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by

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WIND TUNNEL EXPERIMENTS ON A LIFTING JET IN A BLUFF BODY WITH AND WITHOUT WINGS

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W. J. G. Trebble, B. Sc.

SUMMARY

Measurements have been made of the interference loads arising from the interaction between a mainstream and a relatively large jet efflux emerging from the lower surface of a bluff body. As the ratio of mainstream velocity to jet efflux velocity is increased from zero, the lift increment due to the jet is initially reduced and a nose-up moment is produced. The maximum loss is about a quarter of the installed thrust but at higher values of the velocity ratio some lift recovery occurs. Similar trends are observed with a wing fitted but the lift recovery at high velocity ratios and the associated nose-up moments are greater due to additional circulation lift carried on the wing.

An attempt has been made to deduce the interference loads due to an intake from the difference between these results and those for a geometrically similar lifting-fan model. This analysis suggests that the intake flow gives rise to large lift and nose-up moment increments which are augmented by the presence of a wing.

Replaces R.A.E. Technical Note No. Aero 2971 - ARC 26390

CONTENTS

ILLUSTRATIONS

1 INTRODUCTION

Earlier tests made on a bluff body containing a relatively large lifting-fan[1,2] have revealed considerable variation in the lift and nose-up pitching moment increments associated with the lifting system as the mainstream velocity is increased, particularly with wings fitted to the model. There is a region of wake-like flow on the lower surface of the body behind the jet efflux while, at higher mainstream velocities, substantial jet-induced circulation seems to be present. As regards intake conditions, arguments, in which the sink flow at the intake is superposed on mainstream flow, imply lower pressures ahead of the intake exactly balancing higher pressures behind the intake thus giving a nose-up moment but with zero nett change in lift. A corresponding simple theory for the interaction between the mainstream and the jet efflux cannot readily be formulated since a source flow is not appropriate to represent a directed jet. In practice, under the influence of the mainstream, the emergent jet is distorted and deflected rearwards; in the process secondary flows are initiated within the jet which quickly develop into the two trailing vortices typifying the breakdown of a deflected jet. This flow field is not readily amenable to simple theoretical analysis though some progress is now being made at R.A.E. towards this end.

In order to determine the relative magnitude of the intake and efflux effects, it was decided to test a model with only the efflux represented i.e. a model fed with compressed air. These results could then be compared with those available from the similar lifting-fan model[1,2] and the intake interference loads could then be deduced from the differences between them.

2 DETAILS OF MODEL AND TESTS

Tests were made in the No.1 11½ × 8½ ft wind-tunnel at R.A.E. Farnborough on the model illustrated in Fig.2, which is a half scale version of the lifting-fan model of Ref.1 and 2 with only the jet efflux represented. The body could be tested in isolation or with an unswept wing of gross aspect ratio either 1.54 or 3.08 (Fig.3); these represent gross spans of twice and four times the body width. The wing could be fitted in either a high or low position with its mid-chord point halfway along the body; the wing-body angle was zero throughout. A circular dural pressure box (Fig.4) was fitted into the body with its centre at the mid-point of the body. The model was suspended on a strut rig from the overhead balance with the moment centre 4.8 in. above the centre of the jet exit; but the results have been corrected to give moments about the centre of the jet exit.

The external air-feed system is illustrated schematically in Fig.1. Compressed air was passed through a 3 in. diameter ring-main into eight equally spaced flexible tubes and hence into the base of the brass strut leading to the pressure box (Fig.3) inside the model. A strut guard, extending from the floor of the tunnel to a point about 3 inches from the upper surface of the model, was used to protect most of the strut from external aerodynamic forces. The small part of the strut exposed to the mainstream had an elliptic cross-section but, within the strut guard, the section quickly changed to a circle with its diameter equal to the major axis of the ellipse. Inside the body, the top of the pressure-box could be changed (Fig.4) so that, with the strut vertical, the model incidence could be set at angles of -10°, 0 and $+10^\circ$.

The perforated-plate in the pressure-box was designed to choke when passing 3 lb of air per second at a 3:1 pressure ratio in an attempt to provide a reasonably uniform efflux for a jet velocity of 180 ft/sec. Further flow smoothing was obtained from the gauze screen situated $\frac{1}{2}$ in. upstream of the nozzle.

In view of the heavy weight of the brass air-feed strut (45 lb), it was necessary to ensure very good repeatability of incidence in order to avoid prohibitive 'tare' changes in pitching moment readings due to weight redistribution. Incidence was therefore measured by reflecting a beam of light from a concave mirror in the model to a ground glass screen in the tunnel roof. The calibration of this screen gave about 2 inches movement per degree so that the incidence could be maintained within ±0.02 degrees, even with an allowance for model vibrations at relatively high mainstream velocity. The absolute angle of incidence was measured with an inclinometer at zero mainstream velocity. In passing, it should be mentioned that, for later tests[4], the brass strut was replaced with one made from araldite and glass-cloth with a consequent weight reduction from 45 lb to 9 lb.

3 TEST PROCEDURE

The mass-flow rate of the compressed air was measured with the aid of a 4 in. diameter orifice plate in a 6 in. diameter supply pipe. The jet efflux velocity (V_J) was determined from the mass flow, as the mean velocity through the exit which had an area of 0.2 sq ft: fortunately, mainstream flow had no effect on the mass flow for a given supply pressure. Static pressure measurements were also made at the base of the strut and inside the pressure-box.

The uniformity of the jet efflux was investigated with a pitot-static rake mounted in the exit plane of the nozzle. This rake consisted of a central pitot-tube and radial arms, at 60° stagger, each containing three pitot tubes positioned at centres of equal area. Twelve static-pressure tubes were mounted on six radial arms midway between the pitot-tube so that the local velocity could be obtained at 37 equally spaced points in the plane of the exit by taking pressure measurements with the rake at two rotational positions 30° apart. The unmodified pressure-box gave a very high core to the efflux (approximately twice the mean velocity) but this could be reduced by blocking the central holes in the perforated plate. An optimum velocity distribution (Fig.5) was obtained using a blockage circle of $2\frac{3}{4}$ in. diameter (Fig.4) which reduced the variations in velocity to within ±20% of the mean value.

The exit nozzle could be replaced with a blanking plate either for datum measurements on the model without jet efflux or for measuring the constraints imposed on the rig when pressurised. The latter measurements showed that the constraints varied linearly with pressure and at the standard excess pressure of 40 p.s.i. (i.e. the pressure required to give an efflux velocity of 180 ft/sec) amounted to:-

Lift	-1.9 lb
Drag	+0.1 lb
Pitching moment	+0.4 lb ft

Appropriate corrections have been applied throughout.

At angles of incidence of 0 and ±10°, measurements were made of the lift, drag and pitching moment of the model, both with and without wings, over a range of mainstream velocity from 0 to 140 ft/sec with efflux velocities of 0, 110, 150 and 180 ft/sec (pressure-box excess pressures of 0, 20, 30 and 40 p.s.i.). From an assessment of the scatter and degree of correlation of the experimental results, the measuring accuracy is estimated as $\frac{1}{4}$ lb on lift, 1/10 lb on drag and $\frac{1}{4}$ lb ft on moment: these figures should be compared with the installed thrust of 22 lb, 15 lb and 9 lb for input excess pressures of 40, 30 and 20 p.s.i.

4 EXPERIMENTAL RESULTS

The increments in lift, drag and pitching moment (ΔL, ΔD and ΔM) due to the jet efflux have been made non-dimensional by dividing by the installed static thrust (T) or, for the moments, by the product of this thrust and the jet exit diameter (d). Plots of these increments against the velocity ratio (V_o/V_J) are given in Figs.6-13 for the various model configurations at angles of incidence of 0 and ±10° over a range of jet velocity from 110 to 180 ft/sec. All the zero incidence results are compared in Fig.14, but, for clarity, symbols have here been deleted. Although the results are quoted for values of the velocity ratio up to slightly above unity, it will be appreciated that under normal operating conditions it is unlikely that lifting-jet engines would be used at mainstream velocities (V_o) greater than about half the jet efflux velocity (V_J)*.

As the mainstream velocity is raised from zero there is a progressive reduction in the lift increment due to the jet efflux. Initially the lift loss on the isolated body (Fig.6a) appears to be proportional to the square of the mainstream velocity (i.e. ΔC_L = a constant) but, when the velocity exceeds two-fifths of the efflux velocity, there is a reduction in the rate of increase in lift loss and, eventually, a maximum loss of approximately a quarter of the installed thrust occurs when the mainstream velocity is about two-thirds of the efflux velocity. The magnitude of the lift-loss increases with increase of incidence in the positive sense while the velocity ratio at which this maximum loss occurs is simultaneously reduced. Thus at +10° incidence nearly one-third of the installed thrust is lost at a velocity ratio of 0.5 while at -10° incidence the maximum lift loss is reduced to a sixth of the installed thrust and this does not occur until the velocity ratio is 0.7. These lift losses originate in a region of low pressure on the undersurface of the body behind the jet exit which is created by the interference between the efflux and the mainstream. At the higher mainstream velocities, jet-induced circulation leads to some recovery in the lift but, even at the highest velocity ratio tested (V_o/V_J = 1.2), there is still some lift loss at zero incidence. However, full recovery has occurred at either ±10° incidence before the mainstream velocity is equal to the efflux velocity.

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*Higher velocity ratios can occur while the engines are being started or shut-down in flight though these will be of a transient nature while conditions of high velocity ratio are naturally of interest from safety aspects and also to allow for future developments.

The effect of wings on the lift increment can be studied in Fig.14. The presence of the wing increases the initial rate of lift loss as the mainstream velocity is raised, and also slightly increases the magnitude of the maximum loss, particularly for the low wing position. The velocity ratio for maximum lift loss is reduced by increasing the wing aspect ratio as well as by lowering the wing position on the body. However, the lift recovery is far greater than on the isolated body and is raised by increasing the wing span and by lowering the position of the wing on the body. For example, at a velocity ratio of unity with the large-span wing in the low position on the body, the lift increment due to the jet efflux is more than twice the installed thrust.

For fundamental considerations of the mainstream interference effects, it is appropriate to take moments about the centre of the jet exit. Initially the nose-up moment, like the lift decrement, appears to vary as the square of the mainstream velocity (Fig.14b) but, at higher velocity ratios, the rate of increase in moment is reduced until, at velocity ratios above a half, the moment increases linearly with further increase in mainstream velocity. The effect of adding a wing is to produce larger interference moments which increase with wing span. Further, larger moments are experienced with a low wing than with a high wing. These results are consistent with the lift changes.

The thrust component, due to the inclination of the vector with the model at incidence, has been removed from the drag results of Figs.11, 12 and 13 so that the true interference drag loads may be recorded. In general, the drag increment increases as the mainstream velocity is raised. However, at positive incidence there is a small thrust increment at low speeds. This thrust at positive incidence presumably originates from the resolved component of the reduced lower surface pressure which also gives rise to the lift loss. As the velocity ratio is increased, this thrust is overwhelmed by the induced drag associated with circulation lift.

5. INTERFERENCE ASSOCIATED WITH AN INTAKE

The present series of tests have investigated the interference loads associated with the jet efflux from a lifting-jet mounted in a body or nacelle. Other tests[2] have also been made on a geometrically similar lifting-fan model though at twice this scale. An estimate of the intake effects can be obtained from the differences between these two sets of tests provided that the results are in a comparable form. The fan-model results in Ref.2 were made non-dimensional by dividing by the installed static thrust (T_o) and plotted against a velocity ratio V_o/V_{JT} where V_{JT} is defined from $T_o = \rho V_{JT}^2 A_J$. However, measurements in the duct showed that the efflux velocity (V_J) was not only greater than this V_{JT}-value but also increased with mainstream velocity thus simultaneously increasing the installed thrust (T). Incorporating an allowance for this variation of efflux momentum with mainstream velocity, the force and moment increments ($\Delta L/T_o$, $\Delta D/T_o$ and $\Delta M/T_o d$) have now been reduced by a factor $(V_{Jo}/V_J)^2$ and plotted against the velocity ratio V_o/V_J (Figs.15, 17 and 19) where V_{Jo} and V_J are respectively the efflux velocity at zero mainstream velocity and in the presence of the mainstream. Figs.16, 18 and 20 give the deduced interference loads due to the intake and, for comparison, the measured interference loads due to the jet efflux. Unfortunately no measurements were made with a low wing on the lifting-fan model so the results are limited to the high wing configuration.

In the presence of the mainstream, the intake flow produces a positive lift increment thus conflicting with the net lift change of zero predicted from simple sink considerations[3]. On the isolated body this upload is small until the mainstream velocity exceeds about a quarter of the efflux velocity after which it rises rapidly, though linearly, with further increase in velocity ratio at a rate $d\left(\frac{\Delta L}{T}\right) \Big/ d\left(\frac{V_o}{V_J}\right) = 1.0$. Installation of the high wing leads to considerable additional lift increments with quite significant benefits accruing even at the lower values of velocity ratio.

A simple estimate of the intake momentum drag associated with the turning of the mainstream into the duct would give a value $\rho V_o V_J S_i/T = V_o/V_J$. The deduced values are in excess of this estimate (Fig.18) though the rate of increase with velocity ratio is as predicted. There is also a slight tendency for the drag increment to increase with wing aspect ratio.

The moment increment is directly proportional to the velocity ratio (V_o/V_J) and is increased by the presence of the wing though proportionately not to the same extent as that observed in the lift increments. Some of this moment increment is to be expected from the intake momentum drag but even assuming that this acts as much as half an intake diameter above the entry plane, only 70% of the increment can be accounted for on the isolated body and a much smaller proportion when the wing is present.

6 CONCLUSIONS

The interaction between a uniform stream and a relatively large jet efflux emerging from the centre of the lower surface of a bluff body reduces the lift increment due to that jet, at least over the practical range of the ratio of flight velocity to jet velocity. Losses of up to at least a quarter of the installed thrust may be anticipated but, at velocity ratios above about a half, there is some lift recovery. The addition of a wing, particularly in a low position on the body, causes some additional lift loss at the lower values of velocity ratio though the lift recovery at the higher velocity ratios becomes greater, again particularly for the low wing but also for the larger span. At all velocities there are appreciable nose-up moment increments which are increased by the presence of a wing.

It has also been deduced that intake flow gives rise to additional positive lift increments and nose-up pitching moments, with an associated drag which is rather greater than would be predicted from simple momentum considerations. The presence of a wing greatly increases the lift increments but has less effect, proportionately, on the moments although these are also increased.

SYMBOLS

T_o	installed thrust, measured at zero mainstream velocity and zero incidence
T	$T_o \, (V_J/V_{Jo})^2$
V_{JT}	theoretical efflux velocity for lifting fan model (defined from $T_o = \rho V_{JT}^2 S_J$)
V_J	jet efflux velocity (calculated from mass flow)
V_{Jo}	jet efflux velocity at zero mainstream speed
ΔL	lift increment
ΔD	drag increment
ΔM	pitching moment increment
α	angle of incidence
ρ	density of air
d	duct exit diameter
S_J	exit area
S_i	intake area
A	aspect ratio of wing

REFERENCES

No.	Author	Title, etc.
1	Trebble, W.J.G. Williams, J.	Exploratory wind-tunnel investigations on a bluff body containing a lifting fan. A.R.C. C.P. 597, April 1961
2	Trebble, W.J.G.	Unpublished M.O.A. Report.

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No.	Author	Title, etc.
3	Whittley, D.C. Bissell, J.R.	On the nature of aerofoil characteristics with a sink located in the upper surface including comparison of theory with some fan-in-wing experiments. Eighth Anglo-American Aeronautical Conference September 1961.
4	Trebble, W.J.G.	Wind-tunnel experiments on a simple lifting-jet body with and without wings. A.R.C. C.P. 718, March 1963

TABLE 1

Model Dimensions

Body		**Lifting-fan model**	**Lifting-jet model**
Length		27.5 in.	13.75 in.
Width		15.4 in.	7.7 in.
Height		11.0 in.	5.5 in.
Plan area	S	39.7 sq.in.	99.25 sq.in.
Duct intake and exit areas	S_D	115.0 sq.in.	28.75 sq.in.
S_D/S		0.345	
Wing			
Area (gross)		616 and 1232 sq. in.	154 and 308 sq. in.
Span		30.8 and 61.6 in.	15.4 and 30.8 in.
Chord		20 in.	10 in.
Section		15% RAE 102	
Height of chordline above lower surface of body		9.5 in.	0.75 and 4.75 in.

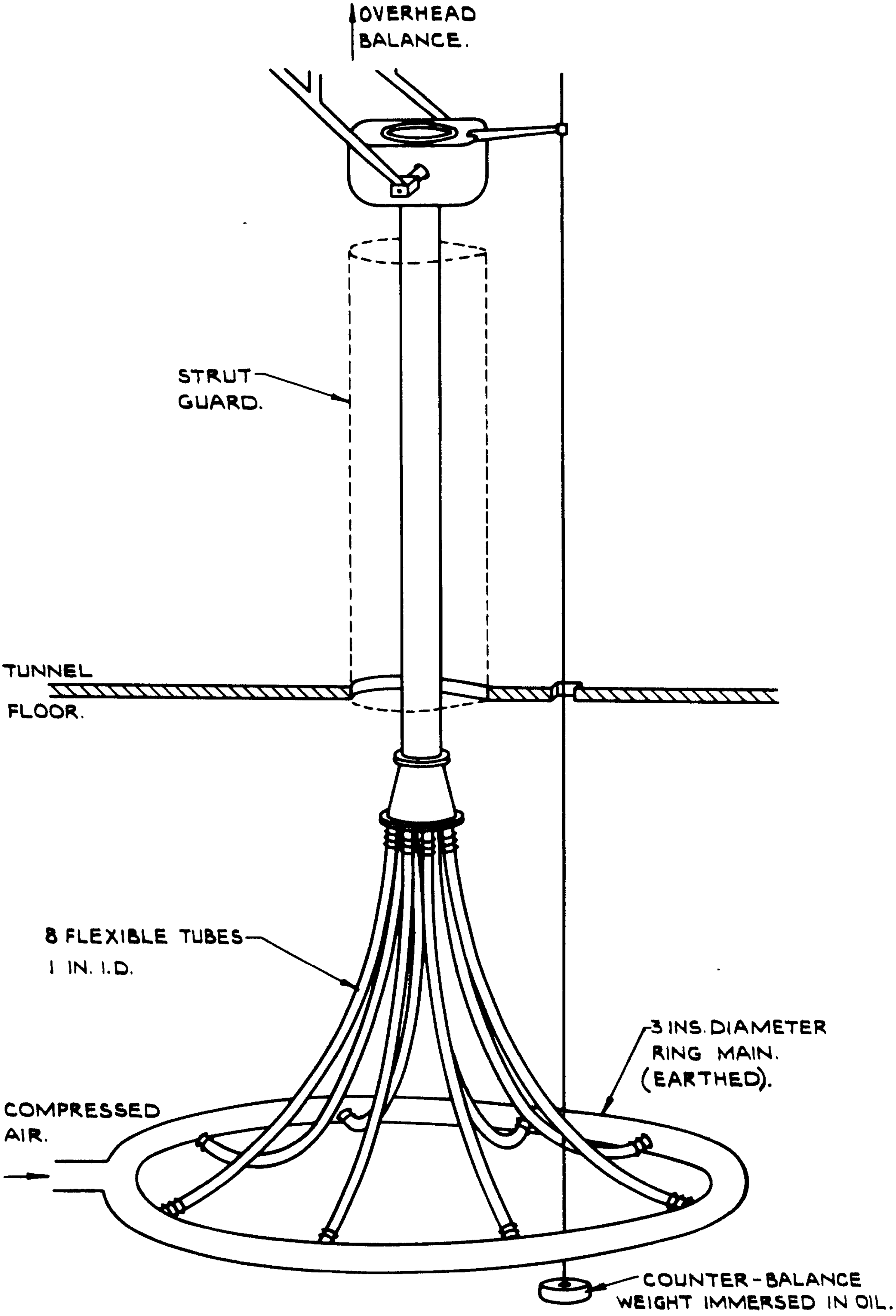


FIG. 1. SCHEMATIC VIEW OF MODEL AND RIG.

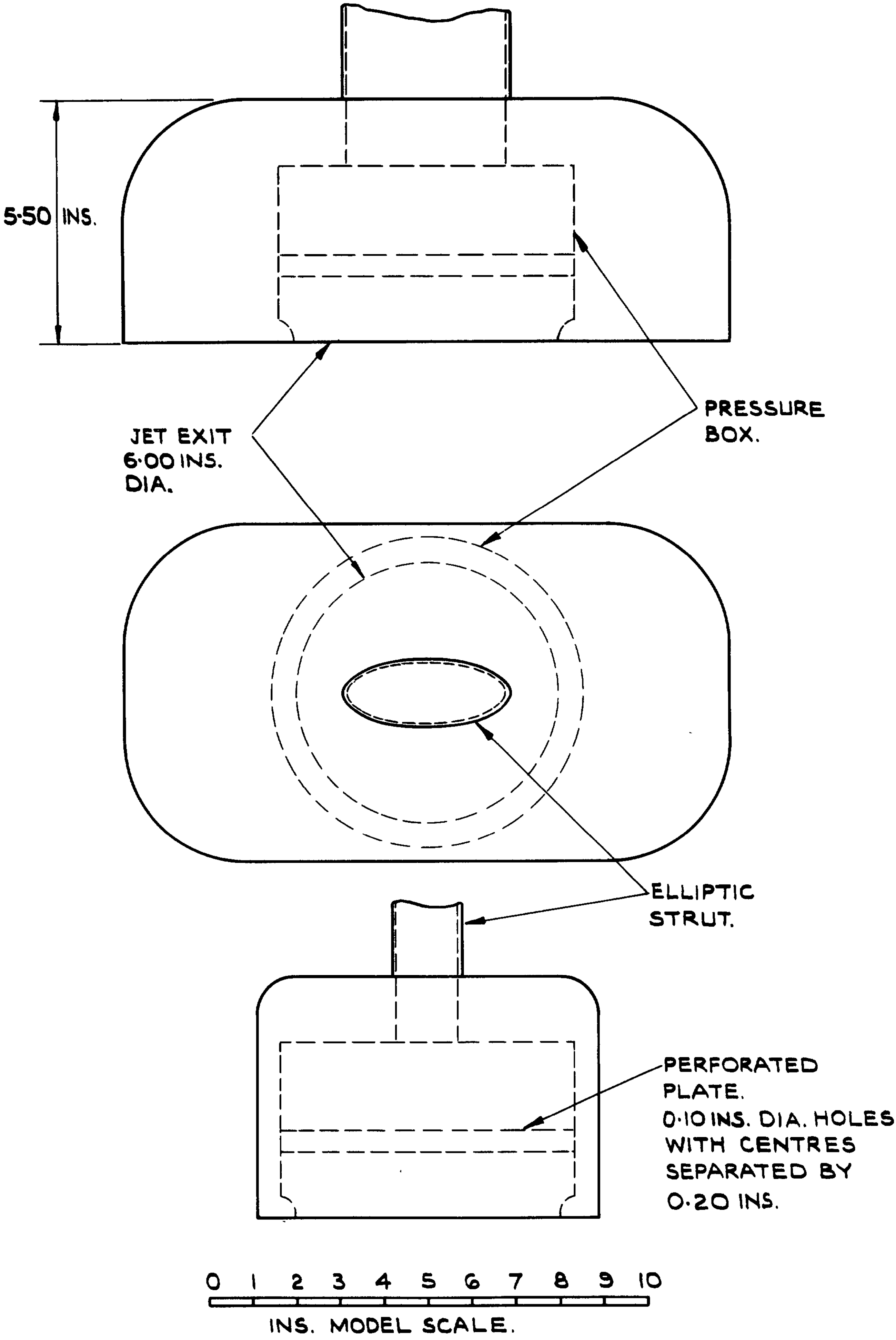


FIG. 2. G. A. OF BLOWING MODEL.

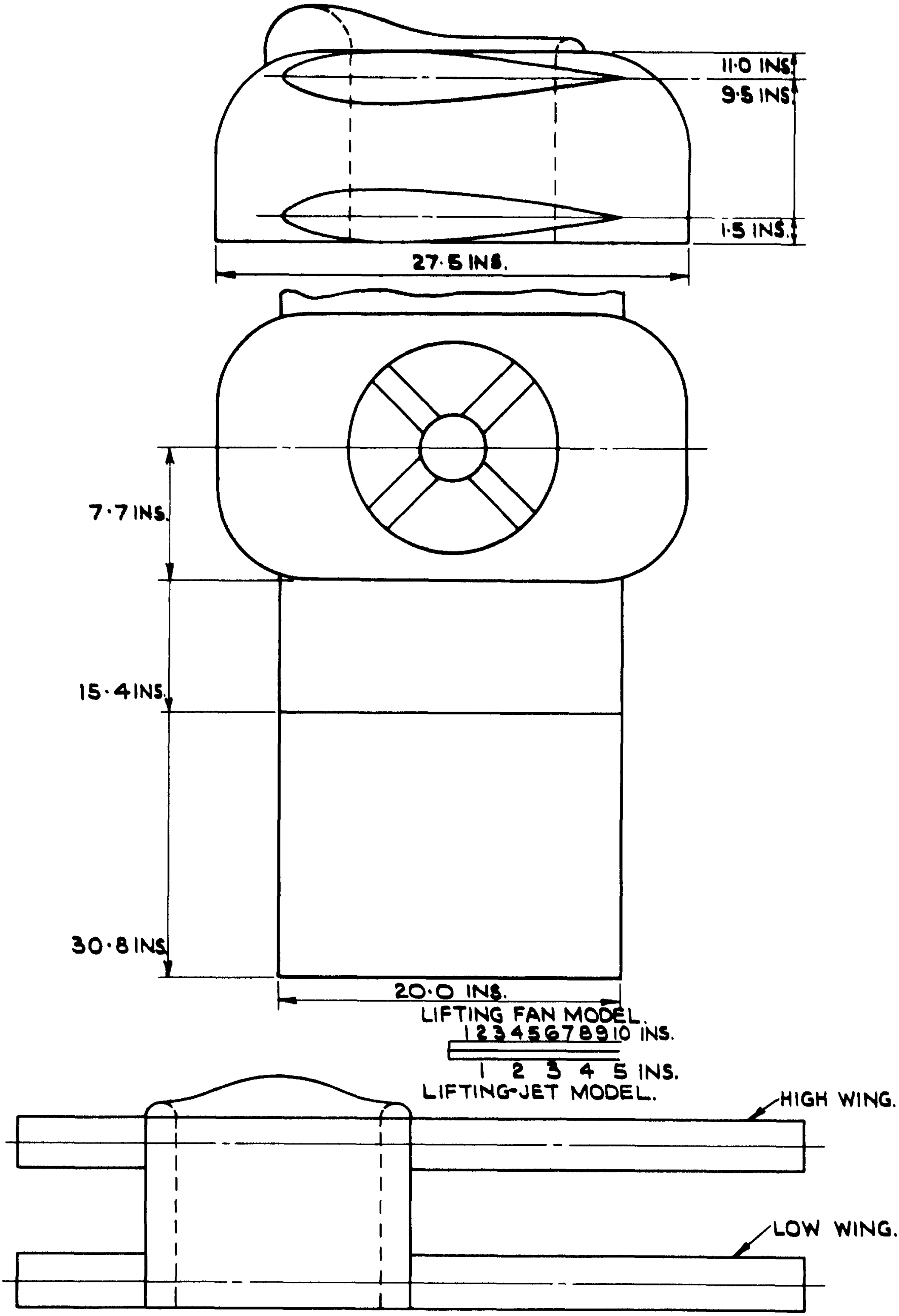
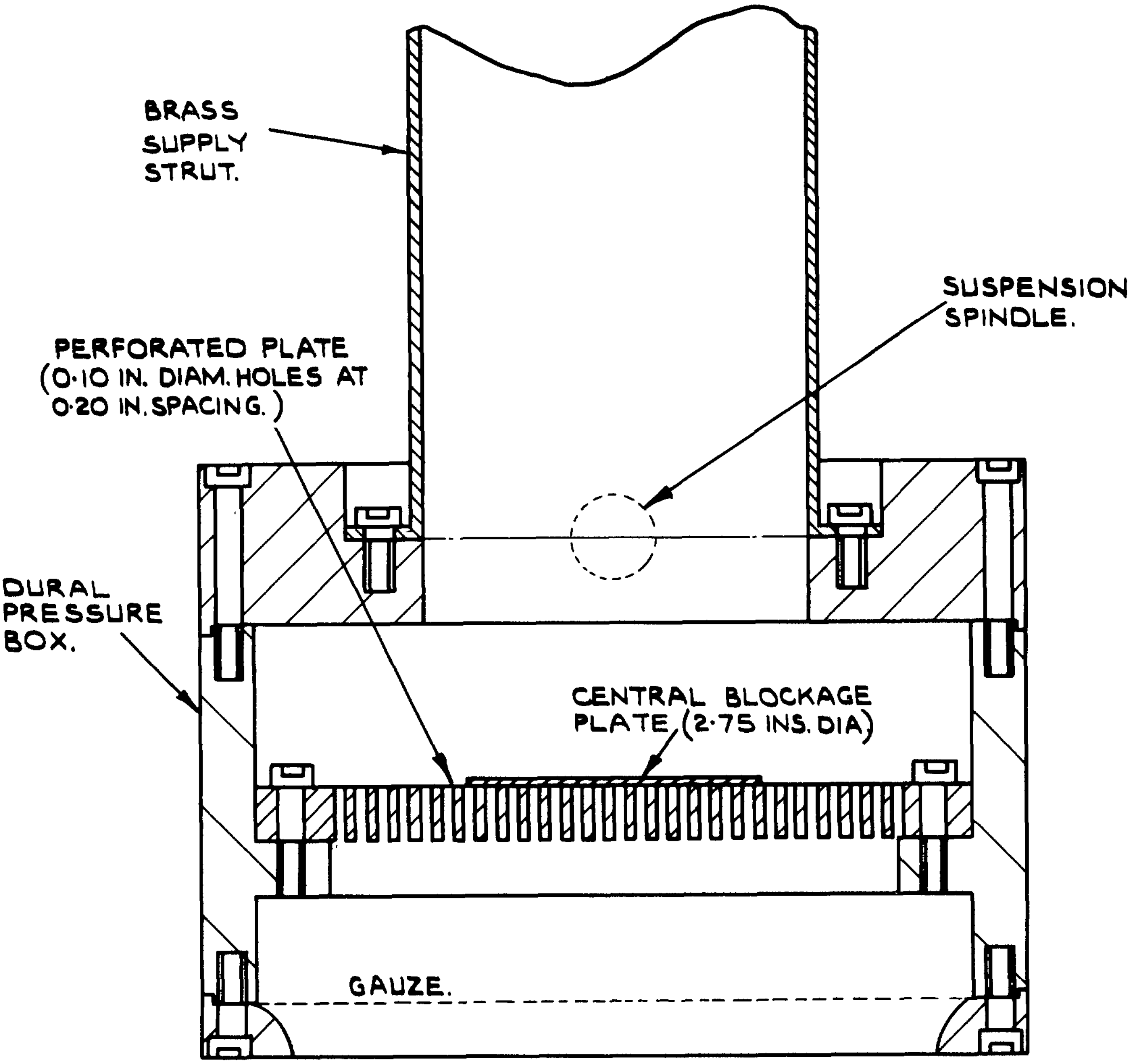
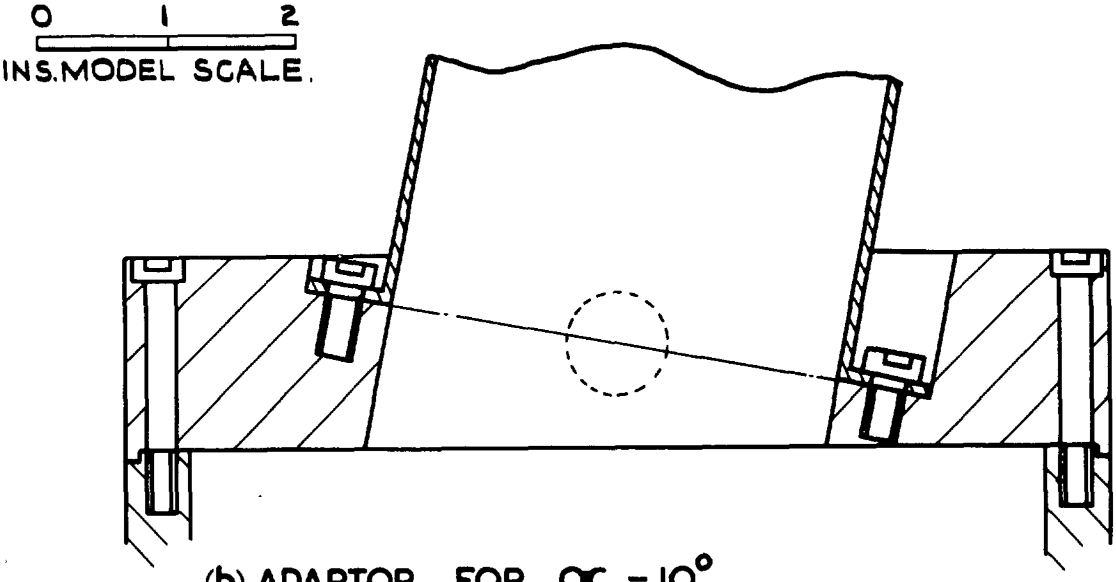


FIG. 3. DETAILS OF WINGS AND LIFTING-FAN MODEL.

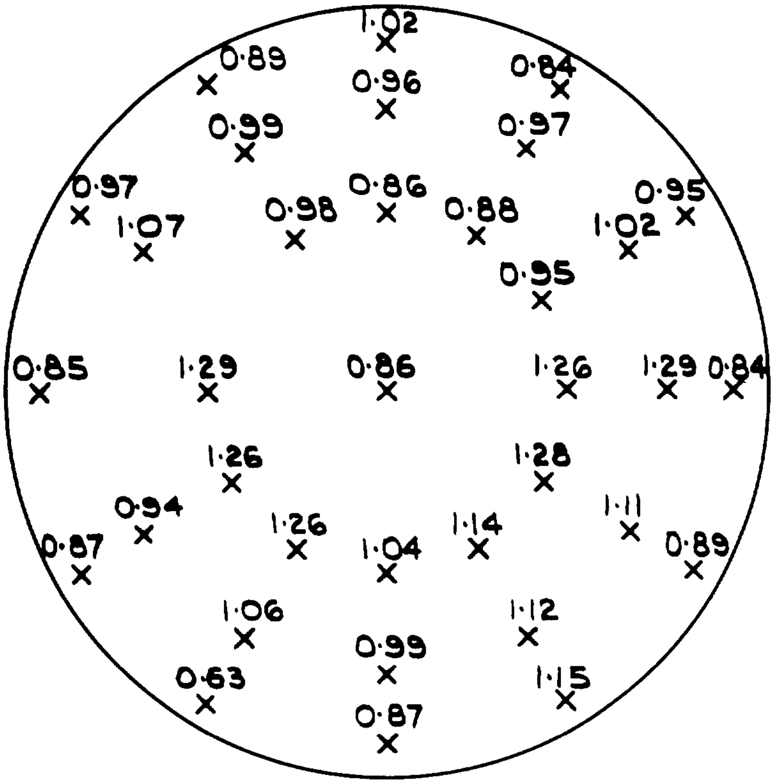


(a) PRESSURE-BOX FOR ZERO INCIDENCE TESTS.

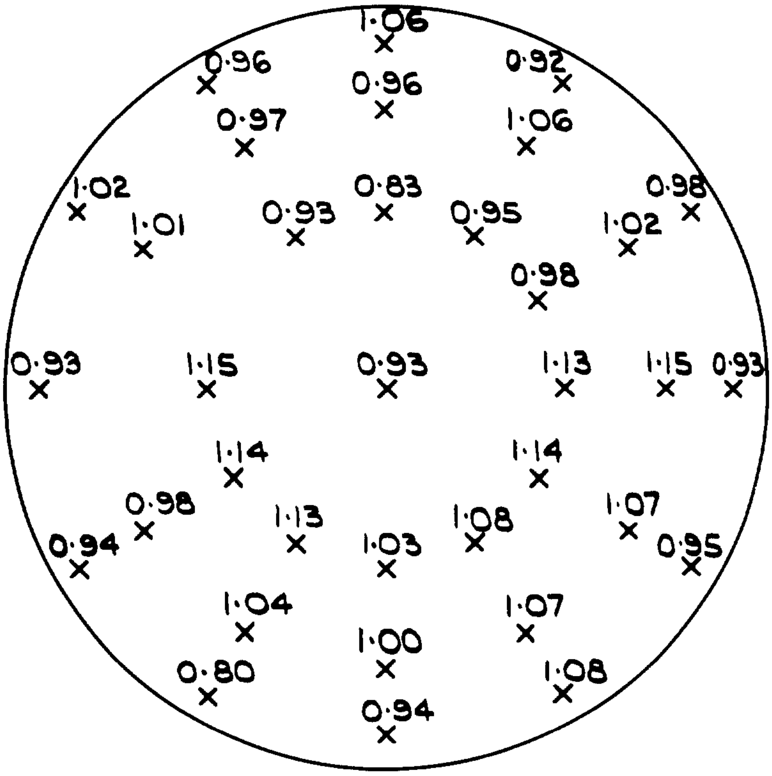


(b) ADAPTOR FOR $\alpha = 10°$

FIG. 4. SECTION THROUGH CENTRE OF PRESSURE BOX.

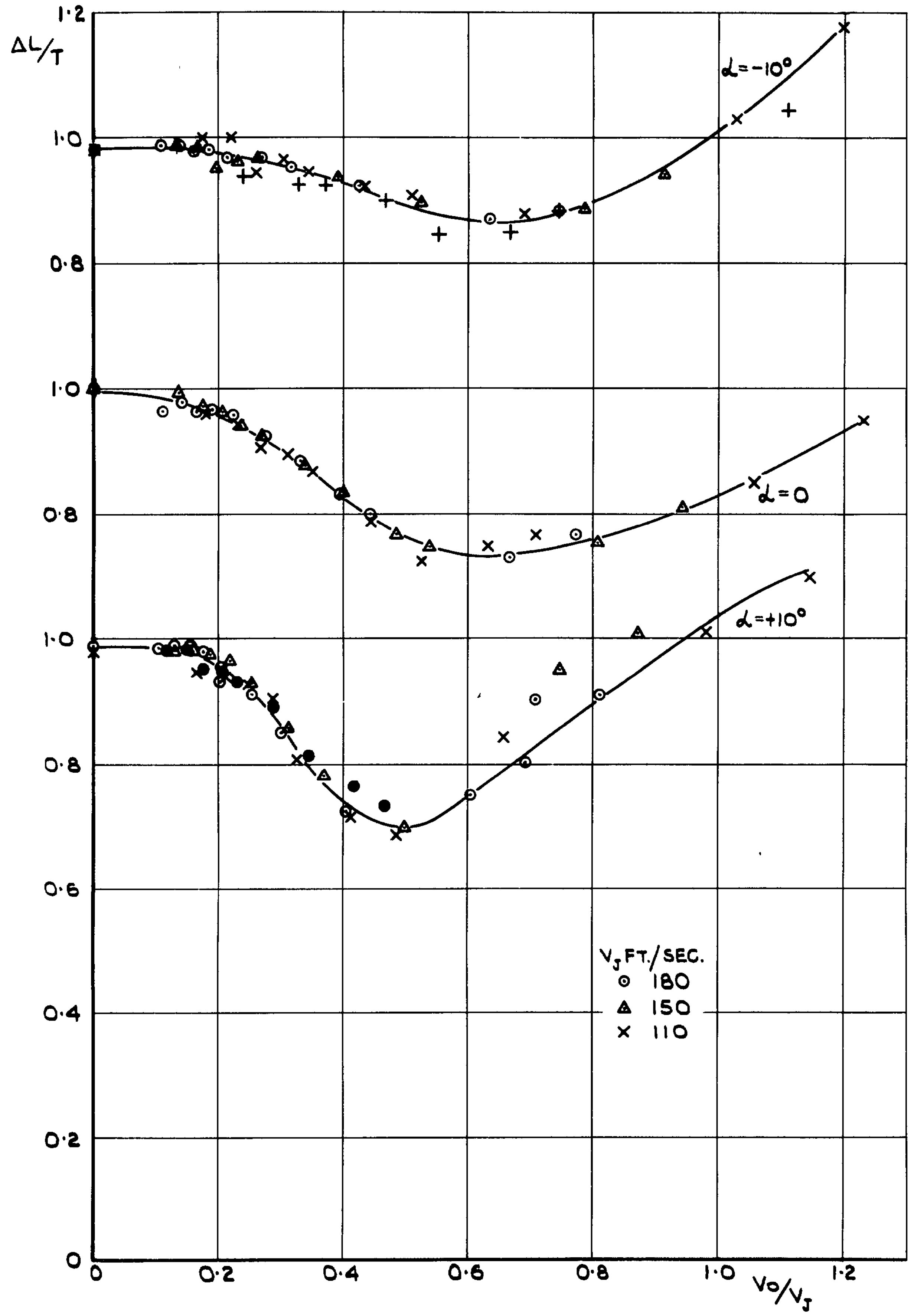


TOTAL HEAD DISTRIBUTION.



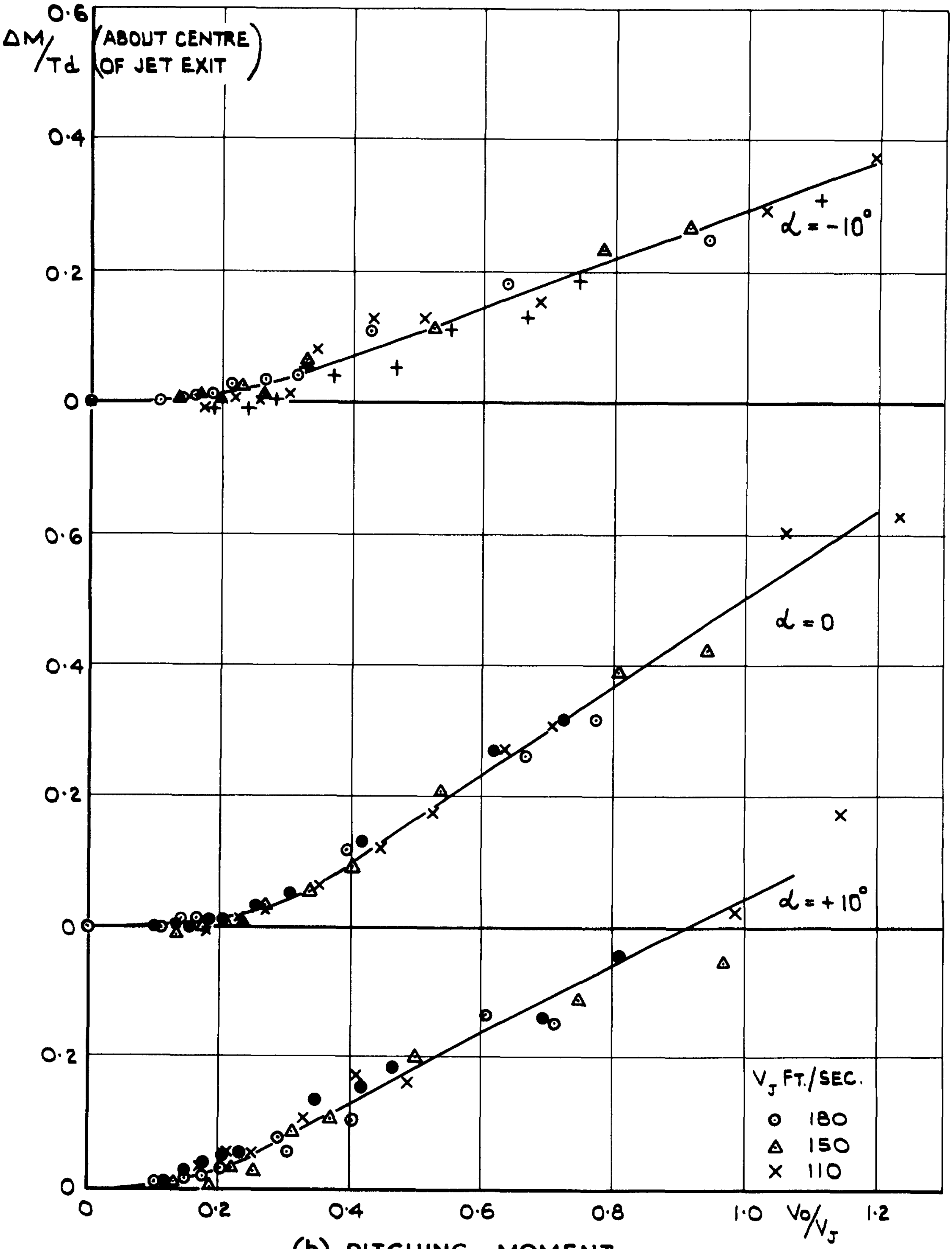
VELOCITY DISTRIBUTION.

FIG. 5. TOTAL HEAD AND VELOCITY DISTRIBUTION IN EXIT PLANE.
NUMBERS INDICATE LOCAL VALUE/MEAN VALUE.



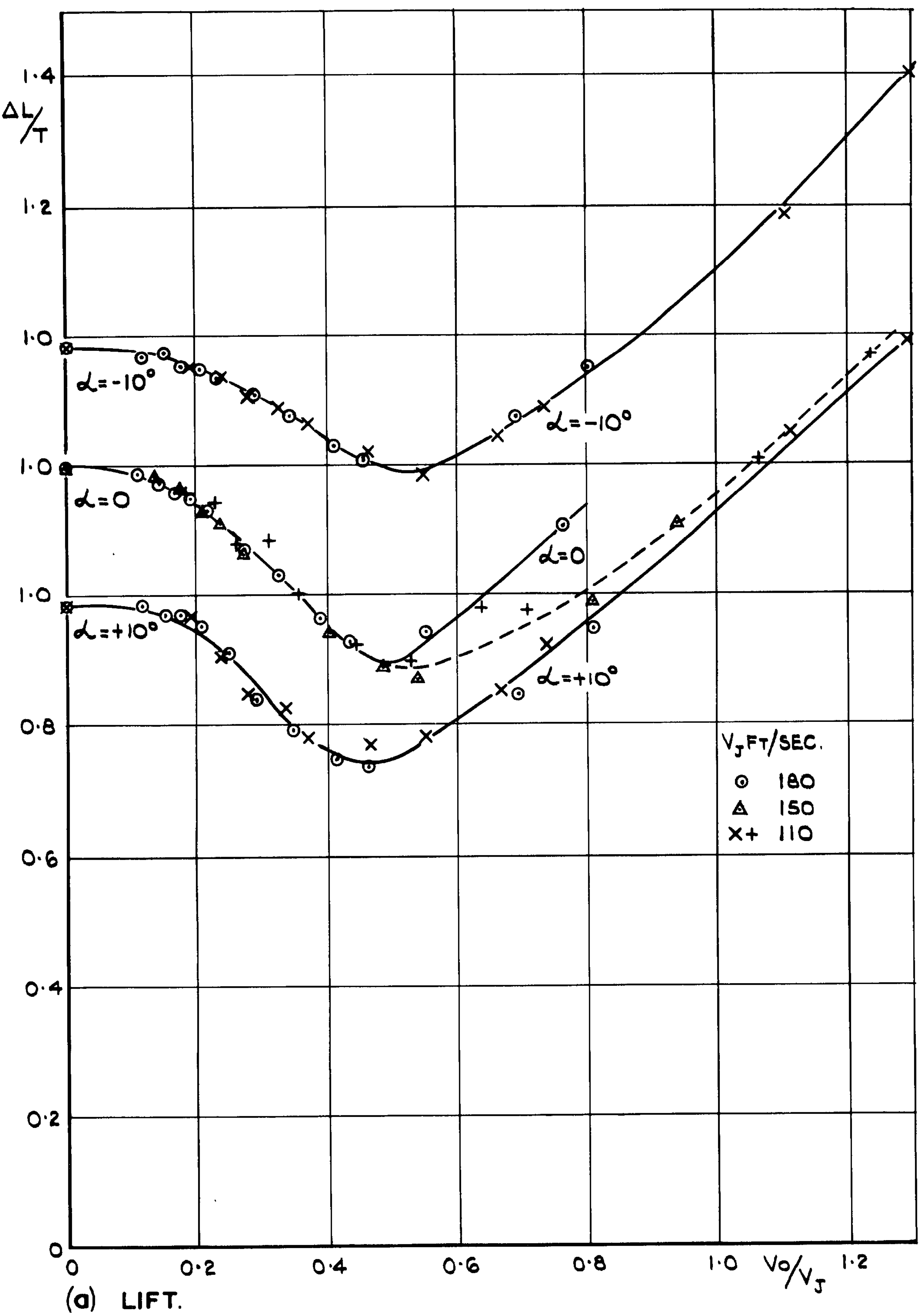
(a) LIFT.

FIG. 6. BLUFF BODY WITHOUT WINGS.



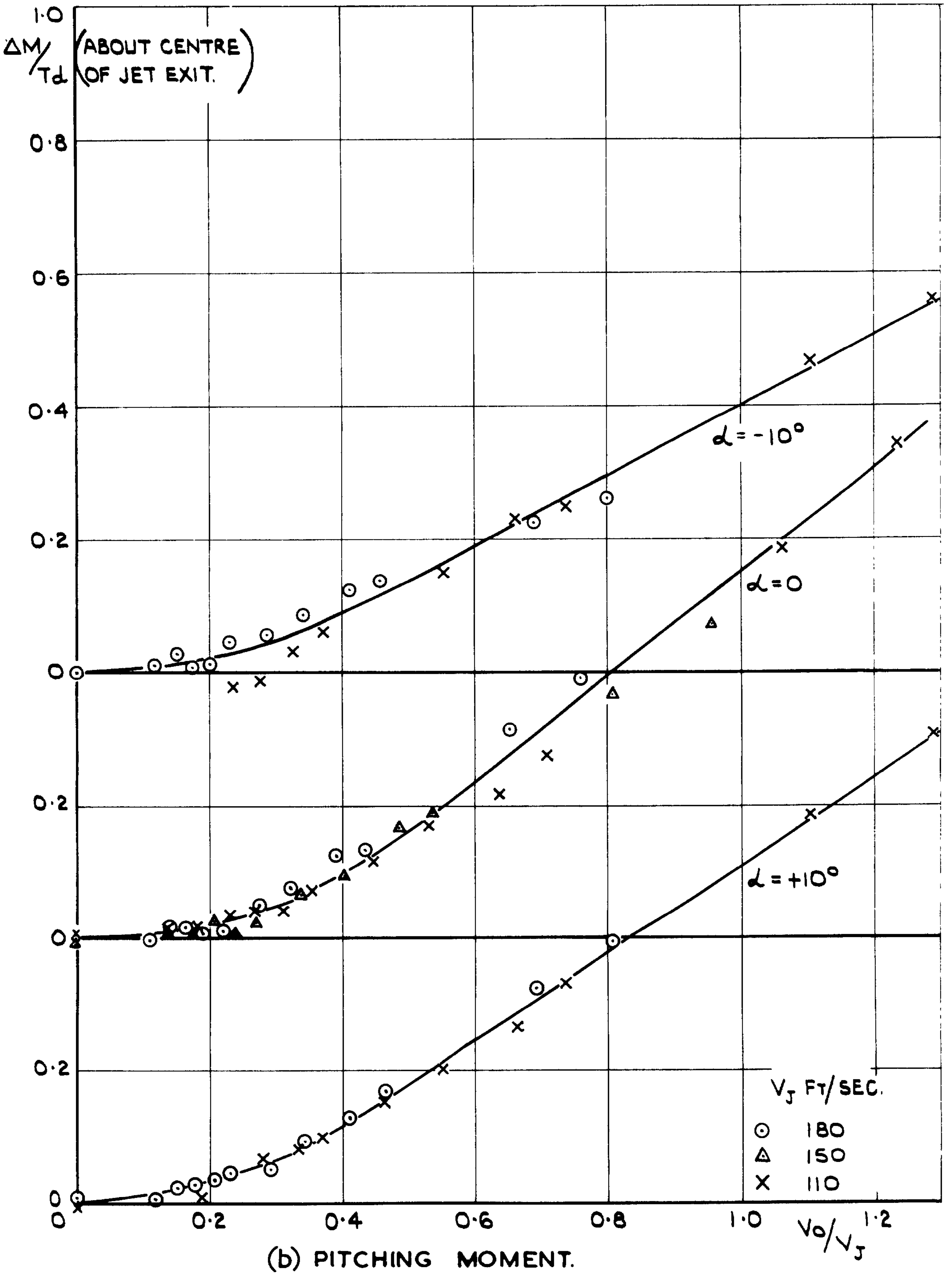
(b) PITCHING MOMENT.

FIG. 6. BLUFF BODY WITHOUT WINGS.



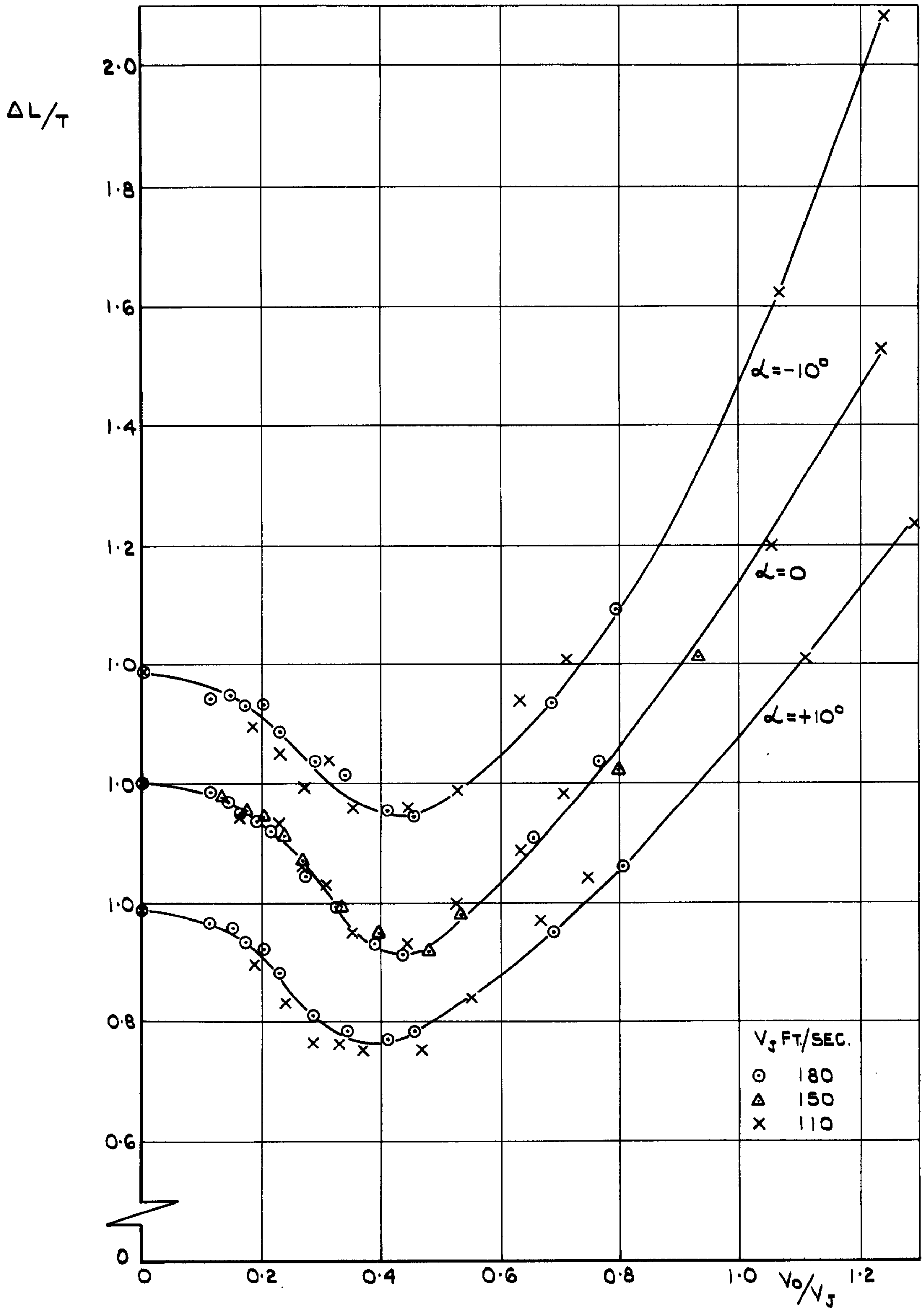
(a) LIFT.

FIG. 7. BLUFF BODY WITH HIGH WING; A = 1·54.



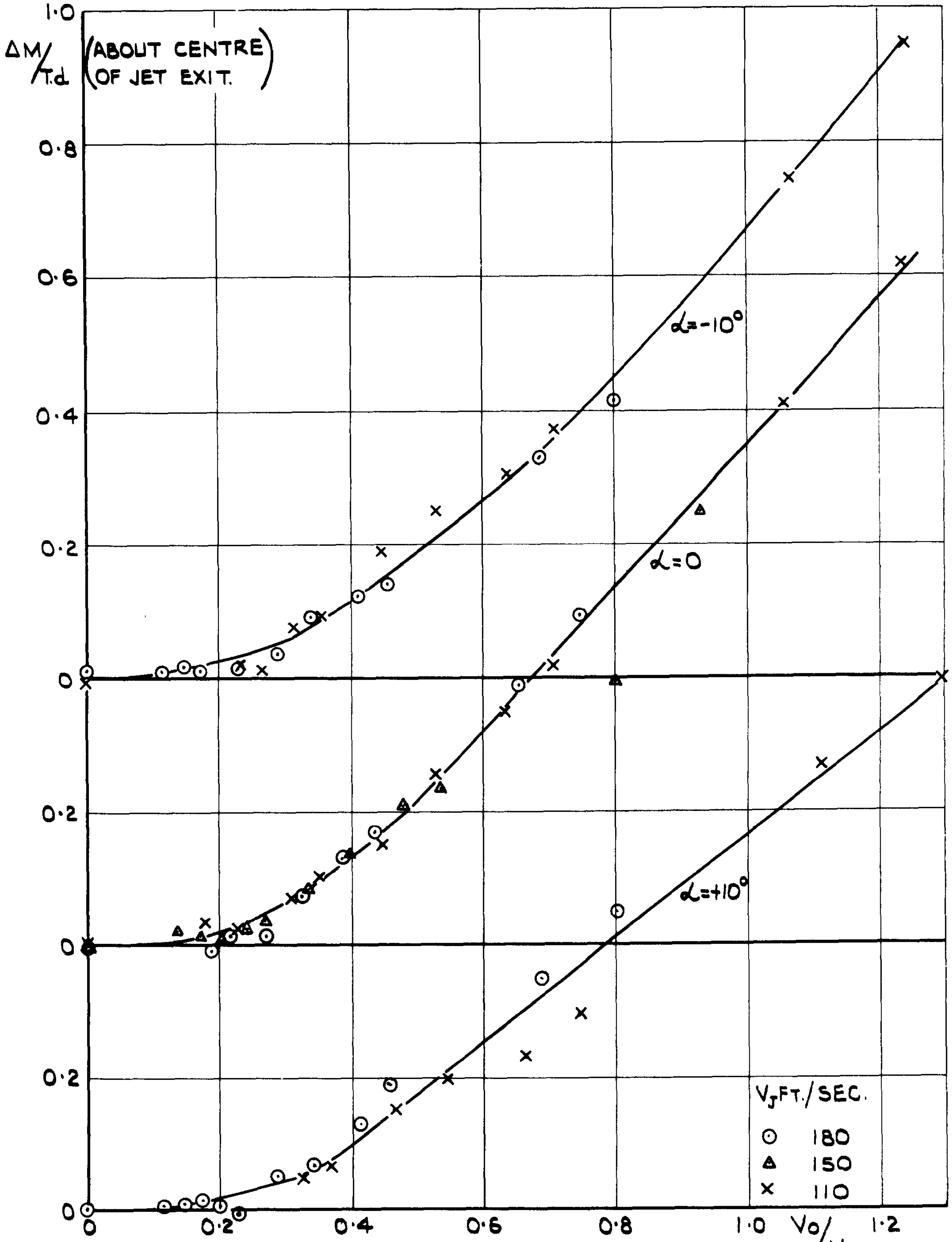
(b) PITCHING MOMENT.

FIG.7. BLUFF BODY WITH HIGH WING; A=1·54.



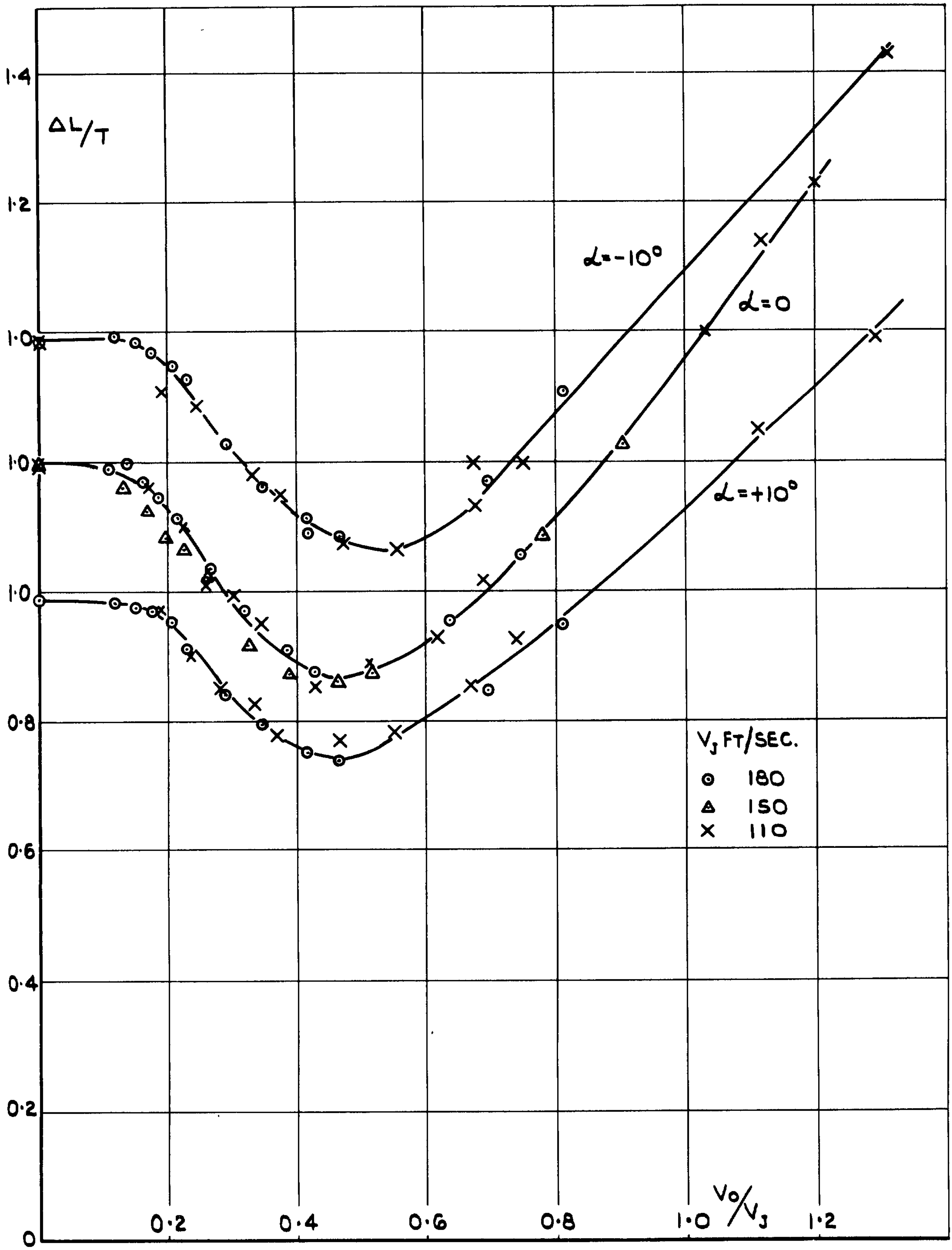
(a) LIFT.

FIG. 8. BLUFF BODY WITH HIGH WING; A = 3·08.



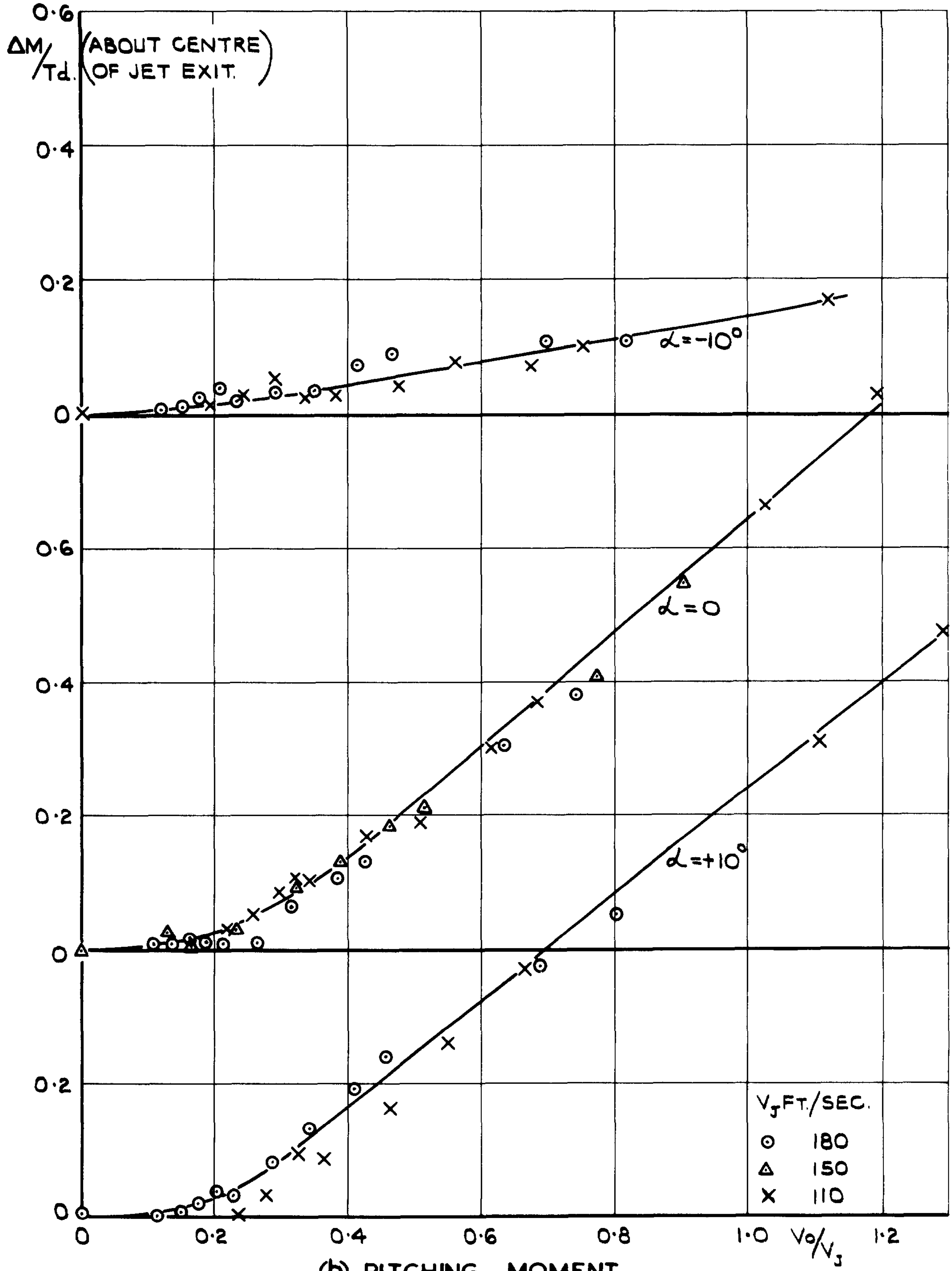
(b) PITCHING MOMENT.

FIG. 8. BLUFF BODY WITH HIGH WING; A=3·08.



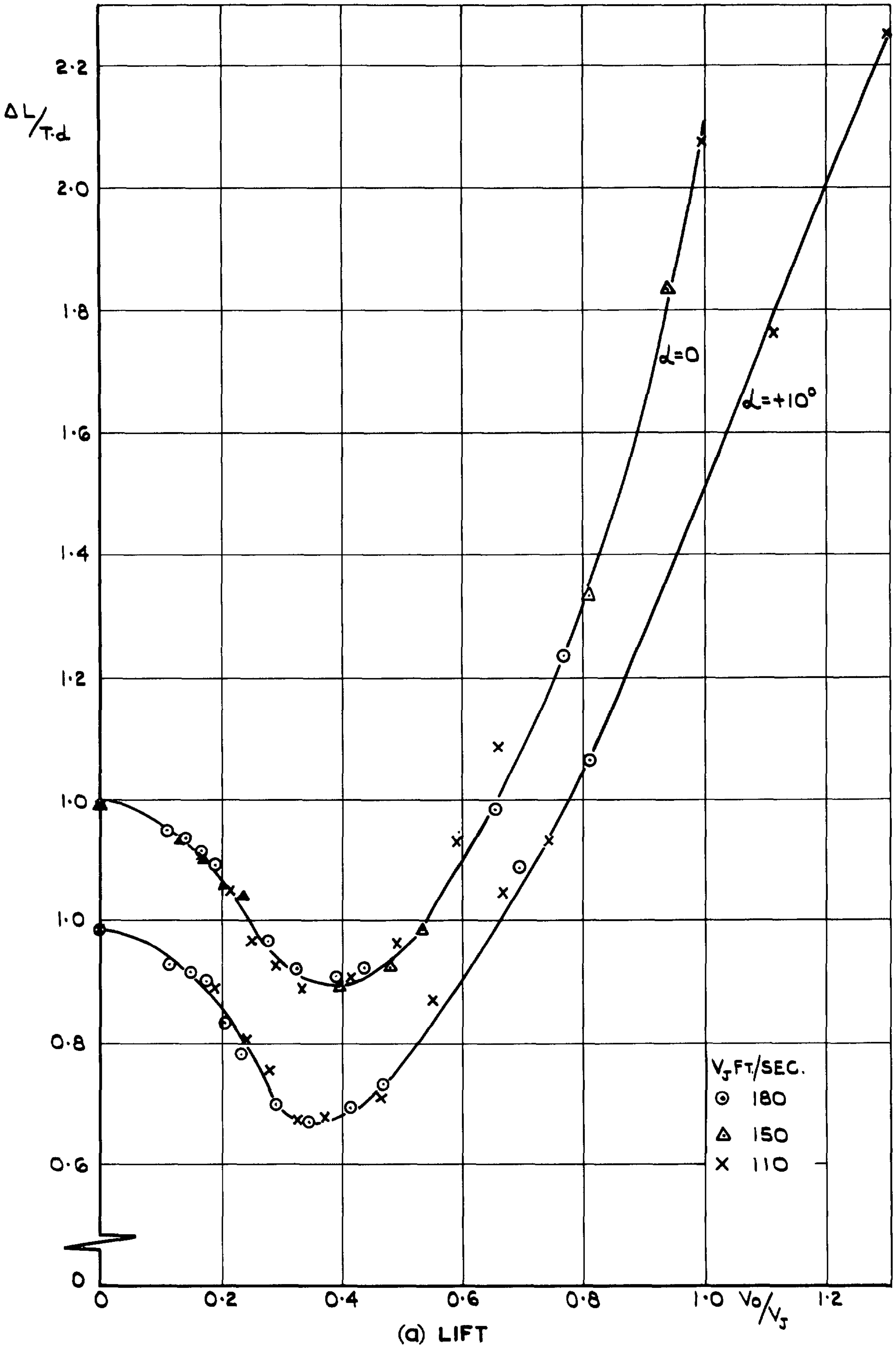
(a) LIFT.

FIG. 9. BLUFF BODY WITH LOW WING; A = 1·54.



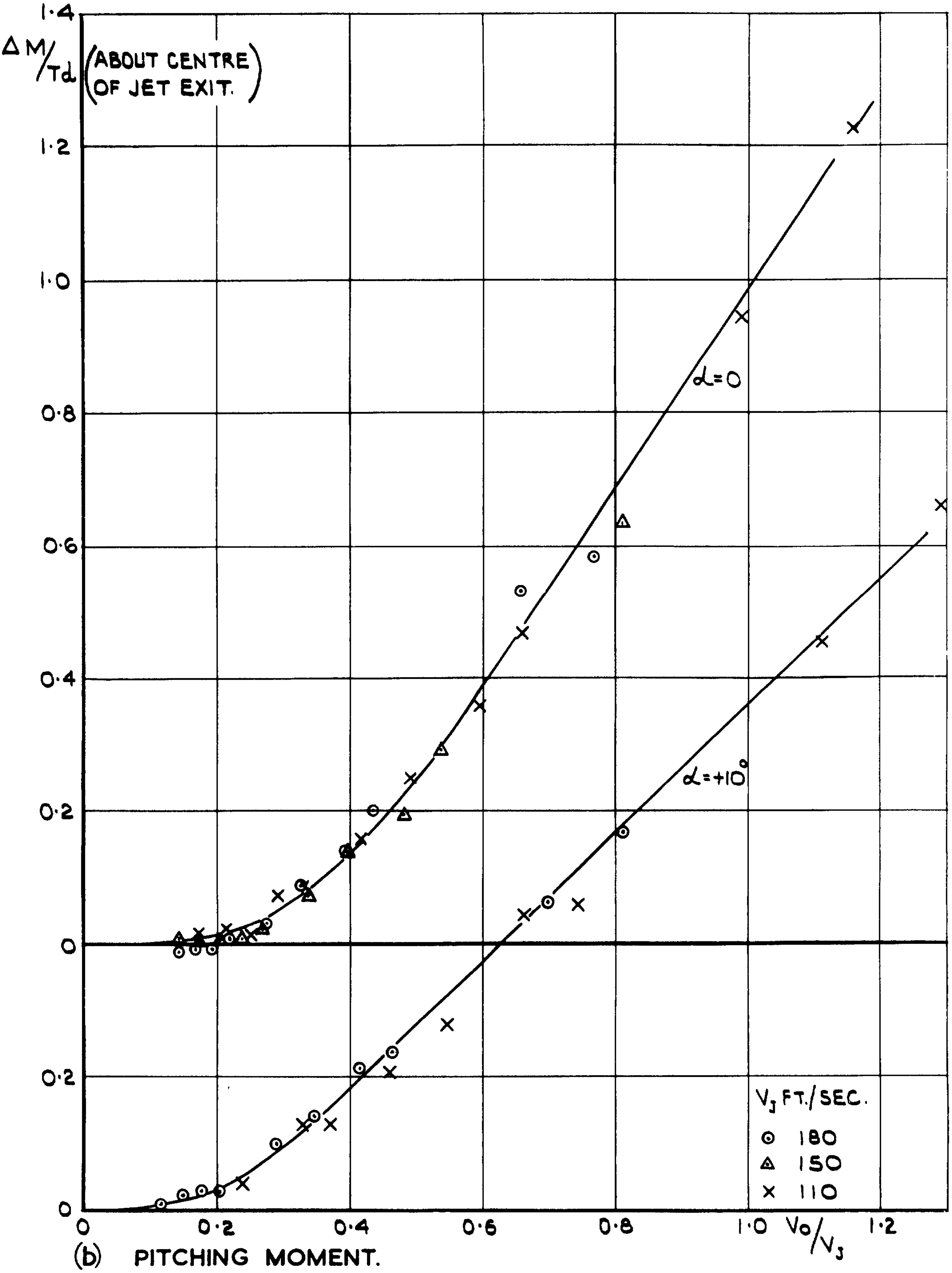
(b) PITCHING MOMENT.

FIG. 9. BLUFF BODY WITH LOW WING; A = 1·54.



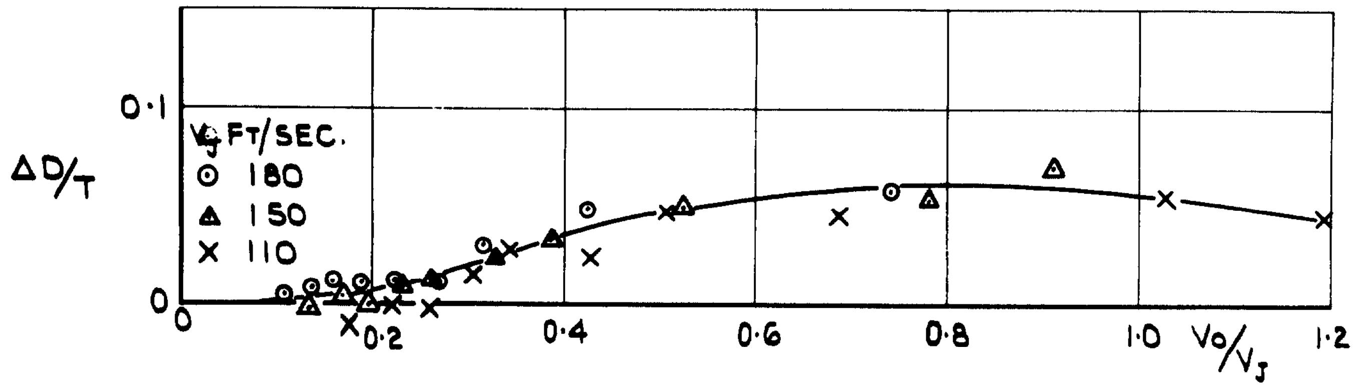
(a) LIFT

FIG. 10. BLUFF BODY WITH LOW WING; A = 3·08.

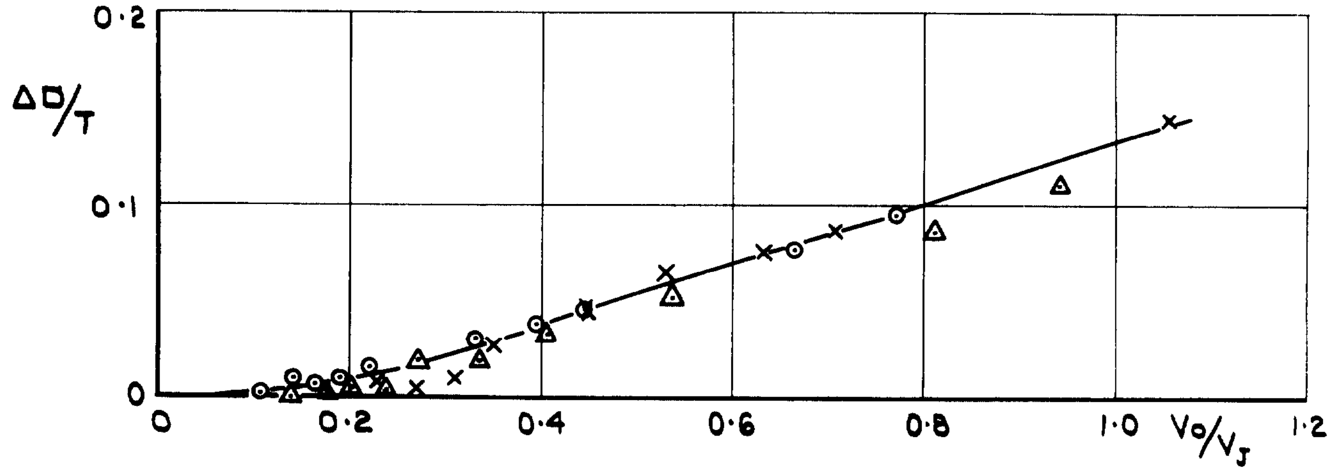


(b) PITCHING MOMENT.

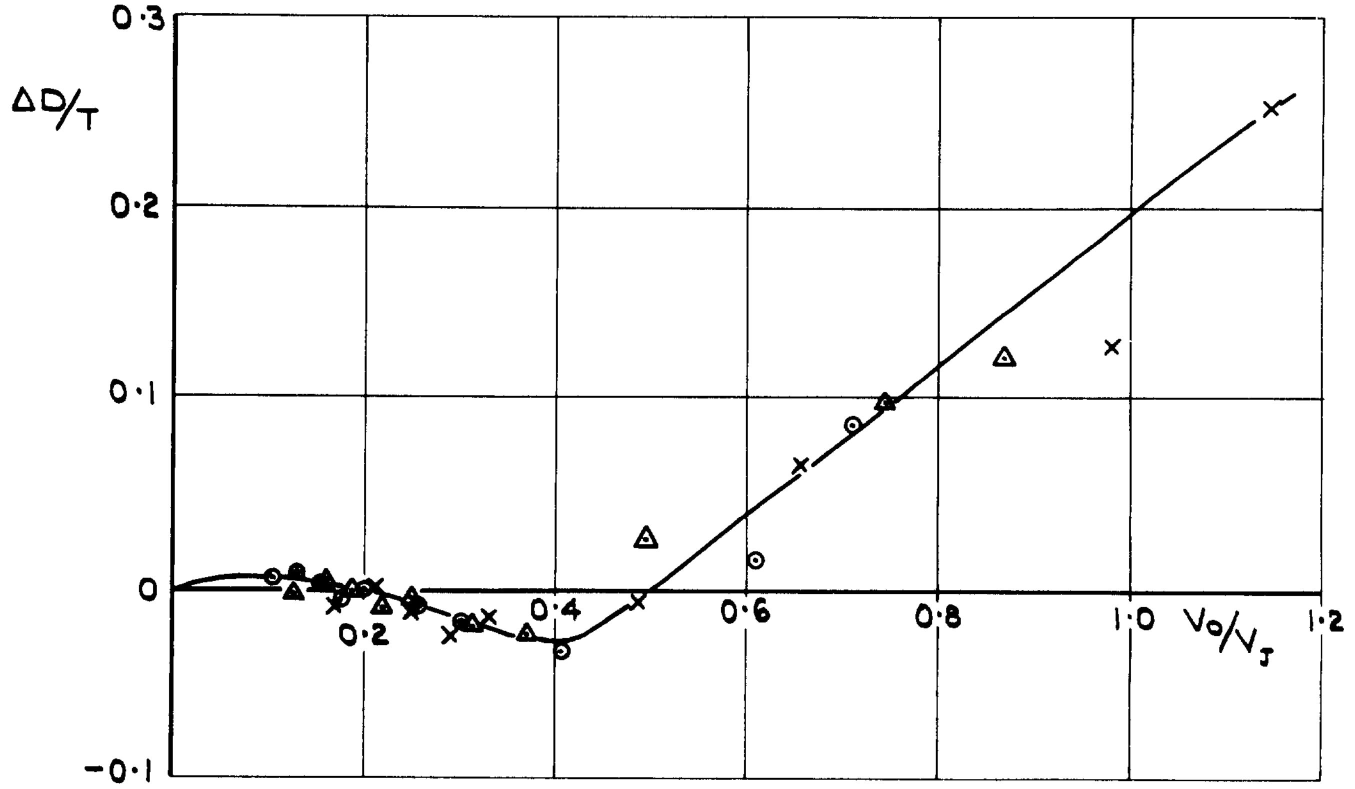
FIG. 10. BLUFF BODY WITH LOW WING; A = 3·08.



(a) $\alpha = -10^\circ$

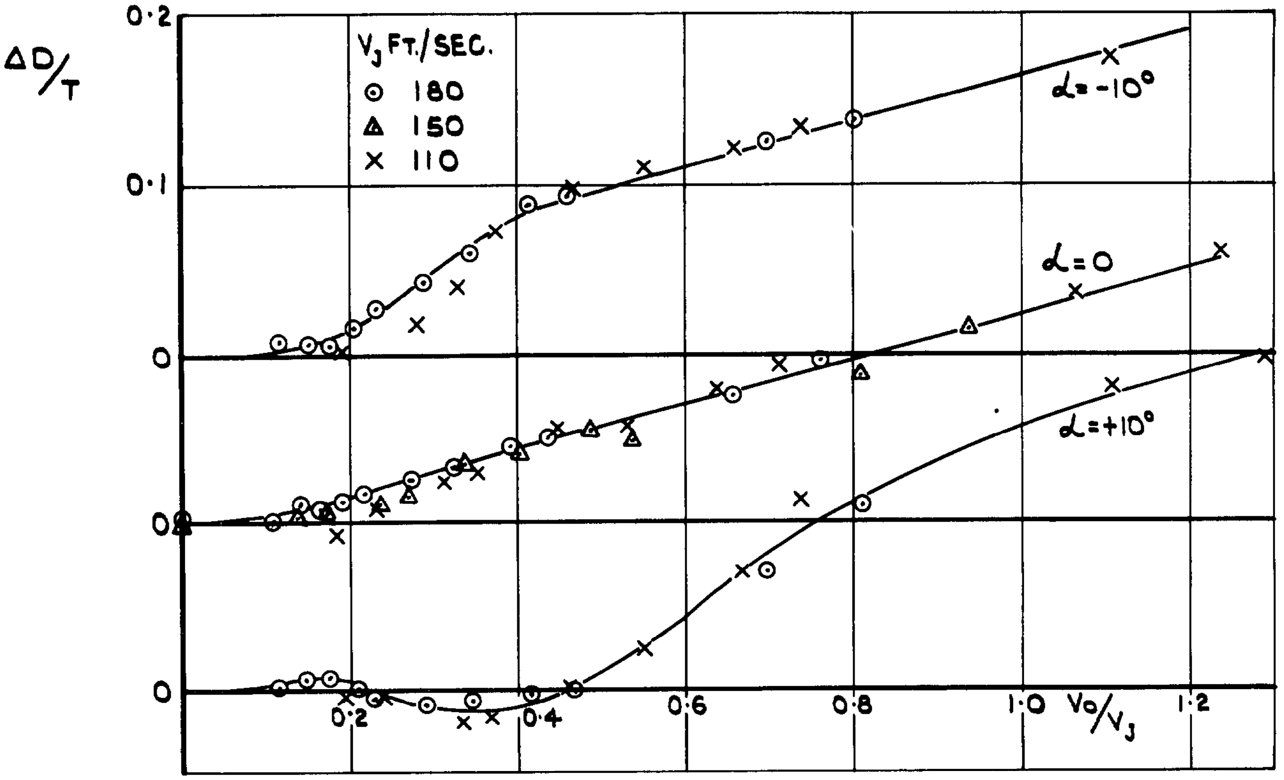


(b) $\alpha = 0$

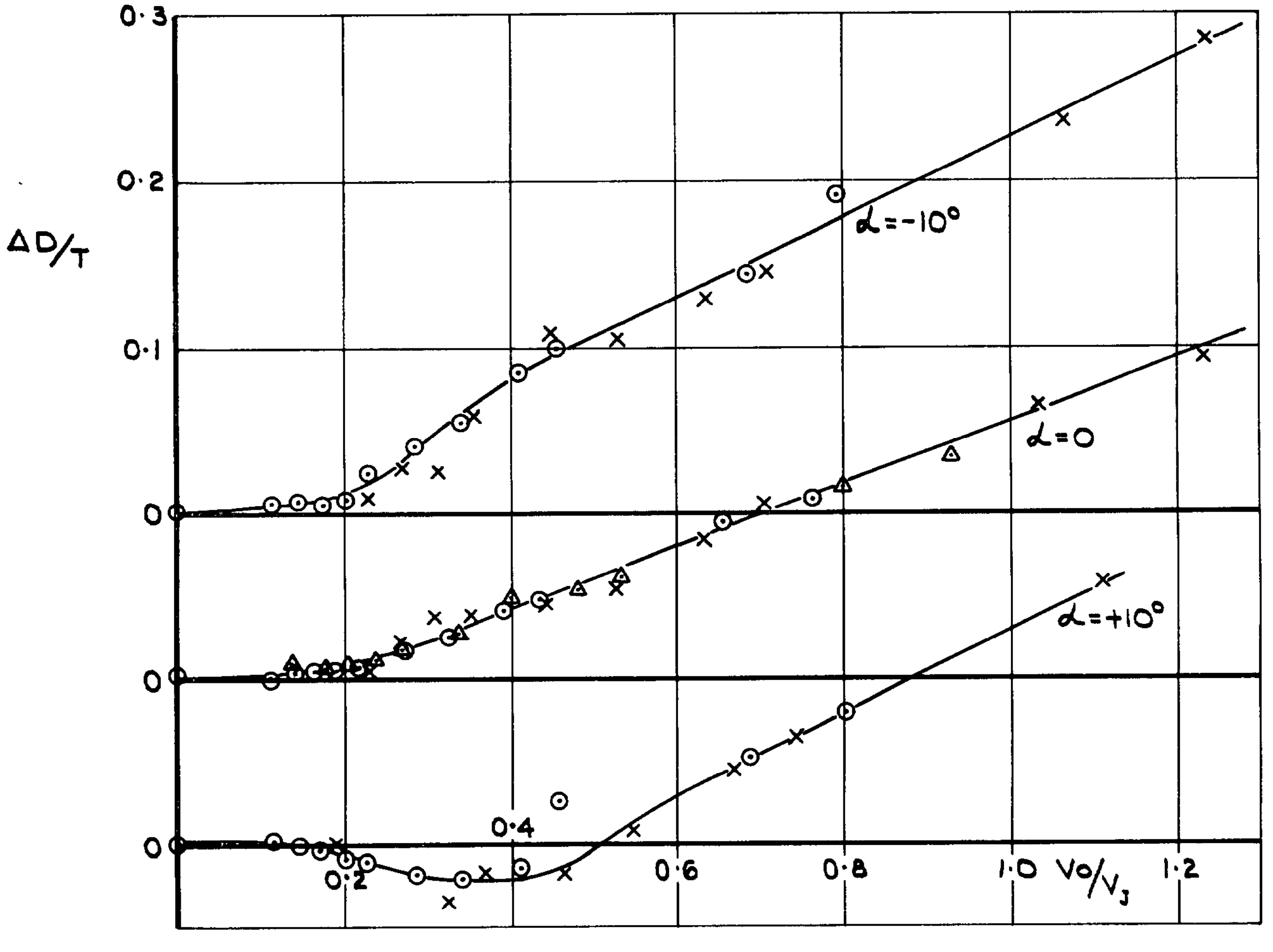


(c) $\alpha = +10^\circ$

FIG. 11. DRAG OF BLUFF BODY WITHOUT WINGS.

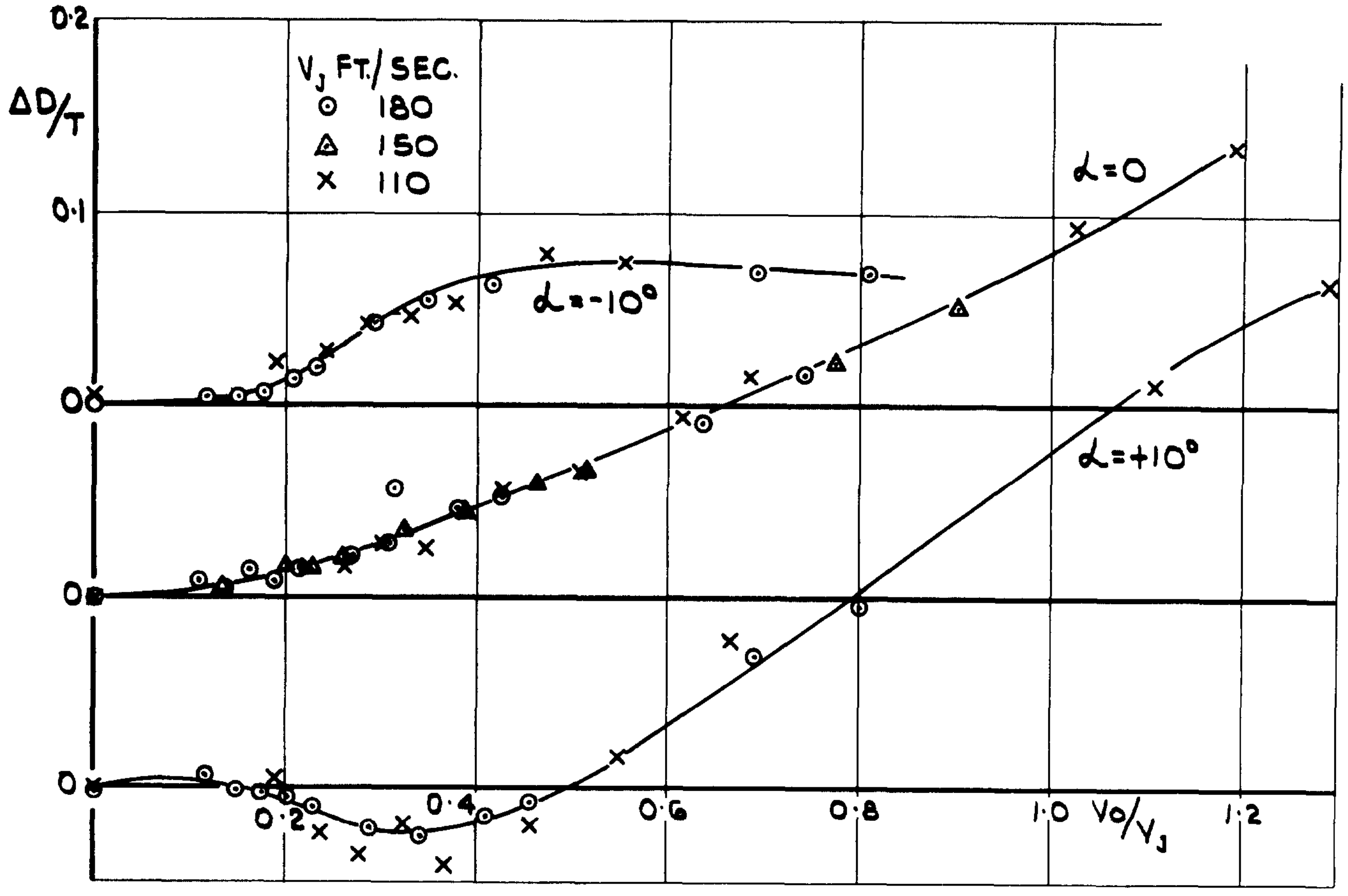


(a) A=1·54.

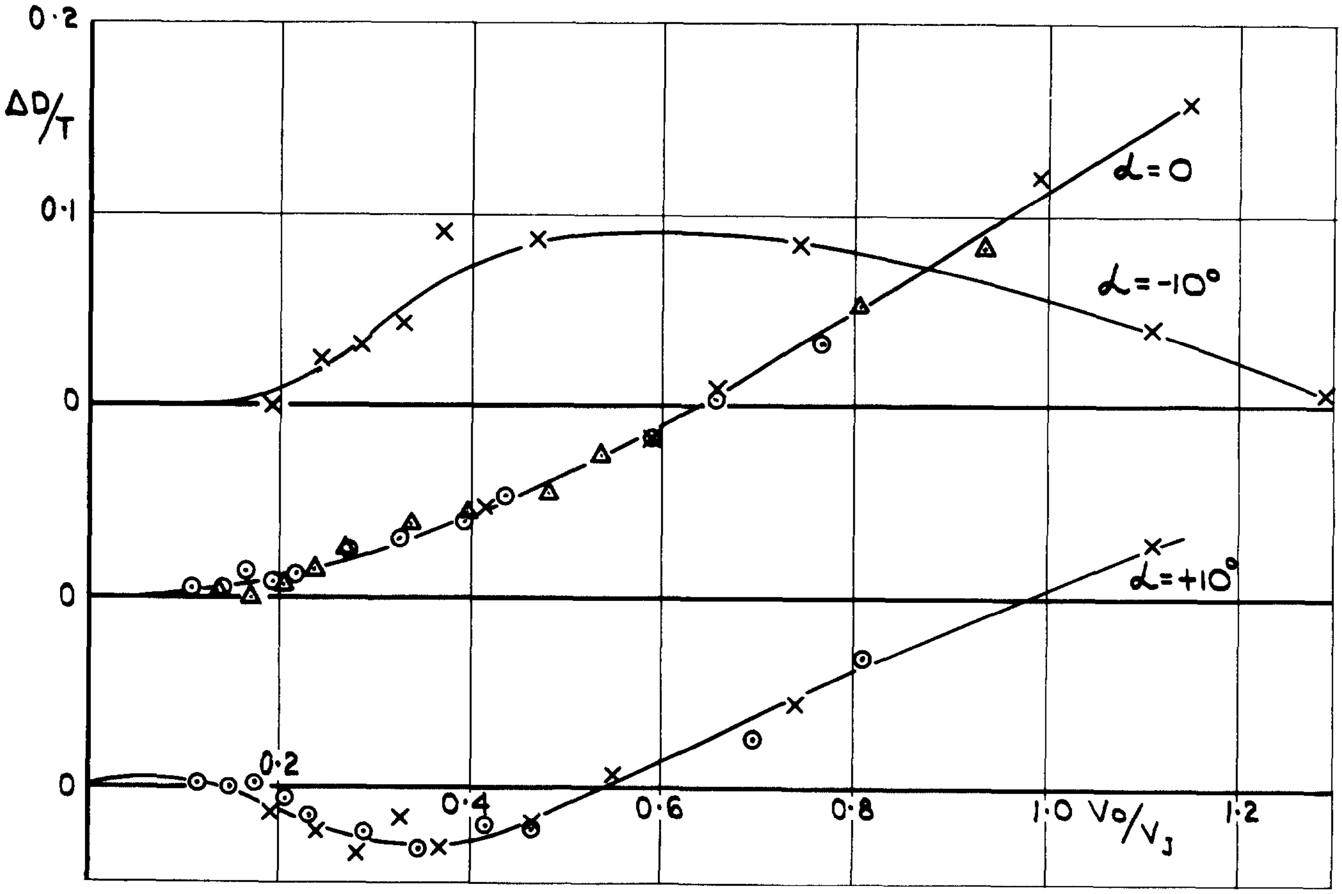


(b) A=3·08

FIG. 12. DRAG OF BLUFF BODY WITH HIGH WING.

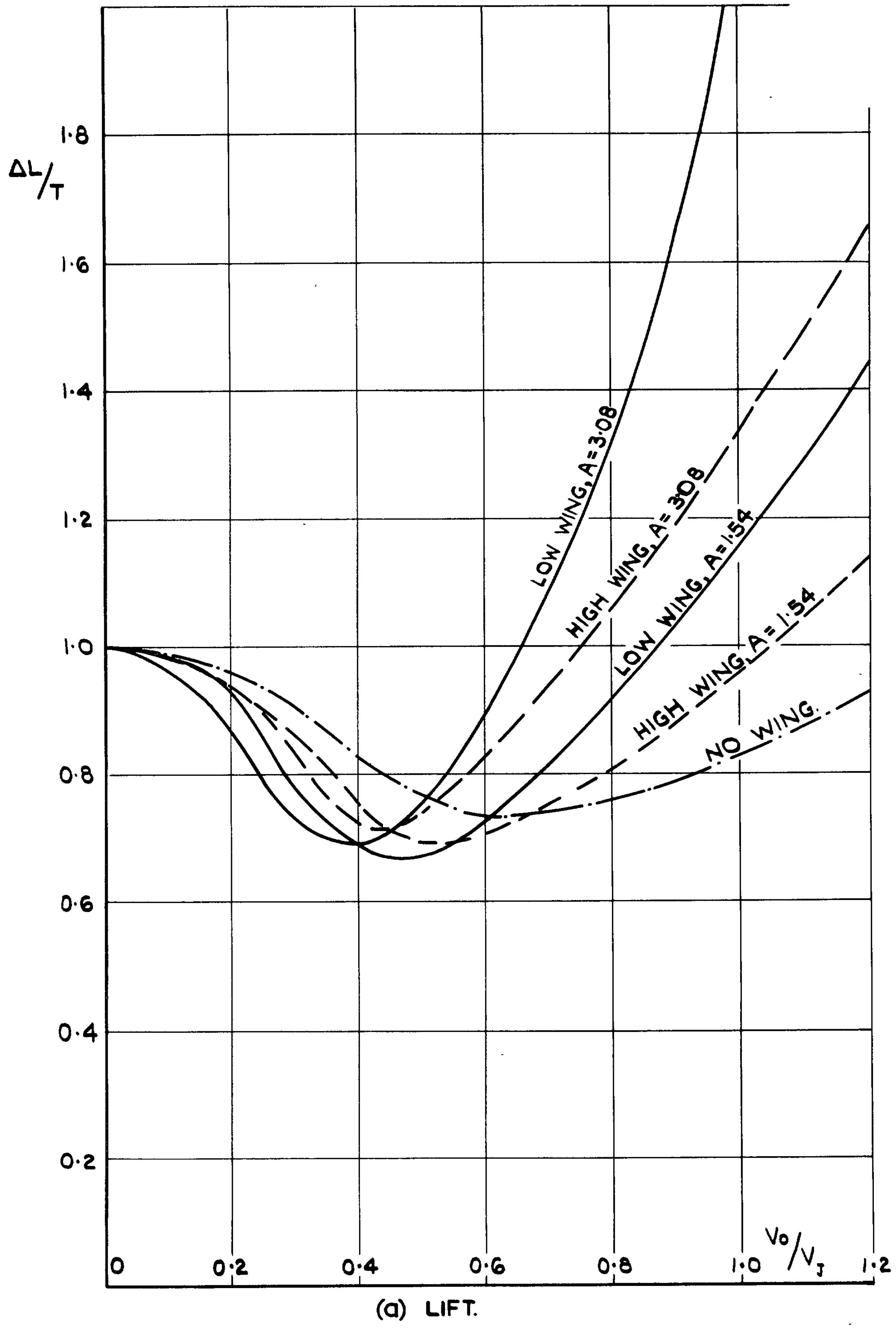


(a) A=1·54



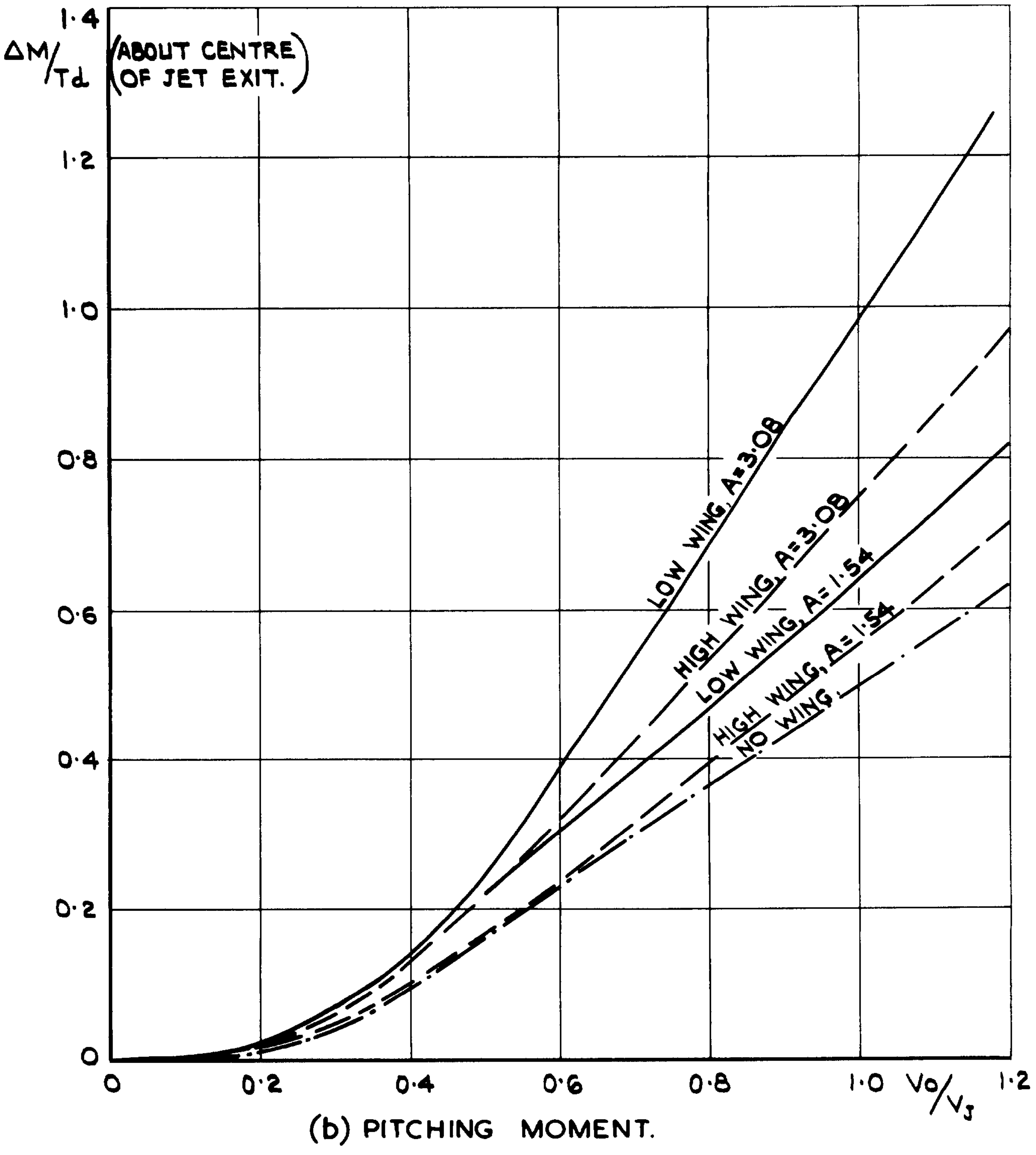
(b) A=3·08

FIG. 13. DRAG OF BLUFF BODY WITH LOW WING.



(a) LIFT.

FIG. 14. EFFECT OF MAINSTREAM AT ZERO INCIDENCE.



(b) PITCHING MOMENT.

FIG. 14. EFFECT OF MAINSTREAM AT ZERO INCIDENCE.

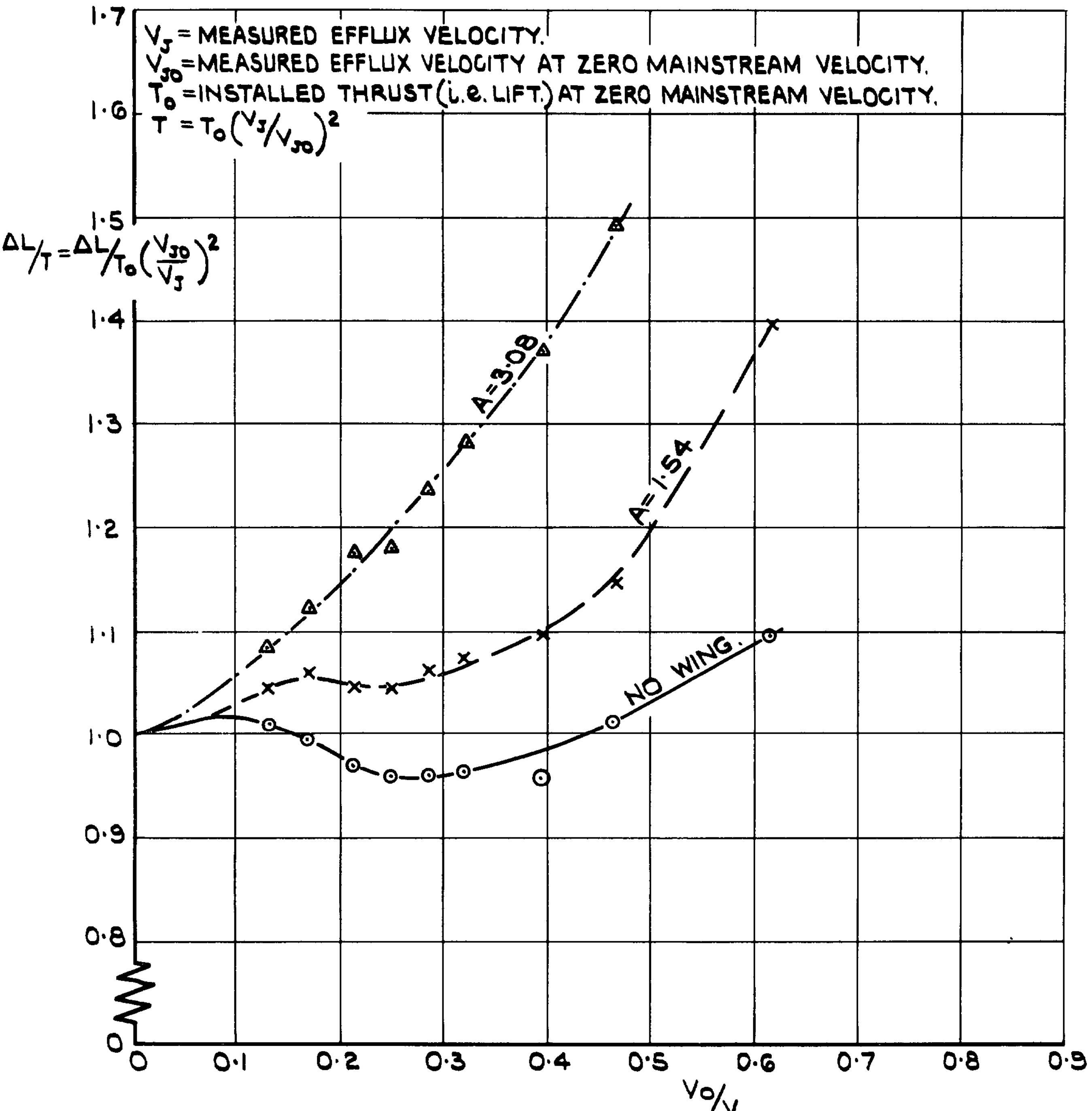


FIG. 15. LIFT OF LIFTING-FAN MODEL. HIGH WING, $\alpha = 0$
(FROM REF. 2.)

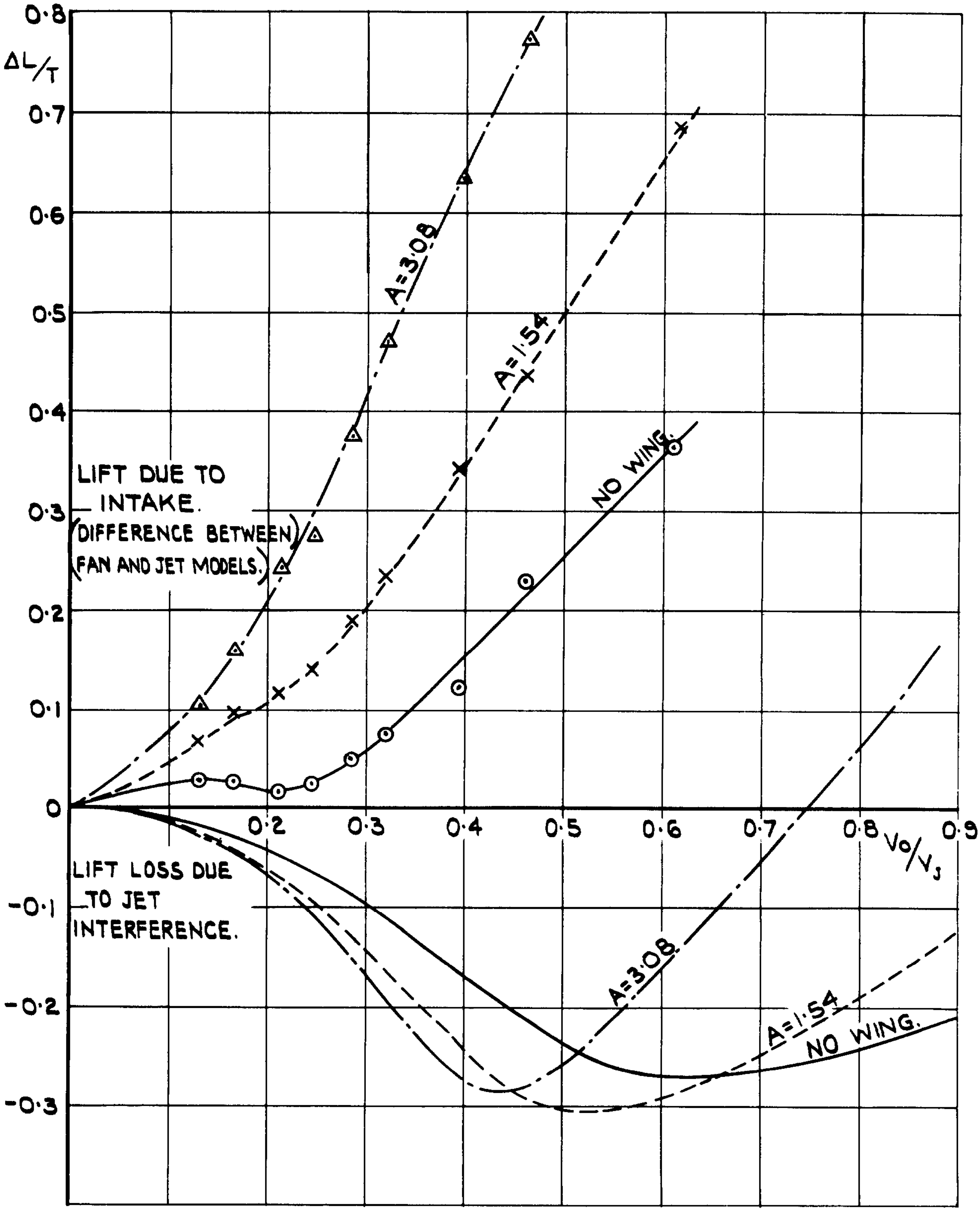


FIG. 16. LIFT INCREMENTS DUE TO INTAKE AND JET HIGH WING; $\alpha = 0$.

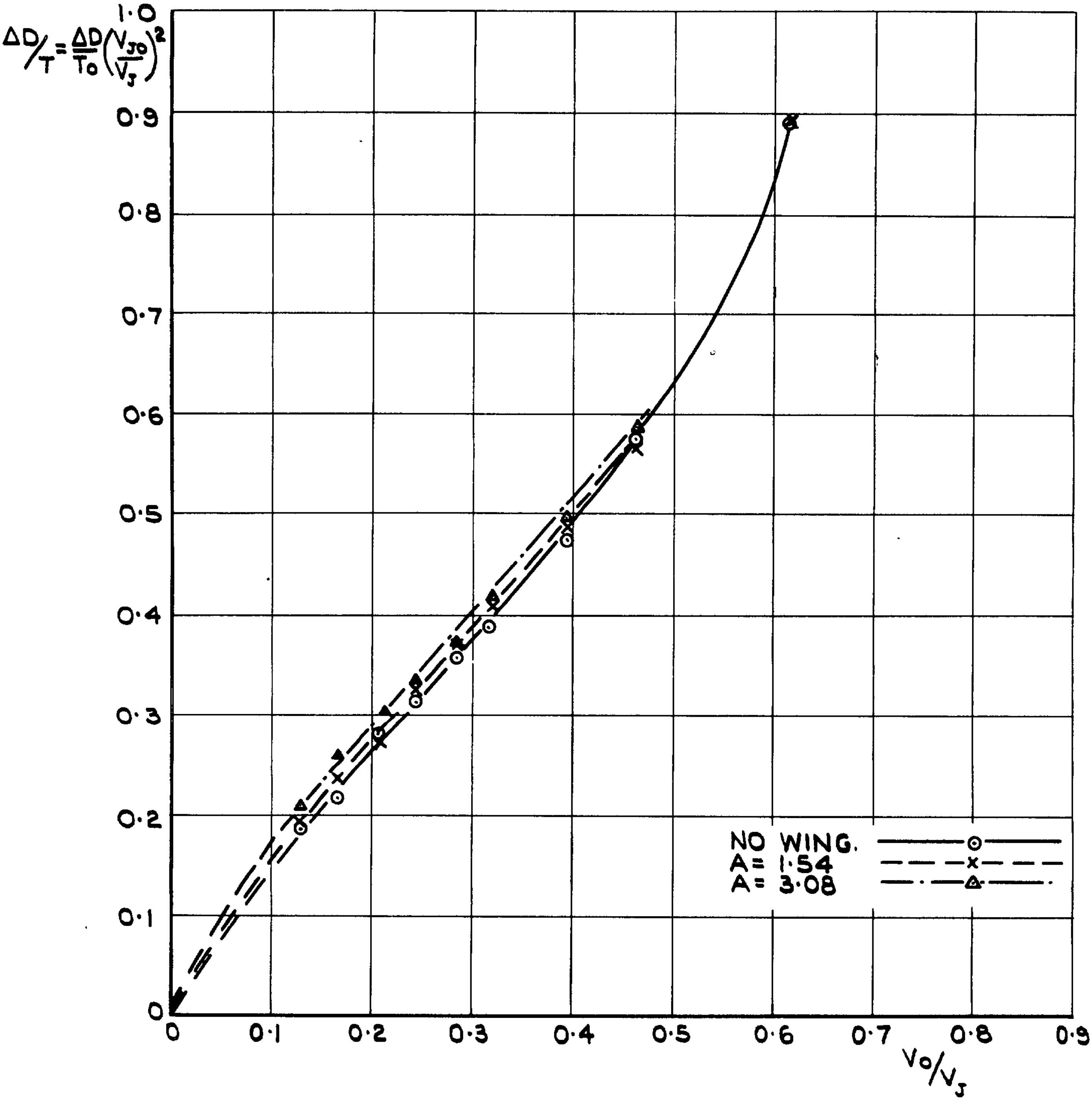
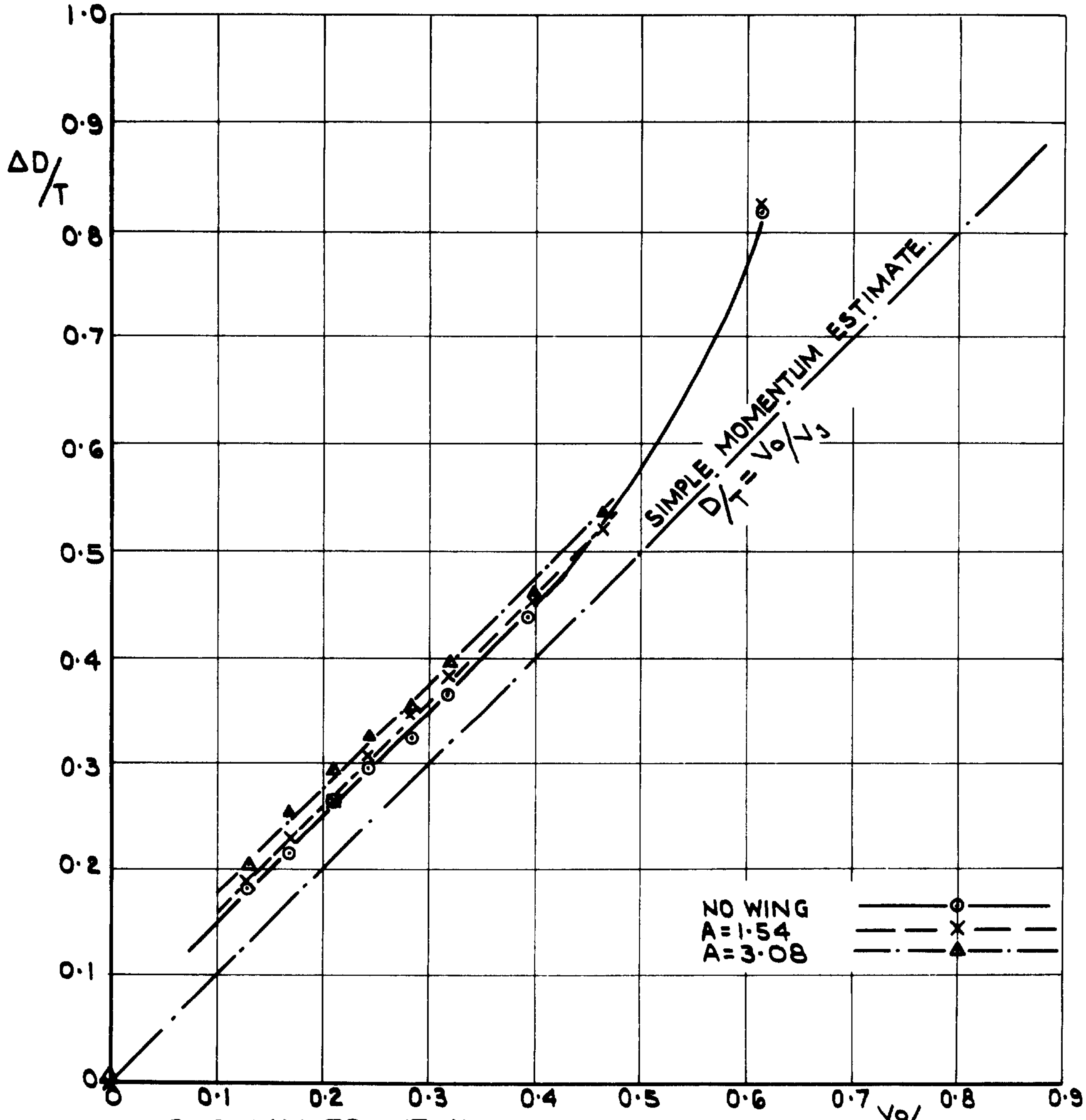
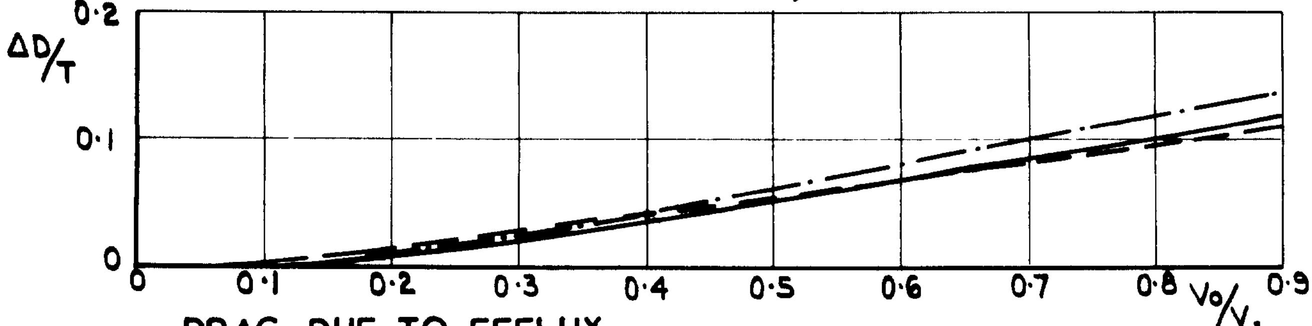


FIG. 17. DRAG OF LIFTING-FAN MODEL HIGH WING, $\alpha = 0$.
(FROM REF. 2.)



DRAG DUE TO INTAKE.
(DIFFERENCE BETWEEN FAN AND JET MODELS.)



DRAG DUE TO EFFLUX.

FIG. 18. DRAG INCREMENTS DUE TO INTAKE AND JET.
HIGH WING; $\alpha = 0$

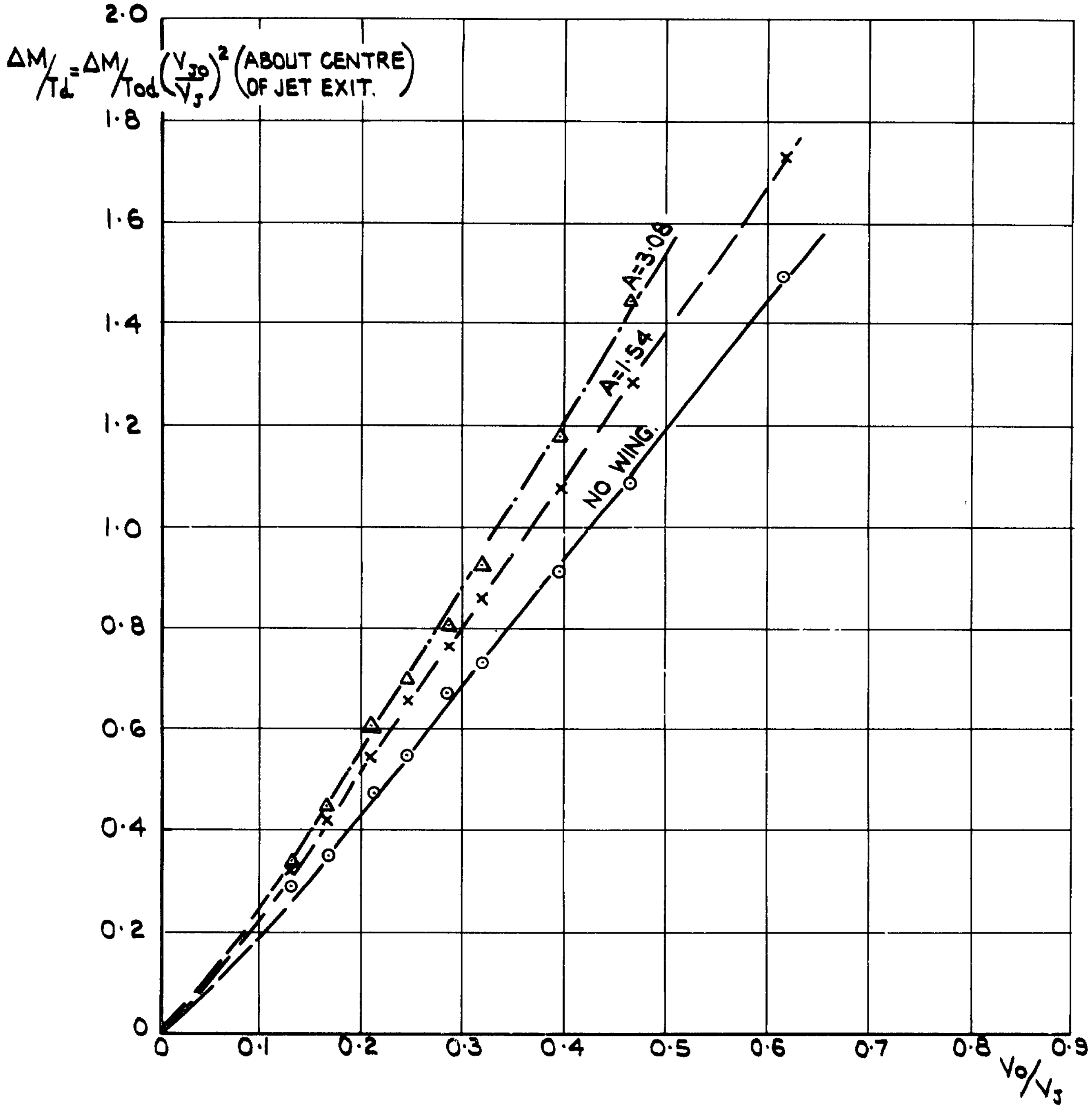
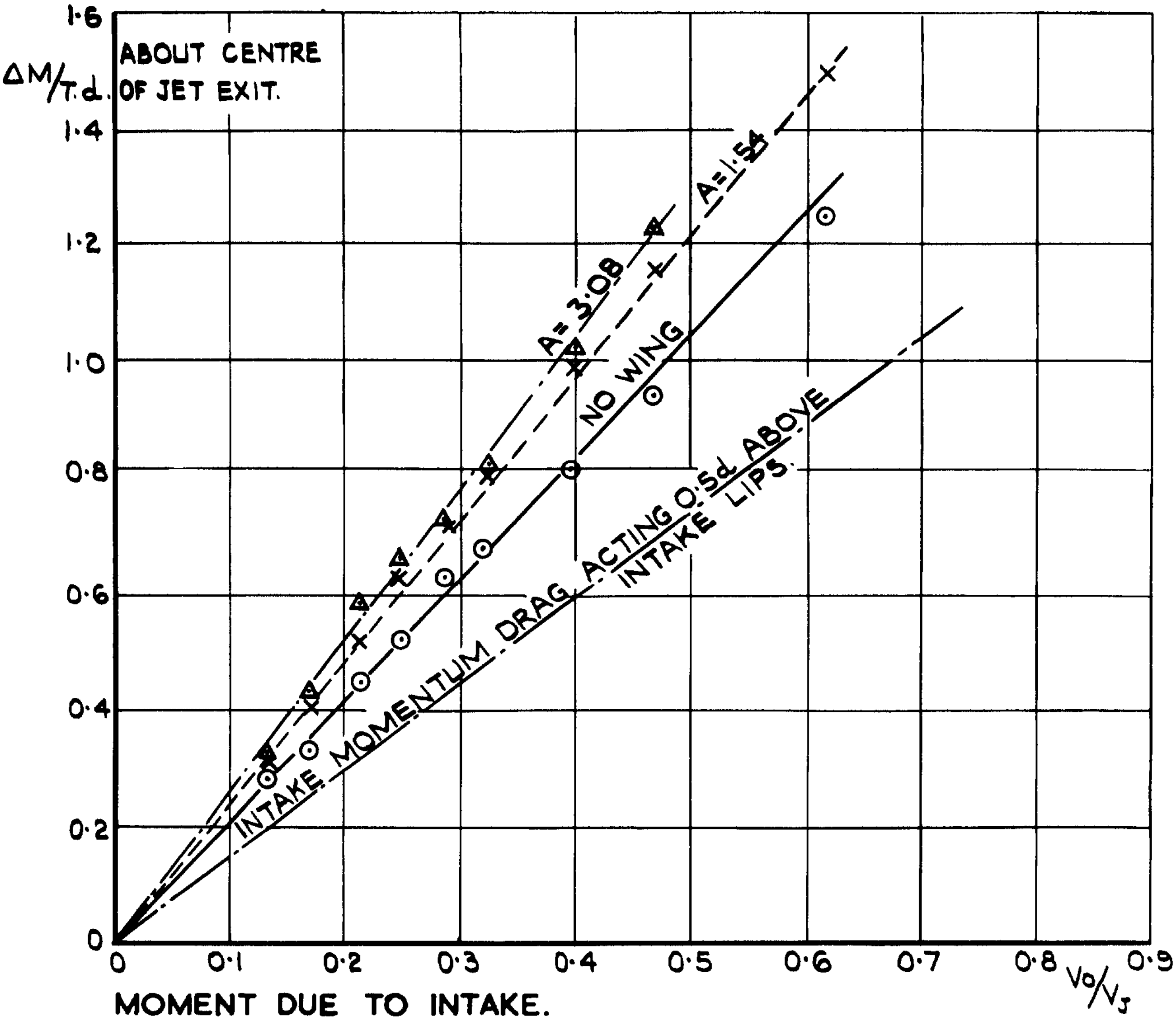
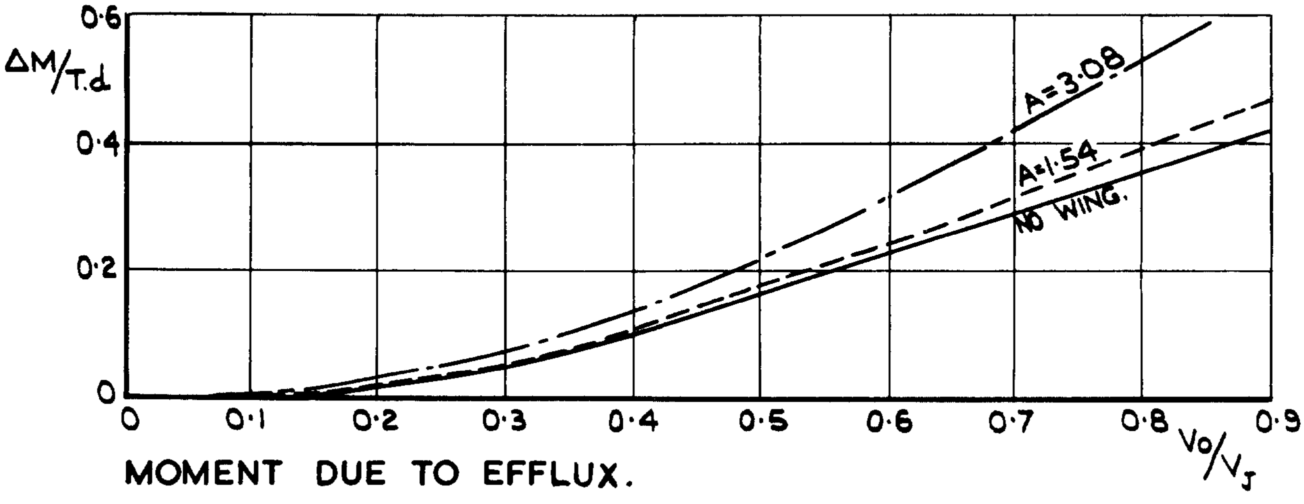


FIG. 19. PITCHING MOMENT OF LIFTING-FAN MODEL. HIGH WING; $\alpha = 0$ (FROM REF. 2.)



MOMENT DUE TO INTAKE.

DIFFERENCE BETWEEN FAN MODEL (REF. 2) AND JET MODEL.



MOMENT DUE TO EFFLUX.

FIG. 20. MOMENT INCREMENTS DUE TO INTAKE AND EXIT.
HIGH WING; $\alpha = 0$.

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WIND TUNNEL EXPERIMENTS ON A LIFTING JET IN A BLUFF BODY WITH AND WITHOUT WINGS. Trebble, W.J.G. July 1964.

Measurements have been made of the interference loads arising from the interaction between a mainstream and a relatively large jet efflux emerging from the lower surface of a bluff body. As the ratio of mainstream velocity to jet efflux velocity is increased from zero, the lift increment due to the jet is initially reduced and a nose-up moment is produced. The maximum loss is about a quarter of the installed thrust but at higher values of the velocity ratio some lift recovery occurs. Similar trends are observed with a wing fitted but the lift recovery at high velocity ratios and the associated nose-up moments are greater due to additional circulation life carried on the wing.

(Over)

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(Over)

DETACHABLE ABSTRACT CARDS

An attempt has been made to deduce the interference loads due to an intake from the difference between these results and those for a geometrically similar lifting-fan model. This analysis suggests that the intake flow gives rise to large lift and nose-up moment increments which are augmented

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