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Tests at M= 1.82 on an Engine Installation with Boundary-Layer Diverter for a Slender Gothic Wing

by

R. T. Griffiths, B.Sc.

Aerodynamics Dept., R.A.E., Bedford

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TESTS AT M = 1·82 ON AN ENGINE INSTALLATION WITH BOUNDARY-LAYER DIVERTER FOR A SLENDER GOTHIC WING

by

R. T. Griffiths, B.Sc.
Aerodynamics Dept., R.A.E., Bedford

FOREWORD

by
E. L. Goldsmith

This Paper should be read in conjunction with A.R.C.26912 (C.P. 866) The absolute values of the results obtained do not have a great significance. Their main interest lies in their relationship to those of C.P. 866. In these two Papers there is effectively an aerodynamic performance comparison between two philosophies of engine installation. In C.P. 866 the objective was to bury the excess area between intake entry and engine maximum cross section in the local wing structure and hence produce (within the limitations of a fixed geometry intake with all-external compression) a low drag installation. In the tests described in the present Paper no attempt was made similarly to bury this excess area when the engines were mounted four in a square per nacelle and hence it was realised that the installation would lead to high wave drag. The pressure field from the cowl forebody was then used to interfere favourably (in a lift and drag sense) with the undersurface of the wing in an effort to offset this high cowl wave drag. This philosophy was particularly accentuated in this model by the choice of short length for both forebody and afterbody of the nacelle. The particular balance desired and achieved when using pressure fields, that produce drag, also to produce lift, is a delicate one (see R & M 3528) and the results of this investigation show that this particular design was probably quite far from the optimum arrangement.

* Replaces R.A.E. Technical Report 67203 - A.R.C. 30107

SUMMARY

R.A.E. Technical Note Aero 2982 reported tests made at M = 1.82 on an engine installation representing a design in which four engines were mounted side by side in each of two nacelles, one on each half of a slender gothic wing, with the engines partly buried in the wing. The present Paper gives comparative results for an installation incorporating a boundary layer diverter; this led to a 2 x 2 square array of engines in each nacelle, with intakes having vertical wedge compression surface. In this case the nacelles were as short as possible and no attempt was made at partial burying in the wing.

With the particular design of boundary layer diverter used, and because of the short nacelles, the nacelle drag was high and the intake pressure recovery was lower than expected. There were small and predictable effects on lift and pitching moment.

CONTENTS

1 INTRODUCTION

A series of tests on various engine installations suitable for slender wings has been made in the 3ft × 3ft wind tunnel at the R.A.E., Bedford.

The first of the series was a "letter box" intake with four engines arranged side by side in each of two nacelles and with the wing boundary layer ducted beneath the engines: the results of these tests are given in Ref.1.

This Paper deals with a configuration, where the wing boundary layer was diverted round the nacelle instead of being ducted beneath it. Again, two separate nacelles at some distance from the wing centre line were used, and the difficulties in incorporating a boundary layer diverter of reasonable angle into an installation with four engines resulted in an installation in which each nacelle had engines arranged in two rows of two, one pair above the other. This installation was designed to be the minimum length thought possible and no attempt was made to integrate the installation with the wing.

The more important geometrical details of the inlet have been kept the same as that of Ref.1, and again the upper surface of the nacelle was made parallel with the wing surface. The inlet area was determined by the mass flow requirements for cruise and this was considerably smaller than the frontal projected area of the nacelle. A vertical wedge compression surface was chosen on the grounds that it would give a slightly shorter intake and probably a more even velocity distribution at the plane of the engine faces.

As no provision was made for burying the engines in the wing, the projected frontal area was about 8% greater than that of the letter box intakes (with the whole of the boundary layer at zero incidence diverted). On the other hand the overall length of the nacelles was reduced by 23% since with the letter box arrangement the engines had to be placed further from the trailing edge, where the wing was thick enough to allow for partial burying of the engines.

Some favourable nacelle-wing interference effects were expected with the nacelles on the lower surface of the wing as the high pressure field behind the intake shock system would be an additional source of lift although this would be counterbalanced to some extent by the lower pressure on the boat tail near the trailing edge. As in Ref.1, the tests were made at both positive and negative incidences so as to give results for upper or lower surface installations.

2 DESCRIPTION OF MODEL

The wing used for the tests was an uncambered gothic wing of aspect ratio 0.75, the same as for the tests reported in Ref.1. Full details of this wing are given in Ref.2. Details of the engine installation are given in the table and in Figs.1 to 6. It was designed to accommodate eight engines of gross diameter 4.4 ft, taking the wing centre line chord as 200 ft. These dimensions gave rise to the minimum nacelle length of 42 ft. The wedge semi angle was 12° with $\theta_{WL} = 46.6^{\circ}$ ($M_{WL} = 1.8$) and 3% internal contraction of the ducts was allowed followed by a length of constant cross sectional area, before diffusing gradually to an exit area of 130% capture area (Fig.5). Mass flow ratio was varied by placing plugs in the duct exits. The boundary layer diverter had an included angle of 52° and its vertex was 2.5 ft (full scale) behind the vertex of the intake wedge. Different values of the boundary layer diverter height were obtained by shims between the nacelles and the wing.

Conditions at the entry plane were assessed from a single pitot rake at the wedge vertex position with the nacelles removed. Static pressures were measured by a hole in the opposite surface of the wing at corresponding negative incidences to avoid interference from the pitot rake. Intake pressure recoveries were measured by pitot rakes behind the nacelles (Fig.7); these rakes also measured the base pressures over the flow control plugs.

Bands of distributed roughness were applied to the leading edge of the wing (Fig.2) to ensure that the boundary layer on the model was turbulent. They consisted of a mixture of carborundum grains and thin aluminium paint applied so that closely spaced individual grains projected from a paint base about 0.001 inch thick; grade 100 carborundum (particle size about 0.007 inch) was used. The sharp leading edge itself was left clear of roughness.

Normal force, pitching moment and axial force were measured by a strain gauge balance and, after correction for balance interaction, were reduced to the usual coefficient forms. The pitching moment coefficients were referred to the quarter chord point of the mean aerodynamic chord.

The drag values quoted are the external drag of the model where:-

$$\text{external drag} = \text{measured drag} - \text{base drag} - \text{internal drag} \quad .$$

The methods of obtaining the base and internal drags are fully described in Ref.1, together with comments on the accuracy of measurement.

From a consideration of the possible sources of error, together with a study of repeat readings it is believed that the accuracy of the results from this balance is as follows:-

$$
\begin{array}{llll}
C_L & \pm 0.003 & & \\
C_m & \pm 0.0005 & & \\
C_D & \pm 0.0004 & \text{at} & C_L = 0 \\
 & \pm 0.001 & \text{at} & C_L = 0.3 \\
\alpha & \pm 0.05^\circ & . &
\end{array}
$$

These limits are overall values and the relative accuracy of results from consecutive incidences is probably better.

3 TESTS

All tests were made at M = 1.82 through an incidence range of -10° to $+10^\circ$ in 2° steps. The Reynolds number was 2.0×10^6 based on the aerodynamic mean chord of 15 inches. This Reynolds number corresponded to total pressure and temperature of 11.58 inches of mercury and 25°C. Tests were made varying the mass flow with a fixed boundary layer diverter height, and then at reduced diverter heights for a fixed value of the mass flow. Finally the wing was tested without the nacelles and some flow visualization tests were made using the oil flow technique.

These tests were made and the preliminary draft report was written in 1961.

For the incidence sign convention the nacelles were assumed to be on the upper surface of the wing.

4 DISCUSSION OF RESULTS

The reduction of data is described at length in Ref.1 and will not be repeated here.

4.1 Entry plane survey

The entry plane survey was made over a wide range of incidence (-17° to 17°) to compare the results with those already obtained at different positions on the wing surface[3]. The variation of boundary layer thickness δ with angle of incidence is shown in Fig.8. There was a rapid thinning of the boundary layer with incidence for $\alpha > 6^\circ$ caused by the inward movement of the wing vortex attachment line, which results in a shortened run of boundary layer on the wing surface, until at $\alpha = 14^\circ$ only one pitot tube remained inside the boundary layer and the value of δ could not be determined (but $\delta < 0.06$ inch for $\alpha > 14^\circ$. The maximum value of δ was 0.22 inch at $\alpha = -5^\circ$ and this decreased gradually with negative incidence to $\delta = 0.17$ inch at $\alpha = -17^\circ$ owing to the reduction in local Mach number.

The variation of the Mach number just outside the boundary layer with incidence is shown in Fig.9. As before[1] there is a greater mean slope at negative incidences than positive; the values being about 0.0230 and 0.0175 per degree respectively, which are both about 0.006 greater than those previously obtained. Taking cruising incidence to be 4° ($C_L = 0.1$), the entry plane Mach number is 1.95 for intakes on the upper surface of the wing and 1.83 for the lower surface.

4.2 Variation of intake performance with incidence and mass flow

A boundary layer diverter height of 0.225 inch, just greater than the maximum thickness of the boundary layer, was used for this test. The value of h/δ depends on the incidence considered.

Fig.10 shows typical pressure distributions at the nacelle exits for subcritical and supercritical flow. In both cases the distribution is symmetrical but in the supercritical case the distribution is poor due to shock wave and boundary layer interaction effects at the diffuser walls. The variation of pressure recovery with mass flow for different angles of incidence is shown in Fig.11. The values of A_∞/A_{en} for full mass flow are greater than unity although the discrepancy reduces with increasing incidence. This has been found to be characteristic of measurements when the flow at the measuring station is non-uniform. Comparison of the exit pressure distributions (Fig.10) with (Fig.19) of Ref.1 shows that the flow is worse for the present installation at subcritical conditions. As the intake geometry is basically the same, the worse distribution in the present tests is probably attributable to the lack of a settling length of approximately constant area before the measuring section. From these curves values of the peak pressure recovery for different incidences have been plotted (Fig.12) and compared with the theoretical estimates. The estimated losses consist almost entirely of shock losses and skin friction losses: the external losses are caused only by the low wave (about ½% off pressure recovery), since all the boundary layer has been diverted and the wing leading edge vortices are clear of the intakes in the range of incidence considered. An empirical formula[4] by Seddon and Haverty shows that for this intake the losses from interaction between the boundary layer on the wedge compression surface and the normal shock are expected to be small because of the length of constant cross sectional area at the throat of the duct.

The experimental results (Fig.12) show that the pressure recovery is appreciably less than estimated and the variation with incidence is different. The results of Ref.1 are also plotted in (Fig.12)*; they show the same deficiency (below estimate) at high incidence, but the deficiency remains almost constant with decrease of incidence instead of increasing as in the present tests. Examination of the oil flow patterns obtained (Fig.13) indicates that the shock from the boundary layer diverter and/or the intake compression wedge is sufficiently strong to give a marked forward effect in the boundary layer flow. This could not be confirmed from schlieren photos as this region is obscured by the sting fairing. The boundary layer would therefore become appreciably thicker than the value measured on the wing without intake and so the intake would ingest some boundary layer air. This hypothesis is confirmed as the losses are similar for both intakes at high incidence where the wing boundary layer is artifically thinned by the wing vortex, and there is a relative decrease in the unaccounted losses at very low incidences where the wing boundary layer again begins to thin.

It should be remembered that the pressure recovery at the engine compressor face would be somewhat greater than the values shown since the duct losses would be less at full scale.

The drag increment at zero incidence caused by adding the nacelles to the wing is high (Fig.14), being 40% of the wing drag when the intakes are running at full mass flow. Theoretical estimates based on two dimensional flow show that this increase is accounted for by the skin friction and wave drag of the nacelle (Fig.14). Thus it would appear that the drag of the diverter system is small or at least comparable with the wing-nacelle interference effects.

As mass flow is reduced,the drag increment increases due to fore spillage.

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* The theoretical values of pressure recovery are practically the same for both intakes.

There is little variation of the installation drag at positive incidence, but a steady decrease occurs as the incidence becomes increasingly negative.

Values of the lift/drag ratio for the nacelles on the upper and lower wing surface are compared with those for the basic wing in Fig.16. Also included is the results for the letter box intakes of Ref.1. The vertical wedge intakes on the upper surface of the wing give a maximum lift/drag ratio of 4.71 which is well below the value of 5.58 for the wing alone. Placing the nacelles on the lower surface of the wing increases the maximum lift drag ratio to 4.82 while the letter box intakes give a maximum lift/drag ratio of 5.34.

4.3 Variation of pressure recovery and drag with boundary layer diverter height

The boundary layer diverter height was reduced progressively from the value used for the test reported above ($h/\delta = 1.11$ at $\alpha = 0$) to values of $h/\delta = 0.97$, 0.85 and 0.71. The resultant values of pressure recovery and drag increment from the nacelles are plotted in Fig.17 for a value of A_∞/A_{en} of approximately 0.93.

Both the pressure recovery and installation drag decrease as the diverter height is decreased, a reduction in h/δ from 1.11 to 0.71 giving a 2% drop in pressure recovery and a reduction of 20% in installation drag or 5% in overall drag.

4.4 Lift and pitching moment

The variation of lift coefficient with angle of incidence is shown in Fig.18. The addition of the nacelles to the wing displaces the lift curve by about $\Delta C_L = -0.012$ at $\alpha = 0$ and there is only a small variation of ΔC_L with incidence. As in the results for the letter box intake[1] there is no noticeable effect from the variation of mass flow ratio or boundary layer diverter height.

The increment of pitching moment coefficient due to the intakes (Fig.19) is +0.0045 at zero incidence and decreases slightly with increase in lift. Again there was no noticeable effect from the variation of intake mass flow or boundary layer diverter height.

Assuming that these changes in C_L and C_m were mainly due to the interference fields from the intake side walls on the wing, the values of the increments were calculated for zero incidence and found to give good agreement with the measured values.

5 CONCLUSIONS

Wind tunnel tests at M = 1.82 on a model of a slender gothic wing incorporating minimum length nacelles with a boundary-layer diverter and no attempt at wing-nacelle integration have shown that:-

(1) With a boundary-layer diverter height of 1.11 times the local undisturbed boundary layer thickness the additional drag of the nacelles at zero incidence was large, being 40% of the wing drag.

(2) There was a reduction in nacelle drag with increasing incidence when the nacelles were mounted on the wing lower surface, but no variation when they were on the upper surface.

(3) It was not possible to obtain the drag of the boundary-layer diverter accurately. Simple two dimensional estimates indicated that most of the nacelle drag was accounted for by its wave and skin friction drag, however reducing the height of the boundary layer diverter caused a large (20%) reduction in measured nacelle drag.

(4) The intake pressure recovery was considerably lower than estimated and varied with incidence in a different way from that predicted. There are indications that this was caused by the shocks produced by the nacelle interacting with the wing boundary layer and thickening it, thus causing the intake to ingest some boundary layer air.

(5) Reducing the diverter height, caused only small further reductions in pressure recovery.

(6) The effect of the nacelles on lift and pitching moment was small and predictable.

Table

DETAILS OF MODEL

Wing

Root chord	20 inches
Span	10 inches
Area	133.3 sq inches
Volume	72 cub inches
Aspect ratio	0.75
Aerodynamic mean chord	15 inches
Thickness chord ratio	8.2%
Body diameter	1.35 inches
Cross section	Diamond
Planform given by	$\frac{y}{s} = \frac{x}{\tau_o}\left(2 - \frac{x}{\tau_o}\right)$

Centre line section given by

$$\frac{Z}{\tau_o} = 0.126 \frac{x}{\tau_o}\left(1 - \frac{x}{\tau_o}\right)\left\{2 - 2\frac{x}{\tau_o} + \left(\frac{x}{\tau_o}\right)^2\right\}$$

Intakes

Position of wedge leading edge	$\frac{x}{\tau_o} = 0.79 \quad \frac{y}{s} = 0.38$
Length	4.2 inches
Height of upper surface from wing surface with h = 0.225 inch	1.01 inches
Maximum width of nacelle	1.11 inches
Wedge semi angle	12°
Inside lip angle	8°
Shock on lip Mach number	$M_{WL} = 1.80$
Internal contraction	3%
Capture area (both nacelles)	$A_{en} = 0.69$ sq inches
Diverter included angle	52°
Diverter vertex position	0.25" behind wedge leading edge

SYMBOLS

M	Mach number	
θ	shock wave angle	
α	angle of incidence	
δ	boundary layer thickness	
h	boundary layer diverter height	
A	area	
P	total pressure	
C_L	lift coefficient	
C_m	pitching moment coefficient	based on wing plan area and aerodynamic mean chord
C_D	drag coefficient	
C_o	centre line chord	
s	semi-span at trailing edge	

Suffices

$(\ )_{WL}$	shock wave on lip
$(\ )_{\infty}$	free stream
$(\ )_{en}$	entry plane
$(\ )_{ex}$	exit plane
$(\ )_{ext}$	external
$(\overline{\ \ })$	mean

REFERENCES

No.	Author	Title, etc.
1	R.T. Griffiths	Tests on an engine installation for a slender gothic wing at M = 1.82. A.R.C. C.P. 866 (1964)
2	L.C. Squire	An experimental investigation at supersonic speeds of the characteristics of two gothic wings, one plane and one cambered. A.R.C. R & M 3211 (1959)
3	R.T. Griffiths	Some boundary layer measurements on a slender gothic wing at supersonic speeds. R.A.E. Technical Note Aero 2675, (A.R.C. 22058) (1960)
4	J. Seddon L. Haverty	Unpublished R.A.E. work.

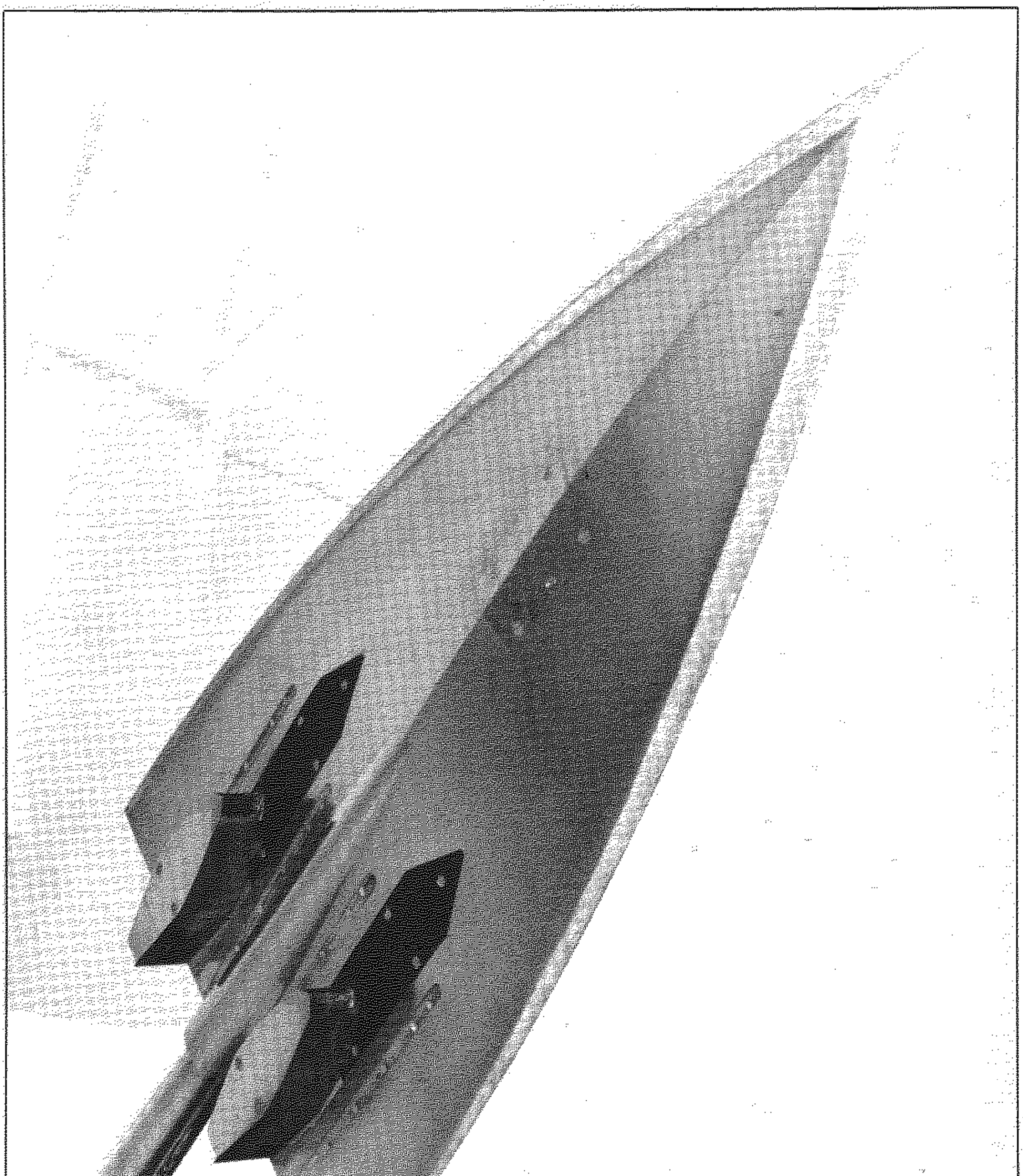


Fig.1 Model.

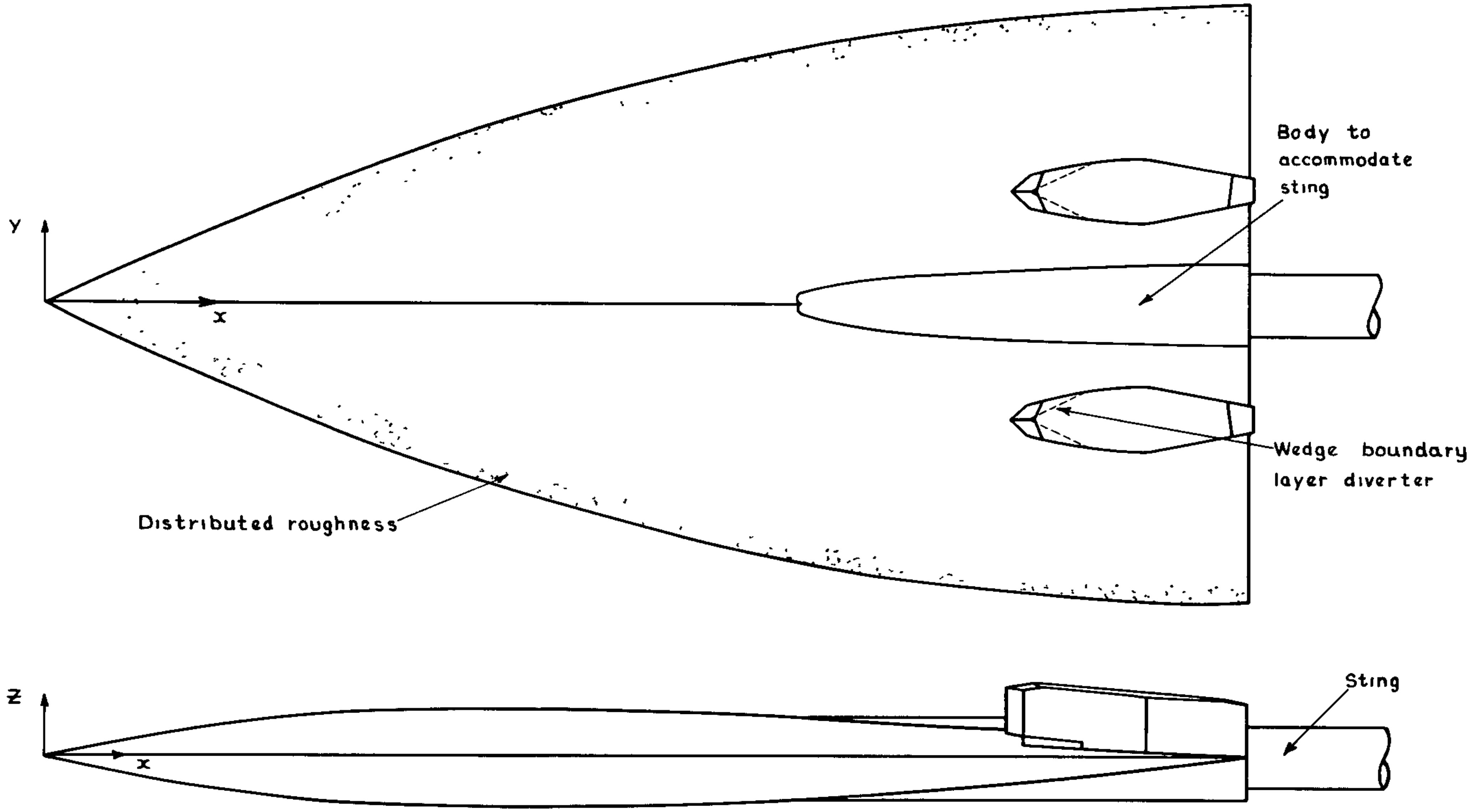


Fig. 2 Drawing of model

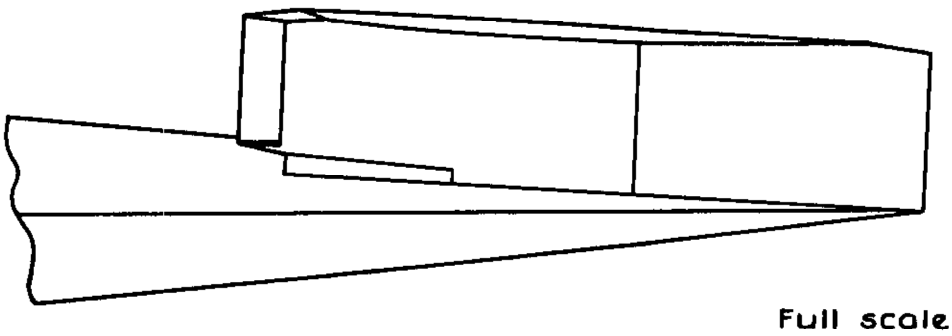


Fig.3 Side view of nacelle

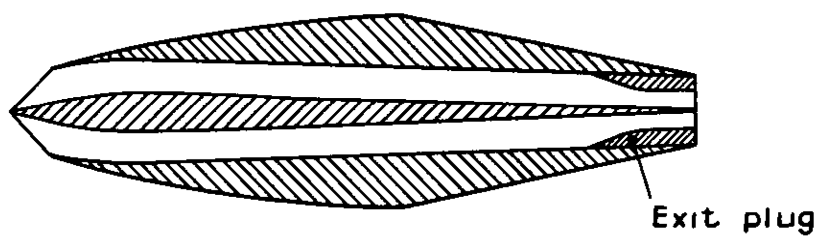


Fig.4 Sectional plan of nacelle

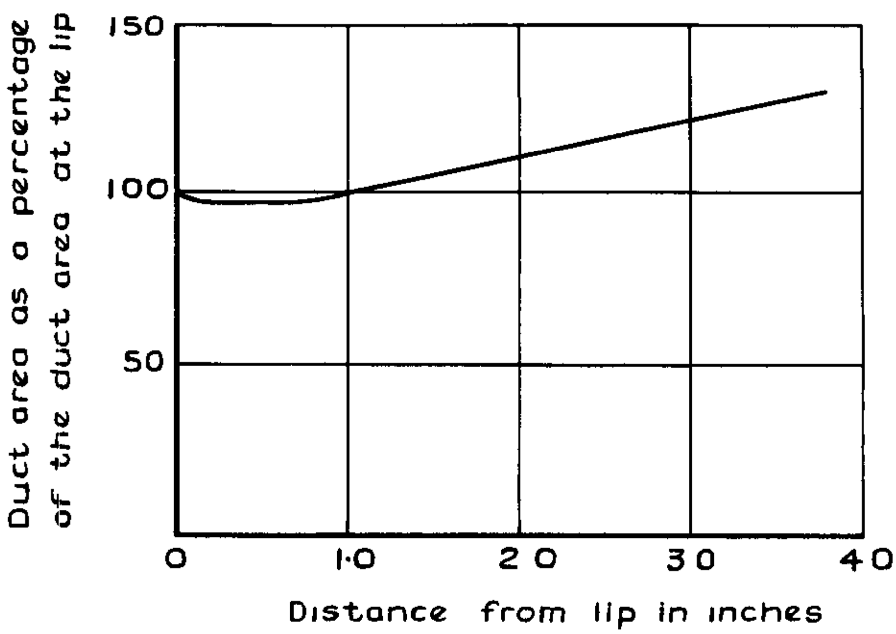


Fig.5 Duct area distribution

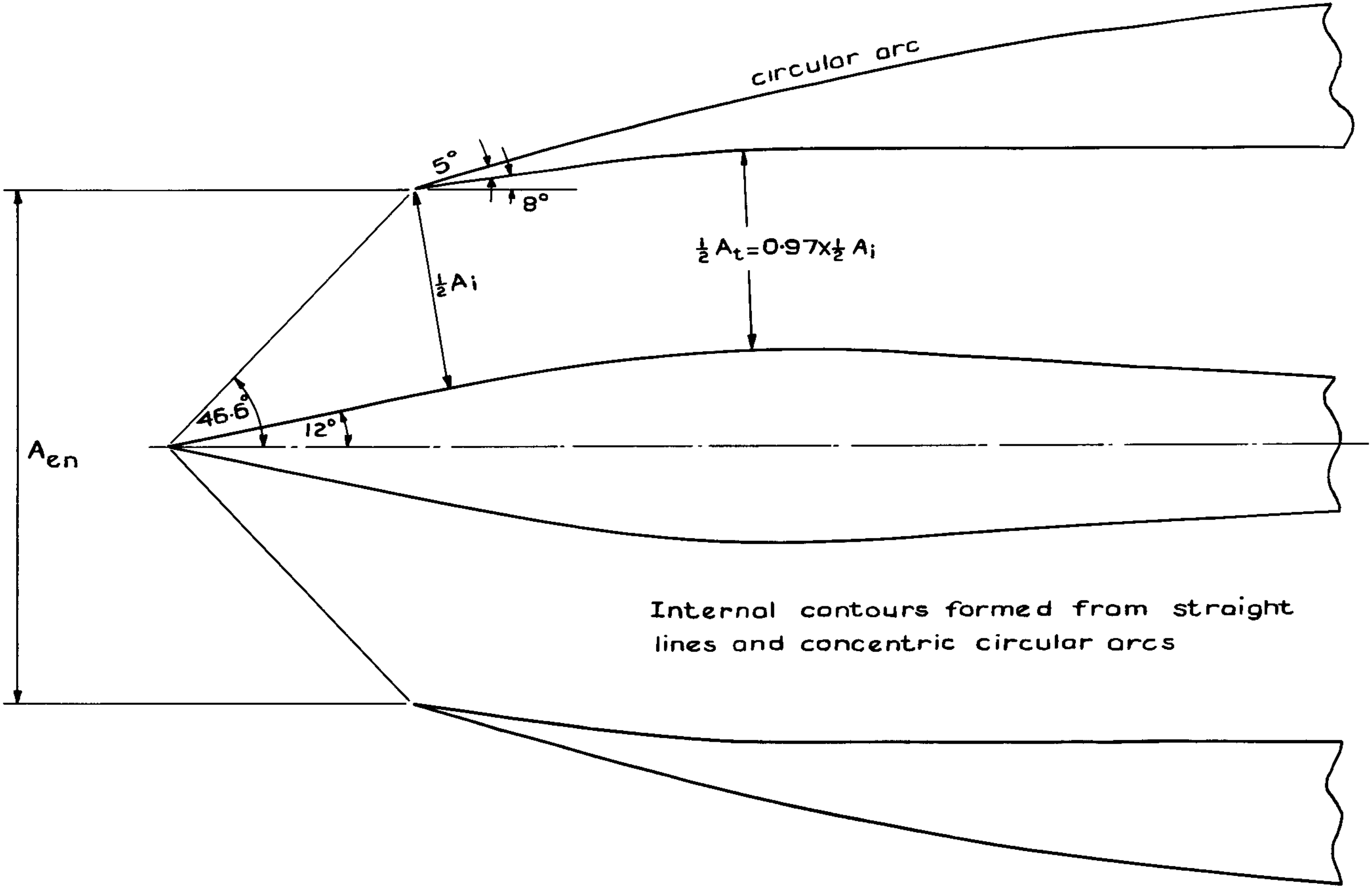


Fig.6 Intake geometry

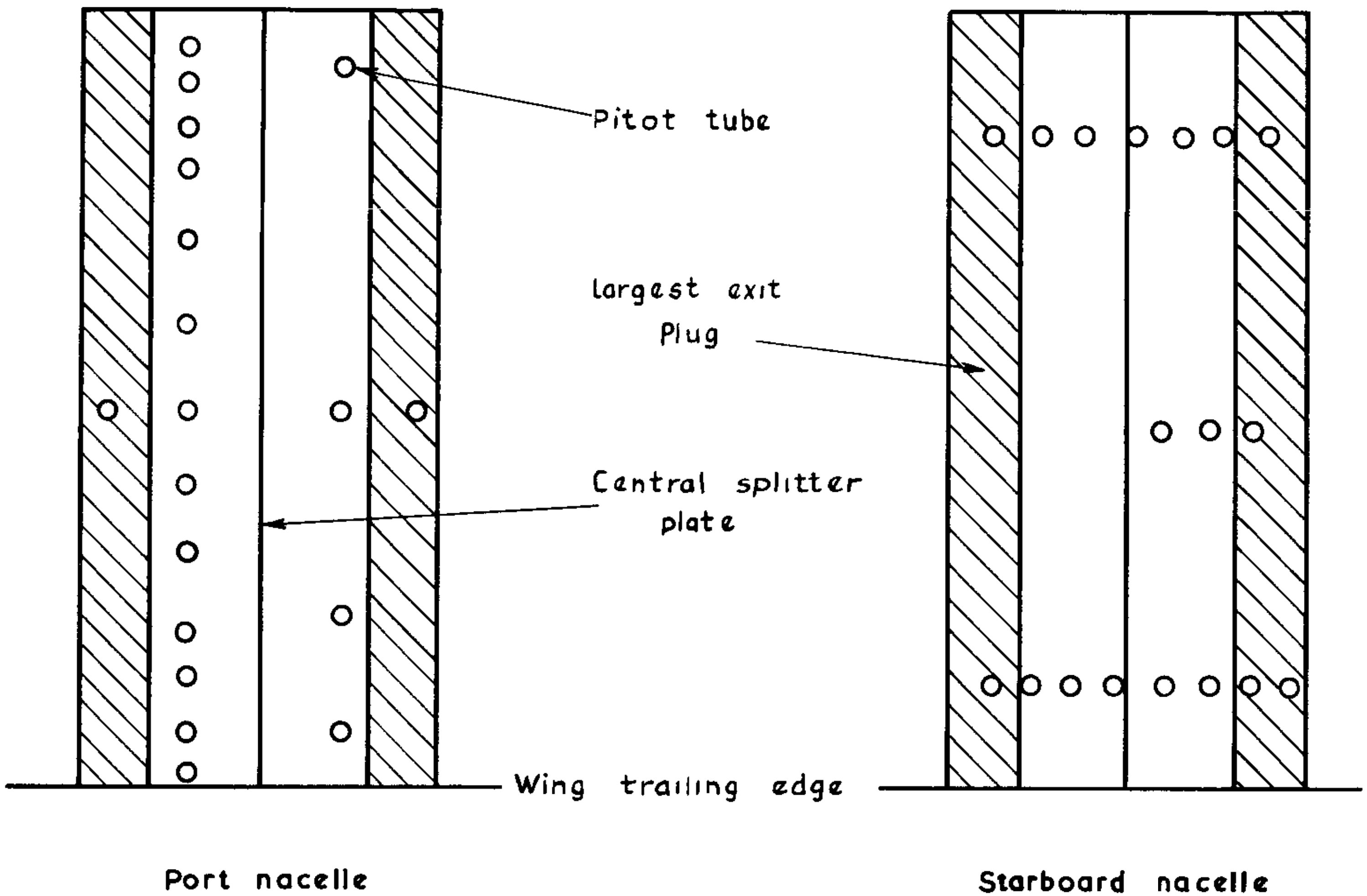


Fig. 7 Diagram showing the positions of the pitot tubes in the exit plane

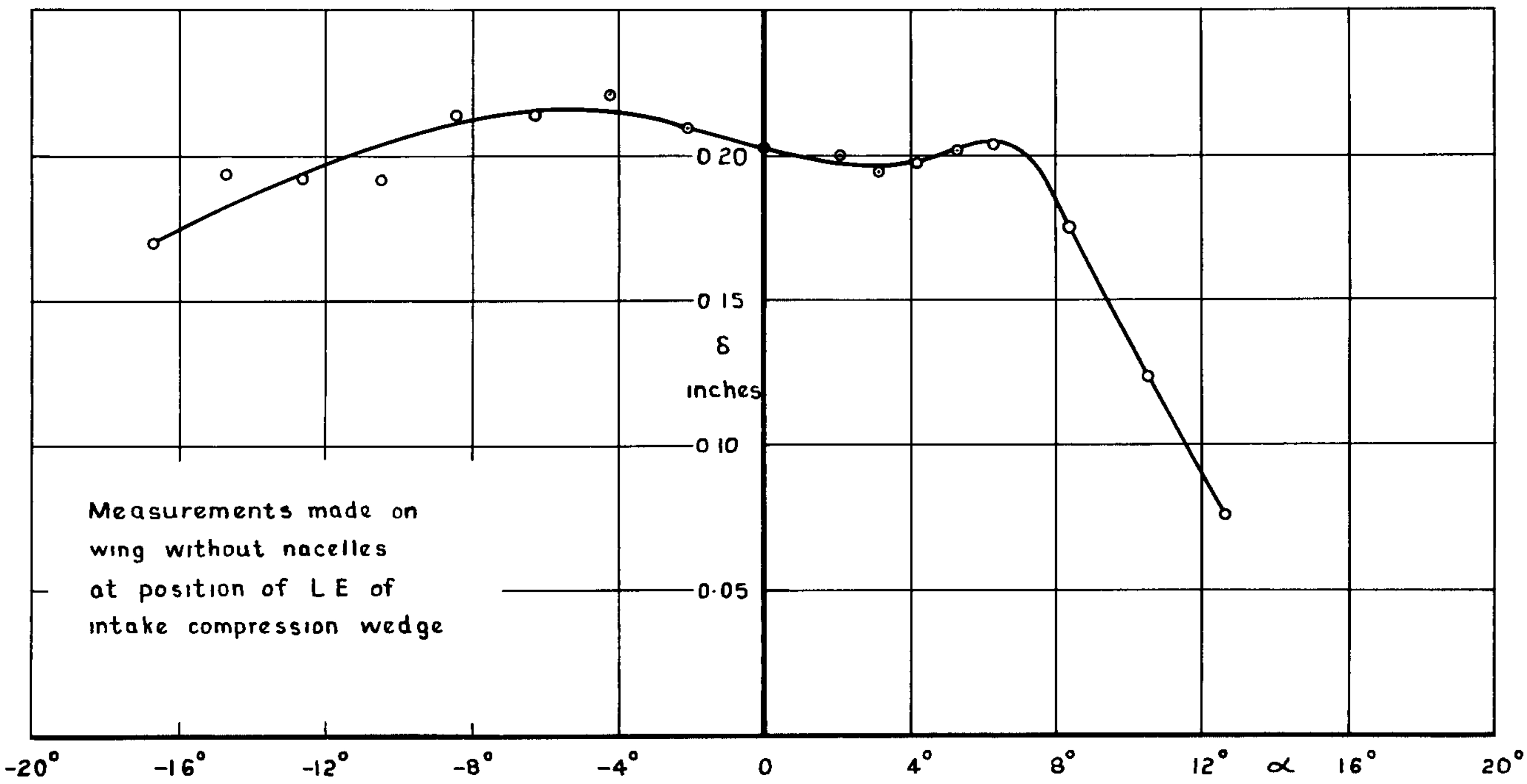


Fig. 8 Variation of boundary layer thickness with incidence

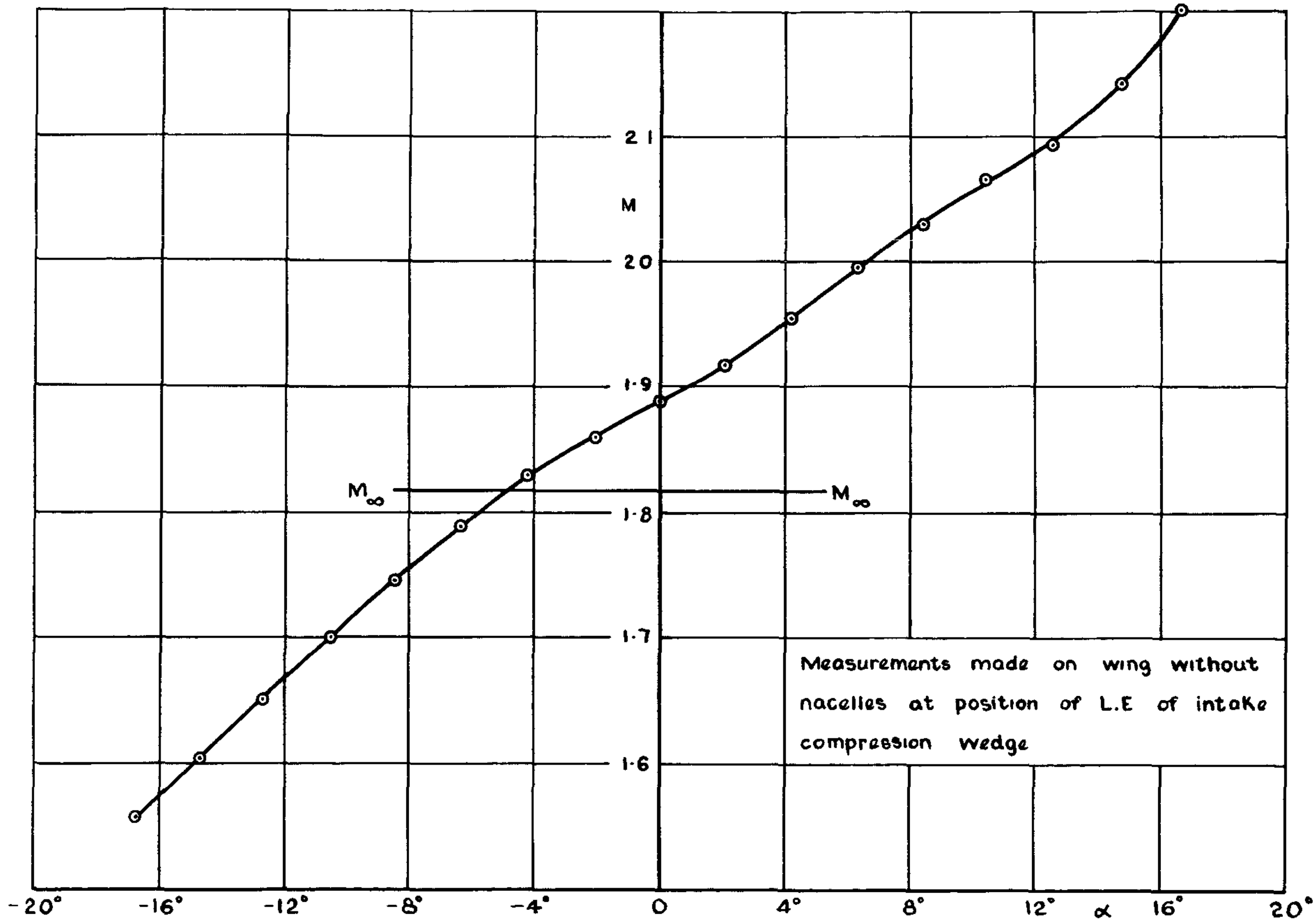


Fig.9 Variation of the mach number just outside the boundary layer with incidence

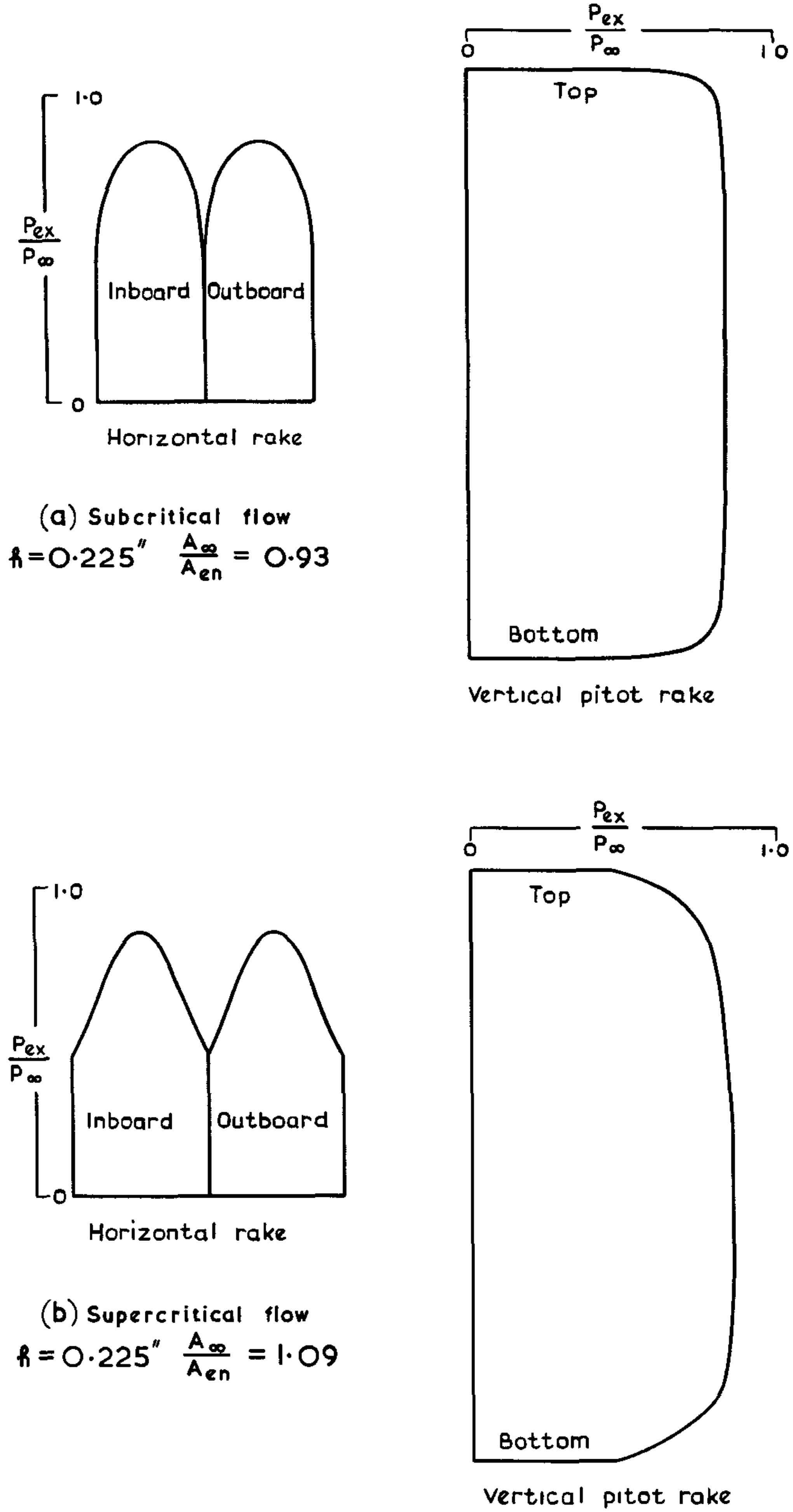


Fig.10 Typical exit plane total pressure distributions at zero incidence

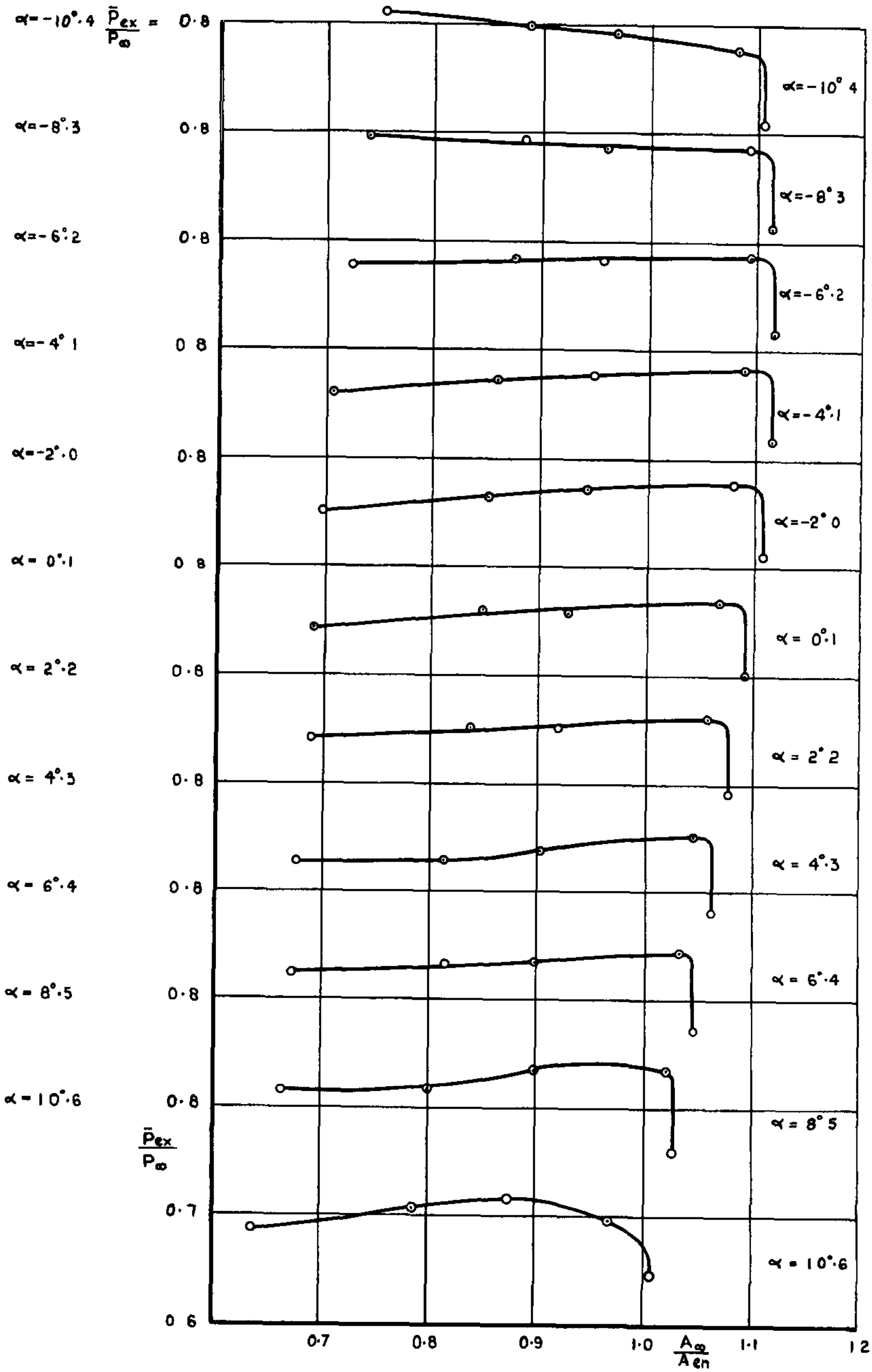


Fig. 11 Variation of pressure recovery with mass flow, h=0·225inch

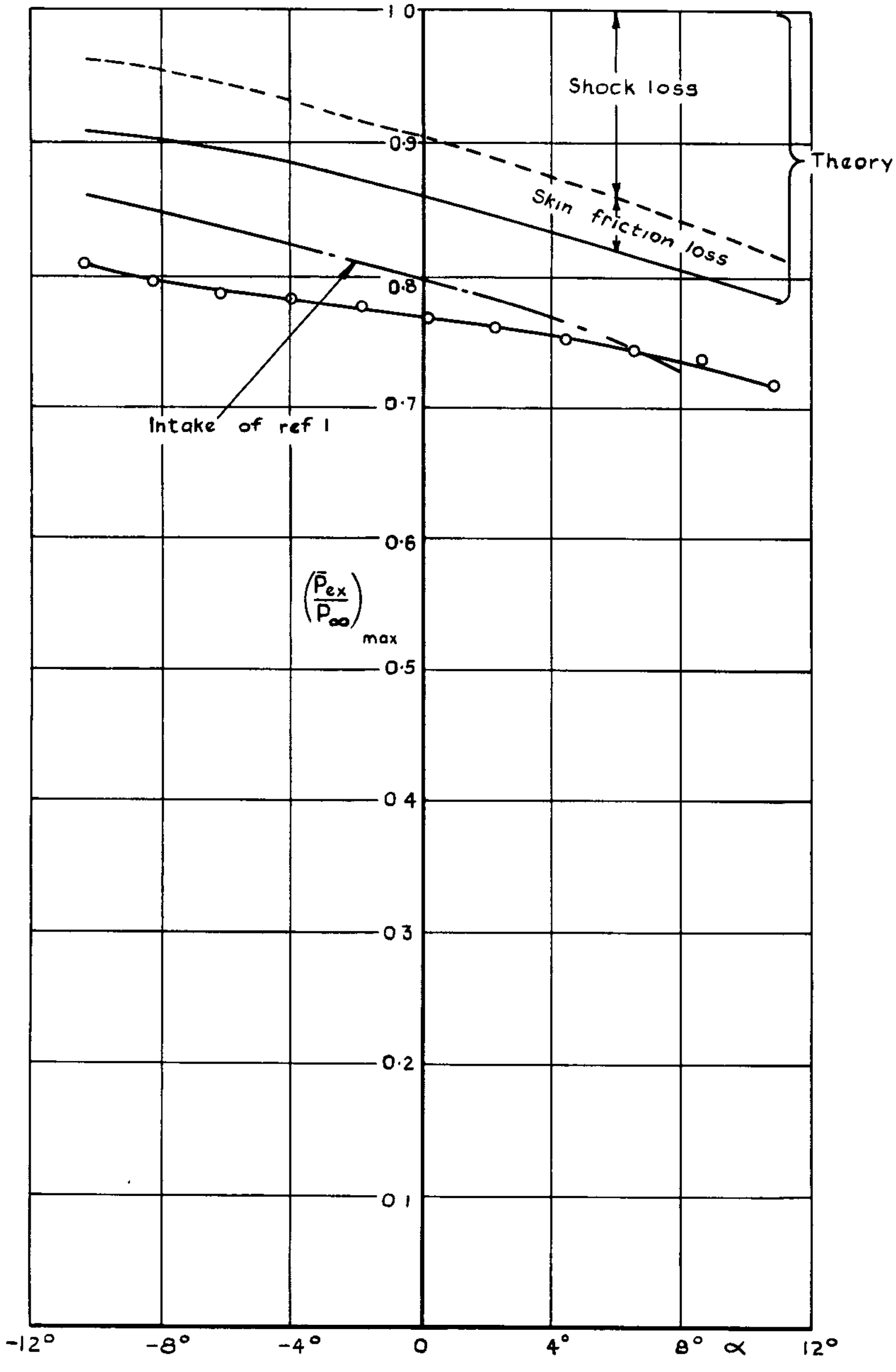
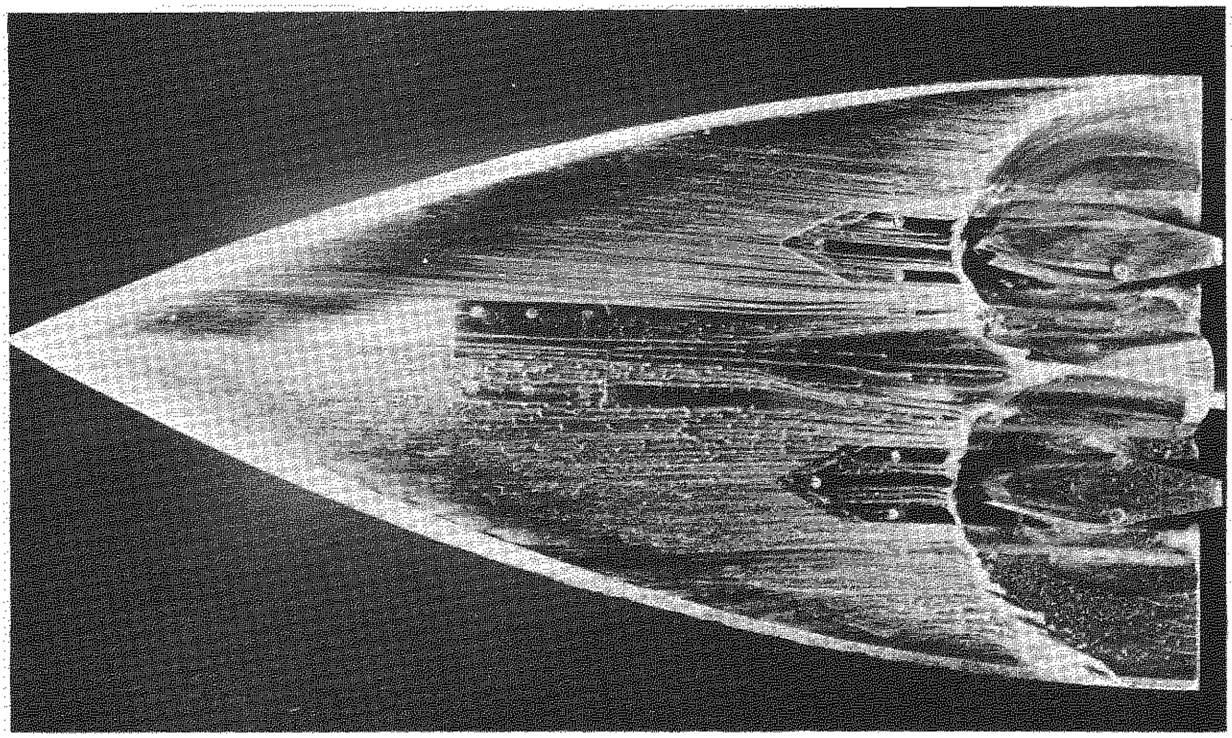
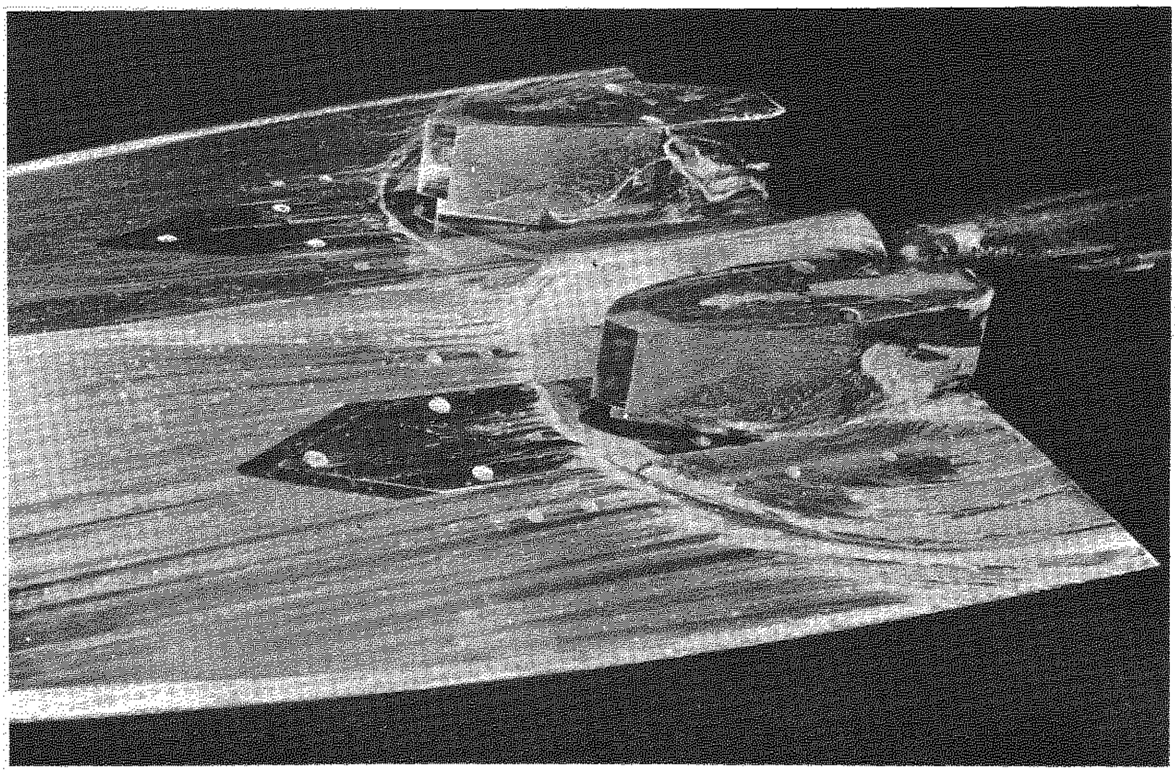


Fig. 12 Variation of maximum pressure recovery with incidence; $h = 0{\cdot}225$ inch

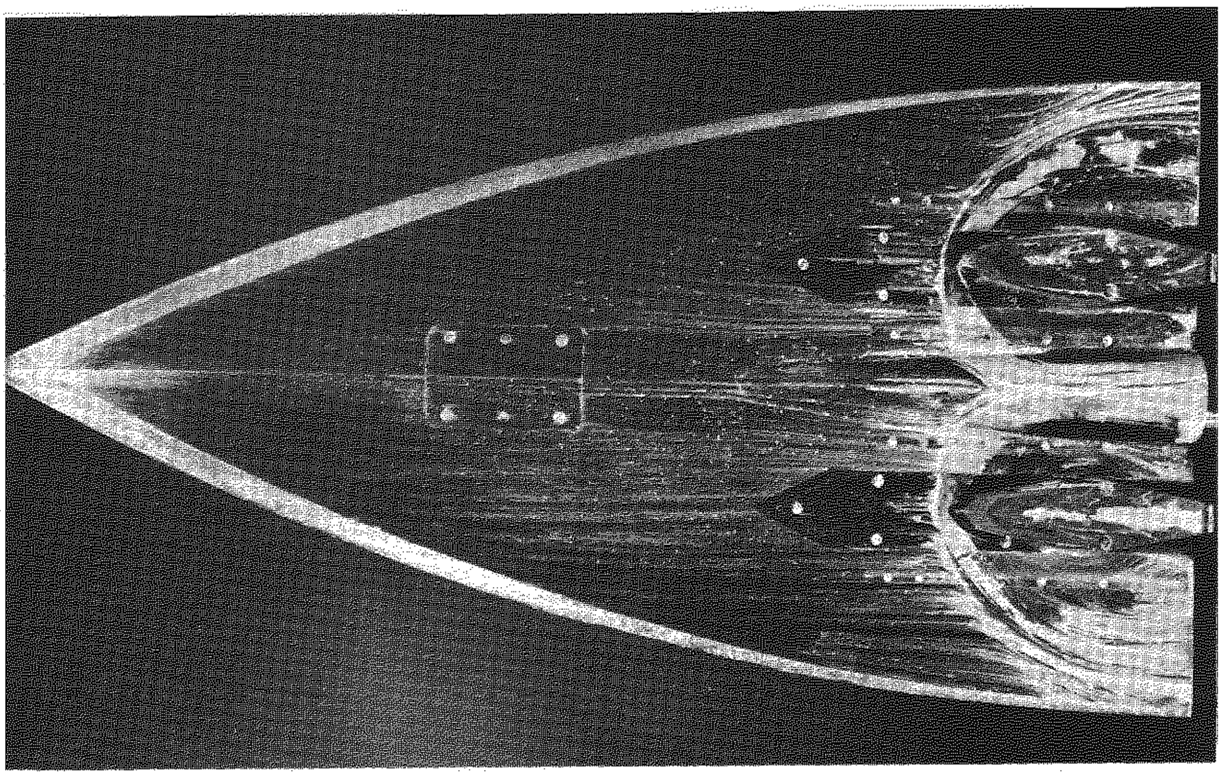


(a) $\alpha = -4^{\circ}.1$

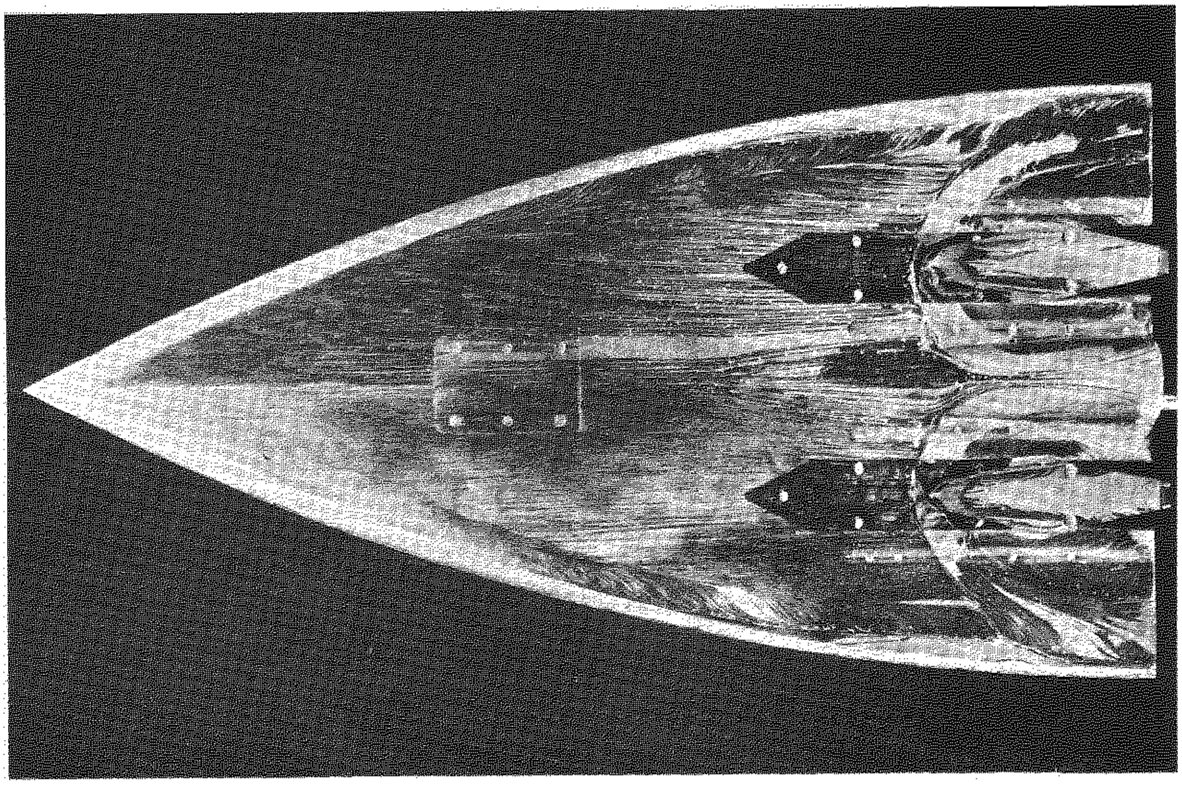


(b) $\alpha = -4^{\circ}.1$

Fig.13a&b Oil flow patterns at $\alpha = -4^{\circ}.1$



(c) $\alpha = 0^{\circ}.1$



(d) $\alpha = +4^{\circ}.3$

Fig.13c&d Oil flow patterns at $\alpha = 0^{\circ}\cdot1$ and $4^{\circ}\cdot3$

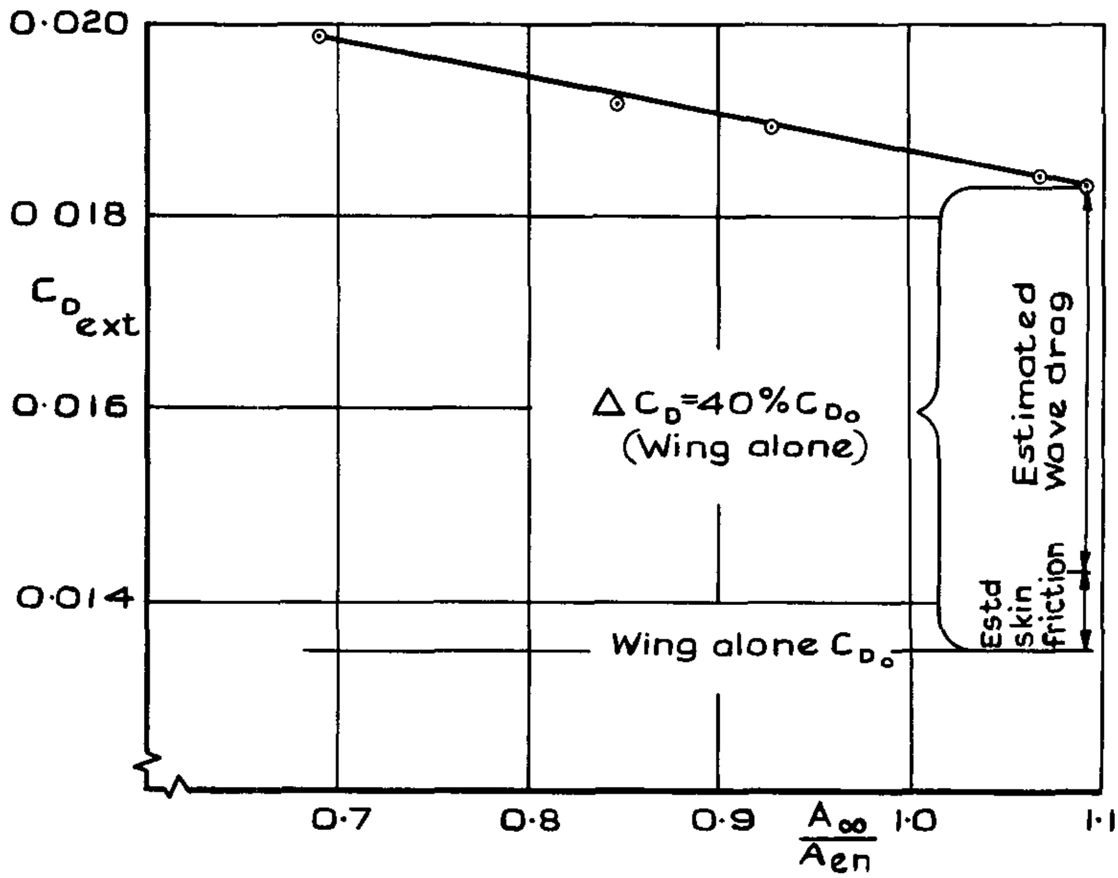


Fig.14 Variation of external drag with mass flow; $h = 0\cdot225$ inch, $\alpha = 0$

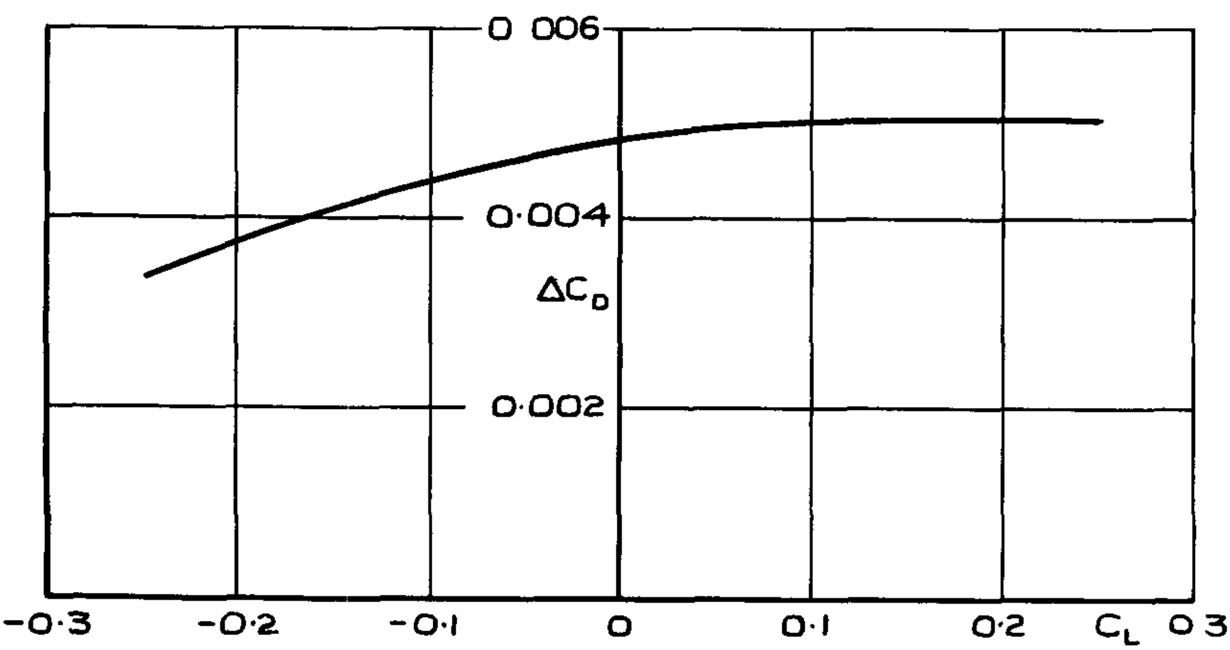


Fig.15 Variation of ΔC_D with lift coefficient for $h = 0\cdot225$ inch (full mass flow)

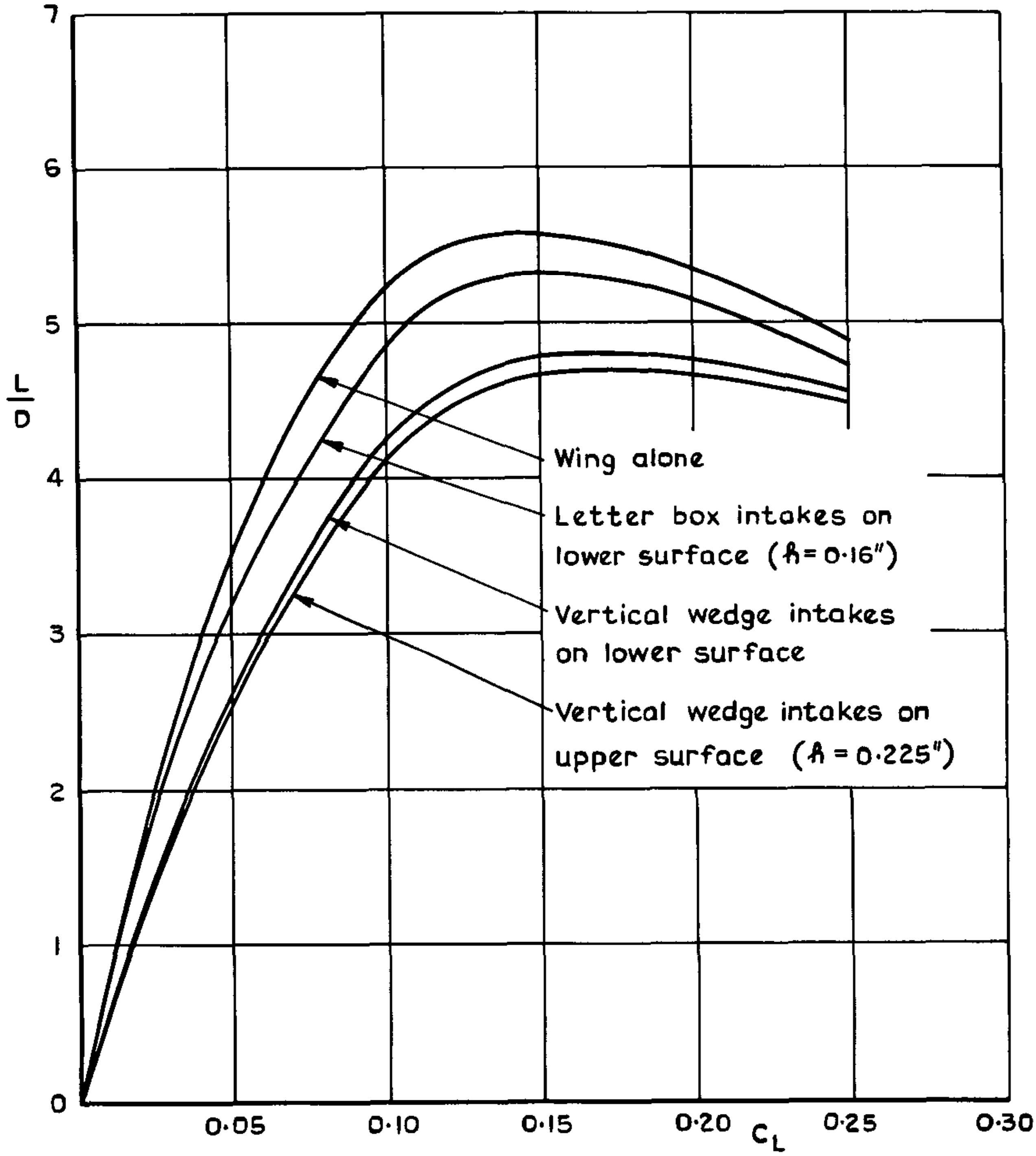


Fig. 16 Variation of lift/drag ratio with lift coefficient

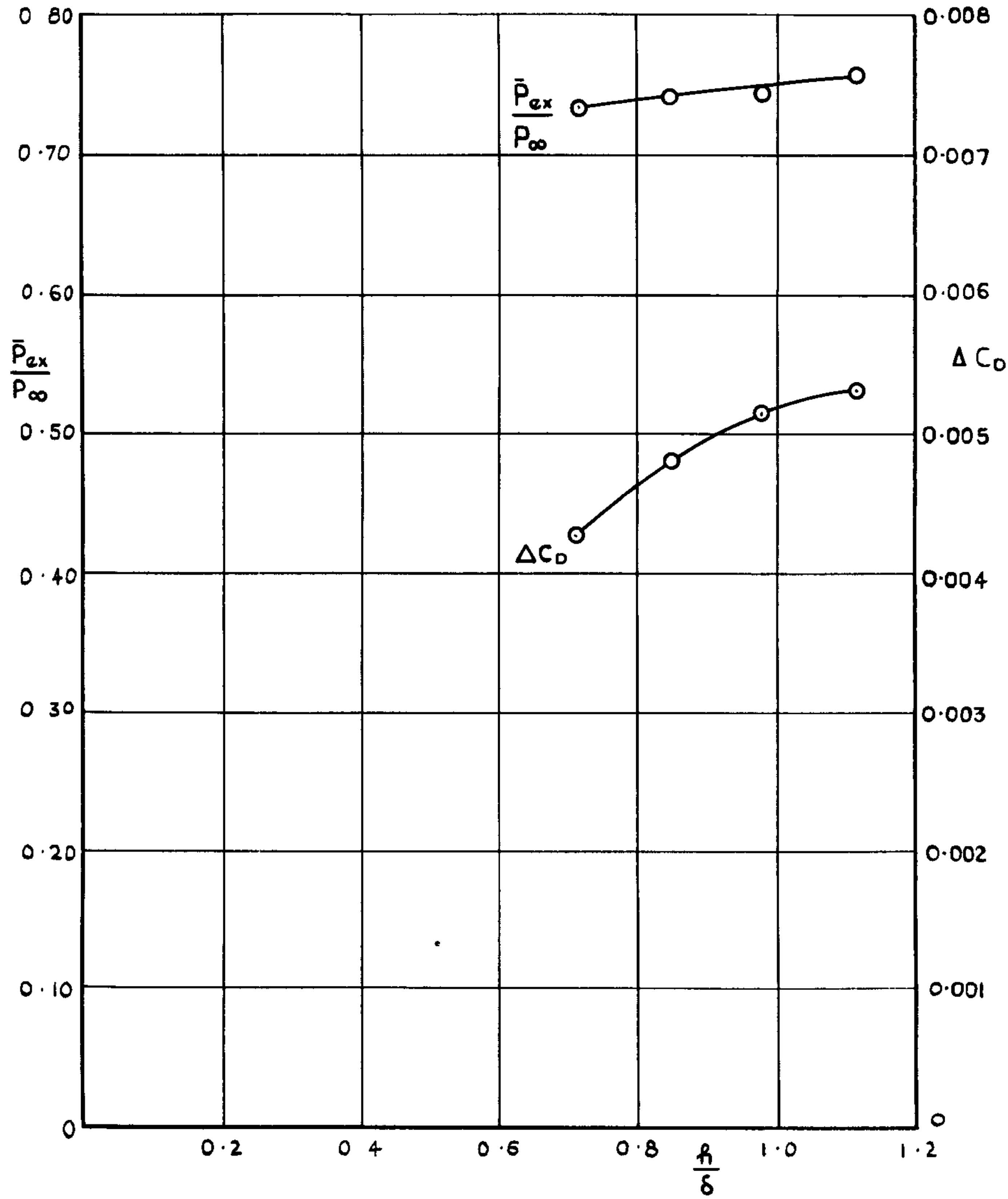


Fig 17 Variation of pressure recovery and ΔC_D with boundary layer diverter height at zero incidence; $\frac{A_\infty}{A_{en}} \simeq 0 \cdot 93$

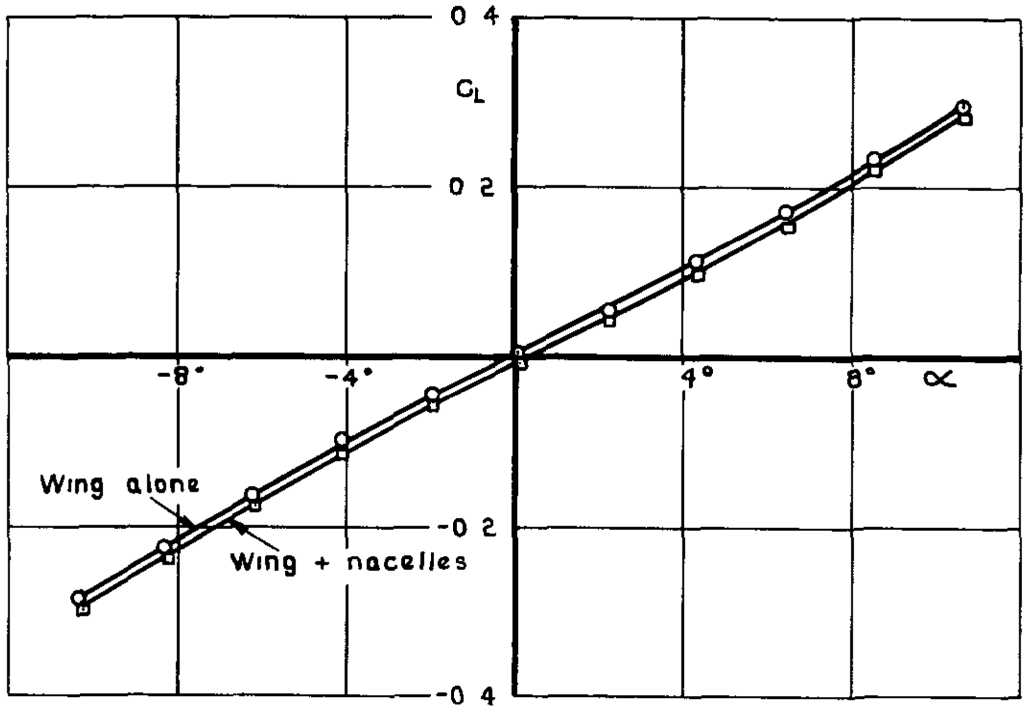


Fig. 18 Variation of lift coefficient with incidence $\left(h = 0{\cdot}225''; \frac{A_{ex}}{A_{en}} = 0{\cdot}84\right)$

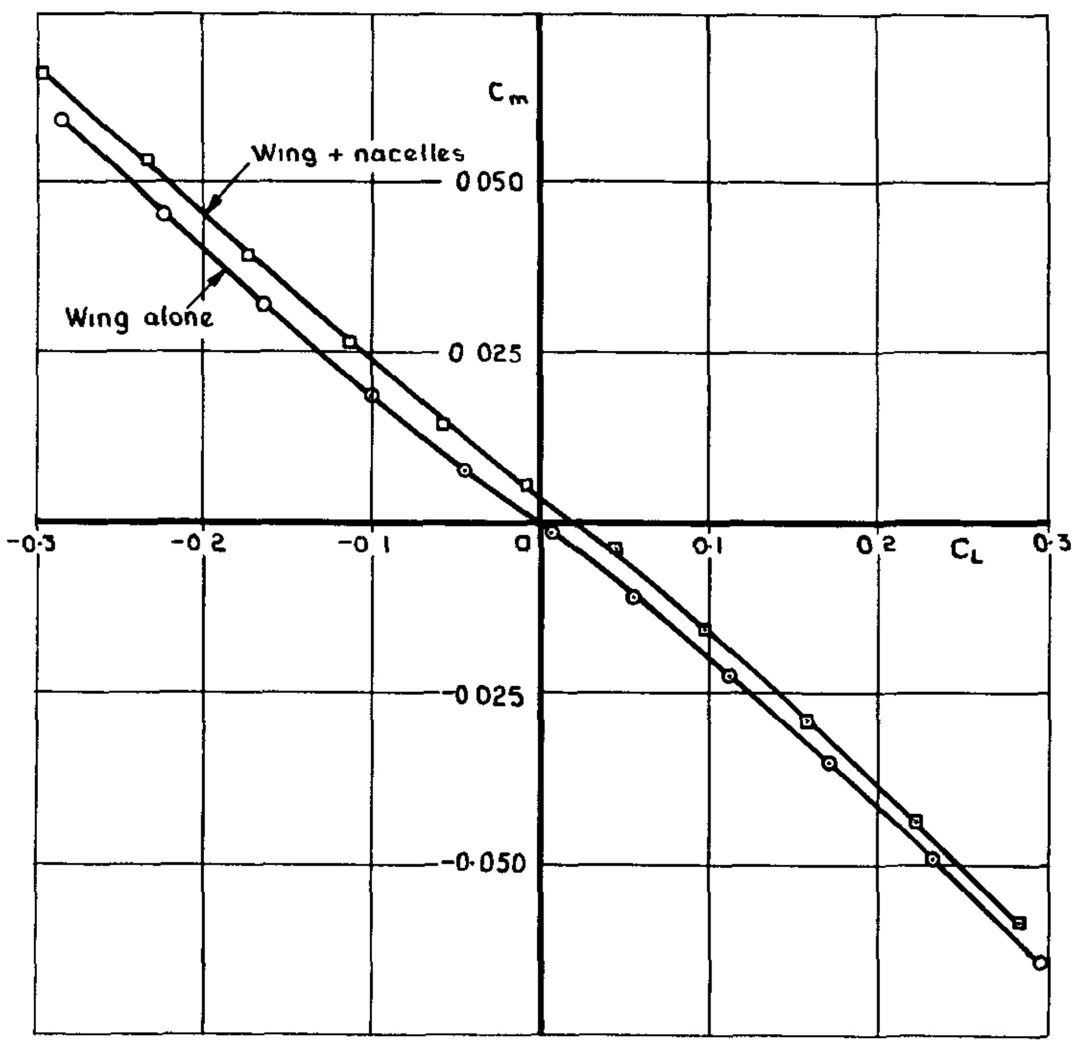


Fig. 19 Variation of pitching moment coefficient with lift coefficient

$\left(h = 0{\cdot}225''; \frac{A_{ex}}{A_{en}} = 0{\cdot}84\right)$

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DETACHABLE ABSTRACT CARDS

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