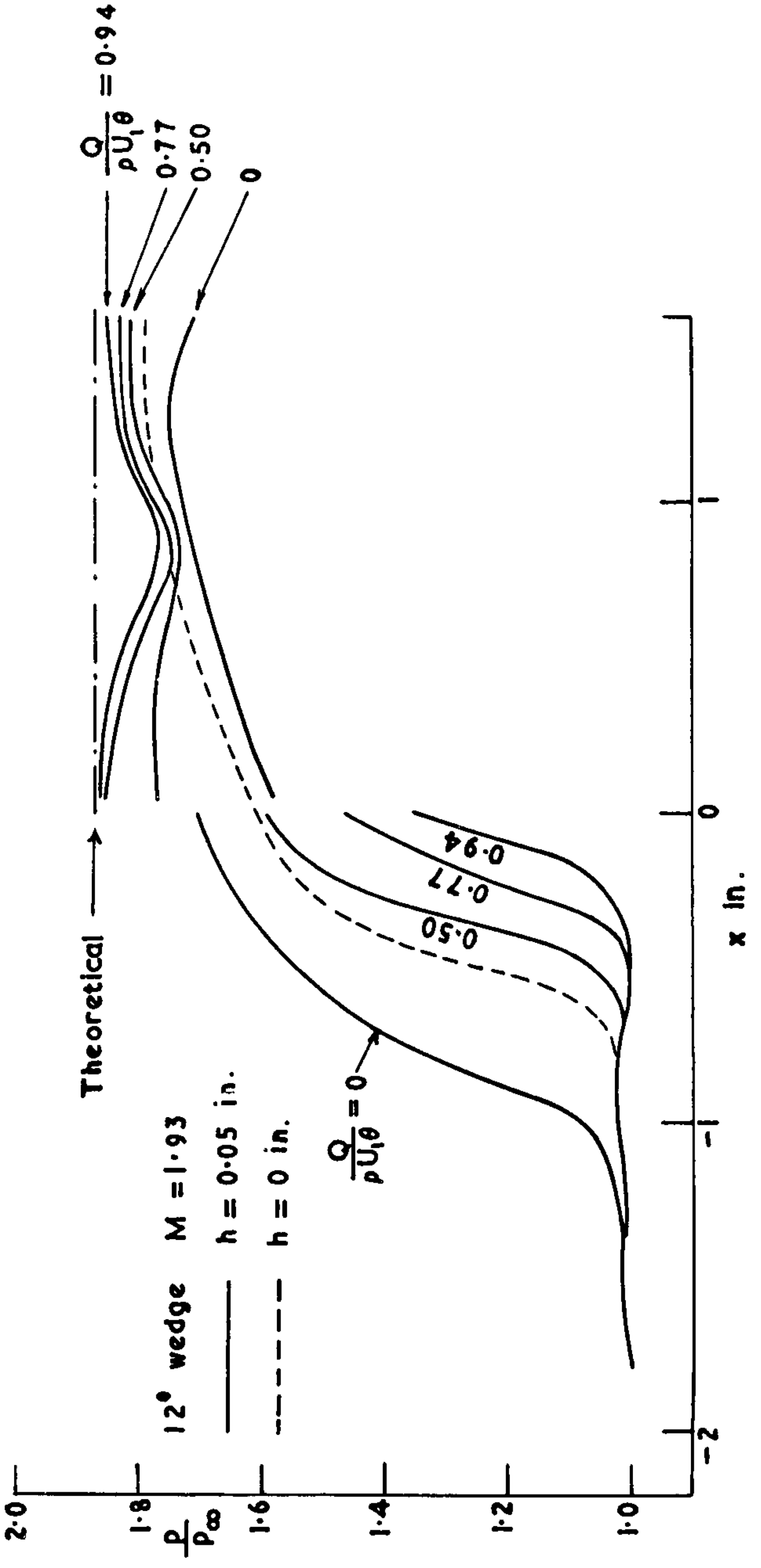
Pressure distributions



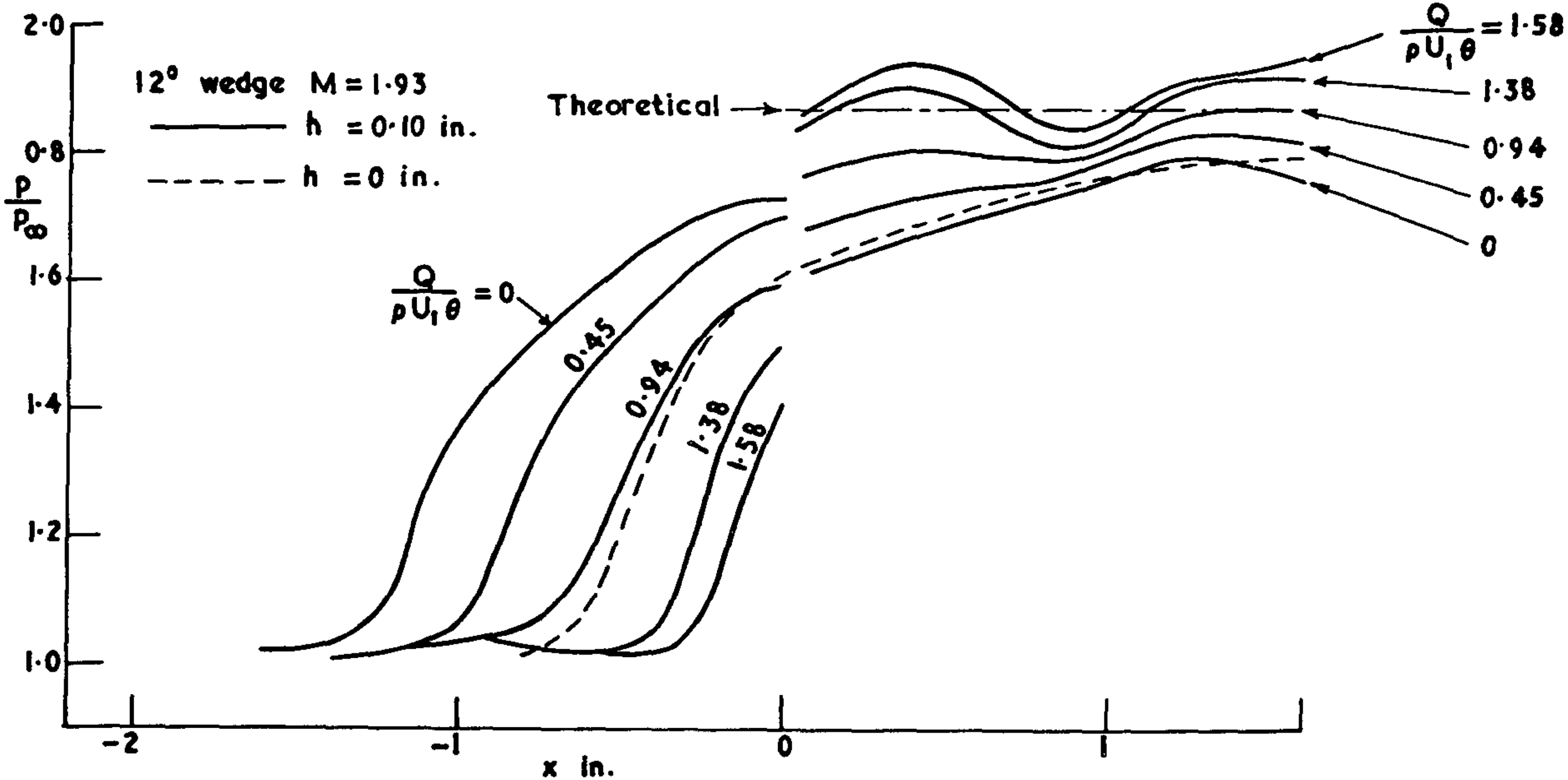
Theoretical
$\frac{Q}{\rho U_1 \theta} = 1{\cdot}74$
1·48
1·24
0·58
0
16° wedge M = 1·93
h = 0·1 in.
h = 0 in.
$\frac{p}{p_\infty}$
$\frac{Q}{\rho U_1 \theta} = 0$
0·58
1·24
1·48
1·74
1·4
2·2
2·0
1·8
1·6
1·4
1·2
1·0
-2
-1
0
1
x in.

FIG.3 b

FIG.3 c



12° wedge M = 1·93
h = 0·05 in.
h = 0 in.
Theoretical
$\frac{Q}{\rho U_1 \theta}$ = 0·94
0·77
0·50
0
$\frac{Q}{\rho U_1 \theta}$ = 0
0·94
0·77
0·50
$\frac{p}{p_\infty}$
2·0
1·8
1·6
1·4
1·2
1·0
−2
−1
0
1
x in.



12° wedge M = 1·93
h = 0·10 in.
h = 0 in.
Theoretical
$\frac{Q}{\rho U_1 \theta} = 1{\cdot}58$
1·38
0·94
0·45
0
$\frac{Q}{\rho U_1 \theta} = 0$
0·45
0·94
1·38
1·58
2·0
0·8
$\frac{p}{p_\infty}$
1·6
1·4
1·2
1·0
−2
−1
0
1
x in.

FIG. 3d

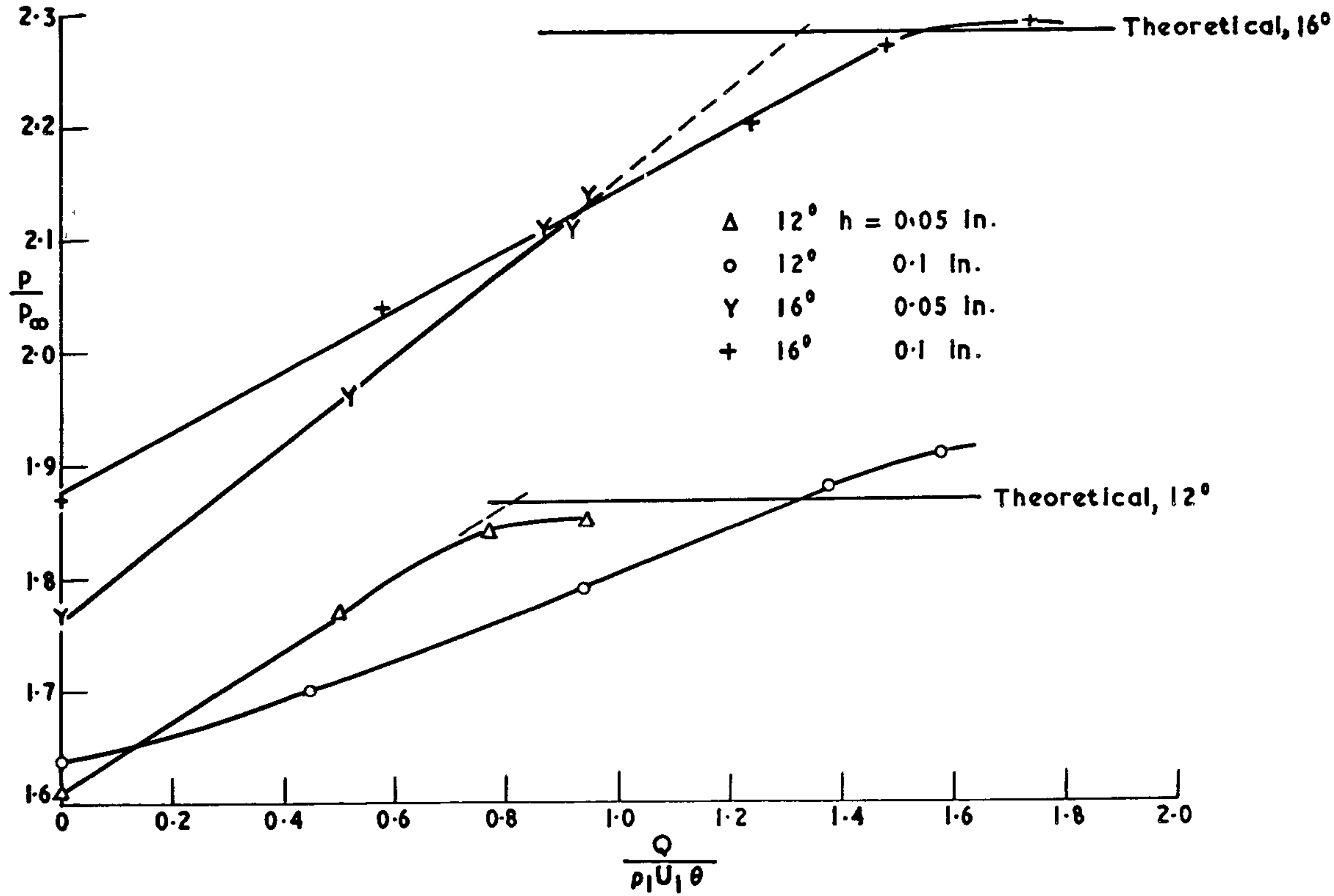
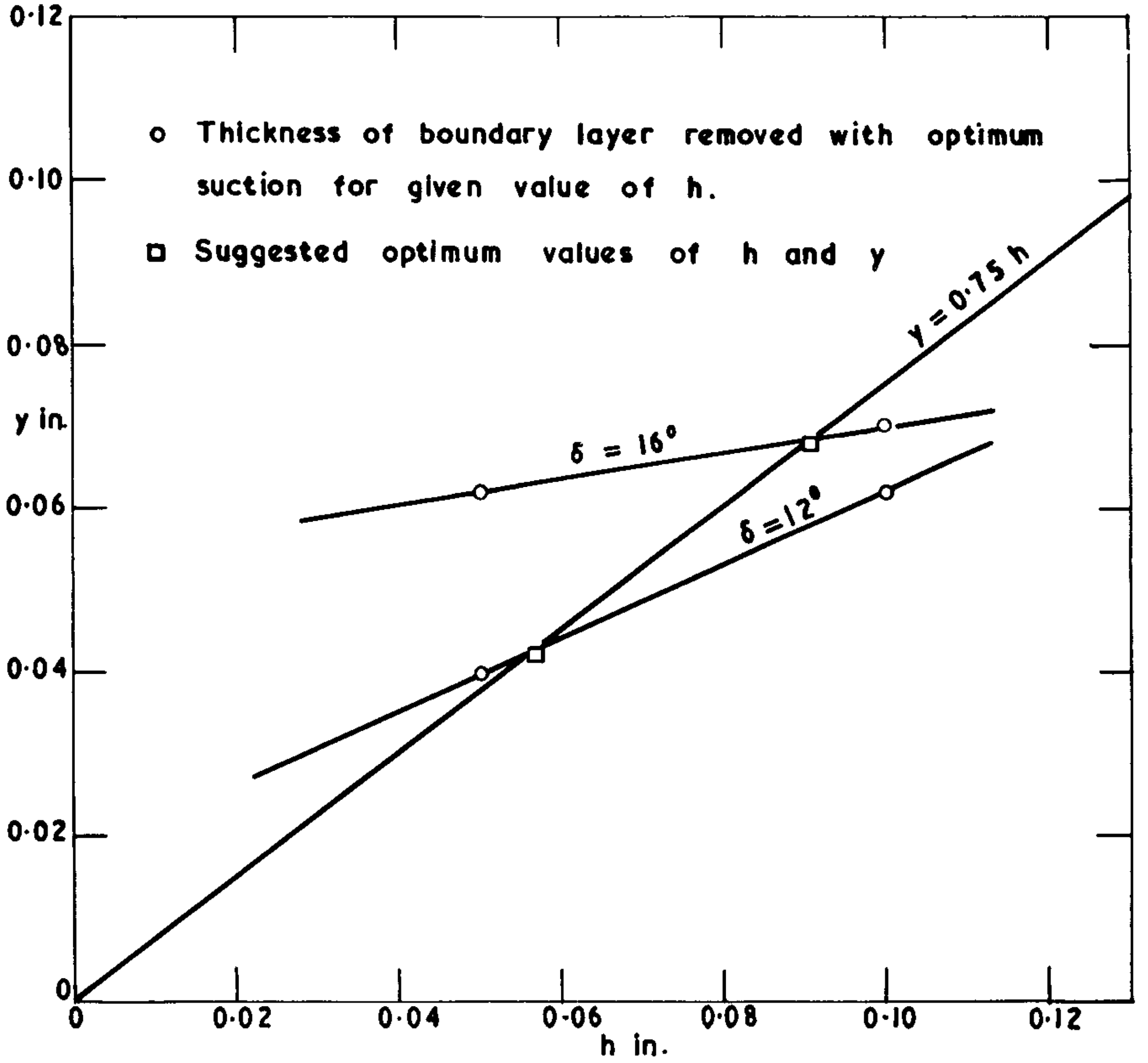


FIG. 4

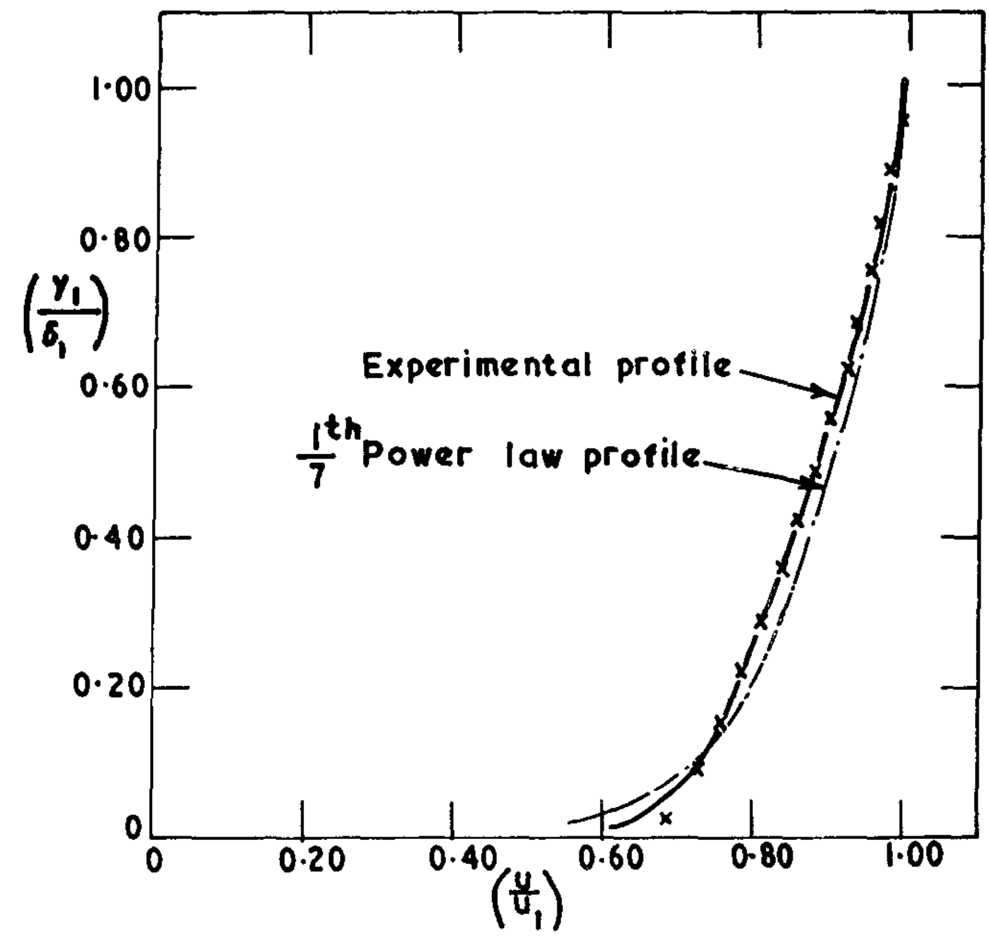
Effect of suction on pressure at first wedge hole

FIG. 5



Thickness of boundary layer removed with optimum suction for given value of h.
Suggested optimum values of h and y
y = 0·75 h
δ = 16°
δ = 12°
y in.
h in.
0
0·02
0·04
0·06
0·08
0·10
0·12

FIG. 6a



Non-dimensional boundary layer velocity profile (flat plate)

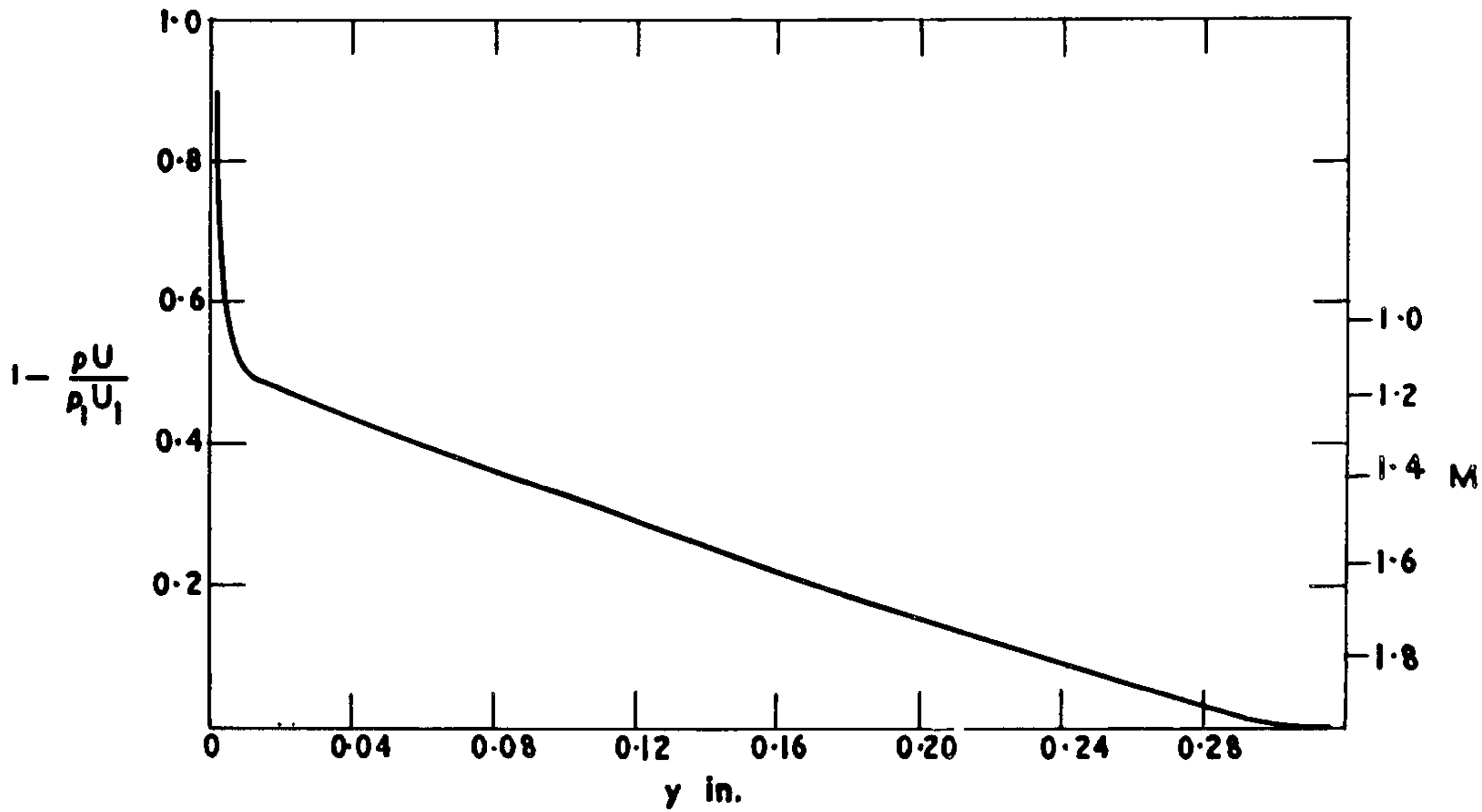
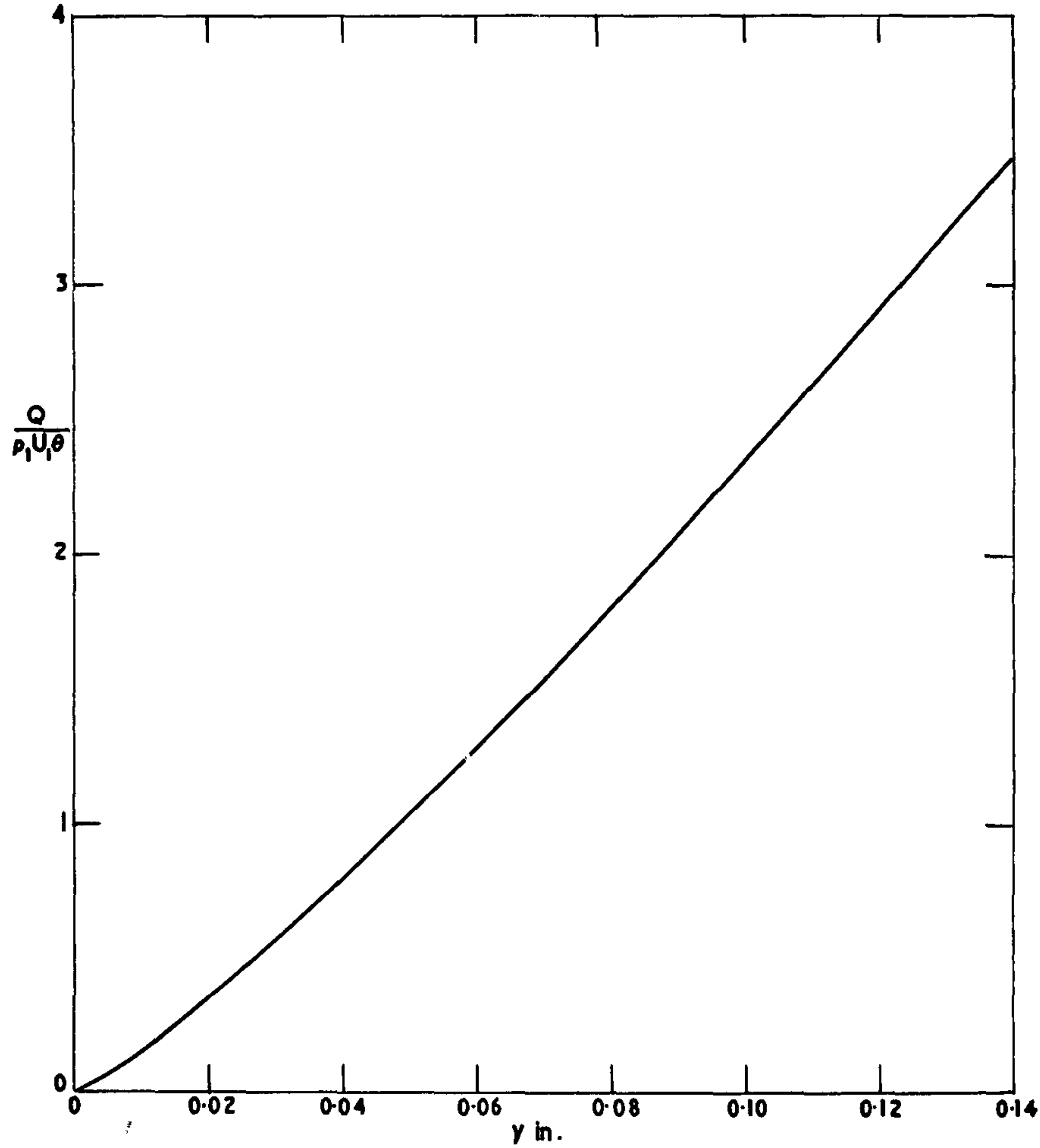


FIG. 6b

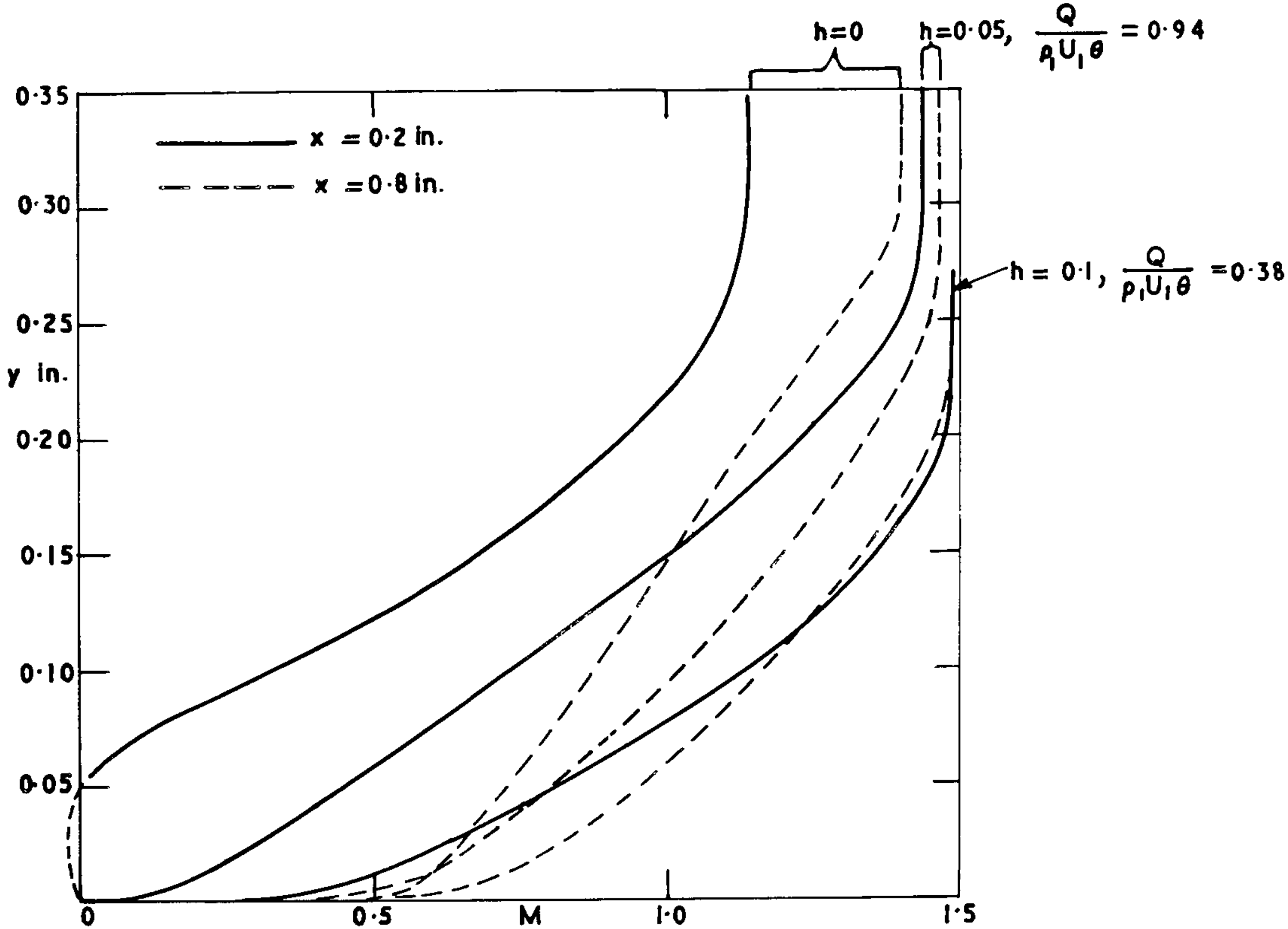
Displacement and Mach number profile

FIG.6 c



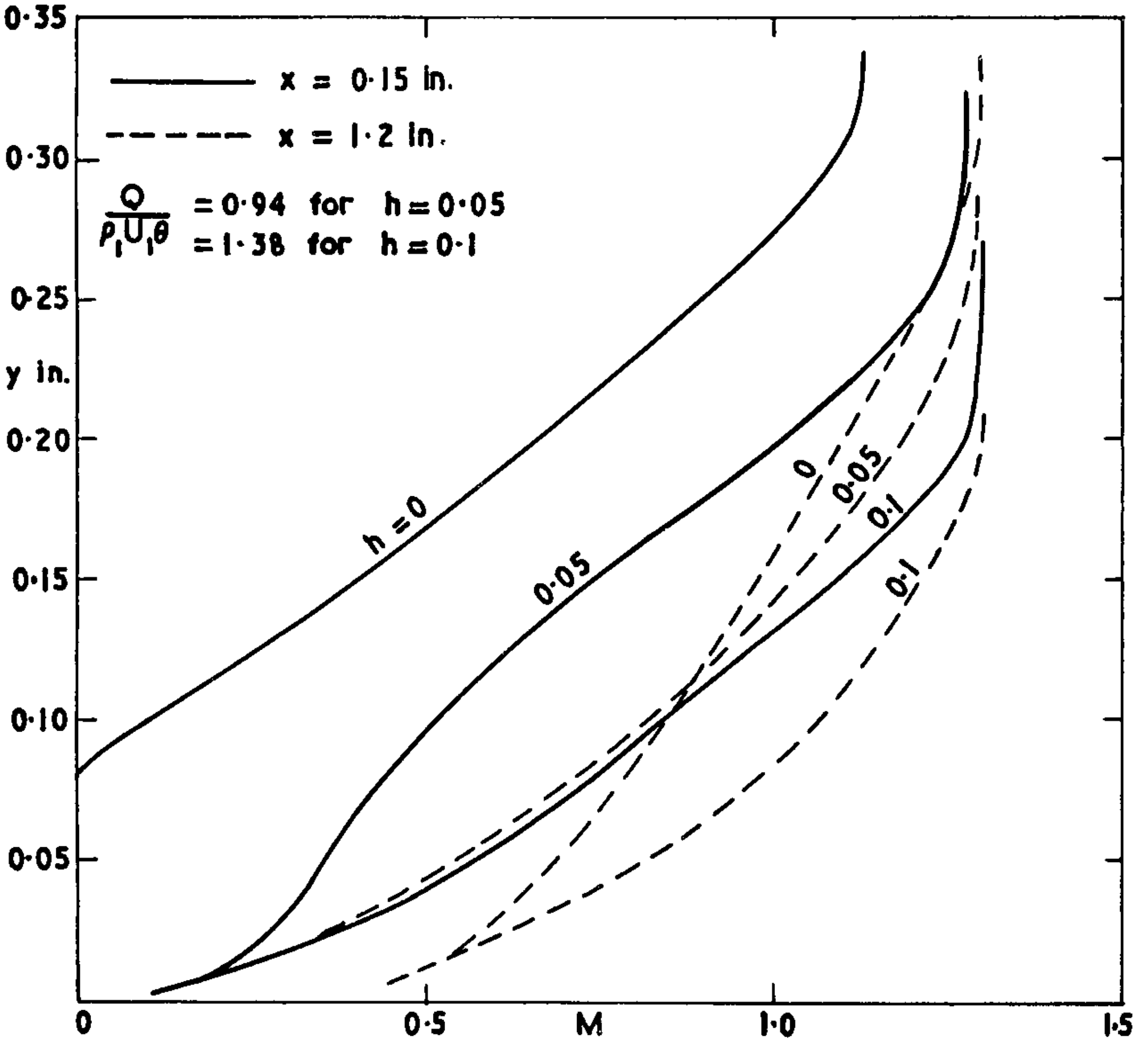
Mass flow in boundary layer

FIG. 7 a



Measured boundary layer profiles on surface of 12° wedge.

FIG. 7 b



Boundary layer profiles on surface of 16° wedge

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Tanner, L.H.
Gai, S.L.

EFFECTS OF SUCTION ON THE INTERACTION BETWEEN SHOCK WAVE AND BOUNDARY LAYER AT A COMPRESSION CORNER

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