C.P. No. 605

C.P. No. 605

MINISTRY OF AVIATION

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

An Investigation of Two Methods of Suppressing Shock Oscillation Ahead of Conical Centre-Body Intakes

by

C. F. Griggs

LONDON: HER MAJESTY'S STATIONERY OFFICE

1962

PRICE 4s 6d NET

U.D.C. No. 533.697.2:533.6.011.72:533.694.71:533.694.73

C.P. No. 605
March, 1958

AN INVESTIGATION OF TWO METHODS OF SUPPRESSING SHOCK OSCILLATION AHEAD OF CONICAL CENTRE-BODY INTAKES

by

C. F. Griggs

SUMMARY

Shock oscillation ahead of conical centre-body intakes has been suppressed by the use of vortex generators on the conical surface and by removal of the boundary layer by suction slots.

Vortex generators on the cone surface gave some increase in the range of stable flow in particular cases but at a slight cost in pressure recovery.

Boundary layer suction through a forward facing slot on the cone surface was more successful and gave a considerable increase in range of stable flow at the test Mach Nos. with the slot positioned correctly. The pressure recovery was unchanged at full mass flow, but considerable increases were recorded for some configurations at reduced mass flow.

The drag increment due to suction was approximately equal to that obtained by spilling the same quantity of air (about 0.7% of engine flow) round the cowl tip. This represented some 25% of the drag (excluding skin friction) of the intake at full mass flow.

Previously issued as R.A.E. Tech. Note No. Aero. 2551-A.R.C.20,068.

LIST OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Contd)

---

1 INTRODUCTION

The shock oscillations which occur ahead of centre-body intakes under certain conditions have been discussed in Ref.1 and were divided there into two types. The first type was shown to be associated with the vortex sheet emanating from the intersection of three shocks ahead of the intake (Fig.1) and a method was given for predicting its onset. No conclusions were however reached with regard to the second type which, it was suggested, was associated with the boundary layer on the centre-body, and in particular with its separation from the surface.

Two methods were used in the present work in an attempt to suppress such a separation and so investigate its effect on oscillation. These involved the use of vortex generators on the cone surface and removal of the boundary layer from the cone by suction.

The tests were made in the R.A.E. Supersonic Wind Tunnels.

2 TESTS WITH VORTEX GENERATORS

2.1 Action of vortex generators

If in aerodynamic flow the pressure rises, then the rise in potential energy is normally compensated by a decrease of kinetic energy. However at a solid boundary the kinetic energy is zero and any rise in potential energy is obtained by transfer of energy across the boundary layer. If the boundary layer cannot transfer energy rapidly enough, the flow separates from the surface and a turbulent layer separates under the influence of a normal shock with Mach numbers greater than about 1.3 (Ref.2). On the conical surface of a centre-body intake however, the layer is laminar in small scale model tests such as the present (Reynolds No. based on nose projection less than 350,000) and may be so on a full scale intake cruising at altitude. The layer then separates at a Mach No. lower than 1.3. As the cone surface Mach number of a 25° semi-angle cone reaches 1.3 at a free stream Mach No. of 1.85, separation of the boundary layer from the cone surface can normally be expected at the second shock (Fig.1) unless artificial means of increasing the transfer of energy are used.

Stream-wise vortices just outside the boundary layer cause rapid interchange of air (and hence energy) across it and so may delay the flow separation to a higher Mach No. In the present tests the vortices were generated from the tips of low aspect ratio aerofoils placed at incidence on the cone surface. Such generators have been used successfully to eliminate separation at low speeds and the present tests represented an attempt to achieve a similar result at supersonic speeds.

2.2 Models and experimental technique

Vortex generators were placed on a typical conical-centre-body model with 30° semi-angle (S.D.6 of Ref.1) at distances 0.5" and 0.8" along the model axis from the conical tip. The generator design was similar to a design recommended by A. Spence except that the spacing between generators was doubled for reason of manufacture on this small scale. Dimensions of the intake are shown in Fig.2 and details of the vortex generators in Fig.3.

The methods of varying and measuring mass flow through the model and pressure recovery were those of Ref.3. A schlieren apparatus was used to determine whether the flow was stable or unstable.

2.3 Test and results

The tests were made in the R.A.E. No.4 Supersonic Tunnel at Mach Nos. of 2.14 and 2.48 with atmospheric stagnation pressure. Two values of lip position parameter θ_ℓ were obtained by varying the cone projection length. The model was tested without generators, with each set of generators separately and with both sets together. The results for both sets of generators together were always worse, from considerations of both stability and pressure recovery, than those for the front set alone and so are omitted. Results with front and rear generators are given in Figs.4 and 5, pressure recovery being plotted over the mass flow range for which the flow was stable.

In all cases the front generators gave some improvement in stability at the expense of a slight loss in pressure recovery. At $M = 2.14$ the improvement in stability was quite marked. The rear generators, on the other hand, in no case improved the range of stability appreciably. It appears therefore that the vortices must be generated well forward to be effective. Fig.6 shows photographs of the model at $M = 2.14$ without generators, with front generators, and with rear generators. The boundary layer appears to have thickened under the influence of the second shock at the station of the rear generators, but not at the front generators. This conclusion is confirmed by the stronger flow disturbances visible from the front generators. The rear generators were therefore masked to some extent which presumably reduced their effectiveness.

Although the front generators postponed oscillation they did not apparently prevent separation of the boundary layer on the centre-body. Fig.7 shows the distribution of total pressure across the duct at a station just behind the entry plane for one model arrangement at $M = 2.14$. The exit area was set at the value at which oscillation began when no generators were present. Total pressure is plotted against r^2. The drop towards the centre-body is an indication of breakaway and this is seen to have been little reduced by the front generators and actually increased by the rear generators.

We are thus unable to offer a full explanation of the success of vortex generators in preventing or delaying shock oscillation in certain cases. Their success, it seems, does not involve complete suppression of the breakaway. Rather it seems to lie in the re-energising of the boundary layer at its interaction with the shock, which presumably alters the nature of the breakaway.

3 SUCTION TESTS

3.1 Tests with surface suction

The initial models tested had centre-bodies with cone semi-angles of 22.5° and 25° placed in the cowl S.D.3 of Ref.3. Slots were cut at right angles to the surface at stations ahead of and behind the entry plane and suction was applied to a low pressure of the order of free stream pressure via a calibrated orifice. The suction was applied to the slots separately and together, but no case was recorded of an increase in stable flow at either $M = 2.14$ or 2.48, though the mass flows through the slots were of the order of two percent of the intake mass flow.

It appeared both from schlieren photographs and measurements of total pressure at a station just downstream at the model entry that, with suction, the flow broke away from the surface immediately behind the slot. It was further found that this breakaway was more violent than without suction. It was thought that this breakaway might be avoided and possibly a more complete removal of the boundary layer achieved, by use of a forward facing slot and by careful design of the ducting for the bleed air just downstream of the slot. Two such models were made as described below.

3.2 Tests with slot suction

3.2.1 Models

Two centre-bodies (25° VI and VII) which had identical basic profiles, but with the slot of one 0.2" behind that of the other were designed for use with the cowl S.D.3. Dimensions are given in Fig.2. The centre-bodies were in two parts; a nose piece screwing into a shroud leaving an annular passage for the bleed flow. The slot height could be varied by altering the nose projection from the shroud with packing washers. The values of lip-position parameter θ_ℓ and of M_{W_ℓ}, the Mach No. at which the cone shock strikes the cowl lip, were of course slightly altered as a result. The nose projection of the whole centre-body could also be varied by packing washers, alternating the value of M_{W_ℓ} and the distance of the slot ahead of the intake. The design washer was 0.05 thick (e.g. 25° VI + 0.05) and a thicker washer meant that the intake had an inefficient subsonic diffuser and gave a somewhat poorer pressure recovery than at the design point. Intakes were however tested with an 0.15" washer to give an additional value of M_{W_ℓ}.

3.2.2 Pressure recovery tests

Models 25° VI and VII were tested with 0.05" and 0.15" packing washers at Mach Nos. of 2.14, 2.48 and 2.90 to give the range of slot positions and values of M_{W_ℓ} shown in Fig.8. Both flush slots, i.e. with the outside surface continuous apart from the bleed, and zero height slots, i.e. with the underneath side of the slot lip in line with the cone, were used. In general it was found that some increase of stability was obtained with flush slots by the use of suction, but that a greater increase was obtained with zero height slots. It was further found that there was no advantage to be obtained by increasing the slot height to positive values. Two comparisons of the stability ranges with zero height and flush slots are shown in Fig.9, for both the suction and non-suction cases. The values of pressure recovery are shown over the stable mass flow range. As in most of the tests reported here, the onset of oscillation was well defined for the suction cases, the flow changing suddenly from stability to large amplitude oscillation.

For the non-suction cases however, the onset of oscillation was not clearly defined, the shock system becoming more and more blurred on reduction of mass flow until eventually the flow was definitely oscillating. Thus it was difficult to judge the onset of oscillation in these cases, and no significance should be attached to small differences in the stability ranges as shown.

The results for zero height slots at $M = 2.48$ and 2.90 are given in Figs.10-13. The results are presented in Figs.10 and 12 in terms of A_∞/A_{en} both for the suction and non-suction cases. The results for the suction cases only are given in Figs.11 and 13 in terms of $A_\infty/A_{\infty max}$ together with values of L_s/R_{en} (i.e. distances of the slots ahead of the entry) and M_{W_ℓ}. Typical values of bleed mass flow are also marked.

Comparing intakes with equal packing washers (which are almost identical except for slot position), it is clear that the slot should be some distance ahead of the entry plane for maximum range of stable flow, but we cannot determine the optimum position from the present limited data. It appears from schlieren photographs (Fig.14) that the flow is stable provided the second shock strikes the cone surface behind or at the suction slot. This criterion presumably breaks down if the slot is too far forward, as is indicated in Fig.14(d) where the second shock is on the slot lip and is just beginning to oscillate. A forward movement of the slot does however reduce pressure recovery somewhat. Fig.15 shows the effect of suction on the shock configuration at full mass flow and at the onset of oscillation.

Although suction can delay the onset of oscillation it does not have the expected effect of preventing breakaway of the boundary layer from the centre-body. In fact the breakaway is even more pronounced at the entry measuring station. This is illustrated in Fig.16 which gives some distributions of total pressure with and without suction across the duct of 25° VII + 0.15". The results are given for the value of exit area at the onset of oscillation without suction, and a somewhat larger exit. This result is in agreement with the tests on vortex generators where again the separation was not suppressed but the stability range was extended. In this case it seems that the thinning of the boundary layer at its point of interaction with the shock leads to an extension of the stable flow range.

3.2.3 Drag tests

The advantages and disadvantaves of boundary layer suction can be fully assessed only when the drag increment associated with it is known. Drag tests were therefore made on 25° VII + 0.083" with zero-height slot using the experimental technique of Ref.3. The bleed air was ducted to the free stream, and no direct measurement of bleed mass flow were made. Measurements were taken at $M = 2.48$ and 2.90 over the range of stability both for the suction and non-suction cases and the results are presented in Figs.18 and 19. The external pressure drag coefficient of the intake $C_{D_{EXT}}$ plus the internal drag coefficient of the bleed $C_{D_{BL}}$ is plotted against A_∞/A_{en}. (A_∞ is the mass flow passing through the intake and does not include the bleed flow).

The results for the model with the same value of nose projection, but without a suction slot, are also presented. The difference between the drag of the two models is then the drag due to the presence of the suction slot.

The results are compared with the theoretical drags for the model without suction slot as calculated by the methods of Ref. 3 on an assumption of no unstable flow. The agreement between theory and experiment is good at $M = 2.48$ for both the suction and comparison models, but there is a discrepancy between the predicted and measured full mass flow at $M = 2.90$. There is however good agreement between the predicted and experimental drag rises due to spillage at both Mach numbers.

Also the experiment points for both models lie on the same curve, but the suction model does not reach quite such a high mass flow due to the quantity of air being sucked away. It thus appears that the drag increment due to sucking away the boundary layer is approximately equal to that due to spilling an equal amount of air around the cowl lip. This represents about a 25% increase in the drag, excluding skin friction of the intake in the cases tested. It is possible that this drag increment could be reduced somewhat by limiting the exit area of the bleed flow and so reducing the internal drag of the bleed.

Results are also presented for the model with slot but without suction. The presence of the slot reduces the mass flow slightly, but with less increase in drag than is normally incurred by spilling.

4 CONCLUSIONS

Vortex generators gave some increase in the range of flow stability of conical centre-body intakes in particular cases, provided they were well forward of the shock boundary layer interaction on the cone surface. There was in general a slight loss in pressure recovery.

Boundary layer suction through flush slots, cut at right angles to the cone surface, gave no increase in flow stability. However, suction through forward-facing slots gave a considerable gain in flow stability in the cases tested, and this gain was found to increase with the distance of the slot ahead of the entry plane, up to a limiting value. No gain in pressure recovery at full mass flow was recorded, but there were considerable gains at reduced mass flow, provided the slot was not far ahead of the entry plane.

It was not found that either vortex generators or boundary layer suction prevented breakaway of the boundary layer from the cone surface, even in the cases where oscillation was suppressed. The precise mechanism whereby the devices were successful in increasing the range of stable flow could not therefore be fully demonstrated.

The drag increment due to suction was found to be approximately equal to that due to spilling round the cowl lip an amount of air equal to that removed by suction. This represented about a 25% increase in the drag, excluding skin friction, of the intake.

LIST OF SYMBOLS

A_∞	cross-sectional area of free stream tube entering the model
$A_{\infty max}$	maximum value of A_∞ for a model at a given Mach No.
$A_{\infty BL}$	cross-sectional area of free stream tube entering the suction slot
A_{en}	circular entry area of cowl $= \pi R^2_{en}$
R	radius
R_{en}	radius of cowl at lip
L_s	distance of suction slot ahead of cowl lip
M	Mach No.
M_∞	free stream Mach No.
M_{w_ℓ}	Mach No. at which the cone shock strikes the cowl lip of a given model
θ_c	cone semi-angle
θ_ℓ	angle with respect to the model axis of the line through the cone vertex and the cowl lip
P	total pressure
P_∞	total pressure in the free stream
P_f	total pressure in the final section of the subsonic diffuser
$C_{D_{EXT}}$	external pressure drag coefficient of intake
$C_{D_{BL}}$	internal drag coefficient of suction slot

LIST OF REFERENCES

No.	Author	Title, etc.
1	Griggs, C.F. Goldsmith, E.L.	Shock oscillation ahead of centre-body intakes at supersonic speeds. A.R.C. 15,634. September, 1952.
2	Seddon, J. Haverty, L.	Experiments at Mach Nos. from 0.5 to 1.8 on side intakes of normal shock type without boundary layer control. Part I. The nature of pre-entry flow and its effect of pressure recovery. A.R.C. 17,398. October, 1954.
3	Goldsmith, E.L. Griggs, C.F.	The estimation of shock pressure recovery and external drag of conical centre-body intakes at supersonic speeds. A.R.C. R & M 3035. November, 1953.

KT.2078.C.P.605.K3 - Printed in England

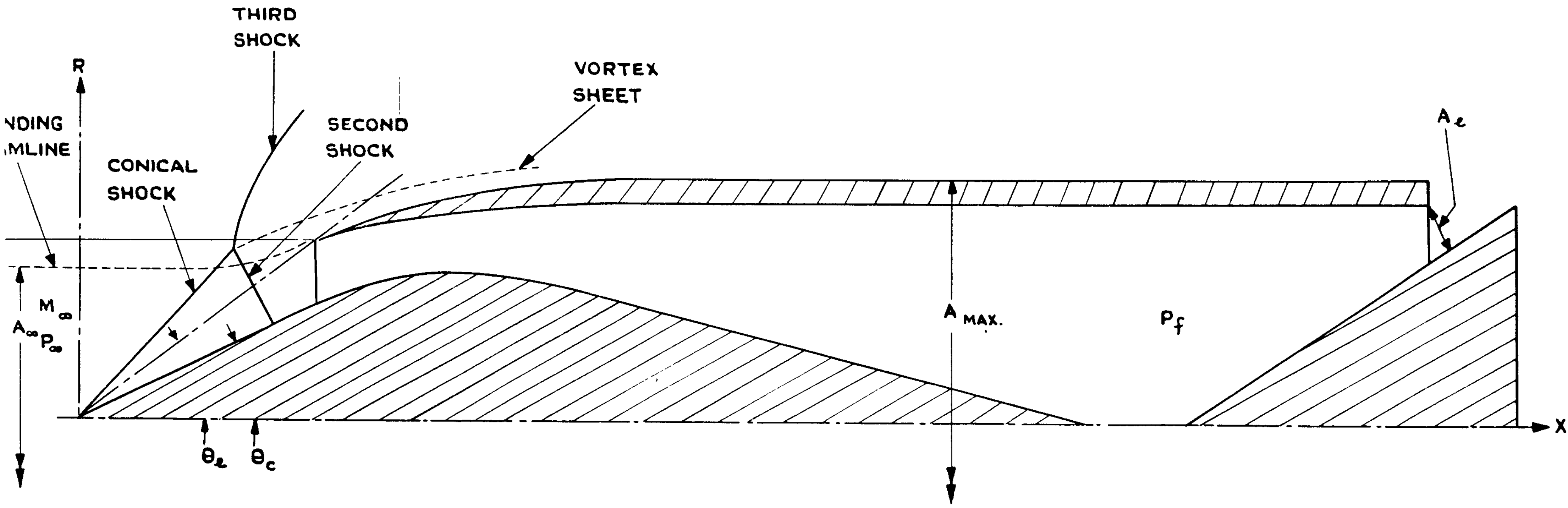
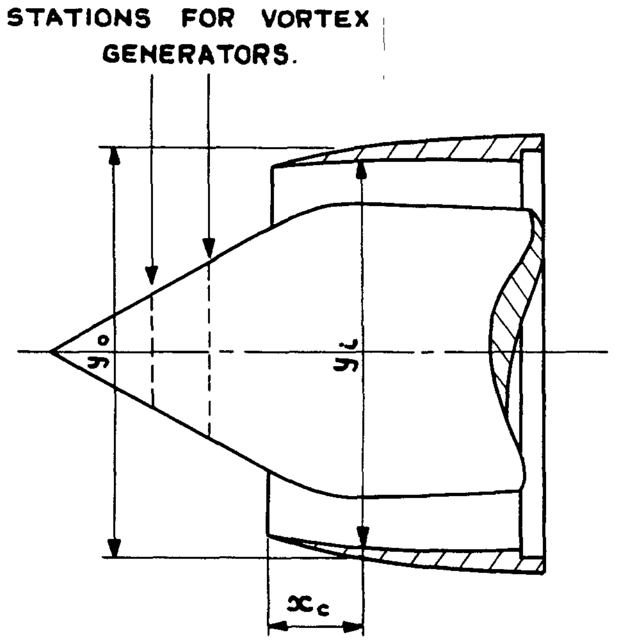


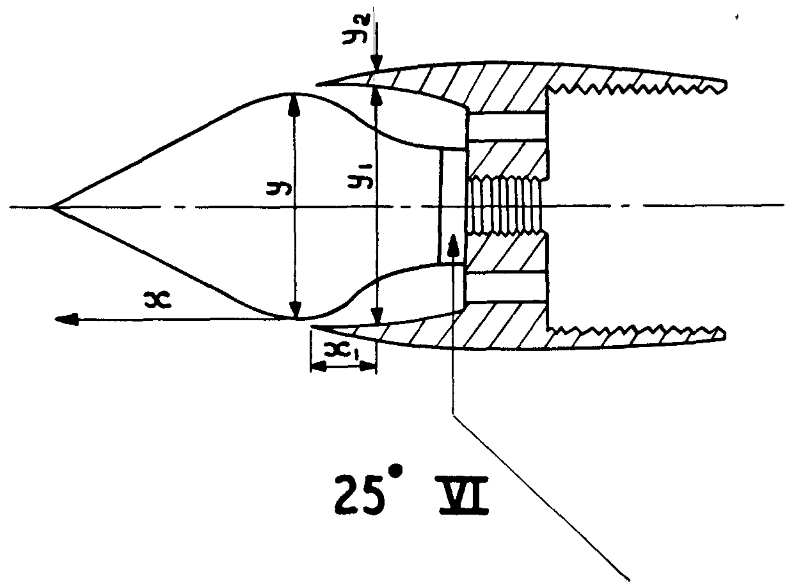
FIG. 1. NOTATION.



30° SD 6.

CONE		COWL		
x	DIA. y	x_c	DIA. y_o	DIA. y_i
0·00	0·007	0·00	1·915	1·905
1·00	1·158	0·10	1·959	1·920
1·20	1·372	0·20	2·002	1·950
1·40	1·483	0·30	2·041	1·972
1·60	1·512	0·40	2·080	1·990
1·80	1·510	0·50	2·112	1·995
2·00	1·503	0·60	2·145	1·998
2·20	1·490	0·70	2·171	1·998
2·40	1·477	0·80	2·196	1·998
2·60	1·456	1·00	2·232	1·998
2·80	1·427	1·10	2·243	1·998
2·90	1·408	1·30	2·250	1·998

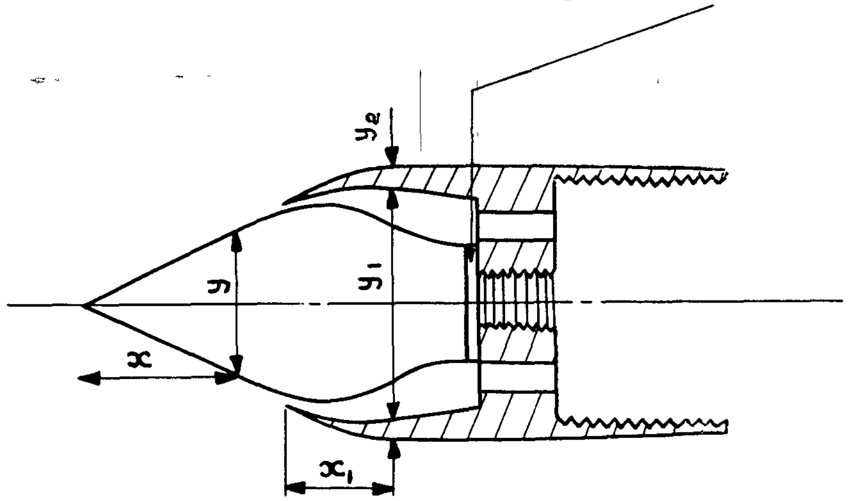
TIP PROJECTION = 1·130 M_{w_ℓ} = 2·93
TIP PROJECTION = 1·180 M_{w_ℓ} = 3·24



25° VI

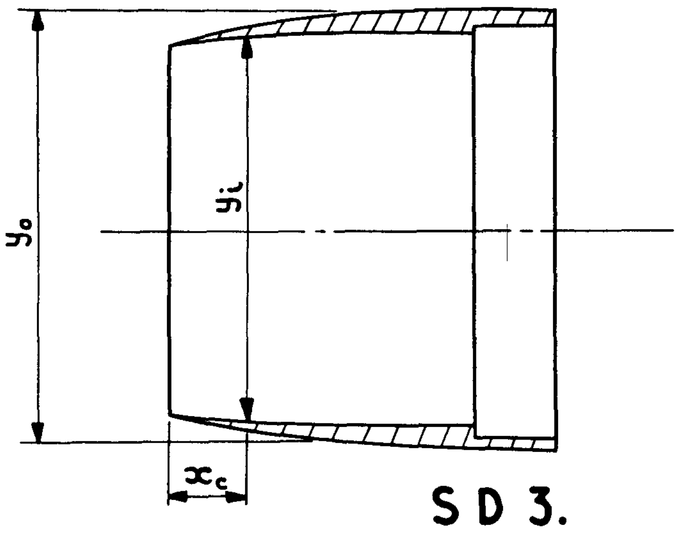
NOSE		SHROUD			
x	DIA. y	x_1	DIA. y_2	x_1	DIA. y_1
0	0·013	0·05	1·2936	0·0	1·237
1·20	1·1374	0·10	1·3267	0·05	1·255
1·30	1·2028	0·20	1·3823	0·10	1·263
1·40	1·2012	0·60	1·4712	0·15	1·269
1·55	1·0493	0·80	1·4763	0·20	1·275
1·75	0·7385	1·10	1·4709	0·25	1·281
1·95	0·6088	1·40	1·4544	0·30	1·281
		1·60	1·4367	0·60	1·205
		1·90	1·4062	0·80	1·122
		2·10	1·3810		

WASHERS VARIABLE TO VARY SLOT HEIGHT.



25° VII

NOSE		SHROUD			
x	DIA. y	x_1	DIA. y_2	x_1	DIA. y_1
0	0·013	0·05	1·1256	0·0	1·043
0·9	0·8530	0·15	1·2194	0·05	1·065
1·00	0·9442	0·25	1·2954	0·10	1·105
1·10	1·0090	0·35	1·3569	0·15	1·135
1·20	1·0351	0·45	1·4052	0·20	1·159
1·30	1·0328	0·55	1·4393	0·25	1·181
1·40	1·0024	0·75	1·4696	0·30	1·201
1·50	0·9407	0·85	1·4739	0·40	1·210
1·60	0·8434	1·55	1·4548	0·80	1·180
1·70	0·7297	1·75	1·4385	1·00	1·122
1·80	0·6504	1·95	1·4159		
1·90	0·6044	2·15	1·3911		
		2·30	1·3728		

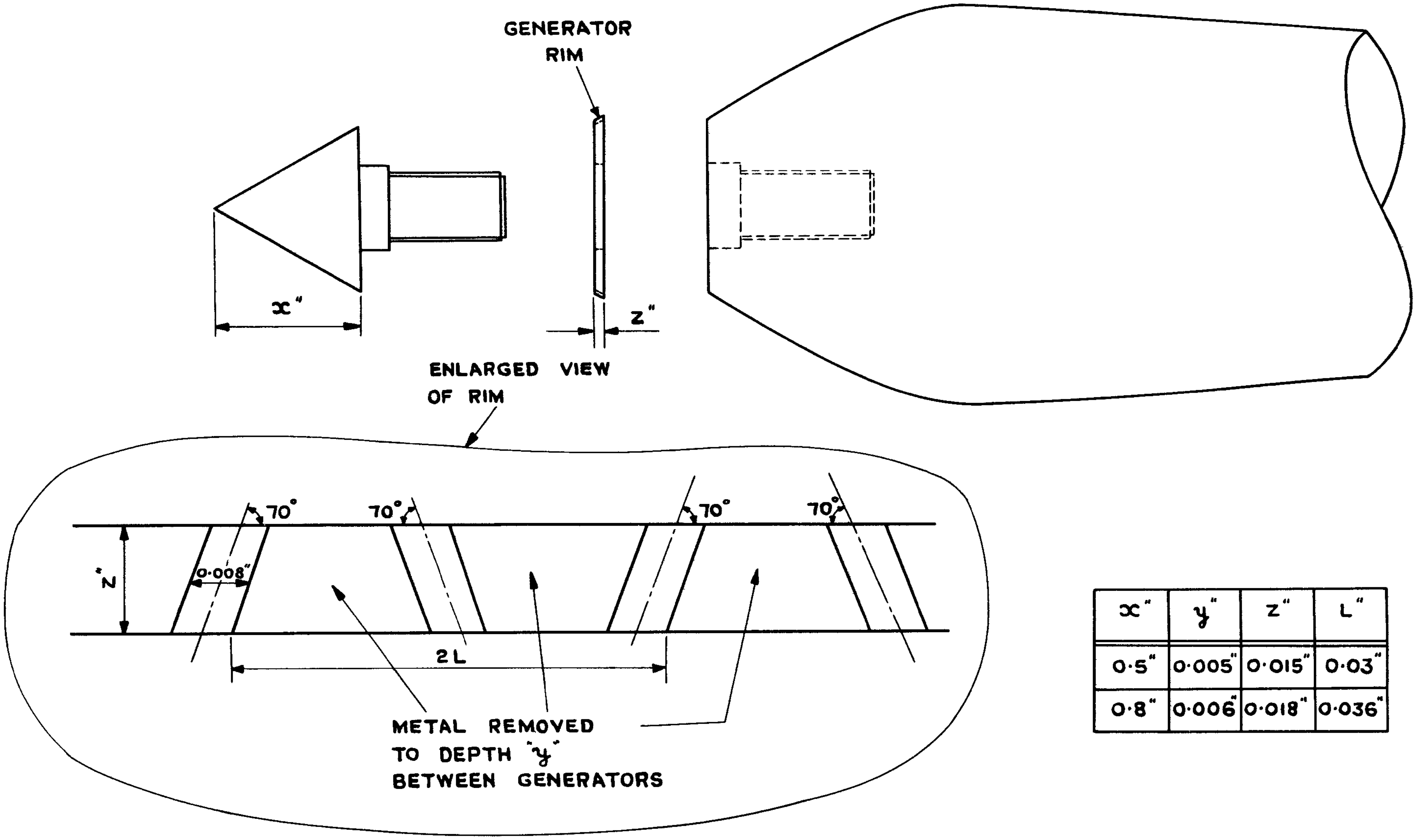


SD 3.

USED WITH 25° VI & VII

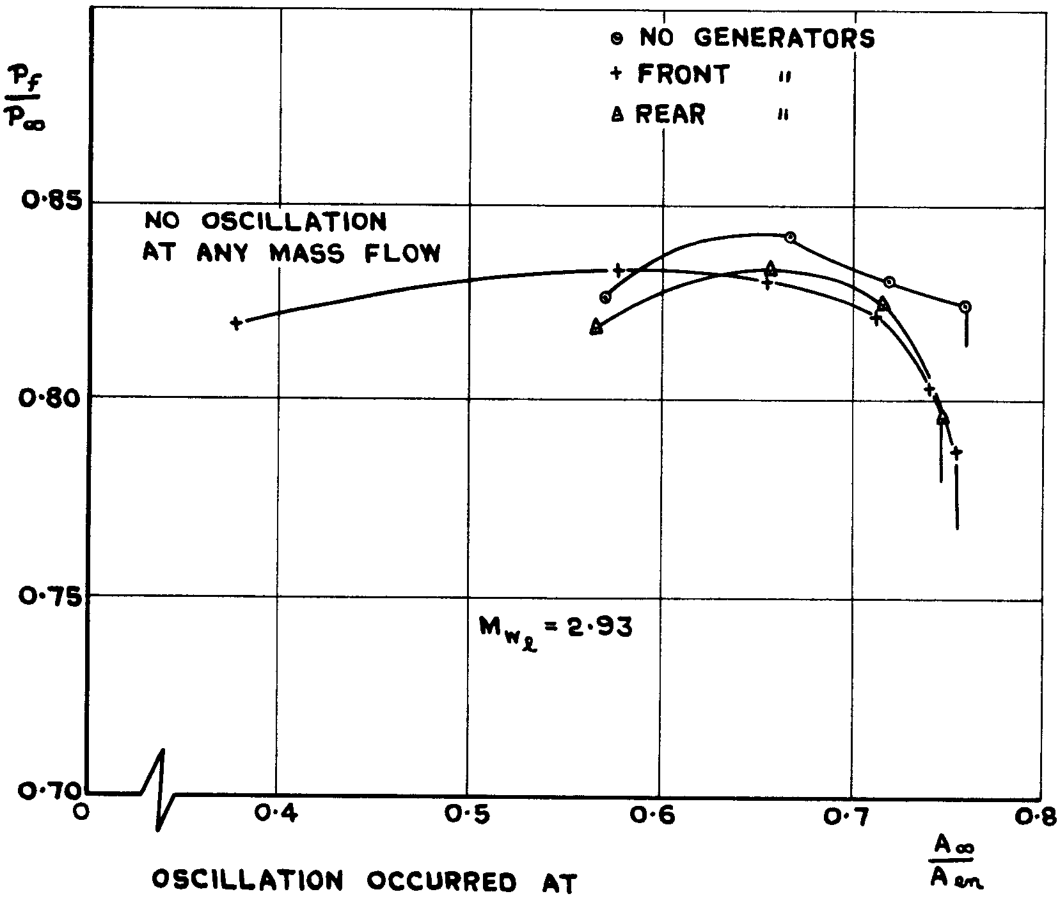
COWL		
x_c	DIA. y_o	DIA. y_i
0·00	1·897	1·885
0·10	1·947	1·923
0·20	1·993	1·955
0·30	2·030	1·979
0·40	2·069	1·990
0·50	2·100	1·998
0·60	2·130	2·000
0·80	2·173	2·000
1·00	2·207	2·000
1·20	2·231	2·000
1·40	2·244	2·000
1·60	2·250	2·000

FIG. 2. MODEL CO-ORDINATES.



x"	y"	z"	L"
0·5"	0·005"	0·015"	0·03"
0·8"	0·006"	0·018"	0·036"

FIG. 3. DETAILS OF VORTEX GENERATORS.



OSCILLATION OCCURRED AT LOWER MASS FLOWS THAN THOSE INDICATED.

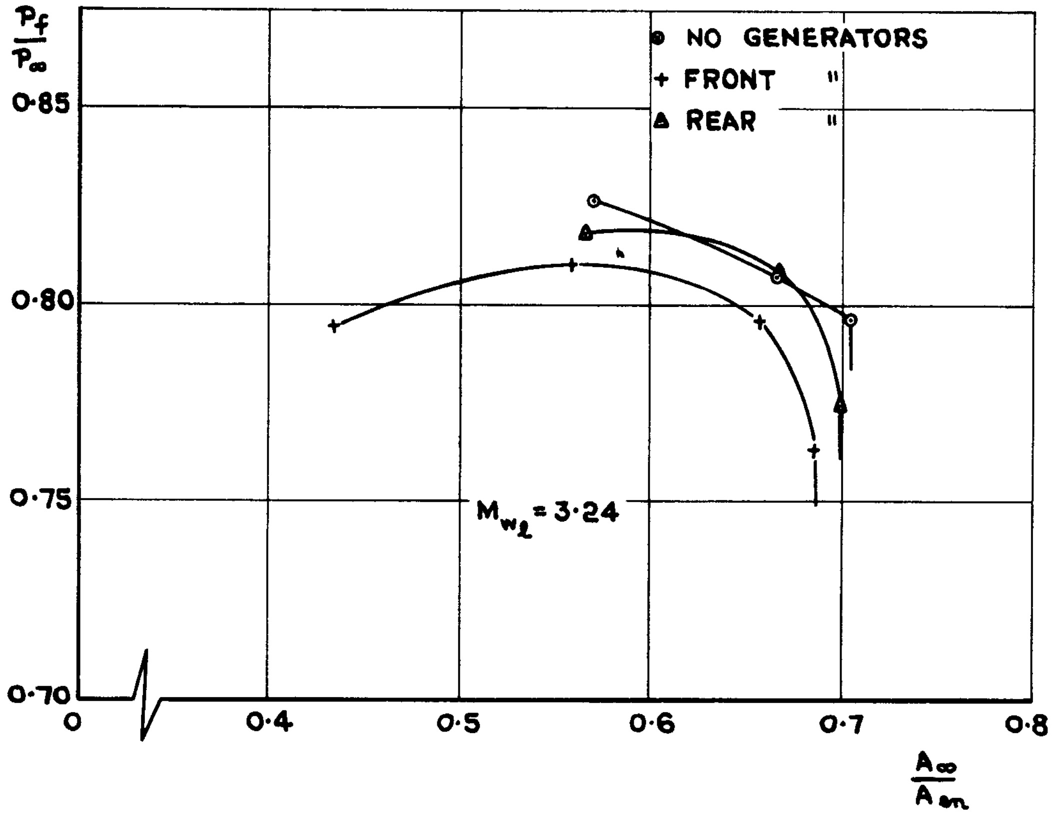
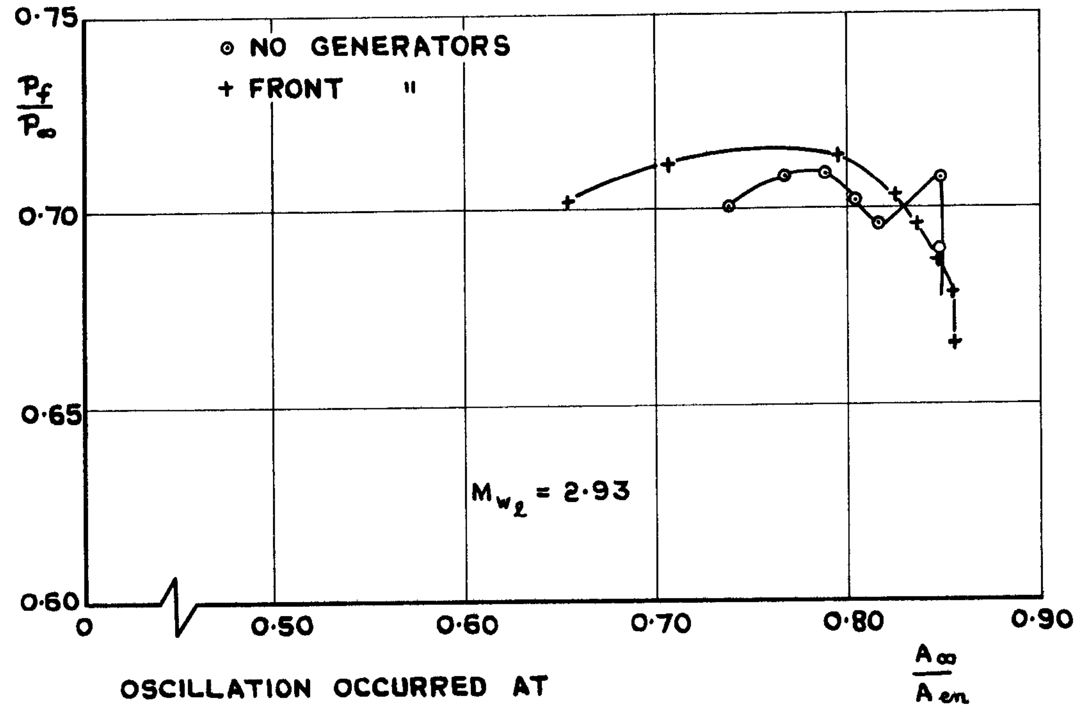


FIG. 4. EFFECT OF VORTEX GENERATORS ON PRESSURE RECOVERY AND FLOW STABILITY AT M = 2·14.



OSCILLATION OCCURRED AT LOWER MASS FLOWS THAN THOSE INDICATED.

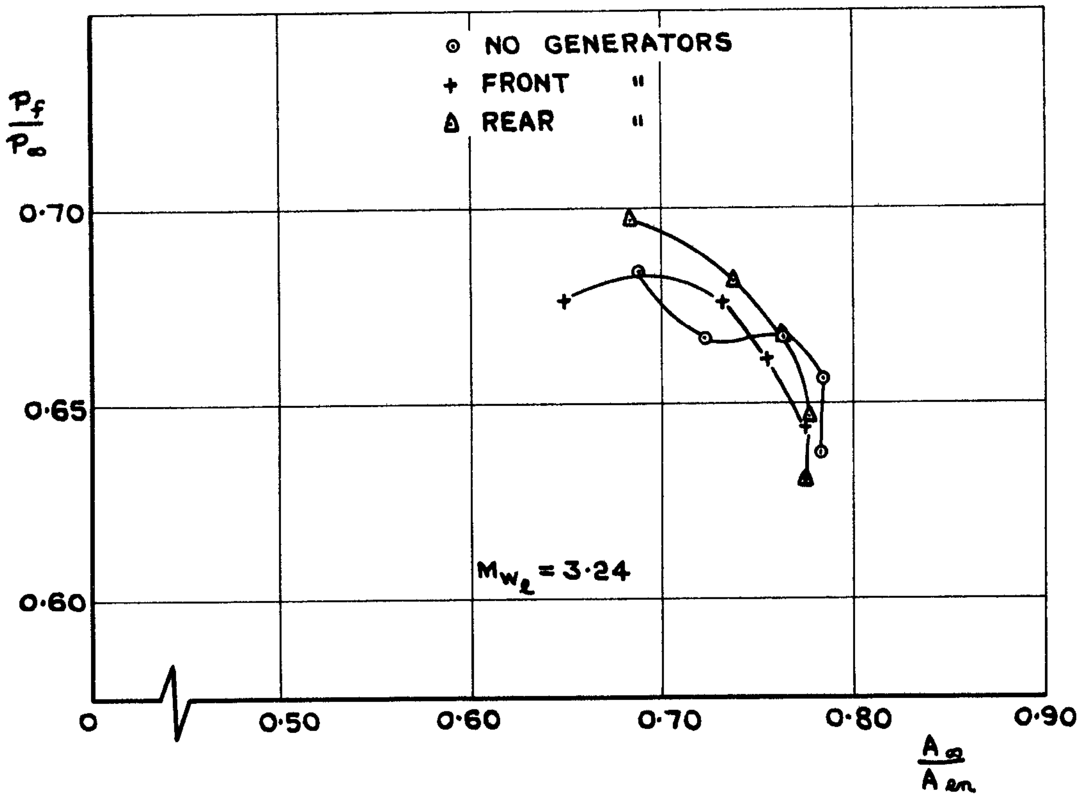
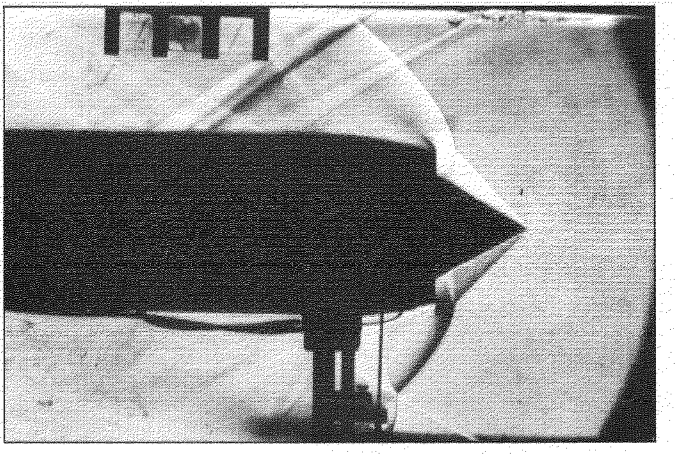
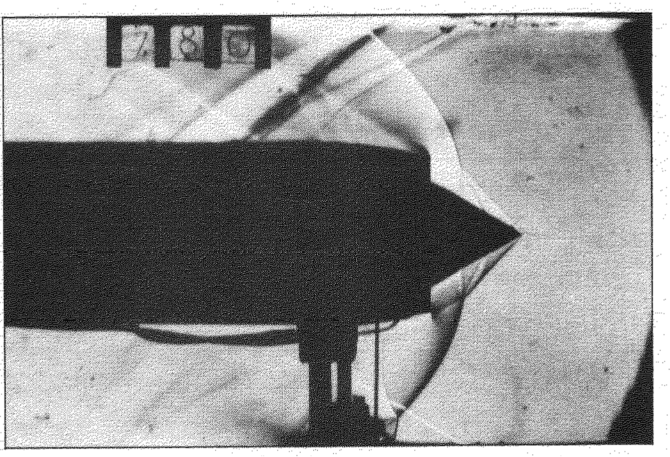


FIG. 5. EFFECT OF VORTEX GENERATORS PRESSURE RECOVERY AND FLOW STABILITY AT M = 2·48.



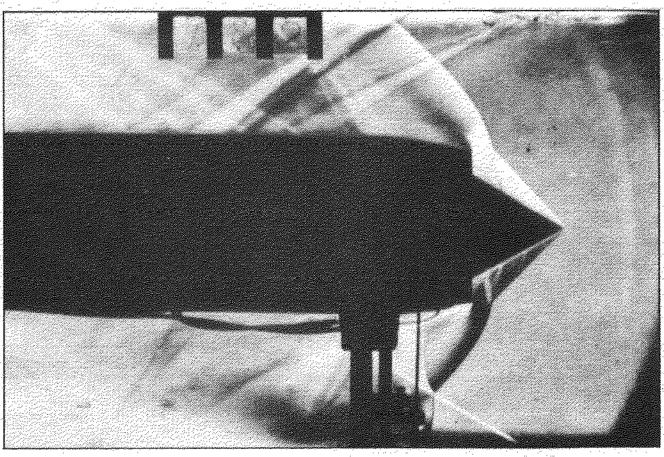
(a) No generators

$$\frac{A_\infty}{A_{en}} = 0.57$$



(b) Front generators

$$\frac{A_\infty}{A_{en}} = 0.432$$



(c) Rear generators

$$\frac{A_\infty}{A_{en}} = 0.565$$

FIG.6a,b & c.

MINIMUM STABLE FLOW CONFIGURATIONS OF S.D.6, $M_{w_\ell} = 3.24$ AT $M_\infty = 2.14$ WITH AND WITHOUT VORTEX GENERATORS

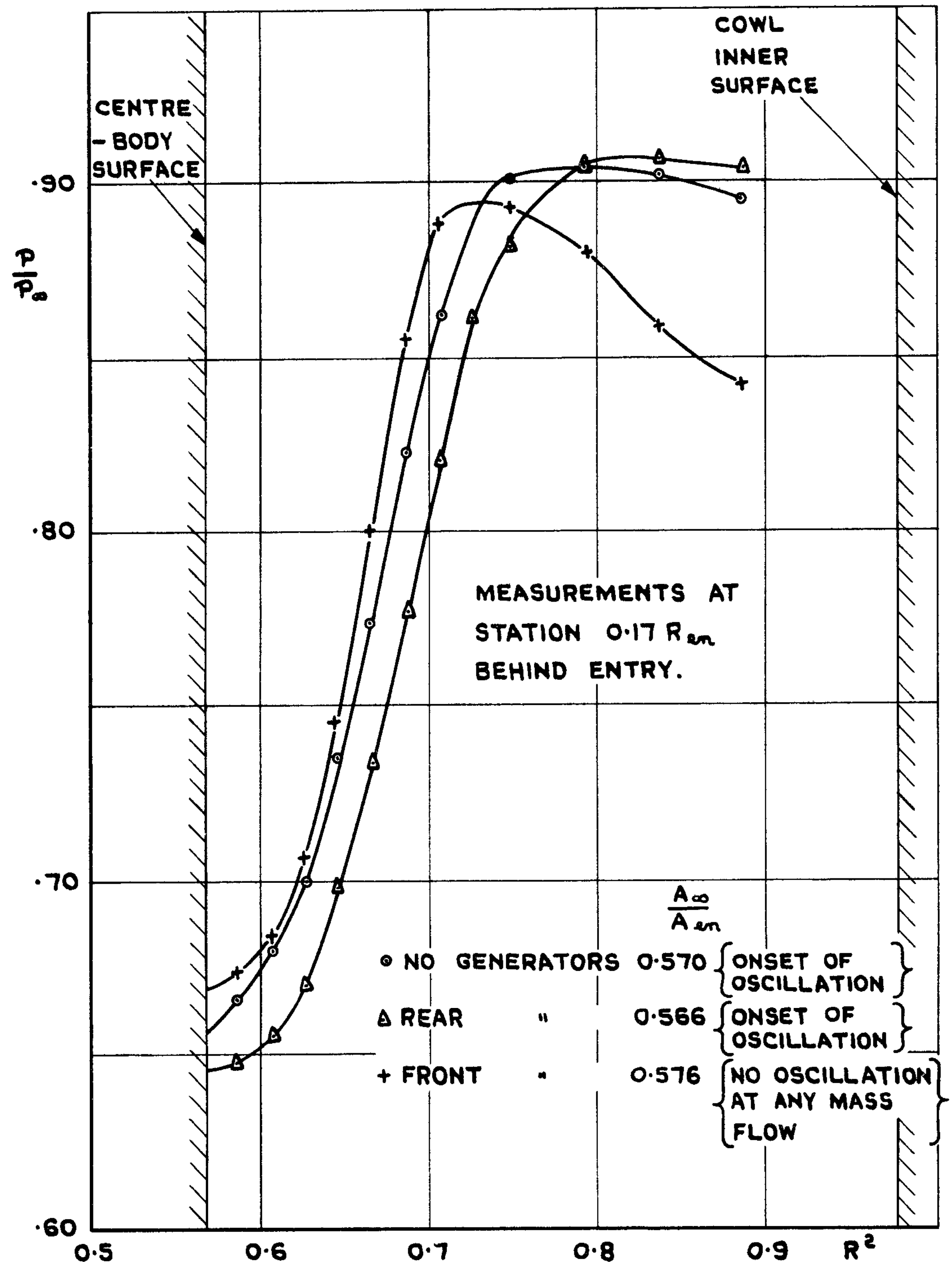
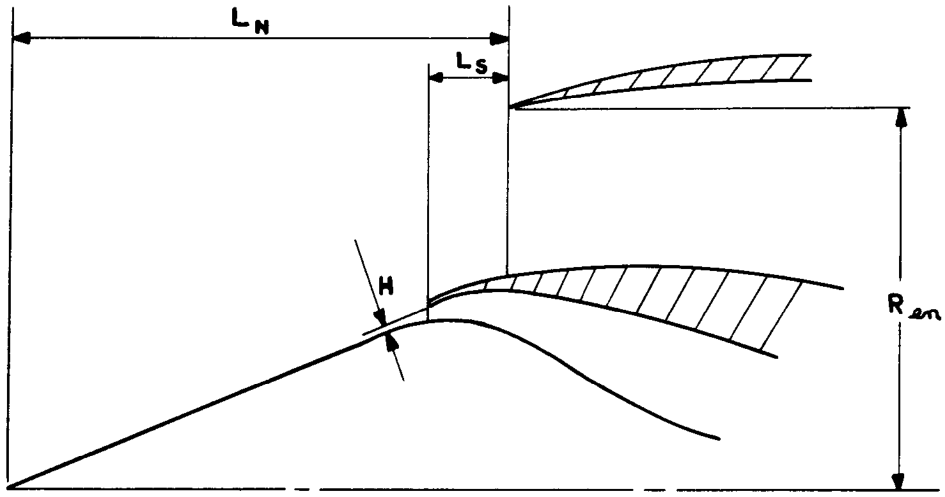


FIG. 7. DISTRIBUTIONS OF TOTAL PRESSURE ACROSS DUCT OF S.D.6. $M_{w_2} = 2{\cdot}93$ AT $M_\infty = 2{\cdot}14$.

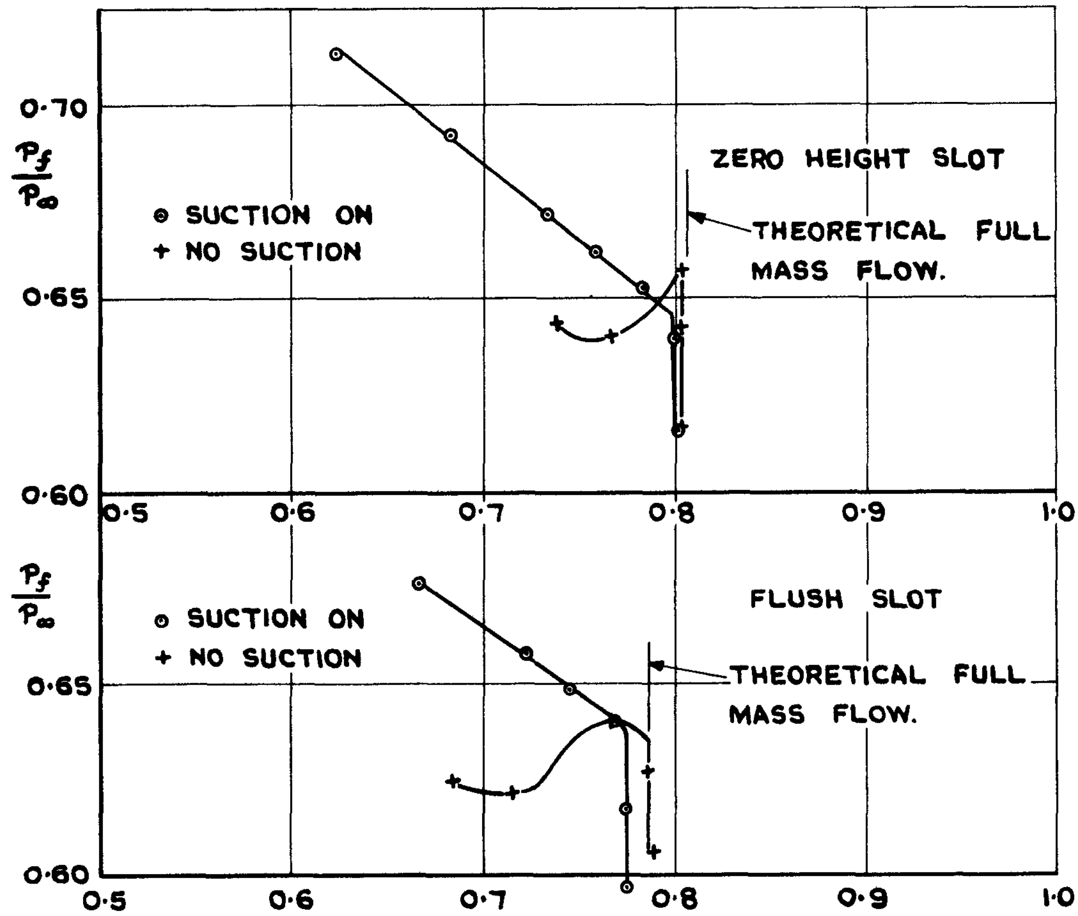


NOTE :- H IS MEASURED FROM UNDERNEATH SIDE OF LIP.

MODEL	H	$\frac{L_S}{R_{en}}$	$\frac{L_N}{r_{en}}$	M_{w_ℓ}
VI +0·05"	0	0·011	1·398	2·78
VI +0·05"	* −0·008"	0·011	1·417	2·85
VI +0·15"	0	0·117	1·504	3·22
VI +0·15"	* −0·008"	0·117	1·523	3·32
VII +0·05"	0	0·216	1·383	2·73
VII +0·05"	* − 0·015"	0·216	1·421	2·87
VII +0·15"	0	0·322	1·489	3·15
VII +0·15"	* −0·015"	0·322	1·528	3·34
VII +0·083"	0	0·251	1·418	2·85
VII +0·083"	* −0·015"	0·251	1·456	3·01

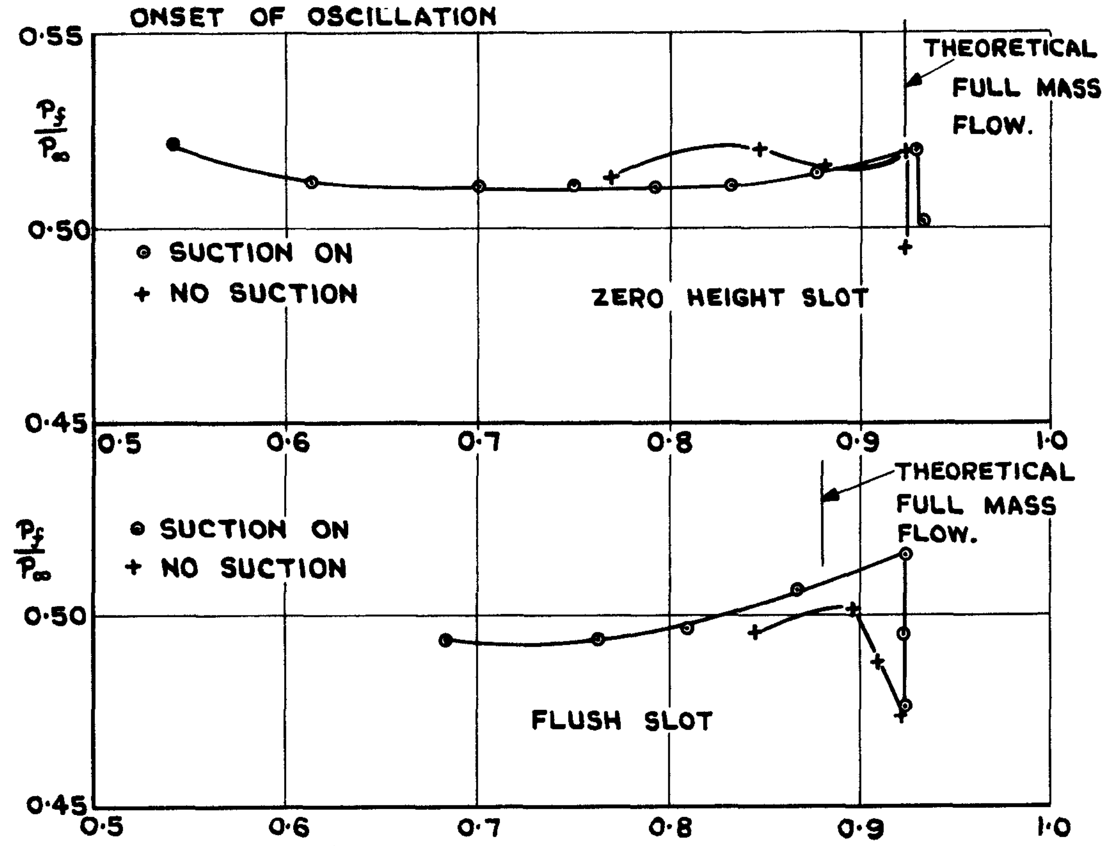
* DENOTES FLUSH OUTSIDE SURFACE .

FIG. 8. DETAILS OF ASSEMBLED MODELS.



(a) 25° VI + 0·15″ AT M = 2·48.

NOTE :- CURVES STOP AT ONSET OF OSCILLATION



(b) 25° VII + 0·15″ AT M = 2·90.

FIG. 9 (a & b). TWO COMPARISONS OF RANGES OF FLOW STABILITY WITH FLUSH AND ZERO-HEIGHT SLOTS.

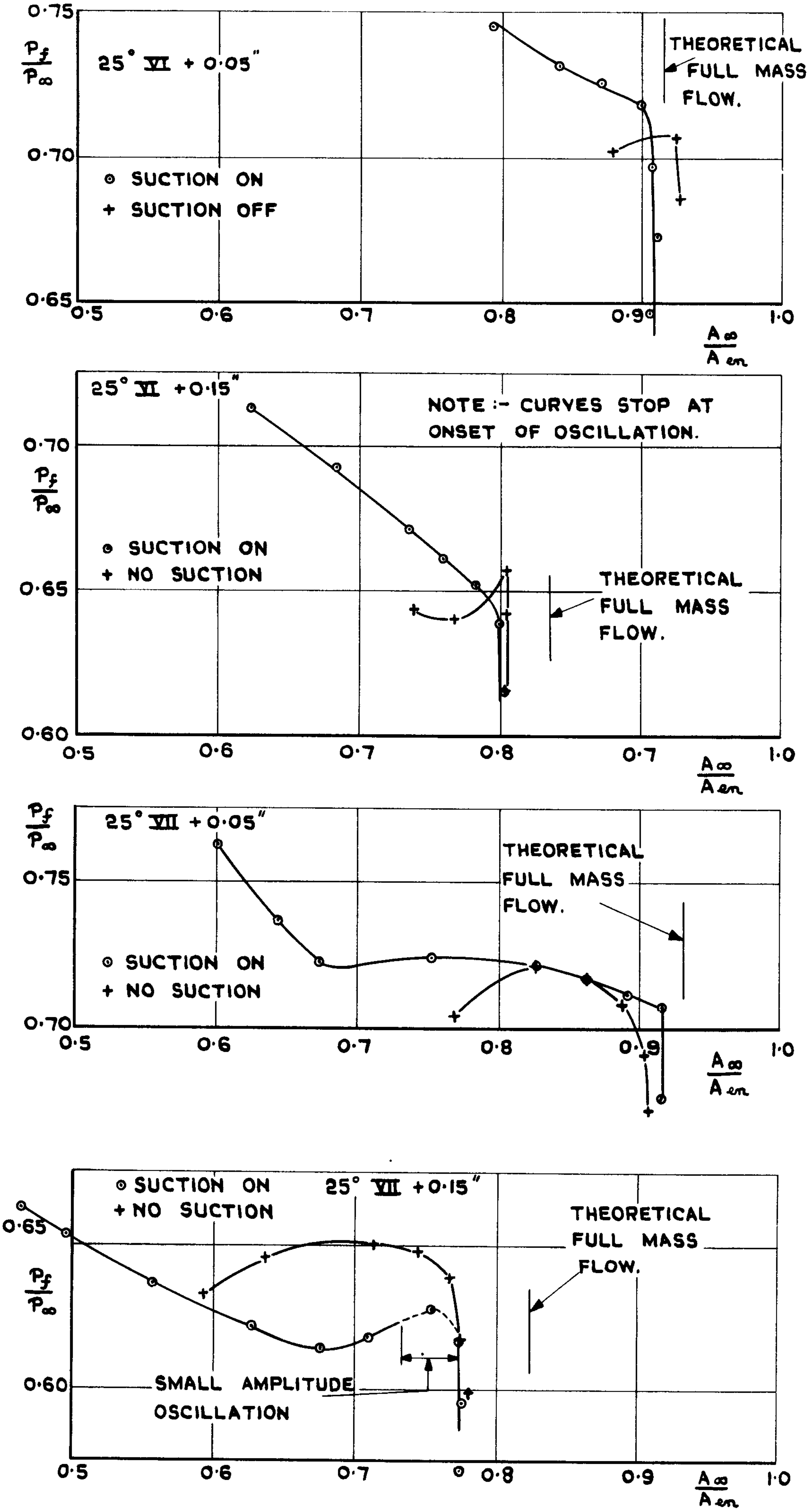
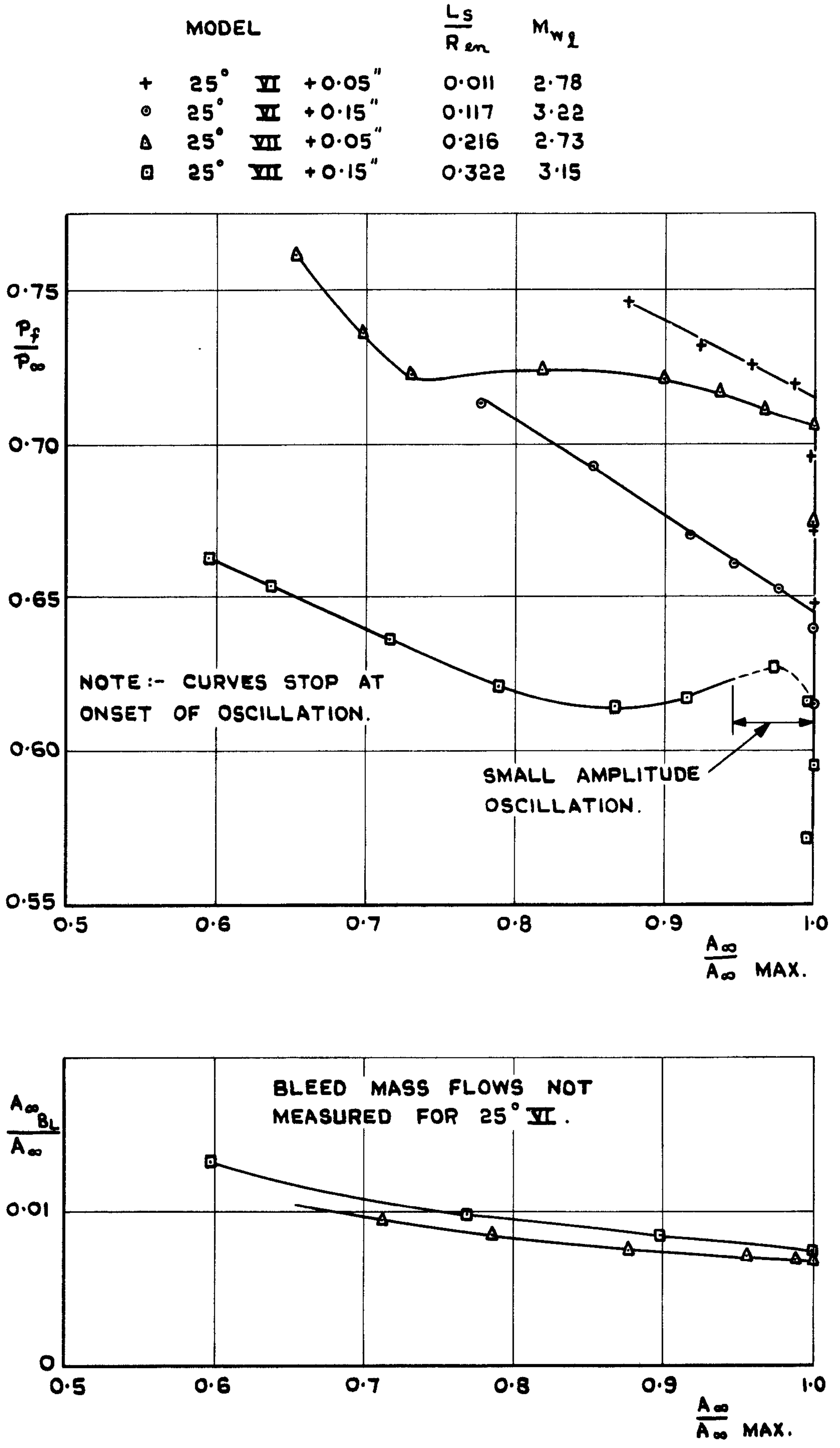


FIG. 10. RANGES OF FLOW STABILITY WITH AND WITHOUT SUCTION FOR ZERO HEIGHT SLOTS AT M = 2·48.

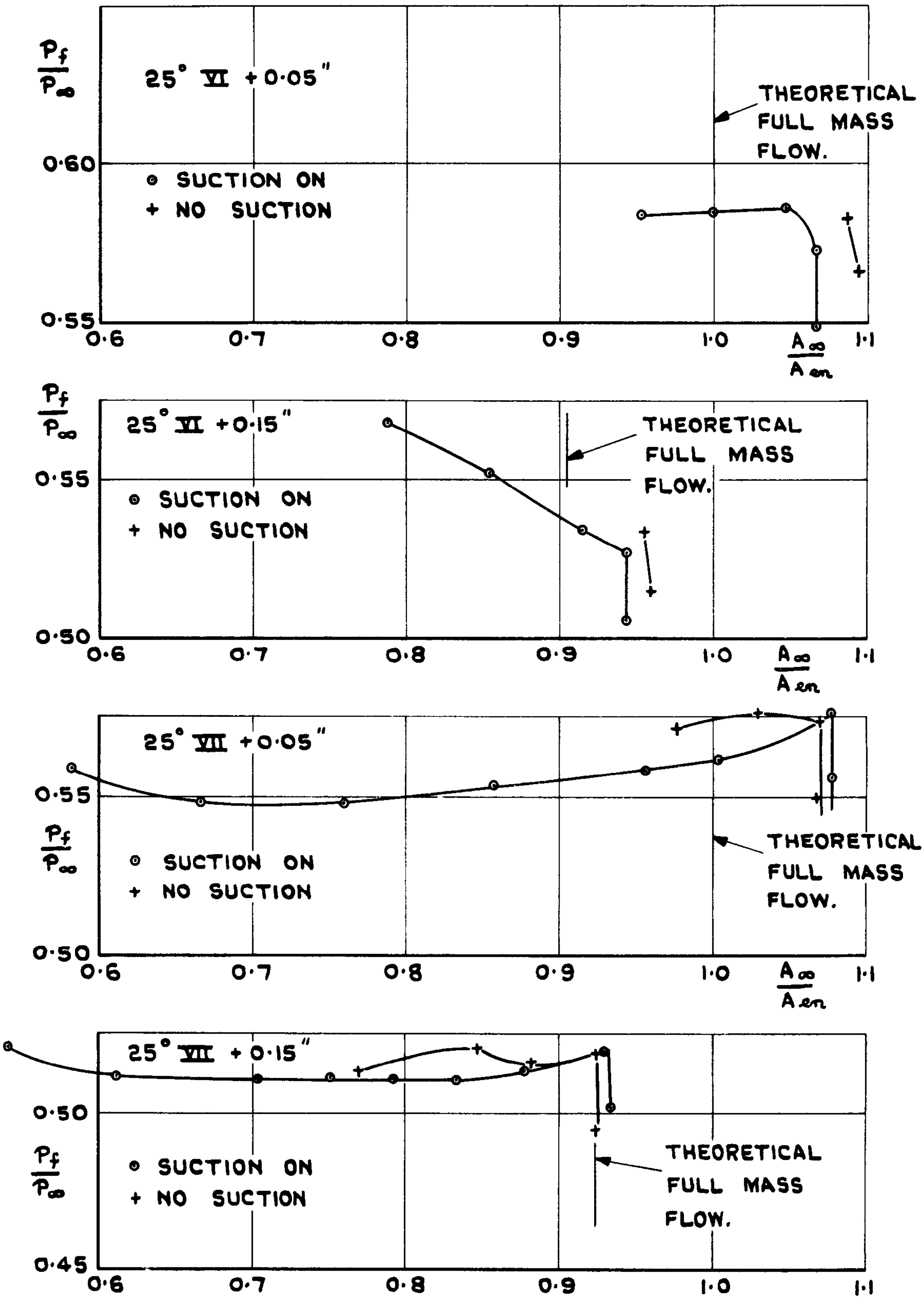


NOTE :- CURVES STOP AT ONSET OF OSCILLATION.

SMALL AMPLITUDE OSCILLATION.

BLEED MASS FLOWS NOT MEASURED FOR 25° VI.

FIG. 11. COMPARISON OF STABILITY RANGES WITH SUCTION FOR ZERO HEIGHT SLOTS AT M = 2·48.



NOTE :- CURVES STOP AT ONSET OF OSCILLATION.

FIG. 12. RANGES OF FLOW STABILITY WITH AND WITHOUT SUCTION FOR ZERO HEIGHT SLOTS AT M = 2·90.

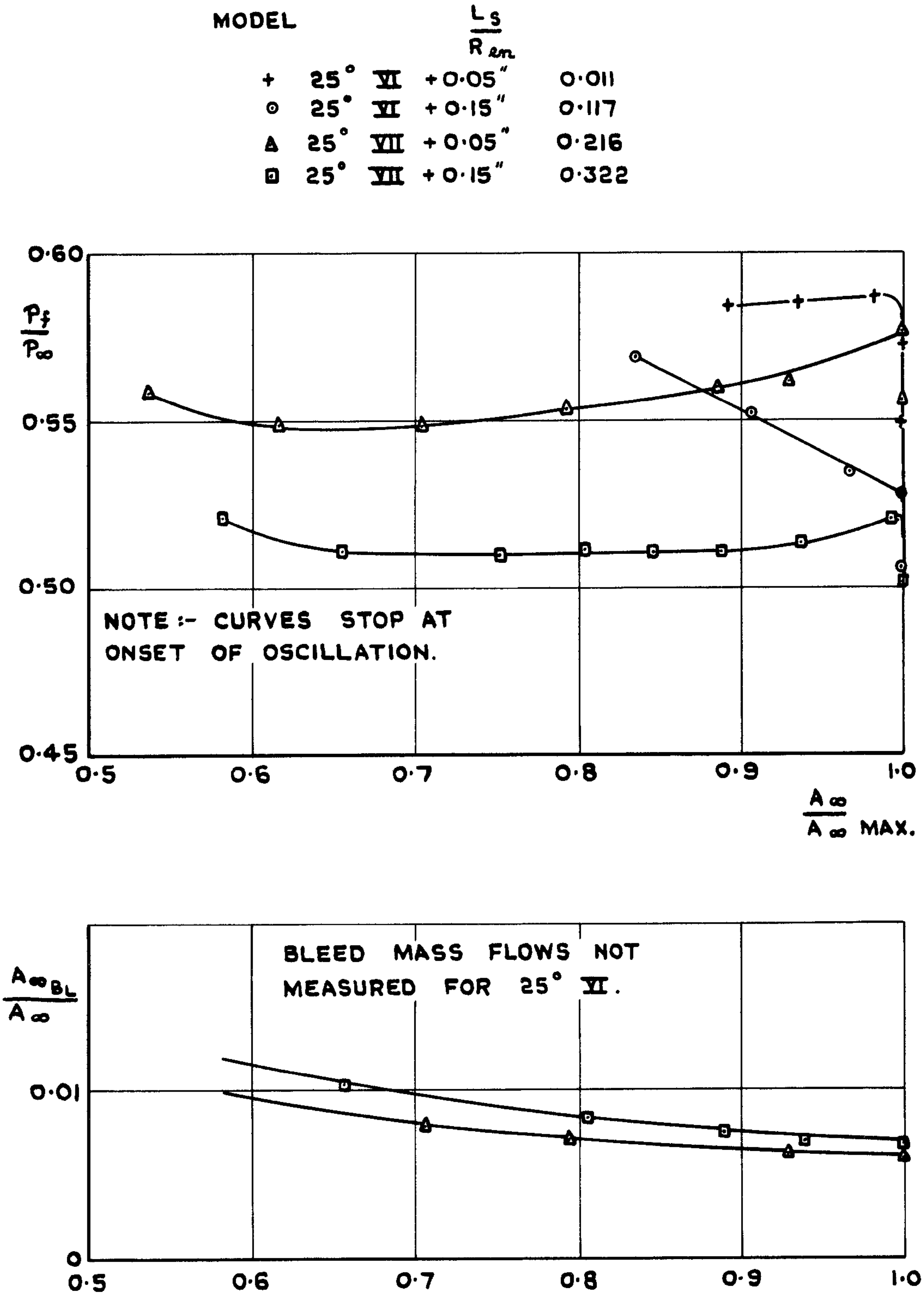
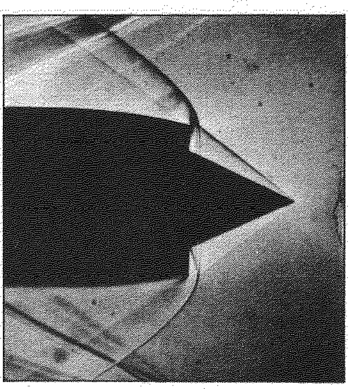
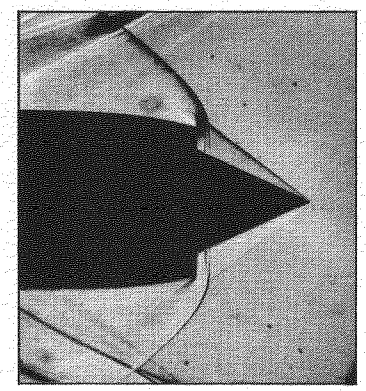


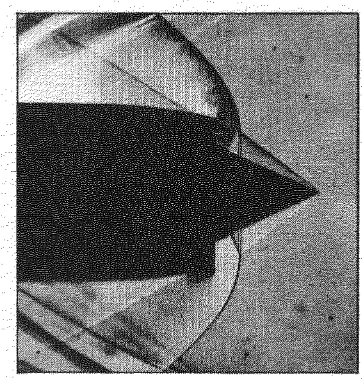
FIG. 13. COMPARISON OF STABILITY RANGES WITH SUCTION FOR ZERO HEIGHT SLOTS AT M = 2·90.



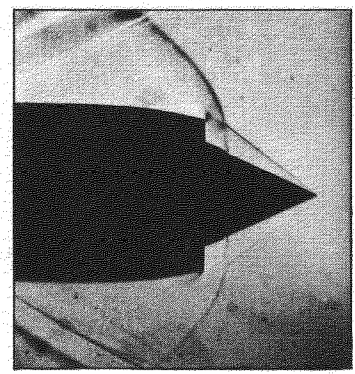
(a)
25°VI + 0.05"
$\frac{L_s}{R_{en}} = 0.011$
$\frac{A_\infty}{A_{en}} = 0.91$



(b)
25°VI + 0.15"
$\frac{L_s}{R_{en}} = 0.117$
$\frac{A_\infty}{A_{en}} = 0.804$

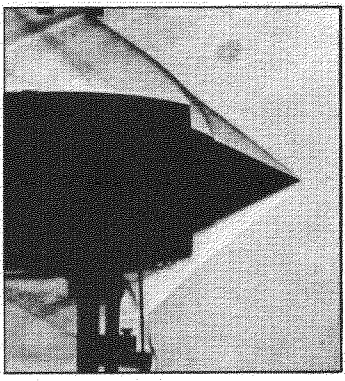


(c)
25°VII + 0.05"
$\frac{L_s}{R_{en}} = 0.216$
$\frac{A_\infty}{A_{en}} = 0.916$

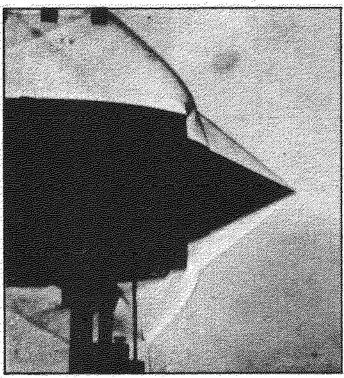


(d)
25°VII + 0.15"
$\frac{L_s}{R_{en}} = 0.322$
$\frac{A_\infty}{A_{en}} = 0.773$

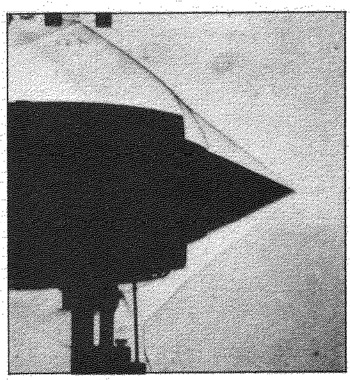
FIG. 14a, b, c & d. CONFIGURATIONS AT MINIMUM STABLE FLOW WITH ZERO HEIGHT SLOTS AT $M = 2.48$



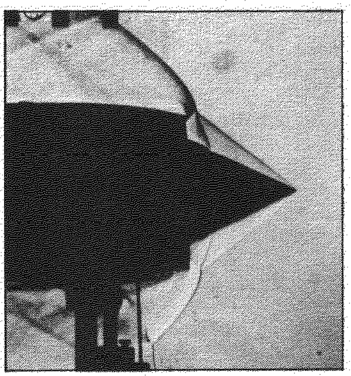
(a)
25°VII + 0.15"
Full mass flow
no suction
$\frac{A_\infty}{A_{en}} = 0.774$



(b)
25°VII + 0.15"
Minimum
stable flow
no suction
$\frac{A_\infty}{A_{en}} = 0.598$



(c)
25°VII + 0.15"
Full mass flow
suction on
$\frac{A_\infty}{A_{en}} = 0.768$



(d)
25°VII + 0.15"
Suction on
$\frac{A_\infty}{A_{en}} = 0.580$

FIG. 15a, b, c & d. FURTHER FLOW CONFIGURATIONS AT $M_\infty = 2.48$

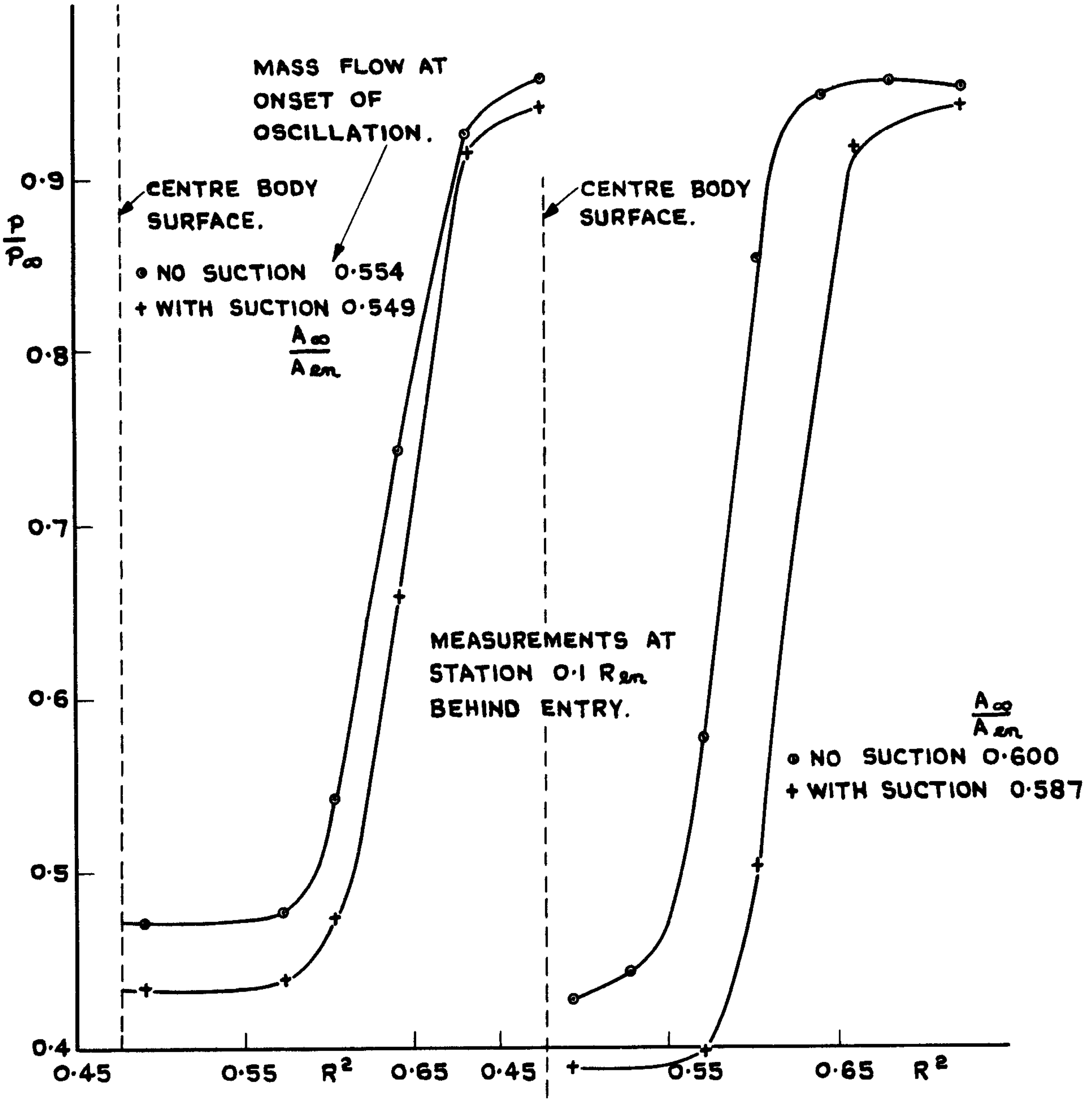


FIG. 16. DISTRIBUTIONS OF TOTAL PRESSURE ACROSS DUCT OF 25° VII AT $M_\infty = 2{\cdot}14$.

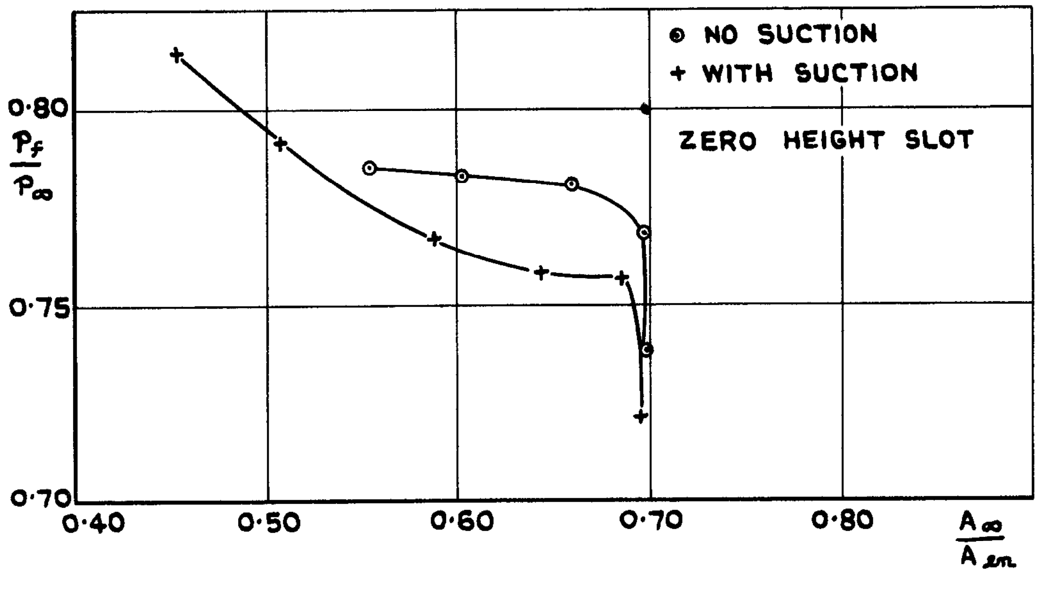


FIG. 17. RANGES OF FLOW STABILITY WITH AND WITHOUT SUCTION FOR 25° VII + 0·15" AT $M_\infty = 2{\cdot}14$.

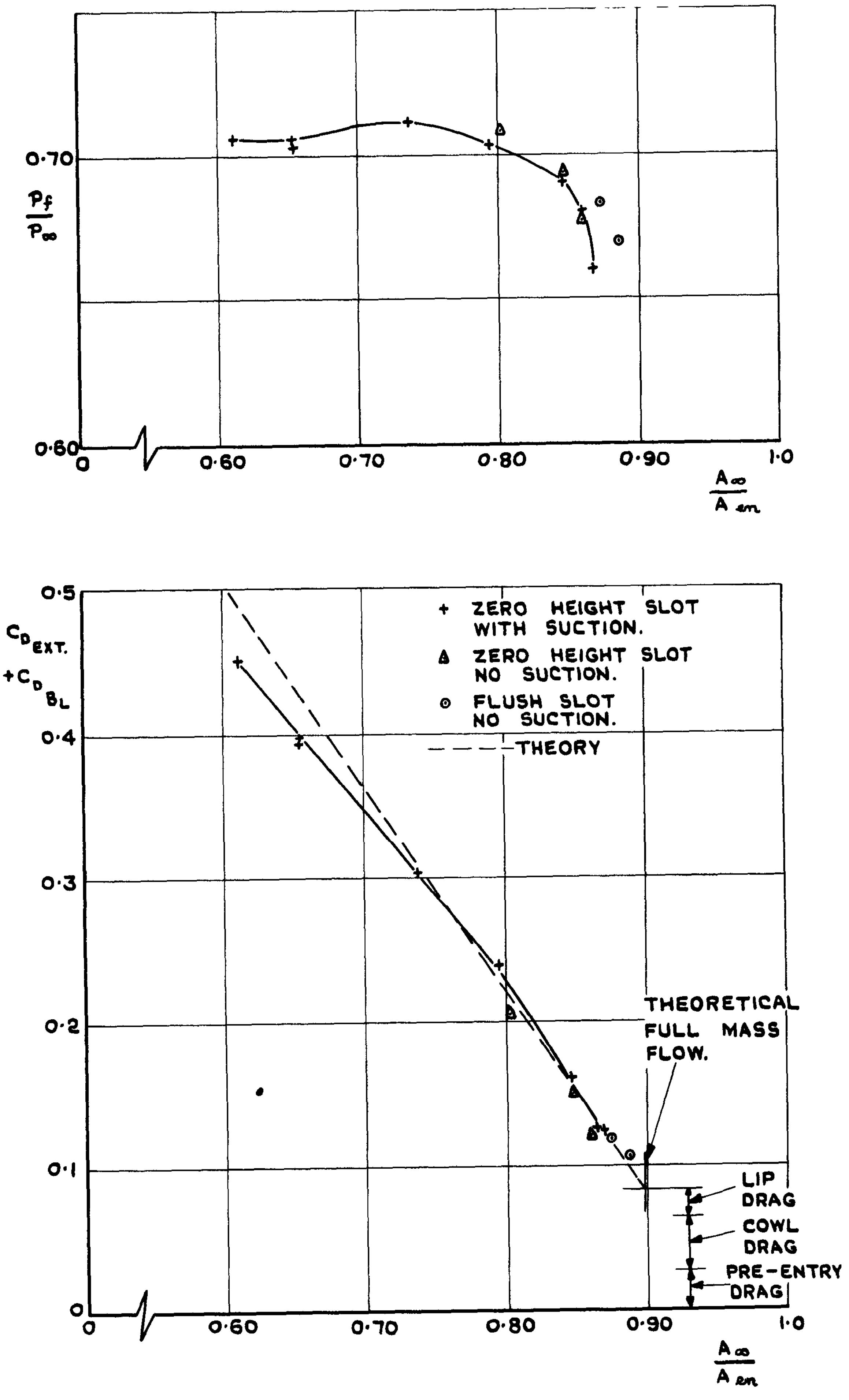


FIG. 18. DRAG AND PRESSURE RECOVERY OF 25° VII $M_{w_\ell} = 2{\cdot}85$ AT $M_\infty = 2{\cdot}48$.

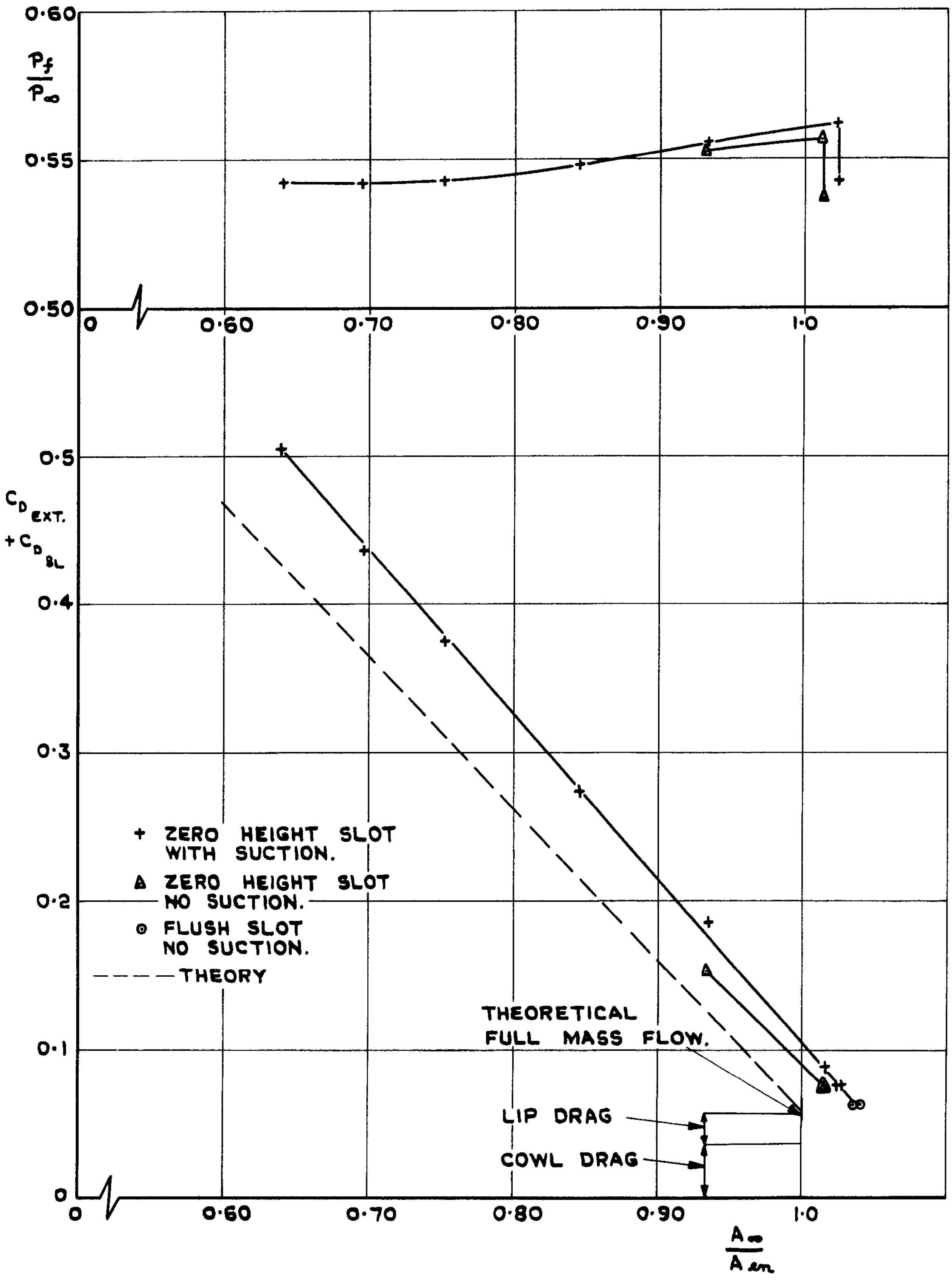


FIG. 19. DRAG AND PRESSURE RECOVERY OF 25° VII $M_{w_l} = 2{\cdot}85$ AT $M_\infty = 2{\cdot}90$.

C.P. No. 605

Published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
York House, Kingsway, London w.c.2
423 Oxford Street, London w.1
13A Castle Street, Edinburgh 2
109 St. Mary Street, Cardiff
39 King Street, Manchester 2
50 Fairfax Street, Bristol 1
35 Smallbrook, Ringway, Birmingham 5
80 Chichester Street, Belfast 1
or through any bookseller

Printed in England

S.O. CODE No. 23-9013-5

C.P. No. 605