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Exploratory Tests on a Thin Delta Wing in the Flow Field of a Rectangular Foreplane at Mach Number 1·8

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SUMMARY

Normal force and pitching moment have been measured at Mach number 1.8 on a delta wing in the field of a lifting foreplane. The interference load was opposed to the lift on the foreplane, and its maximum value, achieved when the foreplane vortices struck the wing leading edge, was somewhat greater than the foreplane lift, giving a negative foreplane lift efficiency for this configuration. The centre of pressure of the interference load lay ahead of that of the isolated wing, but somewhat behind the theoretical position obtained from Sacks' theory. The interference effects were broadly independent of wing incidence.

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LIST OF SYMBOLS

c	foreplane chord
c_o	wing centre-line chord
$\bar{\bar{c}}$	wing second mean chord
C_m	pitching moment of wing about $^2/_3$ centre-line chord point $\div$ q S $\bar{\bar{c}}$
$-C_z$	normal force of wing $\div$ q S
h	distance from wing apex to centre of pressure of interference load
M	Mach number
q	free stream kinetic pressure
s	foreplane semi-span
s'	semi-span of rolled-up vortices behind foreplane
S	wing area
z	height of foreplane above wing normal to the free stream direction, measured from height at which vortices strike the wing leading edge
α_F	foreplane incidence
α_W	wing incidence
β	$\sqrt{M^2 - 1}$
γ	non-dimensional foreplane height, $z \div$ wing semi-span
σ	non-dimensional vortex semi-span, $s' \div$ wing semi-span

1 INTRODUCTION

It became apparent in recent discussions of the problem of trim for supersonic slender-wing aircraft that there is hardly any evidence available on the effect of a foreplane on the lift and pitching moment of a slender mainplane with sharp edges. There exists the well-known theory of Sacks[1], 1957; but, this is concerned with the hypothetical flow where attachment along the leading edges is maintained under all conditions. This theory has not yet been extended to the case with leading-edge vortex sheets; to undertake this would present formidable difficulties. It appeared desirable, therefore, to do some exploratory wind-tunnel tests on a thin delta wing with sharp edges behind a foreplane. The results of such tests, made in the No.18 (9" × 9") tunnel at M = 1.8, are reported here.

The purpose of these tests was to measure the changes in the normal force and in the pitching moment of the mainplane, which arise from the flow field of the foreplane, for different relative positions. Also, some indication of the overall flow pattern was to be obtained. Of particular interest was the question whether there were conditions under which the trailing vortices from the foreplane could be wrapped into the vortex sheets from the leading edges of the mainplane such that the central area of the wing, where fins or engines might be located, would be kept clear of free vorticity.

It was considered sufficient for this purpose to use a simple rectangular plate as the canard surface as this produces a typical flow field. It was considered necessary, however, not to connect the two surfaces so as to be able to measure the lift force and moment on the mainplane alone. The relative height of the foreplane could then be altered without changing the strength of the trailing vortices. This arrangement was considered to give more distinct and at the same time more accurate results than the more usual foreplane-body-wing combination. Thus the present tests form part of a more extensive current programme where two surfaces are independently supported.

2 TEST ARRANGEMENT

A flat-plate delta wing (aspect ratio 4/3, root chord 4 in.) was supported on a rear sting balance capable of measuring normal force, chordal force, and pitching moment. This was mounted on one sidewall of the No.18 (9" × 9") supersonic tunnel. A rectangular plate, $1\frac{1}{4}$ in. span × 1 in. chord, was brazed to a length of 1 mm hypodermic tube through its centre at an angle of 10°. This was threaded onto 24 g piano wire stretched across the tunnel, tensioned by a 56 lb weight (Fig.1). The height of this foreplane above the wing was adjusted by sliding the tube in or out of the tunnel wall. The whole arrangement was reasonably rigid and free from apparent vibration at supersonic speeds, while the interference from the support was reasonably low at M = 1.8.

3 TEST PROCEDURES

All tests were done at nominally zero sideslip. The Mach number was 1.8 and Reynolds number 0.3×10^6 per inch.

3.1 Force measurements

Measurements were made of the normal force and pitching moment on the mainplane, as the foreplane height was varied over a range of two or three wing semi-spans. Mainplane incidence was set at 0° and $+8^\circ$, while the foreplane incidence was at nominal settings of $\pm10^\circ$.

Associated with these measurements, the foreplane lift was calculated from measurements, by wake traverse, of foreplane vortex core span and vortex strength. The foreplane height datum was taken as that at which the vortices intersected the wing leading edges and the heights above this datum have been normalised by dividing by the mainplane semi-span for comparison with theoretical values from Sacks' formulae.

3.2 Vapour screen examination

Using wet air in the tunnel, illuminated by a narrow beam of light, it was possible to see the foreplane vortex behaviour as it passed across the wing surface. However, the vapour screen picture was clear only near the trailing edge, and satisfactory photographs were never obtained.

3.3 Oil flow studies

A range of surface flow patterns was photographed, using the oil flow technique. The oil used was a thinned "Engineer's Blue", and appears dark in the photographs.

Photographs were usually taken after the tunnel had been shut down. Consequently some features of the oil pattern may be obscured by movement during the passage of the shutting-down shocks; when this effect was observed, photographs were taken with the tunnel still running, but this could be done on only one side of the mainplane, as there was a window on one side only.

4 RESULTS

4.1 Force measurements

The normal force measurements showed at once that the interference load on the mainplane was of opposite sign to the foreplane lift, with a peak interference load occurring very nearly when the foreplane vortices struck the wing leading edge.

Fig.2 shows the interference loading on the mainplane at zero incidence with the foreplane at $+10^\circ$. In this figure each point measured is plotted, but in succeeding figures the points are omitted for clarity. In Figs.3 and 4, are shown the interference loads and the pitching moments on the mainplane at mainplane incidences 0 and $+8^\circ$, foreplane incidences $+10^\circ$ and -10°, but in order to emphasize the similarity of the results, those for foreplane incidence -10° have had their signs changed, effectively giving the conditions for positive foreplane incidence and negative wing incidence. The curves are plotted over a height range within which the non-dimensional foreplane height, γ, does not exceed 1.5. Outside this range, interference from the tunnel walls occurs. The plotted values are, therefore, expected to be virtually free from tunnel interference*.

The two curves for the wing at zero incidence give an indication of the overall accuracy of the tests, since the results plotted in this way should be identical assuming symmetry of the wing and of the air flow.

Within these limits of accuracy, there is seen to be little effect of wing incidence on the interference loading, neither is there an asymmetric effect due to the direction of rotation of the foreplane vortices relative to the wing surface. The vortex height above or below the wing is the major factor.

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* The geometry at the test Mach number of 1.8 is such that the foreplane shocks and expansions reflected from the wall boundary layer are likely to strike the wing at about this height ($\gamma = 1.5$).

The overall lift of the foreplane was not measured directly but determined from a wake traverse, and was found to correspond to a lift coefficient based on wing area of 0.084, compared with the linearised theory value of 0.079. This method is open to some doubt and cannot be regarded as very accurate but is considered to be adequate for the present purpose. The peak values of the interference load exceed this figure by some 40%, so giving an overall loss of lift by the use of the foreplane. This surprising result needs some qualification; the foreplane support is not entirely rigid and the set angle could vary from run to run, particularly due to starting and stopping shocks. However, the set angle was checked from time to time and is not thought to have varied by more than 1° to 2° at any time, thus possibly accounting for some 25-50% of this excess interference load. At present, therefore, the possibility of achieving a negative foreplane normal force efficiency must remain.

Even though Sacks' theory does not apply to the present case, some results have been evaluated for comparison. Sacks' theory has been shown by M.C.P. Firmin (unpublished) to give the normal force efficiency in the form

$$\eta_z = \sqrt{1 - \left(\frac{\lambda - \mu}{2\sigma}\right)^2} ,$$

where σ = vortex semi-span ÷ wing semi-span,

$$\lambda^2 = (1+\sigma)^2 + \gamma^2,$$

$$\mu^2 = (1-\sigma)^2 + \gamma^2,$$

from which it is interesting to note that:

$$\sqrt{1 - \eta_z^2} = \frac{\lambda - \mu}{2\sigma} \equiv \text{(difference in distance of one vortex from each wing tip)} \div \text{(vortex span)} .$$

The centre of pressure of the interference load, measured from the wing apex, is given by

$$\frac{h}{c_o} = \frac{1}{1 - \eta_z}\left[\frac{\sigma^2 - \gamma^2}{2\sigma} \sin^{-1}\left\{\frac{\sigma\sqrt{1 - \eta_z^2}}{\sqrt{\sigma^2 + \gamma^2}}\right\} + |\gamma| \cosh^{-1}\left\{\frac{1}{\sqrt{1 - \eta_z^2}\sqrt{\sigma^2 + \gamma^2}}\right\} - \frac{\eta_z}{2}\right].$$

Theoretical results were obtained, using these equations with the measured value of the vortex span, 0.4 × wing span, a value some 20% greater than predicted by theory, i.e.

$$\frac{s'}{s} = 1 - \frac{c}{4 s \beta} .$$

These results have been shown in Figs.3 and 5, the measured normal force efficiency being indicated by the subsidiary scale in Fig.3. The test results show trends which are similar to the theory, but normal force efficiencies are lower than theory, while the centre of pressure of the interference load is behind the theoretical position.

From both these sources the total adverse interference moment on the mainplane is greater than that predicted for Sacks' case, and there is therefore a loss in moment efficiency of the foreplane.

4.2 Vapour screen examination

It was possible to examine the vortices at the trailing edge of the wing only.

When the mainplane was at zero incidence, and the foreplane height was varied, the vortex cores moved from one side of the wing to the other. As they approached the surface they moved together or apart as one would expect from consideration of their images in the wing, viz. as γ tended to zero with the foreplane normal force directed away from the wing the vortices moved apart. When they appeared on the other side of the wing they were close together near the centre-line, and moved out to their original span as the distance, $-\gamma$, was increased. The actual transition from one side of the wing to the other was difficult to observe but the impression was gained that the vortices tended to unroll.

The same sort of behaviour occurred when the wing was at incidence with marked leading edge separations, except that the foreplane vortices wrapped up with the wing vortices as they approached them, subsequently reappearing independently on the other side of the wing.

4.3 Oil flow studies

Oil flow photographs were taken over a range of foreplane height, with foreplane and mainplane incidences corresponding to the force measurement conditions.

The quality of these photographs is poor, making them unworthy of reproduction here, but some general comments may be made.

The flow patterns in general are more to be considered as an effect of the upwash and downwash fields corresponding to the foreplane vortices than as undergoing cross-flow effects from these vortices themselves. In fact, it is difficult to tell, from the oil flow patterns, on which side of the mainplane these vortices have passed. As the vortices traverse across, there is a change in degree rather than of characteristic pattern.

Fig.6 is a sketch derived from the oil flow patterns showing the type of flow experienced on the mainplane at zero incidence when the foreplane is at $+10^\circ$. The sketch is intended to indicate only the overall pattern. It can be seen that the characteristics conform to the presence of downwash at the apex and upwash near the tips. An interesting feature is the way in which the leading edge vortices on the lower surface start at the apex, but become detached from the leading edges at the point where the flow changes from downwash to upwash. This indicates that the induced load on the wing in the opposite sense to that on the foreplane is confined to that area of the wing between the vortices in the same way as in Sacks' case. On the other hand, the separations on both upper and lower surfaces, and the associated non-linear forces, are not catered for theoretically, and it is possible that their presence accounts for the overall negative normal force efficiency previously mentioned.

The detailed behaviour of the vortices and the appropriate stream surfaces arising from the induced loading on the wing is at present a matter for conjecture. For this reason they are not indicated on Fig.6. It is hoped to resolve this experimentally in the near future.

Similar effects are to be seen on the upper surface of the wing at 7° incidence. When the foreplane incidence is positive, the downwash is sufficient to suppress the leading edge separation on the mainplane near the apex. When the foreplane incidence is reversed, the upwash field near the apex causes very strong leading-edge separations, and the flow remains separated from the whole edge.

5 CONCLUSIONS

5.1 The foreplane normal force efficiency and moment efficiency are less than 100% as the interference load on the mainplane is in the opposite direction to the foreplane load.

A negative normal force efficiency has been measured. There is some doubt as to the exact value of the foreplane lift, but this doubt is insufficient to account for this surprising effect in full.

The actual results follow trends similar to those formed theoretically by Sacks for the case of slender wings with attachment along the leading edges, but normal force efficiency is less than in Sacks' case and the centre of pressure of the interference load is some 10% wing chord further behind.

5.2 These interference effects are independent of wing incidence, within the accuracy of these tests.

5.3 Flow over the wing is approximately as would be expected in the appropriate upwash and downwash fields; this must have serious repercussions on camber and twist design if a large foreplane is necessary.

5.4 As the plane of the foreplane vortices approaches that of the wing, the vortices move apart or together, depending on the sense of the foreplane force. Despite this the loading induced on the wing is symmetrical with distance between the wing and vortex planes.

5.5 The foreplane vortices are not wrapped up into the leading-edge vortex sheets on the mainplane, except possibly over a narrow height band where the foreplane vortices are close to the wing surface.

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No.	Author	Title, etc.
1	Sacks, A.H.	Aerodynamic interference of slender wing-tail combinations. NACA Technical Note No.3725, Jan.1957.

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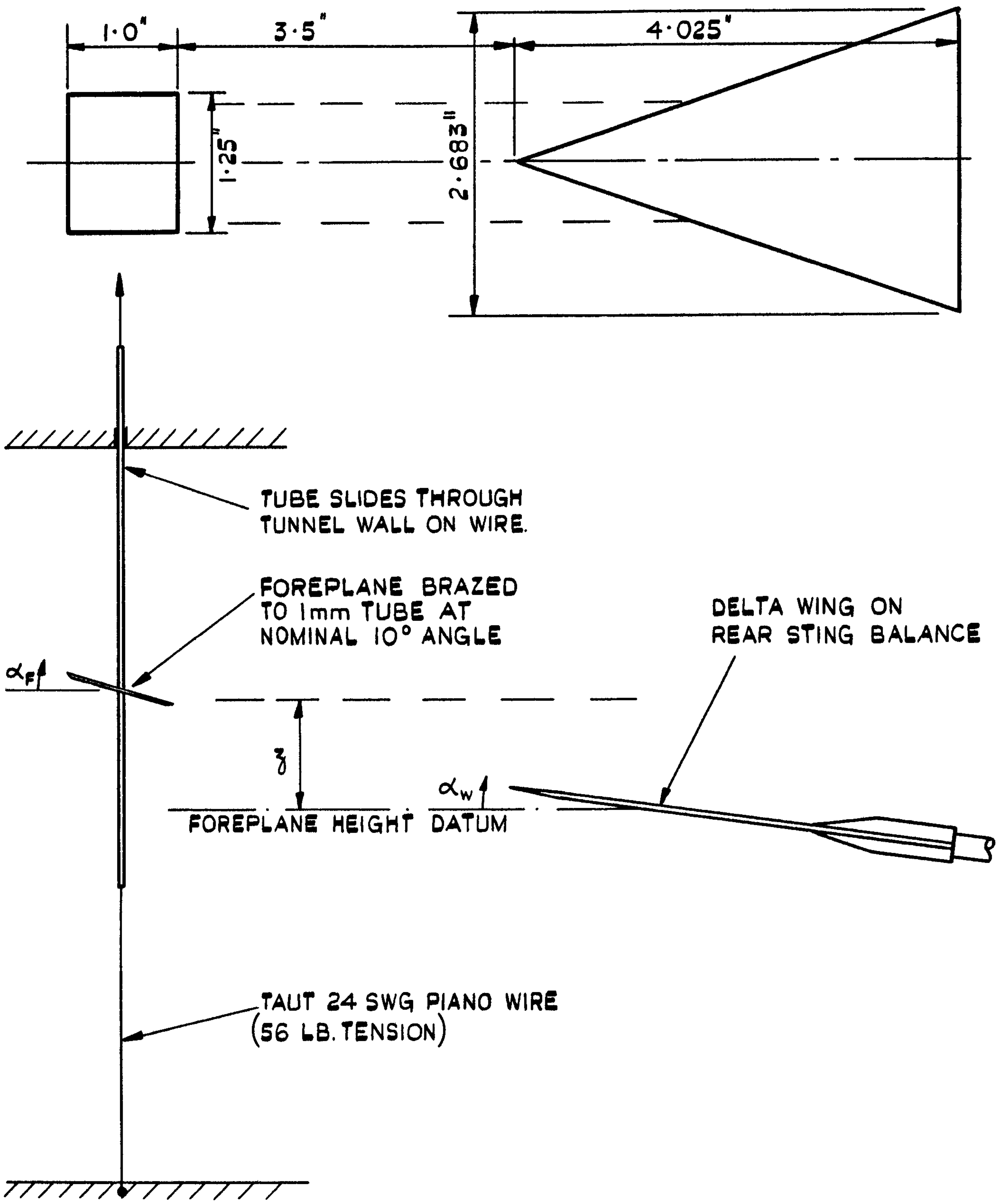

FIG. 1. ARRANGEMENT OF FOREPLANE AND WING IN No. 18 (9" x 9") SUPERSONIC TUNNEL.

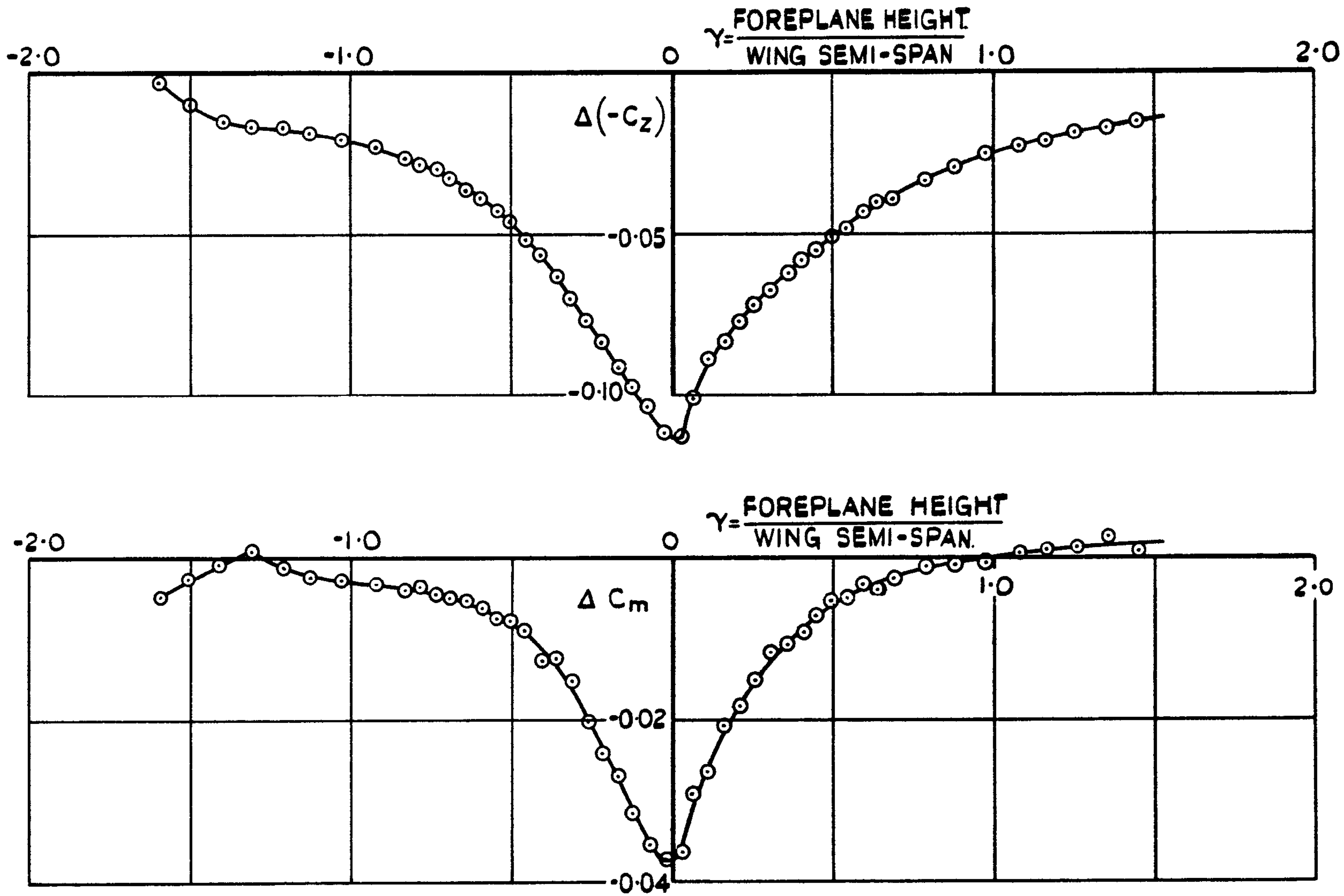

FIG. 2. NORMAL FORCE & PITCHING MOMENT INCREMENT: TYPICAL EXPERIMENTAL DATA

(FOREPLANE INCIDENCE +10°, MAINPLANE INCIDENCE 0°)

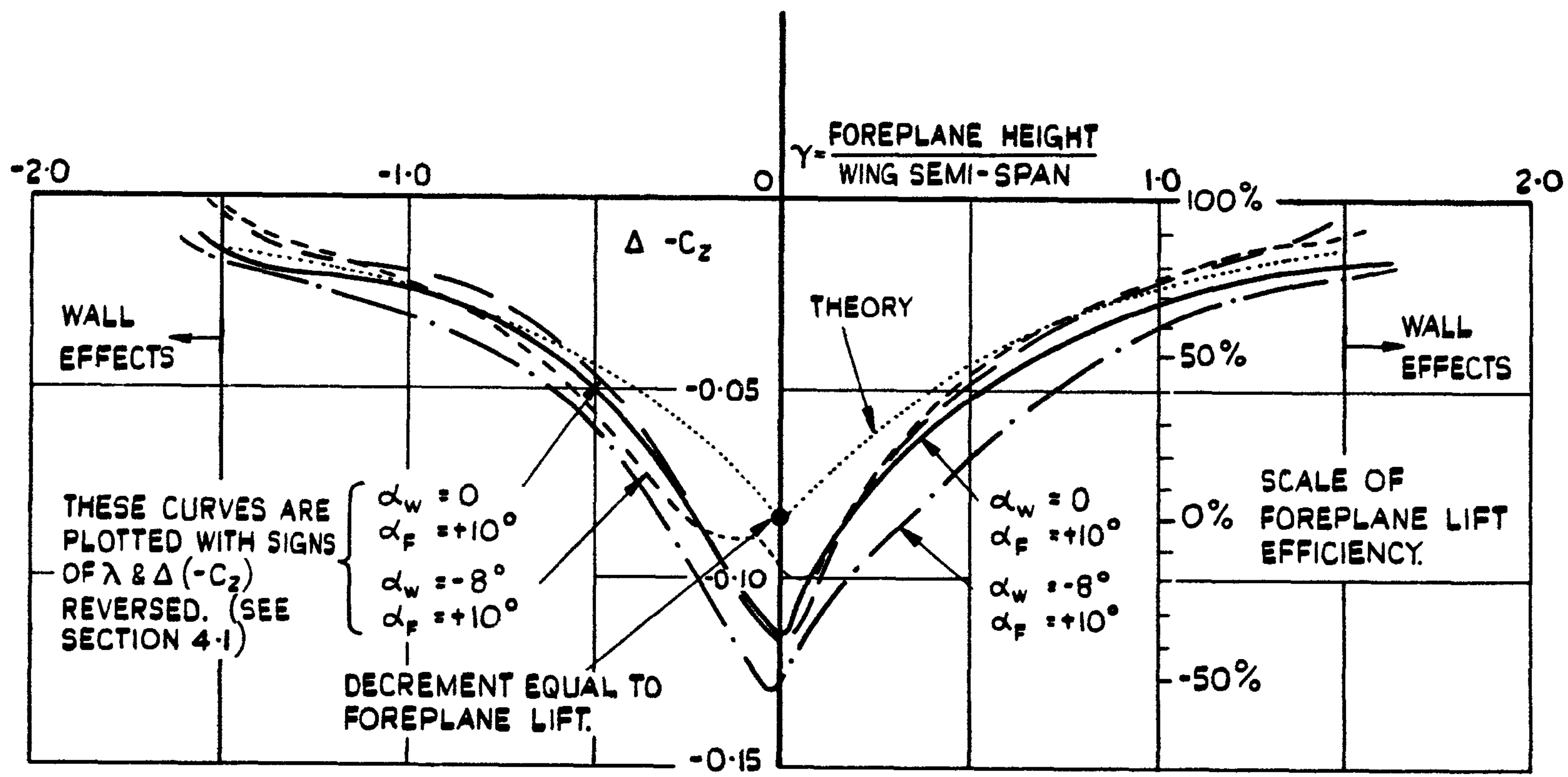

FIG. 3. NORMAL FORCE INCREMENTS ON WING DUE TO FOREPLANE FIELD.

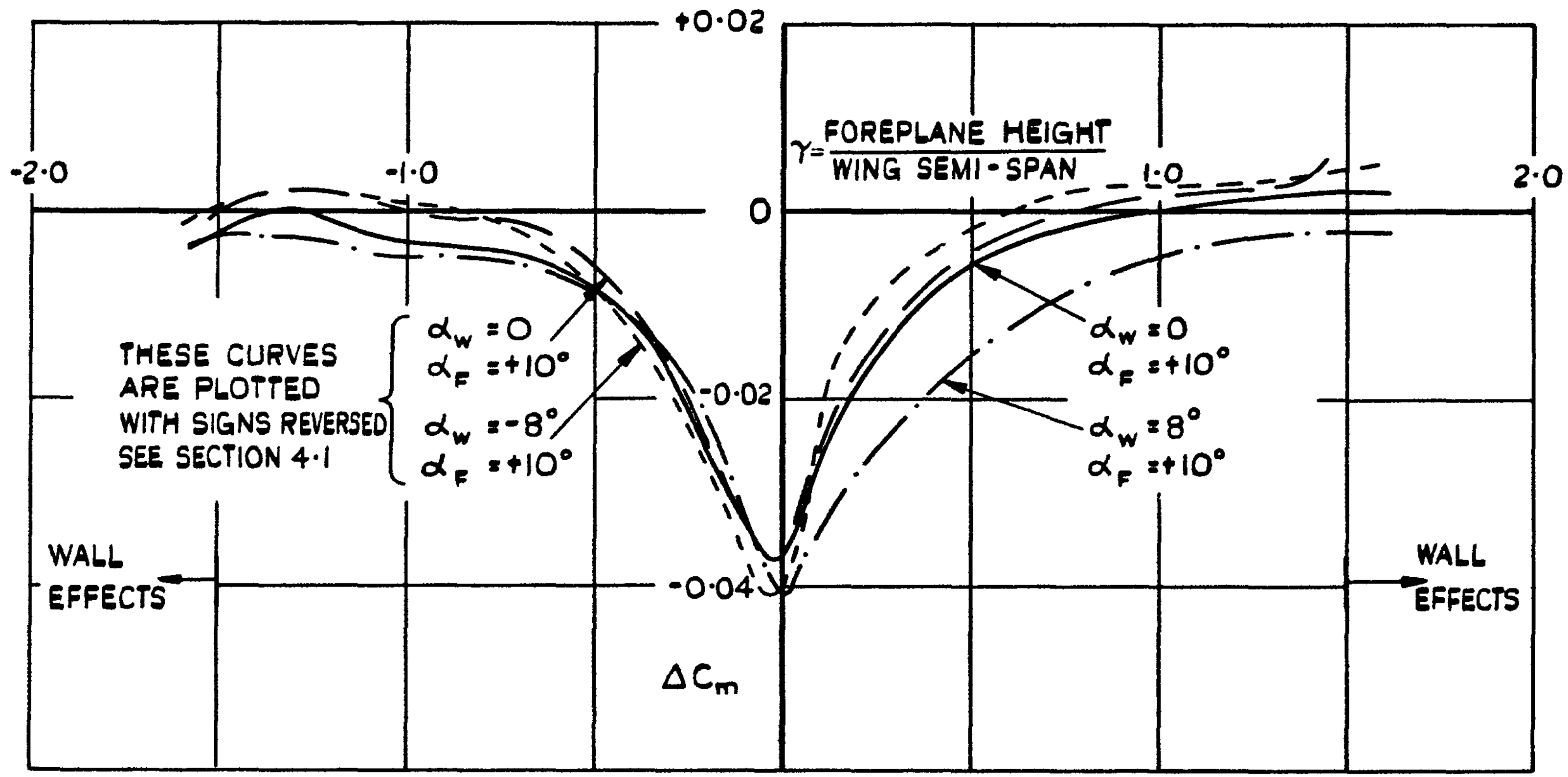

FIG. 4. PITCHING MOMENT INCREMENTS ON WING DUE TO FOREPLANE FIELD

(MEASURED ABOUT 2/3 CHORD POINT.)

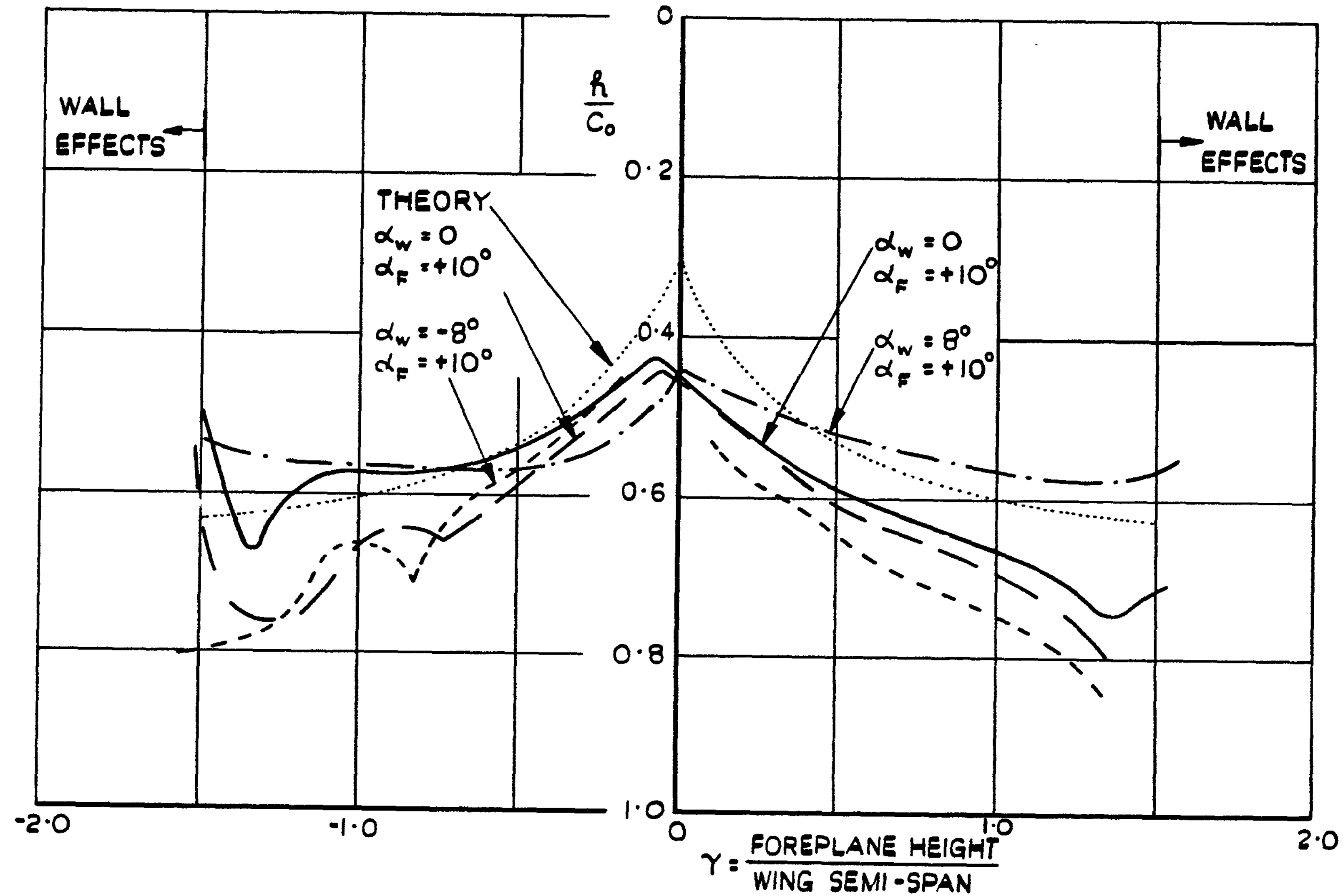

FIG. 5. MOVEMENT OF CENTRE OF PRESSURE OF INTERFERENCE LOAD WITH FOREPLANE HEIGHT.

(SIGN OF γ REVERSED FOR $\alpha_F = -10°$)

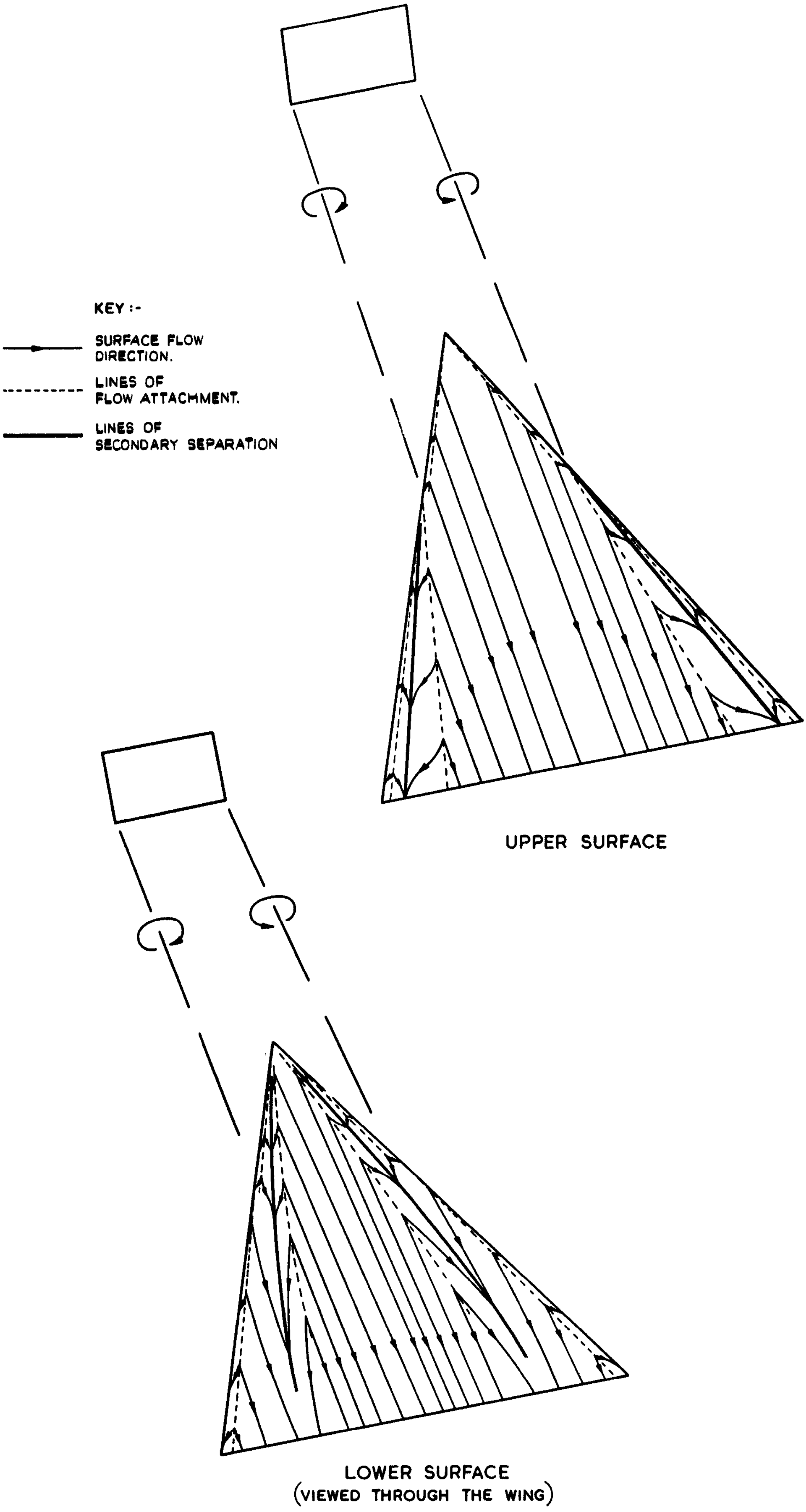

FIG. 6. OIL FLOW PATTERNS ON SLENDER DELTA WING AT ZERO INCIDENCE IN FIELD OF FOREPLANE AT POSITIVE INCIDENCE.

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