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Some Exploratory Jet-Flap Tests on a 60-deg Delta Wing

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Summary.—As a preliminary investigation of the effects of high sweep and low aspect ratio on jet-flap wings, some wind-tunnel experiments were carried out on a half-model of a 60-deg delta wing, already tested with blowing to prevent flow separation over a trailing-edge flap. Much larger values of the blowing-momentum coefficient C_μ' than before were achieved by using a low tunnel speed. Balance measurements were made of lift, pitching moment and thrust for C_μ' values up to 1·5, wing incidences between − 4 deg and + 20 deg, and flap angles of 30, 60 and 90 deg. Although substantial magnification of the direct jet lift occurred, the movement of the centre of lift was appreciable and positive values of the thrust occurred only at the lowest flap angle.

1. *Introduction.*—Comprehensive jet-flap experiments are in progress at the National Physical Laboratory on a rectangular-wing model of variable aspect ratio (3, 6, 9) and jet angle (0 to 90 deg), to follow up exploratory tests already reported on finite aspect-ratio effects[1]. However, the effects of large amounts of sweepback, and very low aspect-ratio are unknown†. As a preliminary study and to provide quickly some data to help jet-flap project work, some balance measurements have been made on an existing half-model of a 60 deg delta wing (aspect ratio 1·65) with the air ejected over a trailing-edge flap.

This delta-wing model was originally designed for experiments with small values of the blowing momentum coefficient, $C_\mu' < 0 \cdot 1$, merely enough to prevent flow separation on the deflected trailing-edge flap[2]. Hence, to attain ' jet-flap ' C_μ' values up to 1·5 without considerably enlarging the blowing slot, the tunnel speed had to be reduced to 30 ft/sec‡. With such a low tunnel speed and the appreciable jet efflux employed, the uniformity of the tunnel mainstream flow may have been somewhat poorer than under normal test conditions. The lift and pitching-moment results are reliable, but the thrust results may only be sufficiently accurate for a qualitative analysis.

2. *Experimental Method.*—2.1. *Model and Test Arrangement.*—A half-model of a 60-deg delta wing was hung horizontally from a three-component overhead balance, with a clearance of less than 0·2 in. between the fuselage centre-plane and a vertical false wall erected along-wind in the working-section of the 13 ft × 9 ft Tunnel. Air was fed to the model along its pitching axis by way of an air-bearing connector specially devised to avoid constraints on the balance[3]. The model construction and test arrangement will be discussed fully elsewhere[2], so only the details essential for an analysis of the jet-flap results are given here.

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† A few results for a 60-deg delta wing are given in Ref. 8, but only for $C_\mu' < 0 \cdot 1$, so that extrapolation to practical jet-flap values is not justified.

‡ For a given blowing pressure, C_μ' is theoretically proportional to w_t/U_0^2, where w_t represents the width of the slot throat.

A plan view of the half-model is shown in Fig. 1. The delta wing had a 5 per cent thick RAE 102 section in the streamwise direction, a leading-edge sweepback of 60 deg, and an unswept trailing edge; the wing tip was clipped ($c_t/c_0 = 1/6$). The trailing-edge flap was of constant chord ($S_f/S' = 1/6$) and extended from the wing-body junction outboard to about 0·8 of the half-model span.

Compressed air was ejected over the upper surface of the flap knee from a slot of constant width ($A_t/S' = 1{\cdot}7 \times 10^{-4}$) in the main wing. The duct stagnation pressure was recorded during the experiments and the rate of mass flow of air to the model was determined from orifice-plate measurements.

2.2. *Range of Experiments*.—Lift, pitching-moment and thrust measurements were made over the range $\alpha_u = -4$ deg to $+20$ deg of uncorrected (geometrical) incidence. At the wind speed of 30 ft/sec, the Reynolds number corresponding to the mean chord c_m was $0{\cdot}7 \times 10^6$. With the available range of blowing pressure, 0 to 46 p.s.i. gauge, the blowing-momentum coefficient C_μ' could be varied between 0·014* and 1·5. Owing to the short time available, tests were only completed at four values of C_μ' for each of the flap angles 30, 60 and 90 deg.

2.3. *Reduction of Observations*.—The values of the lift, pitching-moment and thrust coefficients were obtained from the corresponding balance measurements as follows, corrections being applied to allow for boundary lift-constraint effects†. The pitching moments are referred to the flap hinge axis (*see* Fig. 1), which was the pitching axis of the model in the experiments.

$$C_L = \text{lift}/q_0 S\ , \qquad C_m = \text{pitching moment}/q_0 S\bar{c}\ ,$$
$$C_T = \text{thrust}/q_0 S - 0{\cdot}0175 C_L^2\ ,$$
$$\alpha\ (\text{deg}) = \text{geometrical incidence} + 1{\cdot}0\, C_L\ (\text{deg})\ .$$

The blowing-momentum coefficient $C_\mu'[\equiv Mv_j/q_0S']$ used for the correlation of results was evaluated as usual from the measured mass-flow rate M (slugs/sec), and the theoretical velocity v_j (ft/sec) reached on isentropic expansion from the duct stagnation pressure to the main-stream static pressure[3, 4]. For comparison, a few measurements of the jet reaction J on the model were made with blowing over the flap at zero main-stream speed, but time did not permit detailed investigations. The values obtained for the total jet-reaction coefficient $C_j'[\equiv J/q_0S']$ at various flap deflections were appreciably less than the C_μ' values for the same blowing pressure. Even when a correction is made for the drag on the wing ahead of the flap due to the surface flow induced by the jet efflux, $C_j' \gg 0{\cdot}7C_\mu'$; the difference can partly be attributed to the skin friction on the flap upper surface due to the high-velocity jet. More detailed comparisons of jet-reaction and jet-momentum coefficients are to be carried out on the rectangular-wing model.

3. *Experimental Results*.—3.1. *Lift*.—Values of $C_L/\sin\eta$ at true zero incidence are plotted against C_μ' in Fig. 2, and are nearly independent of flap angle η when C_μ' exceeds 0·25; this C_μ' value is roughly that needed to prevent flow separation over the flap when $\eta = 90$ deg. Even at the highest C_μ' value of 1·5, $C_L/\sin\eta$ is more than twice the value $C_\mu \equiv S'C_\mu'/S = 0{\cdot}63C_\mu'$, corresponding to the direct lift from a jet inclined at an angle η to the main-stream direction, and $(dC_L/dC_\mu')/\sin\eta$ is still as much as 0·75.

Lift-incidence curves at C_μ' values of 0·014, 0·34, 0·67 and 1·54 are shown in Figs. 3a, 3b and 3c for $\eta = 30$, 60 and 90 deg respectively; for comparison, the lift-incidence curve of the plain wing ($\eta = C_\mu' = 0$) is also included. For the two smaller flap angles, the slope of the lift-incidence curve tends to rise as C_μ' increases, but not for the largest. When $\eta = 90$ deg and $C_\mu' = 1{\cdot}5$, the slope becomes very small, presumably because of extensive flow separation over the wing ahead

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* This was originally intended to be zero but, to avoid delay, the small leak from the air-bearing supply was not sealed off from the model blowing duct.

† $\Delta\alpha$ deg $= 57{\cdot}3\delta(S/C)C_{Lu}$, where $\delta = 0{\cdot}12$; the gross wing area S' was 10·10 sq ft and the cross-sectional area C of the working-section was 65·7 sq ft.

of the flap. This separation region could certainly be reduced, if not completely eliminated, by boundary-layer control near the wing leadin-gedge or at the knee of a leading-edge flap. However, in the present tests, the largest lift was achieved with $\eta = 60$ deg, when $C_L = 2 \cdot 9$ for $C_\mu' = 1 \cdot 5$ and $\alpha = 23$ deg. This yields an increment of $2 \cdot 0$ over the value $C_L = 0 \cdot 9$ achieved at the same incidence with $\eta = C_\mu' = 0$.

Theoretical estimates of the lift could be attempted using Spence's two-dimensional linearised theory[5] and aspect-ratio corrections based on the downwash arguments put forward by Maskell[6] and Berndt[7]. However, no theoretical investigations have yet been made of the effects of large amounts of sweepback, low aspect ratio and part-span blowing on jet-flap wings. The present experiments are too limited to justify putting forward semi-empirical factors for these effects, especially since the values of the jet angle and flap-chord ratio needed for theoretical prediction of these experimental results are not easily specified. Furthermore, except at the smallest flap angle tested ($\eta = 30$ deg), gross errors may arise because only a linearised two-dimensional theory is available.

3.2. *Pitching Moments.*—The pitching moment about the flap hinge axis is plotted against the lift in Fig. 4, for prescribed values of C_μ' and α_u. The slope dC_m/dC_L of the curve for the plain wing ($\eta = C_\mu = 0$) at moderate incidences is about $0 \cdot 57$, so that the aerodynamic centre is located roughly $0 \cdot 57\bar{c}$ ahead of the flap hinge line, *i.e.*, at about $0 \cdot 35\bar{\bar{c}}$ aft of the leading edge of the mean aerodynamic chord. The slopes of the curves for constant C_μ' and flap angle (α_u varied) in general decrease with increasing C_μ', except at high incidences and at the largest flap angle ($\eta = 90$ deg). This implies that the aerodynamic centre tends to move slightly aft with increasing C_μ' except when extensive flow separation is present on the delta wing.

The centre of lift for $\alpha_u = 0$, $\eta = 30$ deg, and $C_\mu' = 1 \cdot 5$ is located about $0 \cdot 125\bar{c}$ ahead of the flap hinge line, *i.e.*, at about $0 \cdot 75\bar{\bar{c}}$ aft of the leading edge of the mean aerodynamic chord. In general the centre of total lift moves forward appreciably with increasing α or decreasing C_μ', but changes only slightly with η.

3.3. *Thrust.*—Because completely reliable thrust measurements could not be obtained in these tests, not more than a qualitative examination of the thrust results is warranted. Some curves of thrust against lift with prescribed values of α_u or C_μ' are shown in Figs. 5a, 5b and 5c for $\eta = 30$, 60 and 90 deg respectively. Although, for the lowest flap angle, the thrust first decreases with increasing C_μ' when α is positive, it later begins to increase again; provided $\alpha \leqslant 10$ deg, the thrust always becomes positive before C_μ' reaches the maximum value tested. However, for the two higher flap angles, the thrust steadily decreases with C_μ' up to the maximum value tested, except for $\eta = 60$ deg with $\alpha \leqslant 2$ deg; furthermore, the thrust on the wing never becomes positive.

4. *Conclusions.*—The experimental results for the delta wing with blowing over a trailing-edge flap at large C_μ' values demonstrate that substantial magnification of the direct jet lift occurs even with considerable leading-edge sweepback (60 deg) and low aspect ratio ($1 \cdot 65$). For example, $C_L = 2 \cdot 25 \sin \eta$ at zero wing incidence when $C_\mu' = 1 \cdot 5$, more than double the corresponding jet-reaction lift $0 \cdot 63 C_\mu \sin \eta$. The largest lift measured in the tests was $C_L = 2 \cdot 9$, at the highest incidence of 23 deg and highest C_μ' of $1 \cdot 5$ ($C_\mu = 0 \cdot 95$), but with $\eta = 60$ deg, *i.e.*, not at the highest flap angle. Movement of the centre of lift with varying α and C_μ' was appreciable. Positive values of the thrust occurred only at the lowest flap angle ($\eta = 30$ deg).

Although highly swept jet-flap wings of low aspect ratio present an interesting research problem, their practical possibilities do not appear to warrant immediate priority for further experiments. Nevertheless, even if the application of large C_μ' values cannot be readily justified, the usefulness of low C_μ' values ($\simeq 0 \cdot 1$ or $0 \cdot 01$) for either lift augmentation or control should not be overlooked[2].

Acknowledgements.—Mr. I. Thompson assisted with the tunnel experiments and the reduction of observations. The model was designed by Mr. N. Marcus, and was constructed by Mr. J. Moore and Mr. P. Robinson in the Aerodynamics Division workshop, N.P.L.

NOTATION

A_t	Slot throat area
C_L	Lift coefficient $= L/q_0S$
C_m	Moment coefficient about flap hinge axis $= m/q_0S\bar{c}$
C_T	Corrected thrust coefficient $=$ thrust$/q_0S - 0{\cdot}0175C_L^2$
C_μ'	'Sectional' blowing-momentum coefficient $= M_jv_j/q_0S'$
C_μ	'Overall' blowing-momentum coefficient $= M_jv_j/q_0S = 0{\cdot}63C_\mu'$
c_0	Root chord of wing = 6·0 ft
c_t	Tip chord of wing = 1·0 ft
$\bar{c}$	Mean geometric chord of wing = 3·5 ft
$\bar{\bar{c}}$	Mean aerodynamic chord $= \frac{1}{S}\int_0^s c^2\,dy = 4{\cdot}09$ ft
c_f	Flap chord = 0·6 ft
M_j	Mass flow (slugs/sec) of air fed to model
s	Span of half-wing
S	Gross wing area = 10·10 sq ft
S'	Reference wing area corresponding to spanwise extent of blowing slot = 6·33 sq ft
S_f	Flap area = 1·05 sq ft
q_0	Main-stream dynamic head (lb/sq ft)
v_j	Blowing velocity, evaluated theoretically by assuming isentropic expansion from the duct stagnation pressure to the main-stream static pressure
α_u°	Uncorrected (geometrical) wing incidence (deg)
α°	Corrected wing incidence $= \alpha_u^\circ + C_L$ (deg)
η	Flap angle

REFERENCES

No.	*Author*	*Title, etc.*
1	J. Williams and A. J. Alexander	Some exploratory three-dimensional jet-flap experiments. *Aero. Quart.*, Vol. VIII, p. 21. February, 1957. Three-dimensional wind-tunnel tests of a 30-deg jet flap model. C.P. 304. November, 1955.
2	J. Williams and A. J. Alexander	Preliminary note on a wind-tunnel investigation of trailing-edge flap blowing on a 5 per cent thick 60-deg delta wing. NPL/Aero/321. March, 1957. (Report in preparation.)
3	A. Anscombe and J. Williams ..	Some comments on high-lift testing in wind-tunnels with particular reference to jet-blowing models. *J.R.Ae.S.*, Vol. 61, p. 529. 1957.
4	J. Williams..	An analysis of data on blowing over trailing-edge flaps for increasing lift. C.P. 209. September, 1954.
5	D. A. Spence	The lift on a thin aerofoil with a blown flap. *Aero. Quart.*, Vol. IX, p. 257. 1958.
6	E. C. Maskell	A theory of the jet flap in three dimensions. (To be published as an R.A.E. report.)
7	S. B. Berndt	A note on the drag due to lift as influenced by a jet flap on a wing of finite span. FFA (Sweden) Rep. Ae.–398. 1956.
8	L. Malavard, Ph. Poisson-Quinton and P. Jousserandot	Recherches théoriques et expérimentales sur le contrôle de circulation par soufflage appliqué aux ailes d'avions. O.N.E.R.A. Note Tech. 37. 1956.

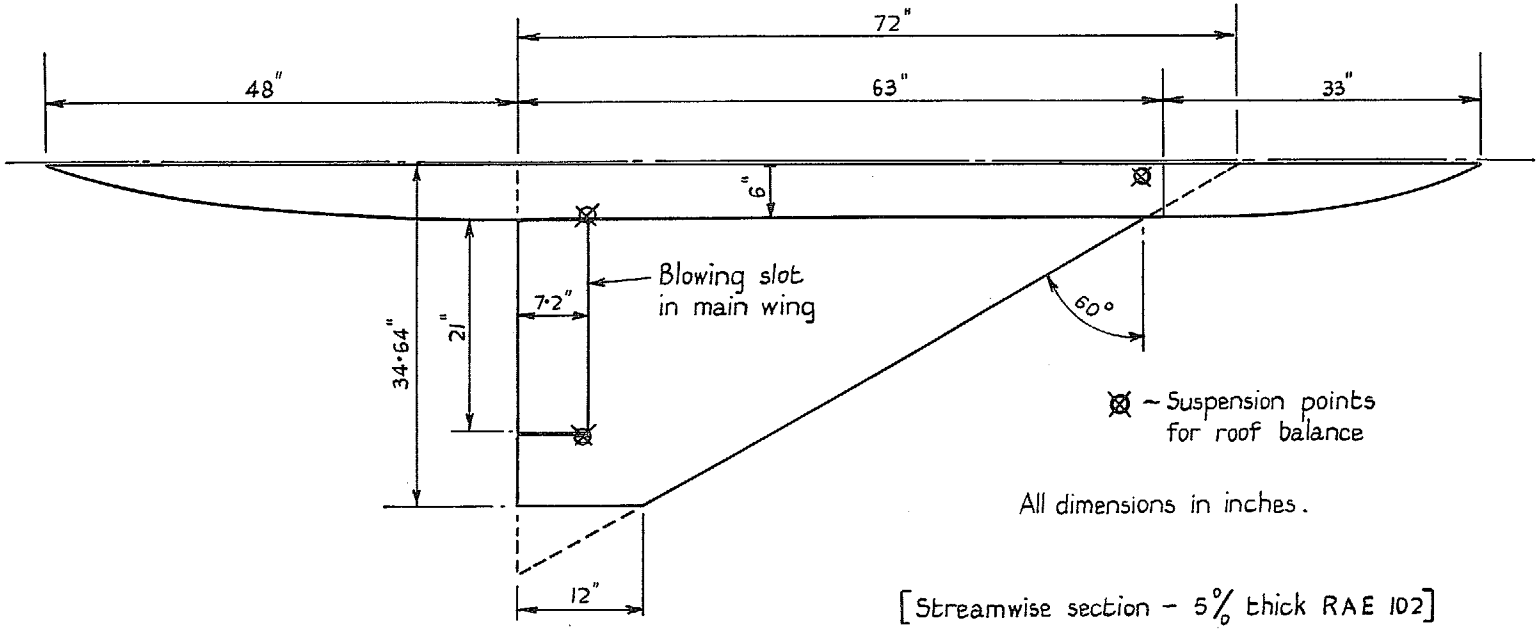


FIG. 1. Half-model of 60-deg delta with trailing-edge flap blowing.

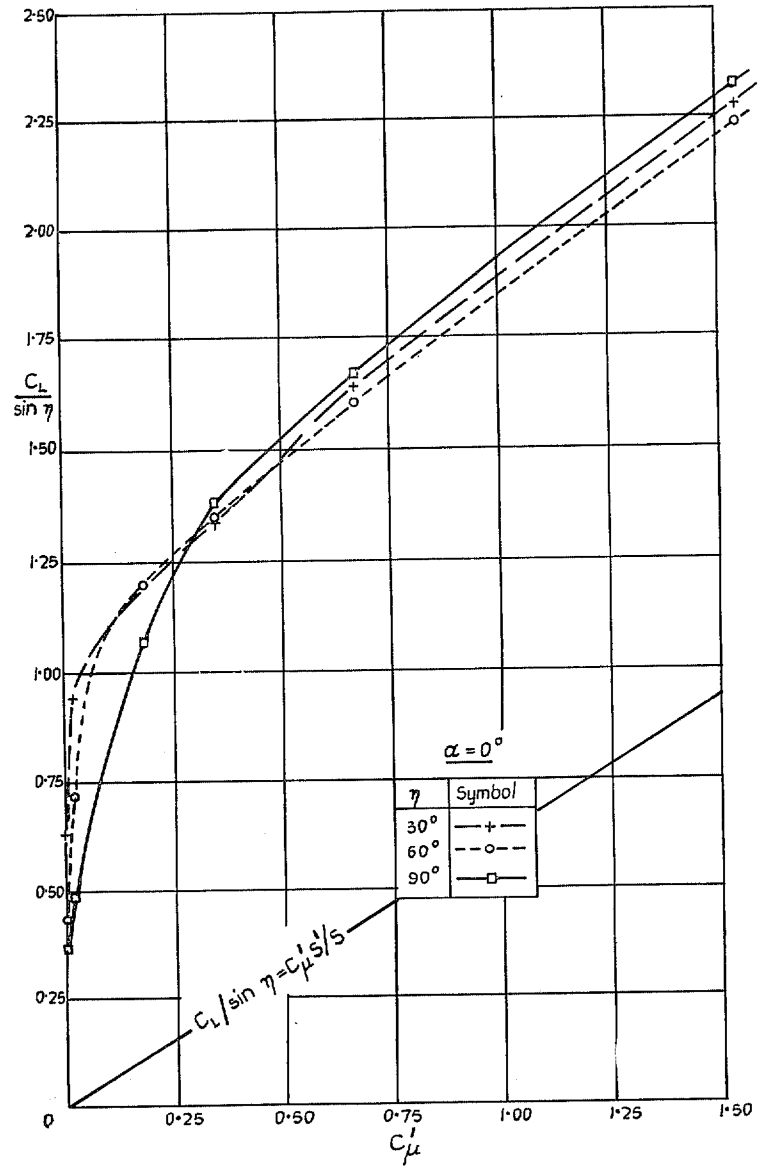


FIG. 2. Variation of lift with momentum coefficient at zero incidence.

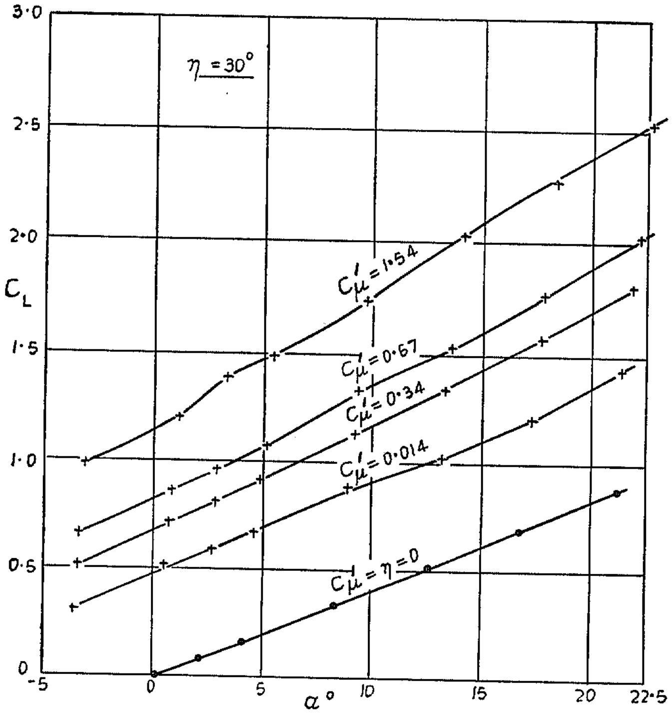


FIG. 3a. Variation of lift with incidence at constant C_μ', for $\eta = 30$ deg.

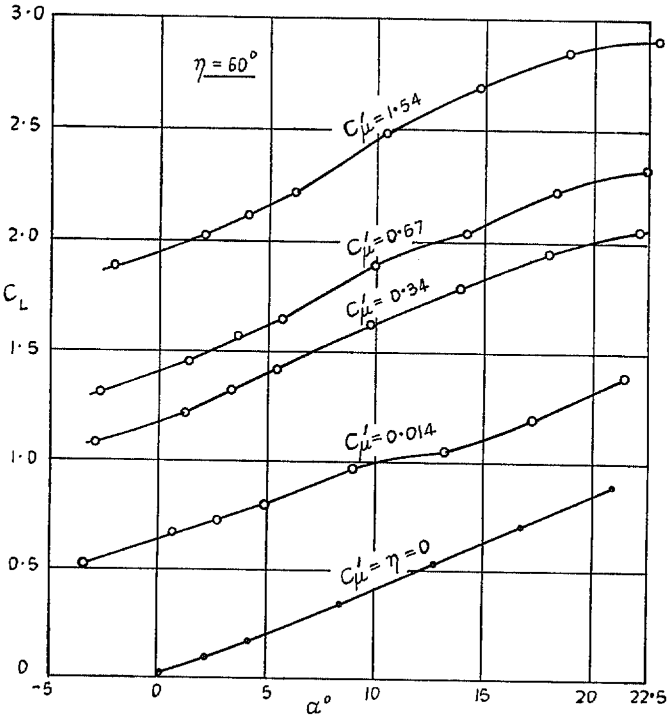


FIG. 3b. Variation of lift with incidence at constant C_μ', for $\eta = 60$ deg.

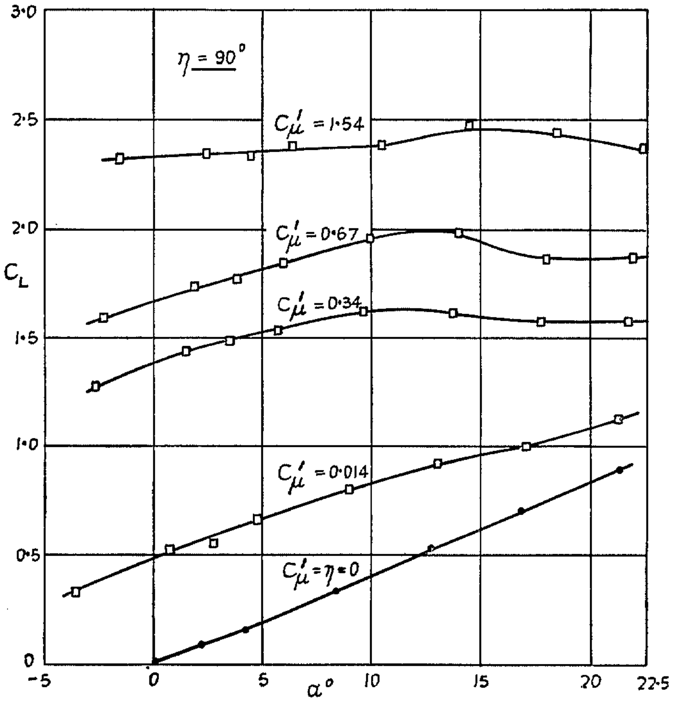
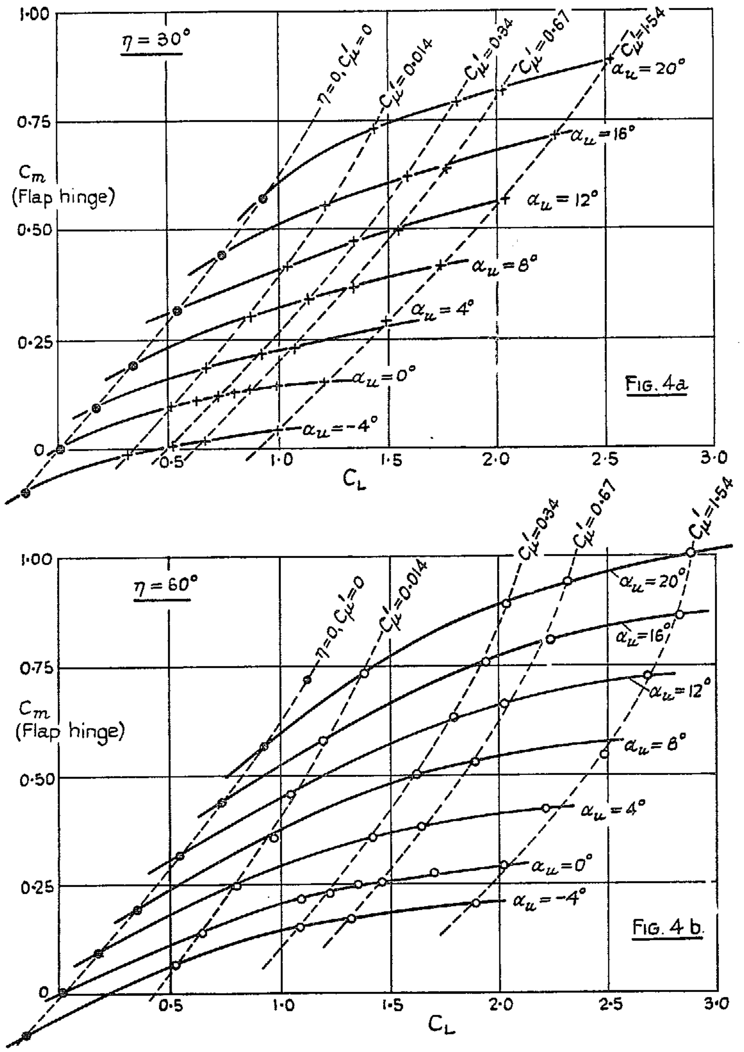


FIG. 3c. Variation of lift with incidence at constant C_μ', for $\eta = 90$ deg.



FIGS. 4a and 4b. Variation of pitching moment with lift.

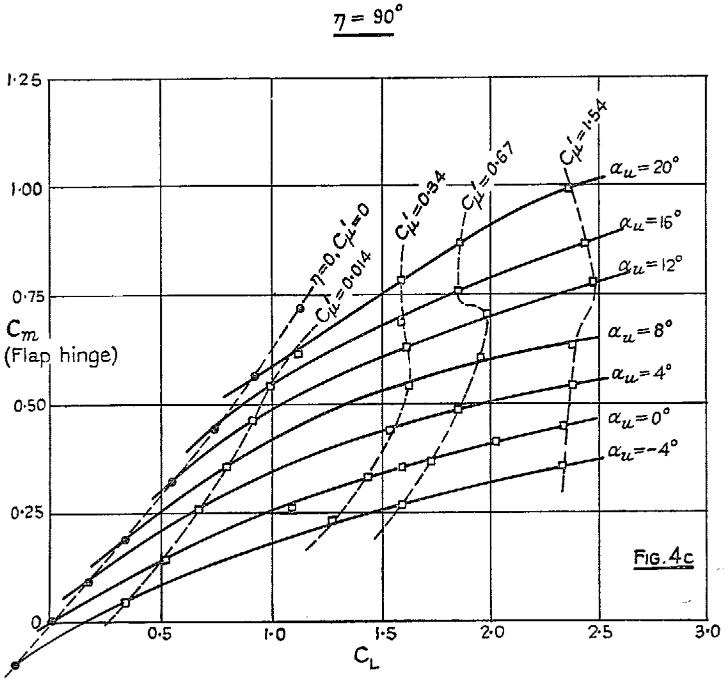


FIG. 4c. Variation of pitching moment with lift.

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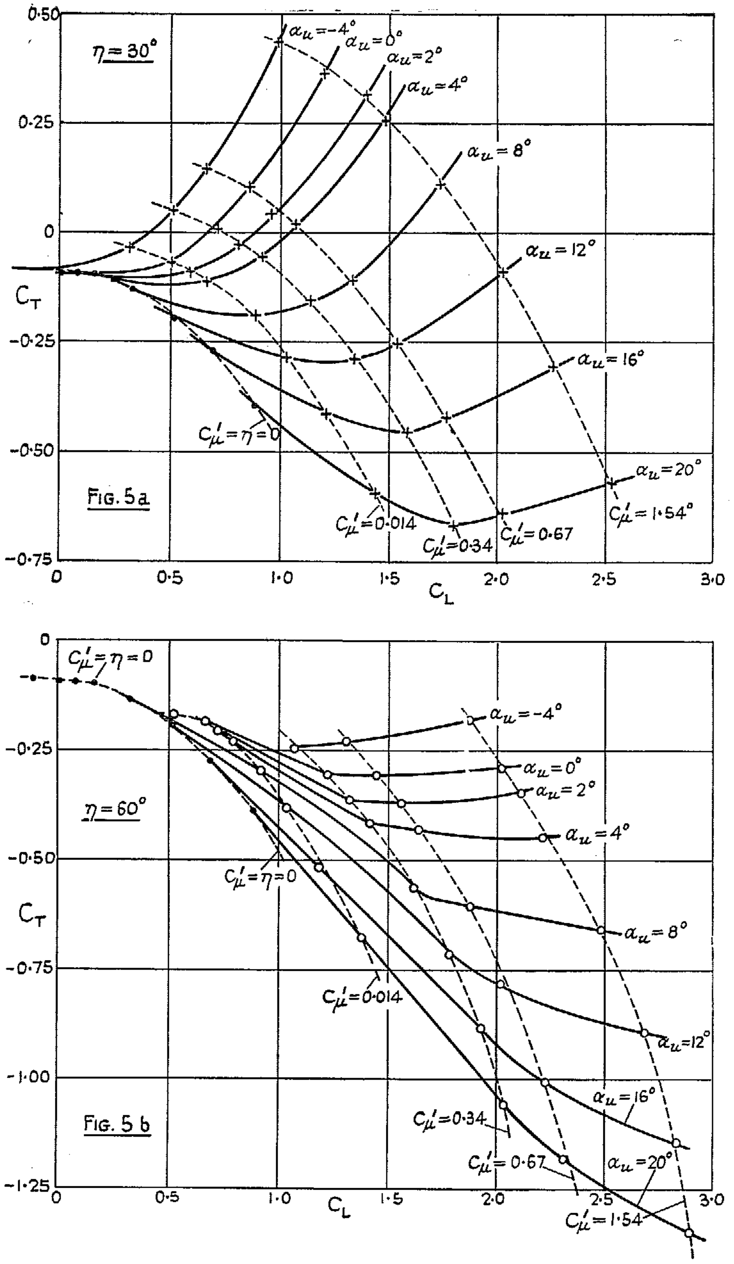

FIGS. 5a and 5b. Variation of thrust with lift at constant α_u or C_μ'.

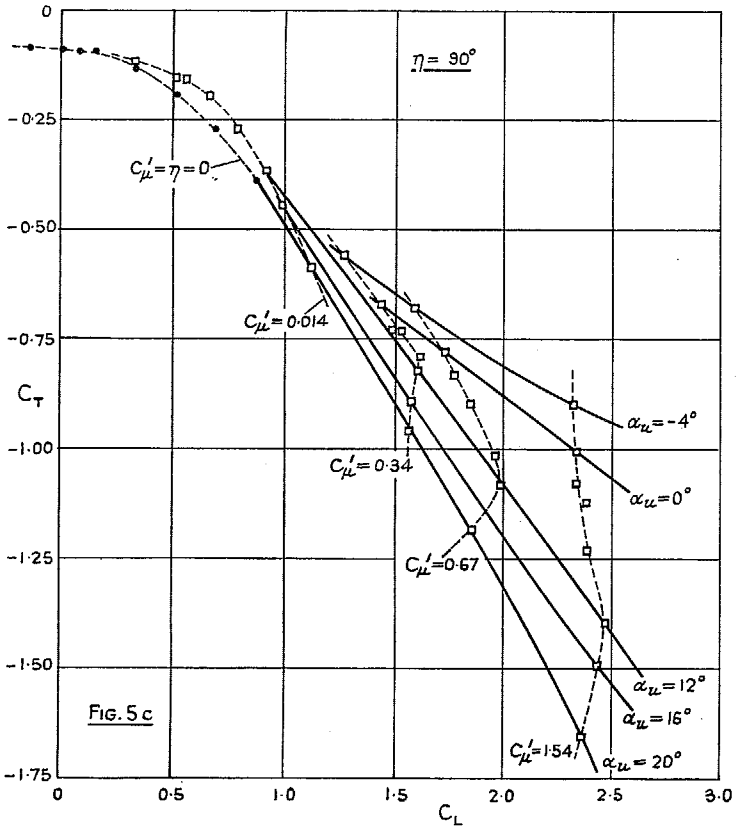

FIG. 5c. Variation of thrust with lift at constant α_u or C_μ'.

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