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Low-Speed Wind-Tunnel Measurements on a Thin Sharp-Edged Delta Wing with 70° Leading-Edge Sweep, with Particular Reference to the Position of Leading-Edge-Vortex Breakdown

By J. A. LAWFORD, B.Sc. and A. R. BEAUCHAMP, B.Sc.

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COMMUNICATED BY THE DEPUTY CONTROLLER AIRCRAFT (RESEARCH AND DEVELOPMENT),
MINISTRY OF AVIATION

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Summary.

The position of the breakdown of the tightly rolled leading-edge vortex was observed using a smoke technique. The breakdown point moved forward with increasing incidence, and reached a point above the trailing edge at an incidence of 32°. It moved forward to transverse planes through 0·5 and 0·28 of the centre-line chord at 34° and 37° incidence respectively.

The root-mean-square intensity and the low-frequency component of pressure fluctuations both began to rise rapidly at approximately the same incidence (31°) at four widely spaced points on the wing. This rise in pressure fluctuations was accompanied by a similar increase in the low-frequency component of normal-force fluctuations.

The lift slope decreased at incidences above 21°, coinciding with a marked decrease in longitudinal stability. The drag coefficient varied linearly with C_L^2 up to an incidence of about 24°.

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* Replaces R.A.E. Tech. Note No. Aero. 2797—A.R.C. 23,725.

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1. *Introduction.*

This paper reports part of a Royal Aircraft Establishment investigation into the behaviour of the air flow round sharp-edged delta wings. It has been established that the tightly rolled vortex from a swept leading edge breaks down—that is, it transforms within a very short streamwise length into a much more diffuse vortex. At low incidences this breakdown occurs well downstream of the trailing edge; with increase of incidence the breakdown point moves upstream so that at high incidence it is above the wing upper surface. The present tests were made to find the relationship between the position of vortex breakdown, the fluctuations of pressure and normal force on the wing surface, and the total forces, on a thin sharp-edged delta wing with 70° leading-edge sweep. They were carried out in the R.A.E. 4 ft × 3 ft Low Turbulence Wind Tunnel.

2. *Model and Rig Details, and Scope of Tests.*

Two geometrically similar mild-steel models were used. The ratio of wing thickness to aerodynamic mean chord was 0·024, and the leading edges were chamfered on the lower surface only at an angle of 30° measured normal to the edge.

The model shown in Fig. 1, suspended by wires from the tunnel balance, was used for the vortex breakdown, three-component balance measurements and pressure fluctuation measurements, using a wind speed of 100 ft per sec ($R = 0\cdot 7 \times 10^6$ based on $\bar{c}$).

The position of the breakdown of the leading-edge vortex was determined by observing smoke discharged from a small hole in a pipe held about three feet upstream of the model, over the relevant part of the incidence range (32° to 37°).

Fluctuations of pressure difference between the upper and lower surfaces were measured by variable capacitance-type pressure transducers[1]. Their locations and the numbers by which they are designated in this paper are shown in Fig. 1.

Lift, drag and pitching moment were measured on the tunnel balance over an incidence range from 0° to 45°.

A smaller model, with centre-line chord of 11·72 in., was used for the measurement of fluctuations of normal-force coefficient. It was mounted on a sting and the measurements were made using a strain-gauge balance (Fig. 2). An incidence range from 0° to 50° was covered, using a wind speed of 80 ft/sec ($R = 0 \cdot 33 \times 10^6$ based on $\bar{c}$).

3. *Results and Discussion.*

3.1. *Leading-Edge-Vortex Breakdown.*

The breakdown of the leading-edge vortex was clearly visible when smoke was released from a small hole upstream of the model at a position giving a flow into the vortex core. The approximate position of the breakdown, in terms of the centre-line chord C_0 was as follows:

$\alpha°$	Breakdown point
32	$1 \cdot 0 C_0$
34	$0 \cdot 5 C_0$
36	$0 \cdot 35 C_0$
37	$0 \cdot 28 C_0$

The rate of forward movement of the breakdown with increase of incidence became much less rapid when it was forward of the centre-line mid-chord point.

3.2. *Pressure Fluctuations and Mean Pressure Difference across the Wing.*

The theory and technique of the measurement of pressure fluctuations are discussed in detail in Ref. 1. The quantities used here are defined as follows:

p = root-mean-square intensity of pressure fluctuation

q = $\frac{1}{2}\rho V^2$

$\bar{c}$ = aerodynamic mean chord = $\int_{-b/2}^{b/2} c^2 dy \Big/ \int_{-b/2}^{b/2} c\, dy$

n = non-dimensional frequency parameter = $\frac{f\bar{c}}{V}$

f = frequency

$F(n)$ = spectrum function, such that $F(n)dn$ is the contribution to $(p/q)^2$ of frequencies from n to $n + dn$ and hence

$$\left(\frac{p}{q}\right)^2 = \int_0^\infty F(n)dn = \int_{-\infty}^\infty nF(n)d(\log n).$$

It is shown in Ref. 1 that probable buffeting excitation at any given frequency is proportional to the value of $\sqrt{\{nF(n)\}}$ at that frequency, and spectra of pressure fluctuations through a frequency range are therefore presented as curves of $\sqrt{\{nF(n)\}}$ against n. It is convenient to use a logarithmic scale for n and this has the advantage that, since

$$\int_{-\infty}^{\infty} nF(n)d(\log n) = \left(\frac{p}{q}\right)^2 ,$$

an integrable power spectrum can be obtained by squaring the ordinates of spectra presented in this way.

Buffeting occurs at low frequencies, and it is therefore useful to select a value of n which represents a likely buffeting frequency and to present $\sqrt{\{nF(n)\}}$ at this value as a quantity which may indicate liability to buffet. This quantity is usually referred to as the 'low-frequency component' of pressure fluctuation, the value of n used being usually $0 \cdot 2$. While the present paper is not primarily concerned with buffeting as such, the results appear directly relevant and it seems desirable to adhere to the accepted form of presentation for such measurements.

The results of the present tests are given in Figs. 3 and 4. Both the total intensity and the low-frequency component of the pressure fluctuations rise sharply at an incidence, sensibly independent of transducer position, of 31° approximately. This corresponds to the forward movement of the vortex breakdown position over the trailing edge. If the increase in pressure fluctuations were a *local* effect of the vortex breakdown, it should have occurred at an incidence about 2° higher at the forward transducer position than at the rear. Since it did not, the increase in pressure fluctuations was probably due to a change in the entire flow pattern, which may be closely associated with the forward movement of vortex breakdown across the trailing edge.

Too much significance should not be attached to the measured intensities of pressure fluctuation at low incidence. Recent tests[2] on a delta wing of 76° leading-edge sweepback have shown that these are sensitive to the position of transition, which was not fixed during the tests reported in this paper.

Mean pressure differences across the wing were obtained from the mean transducer capacities, and are plotted against incidence in Fig. 5.

3.3. *Normal-Force Fluctuations.*

Methods of measuring and presenting normal-force fluctuations are discussed in Ref. 3, and are very similar to those for pressure fluctuations. The transducer, together with its oscillator and pre-amplifier, are replaced by a strain-gauge-balance circuit and a suitable amplifier, but otherwise the same apparatus is used. The following quantities are employed in addition to those already defined:

c_N = the root-mean-square intensity of fluctuation of the normal-force coefficient C_N

$F(n)$ = the spectrum function, such that $F(n)dn$ is the contribution to $c_N{}^2$ of frequencies from n to $n + dn$ and hence

$$c_N{}^2 = \int_0^{\infty} F(n)dn = \int_{-\infty}^{\infty} nF(n)d(\log n) .$$

[Suffices are used where required to indicate whether $F(n)$ relates to $(c_N)^2$ or $(p/q)^2$.]

The results of the normal-force fluctuation measurements are presented in Fig. 6 as a curve of $\sqrt{\{nF(n)\}}$ at $n = 0 \cdot 2$ plotted against incidence. The total r.m.s. intensity c_N, and spectra over a frequency range, are not given because they cannot be measured by the present technique. In any measurement of fluctuating quantities of this nature the results are valid only up to a frequency of about one third of the lowest natural frequency of the measuring system. In the case of a pressure transducer this limit can be made high enough to avoid the exclusion of much of the total energy of the spectrum. For normal-force fluctuations, however, the relevant natural frequency is that of the complete model on its sting and strain-gauge balance, and, in spite of rigid construction and a fairly light model, this is low. Analysis was made at the highest frequency which could be used without introducing errors due to dynamic effects in the rig, but even so the required value of n could be obtained only by using the comparatively low tunnel speed of 80 ft/sec.

The fluctuation at zero incidence was probably due almost entirely to extraneous effects in the tunnel. The known incidence fluctuation in the empty tunnel is sufficient to account for about a third of it, and most of the remainder was probably due to interference between the tunnel-wall boundary layer and the rig. The true datum level for the curve of normal-force fluctuation against incidence is therefore not clearly established, and this prevents quantitative comparison of the normal-force-fluctuation and the pressure-fluctuation results when the measured values were of the same order of magnitude as the datum fluctuation. But, when vortex breakdown was occurring well forward on the wing, the level of fluctuation was large compared with the datum, and of the same order of magnitude as the local pressure fluctuations. This indicates that the correlation of pressure fluctuations was high at the low frequencies of the present measurements.

3.4. *Balance Measurements.*

The results of the balance measurements are given in Table 1 and in Figs. 7 and 8. A correction to tunnel speed for wake blockage has been applied, based on Maskell's theory[4]. The pitching-moment coefficients are presented in terms of the aerodynamic mean chord $\bar{c}$, and are given about the quarter-chord point of the a.m.c., which in the case of a delta wing coincides longitudinally with the mid-point of the centre-line chord.

The lift-curve slope increased with incidence from $\alpha = 0°$ to $\alpha = 21°$, and the pitching moment varied linearly with lift in this range ($-dC_m/dC_L = 0{\cdot}12$). Above $\alpha = 21°$ the lift slope decreased, a maximum lift coefficient of $1{\cdot}305$ being reached at $\alpha = 34°$, and the static stability decreased to a minimum value of $-dC_m/dC_L$ of about $0{\cdot}035$ at a lift coefficient of $1{\cdot}2$ ($\alpha = 27°$). The drag coefficient varied almost linearly with $C_L{}^2$ up to a C_L of about $1{\cdot}1$ ($\alpha = 24°$). The maximum value of C_L/C_D was about $5{\cdot}1$ at $C_L = 0{\cdot}22$ ($\alpha = 6°$).

4. *Conclusions.*

The breakdown of the leading-edge vortex moved forward from downstream with increase of incidence, and occurred above the trailing edge at an incidence of 32°, in a transverse plane through the mid-point of the centre-line chord at 34°, and in a similar plane at $0{\cdot}28\ C_0$ at 37°.

The fluctuations in pressure difference between the upper and lower surfaces, and the low-frequency component of these fluctuations, began to rise sharply at an incidence, practically independent of chordwise or spanwise position, of 31°. This increase of fluctuation in pressure difference was accompanied by a similar rise in the low-frequency component of fluctuation of normal force, and occurred in the incidence range within which the breakdown of the leading-edge vortex was advancing across the trailing edge.

The maximum lift coefficient was $1{\cdot}305$ at an incidence of 34°. A decrease of lift slope and a reduction of static stability began to occur at an incidence of about 21°, and a departure from a linear C_D vs. $C_L{}^2$ relationship at about 24°. The maximum value of C_L/C_D was about $5{\cdot}1$ at $C_L = 0{\cdot}22$.

REFERENCES

No.	*Author(s)*	*Title, etc.*
1	T. B. Owen	Techniques of pressure fluctuation measurements employed in the R.A.E. low-speed wind-tunnels. A.G.A.R.D. Report 172. March, 1958.
2	T. B. Owen	Pressure fluctuations associated with leading-edge vortex flow on a slender wing at low incidence. Unpublished M.o.A. Report.
3	T. B. Owen	Techniques of normal-force fluctuation measurement employed in the R.A.E. low-speed wind-tunnels. A.R.C. 20,780. February, 1958.
4	E. C. Maskell	A theory of wind-tunnel blockage effects on stalled flows. Unpublished M.o.A. Report.

TABLE 1

Lift, drag and pitching-moment coefficients

$\alpha°$	C_L	C_D	C_m
0	−0·002	0·020	+0·0029
5·1	+0·187	0·037	−0·0221
10·2	+0·392	0·092	−0·0433
15·35	+0·639	0·198	−0·0768
20·5	+0·900	0·355	−0·1090
25·65	+1·137	0·567	−0·1303
30·75	+1·273	0·773	−0·1357
32·75	+1·301	0·852	−0·1403
34·8	+1·304	0·925	−0·1455
36·8	+1·275	0·967	−0·1499
38·75	+1·186	0·970	−0·1477
40·7	+1·114	0·978	−0·1440
42·65	+1·035	0·981	−0·1469
45·55	+0·831	0·915	−0·1725

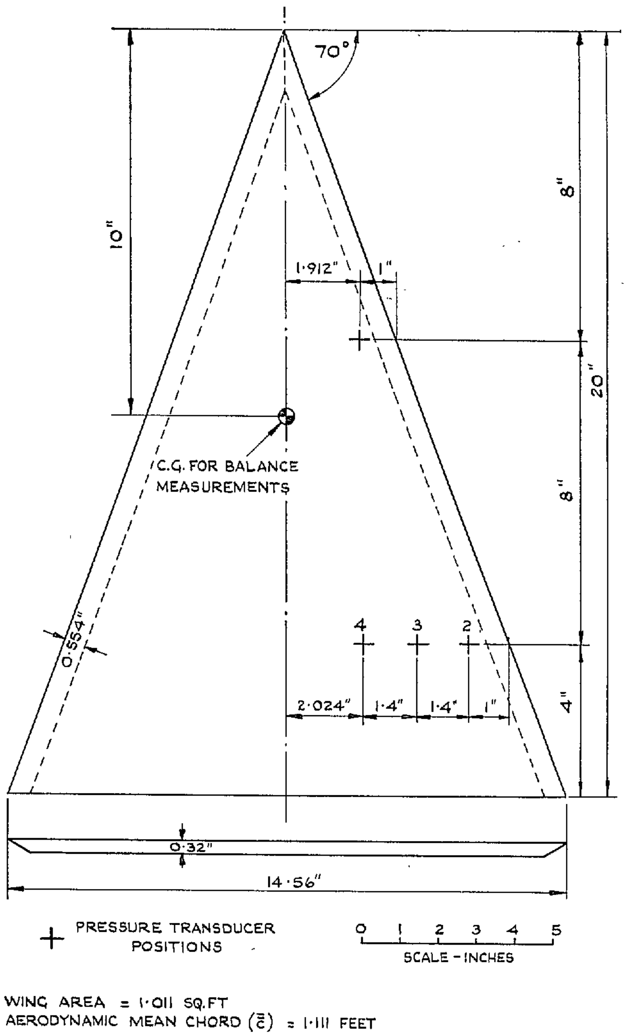


FIG. 1. General arrangement of model.

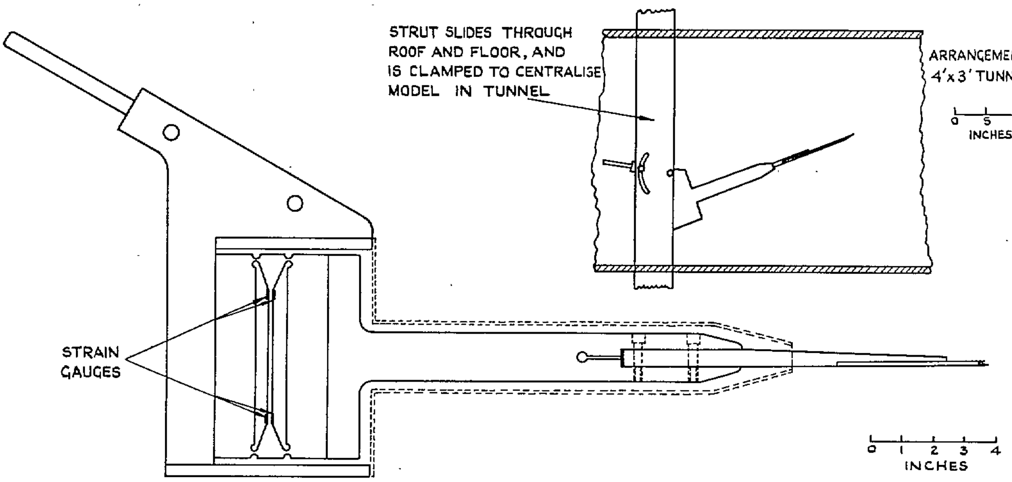
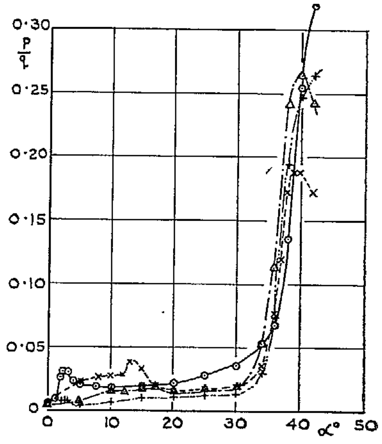
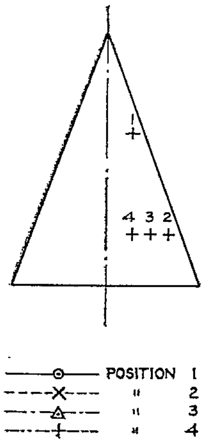
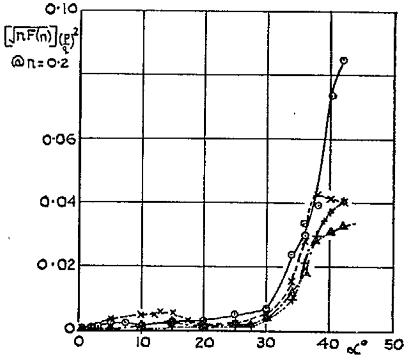


FIG. 2. General arrangement of strain-gauge balance for measurement of normal-force fluctuations.



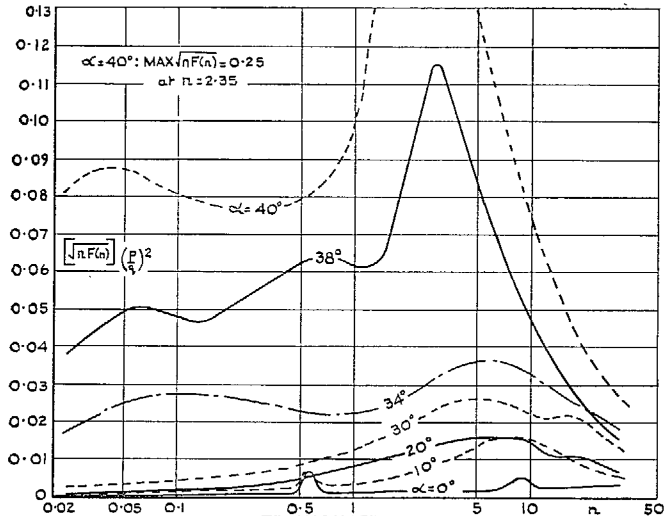
R.M.S. PRESSURE FLUCTUATION.



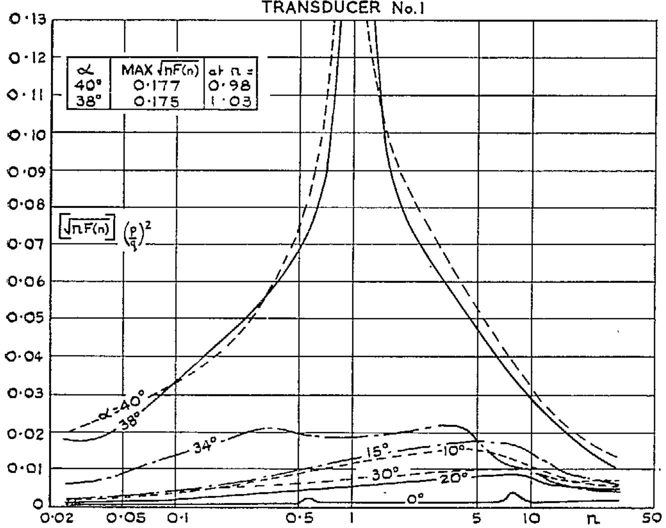


'LOW-FREQUENCY COMPONENT' OF PRESSURE FLUCTUATION.

FIG. 3. Variation of pressure fluctuations with incidence.



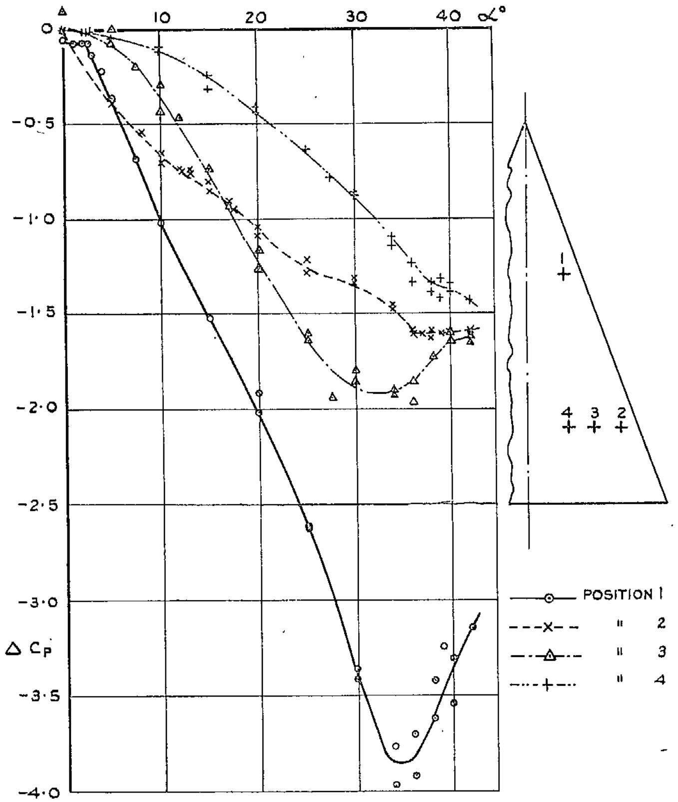
TRANSDUCER No. 1



α	MAX √nF(n)	at n =
40°	0·177	0·98
38°	0·175	1·03

TRANSDUCER No. 2

FIG. 4. Spectra of pressure fluctuations.



$\Delta C_P = C_{P_{\text{UPPER SURFACE}}} - C_{P_{\text{LOWER SURFACE}}}$

FIG. 5. Pressure difference across the wing.

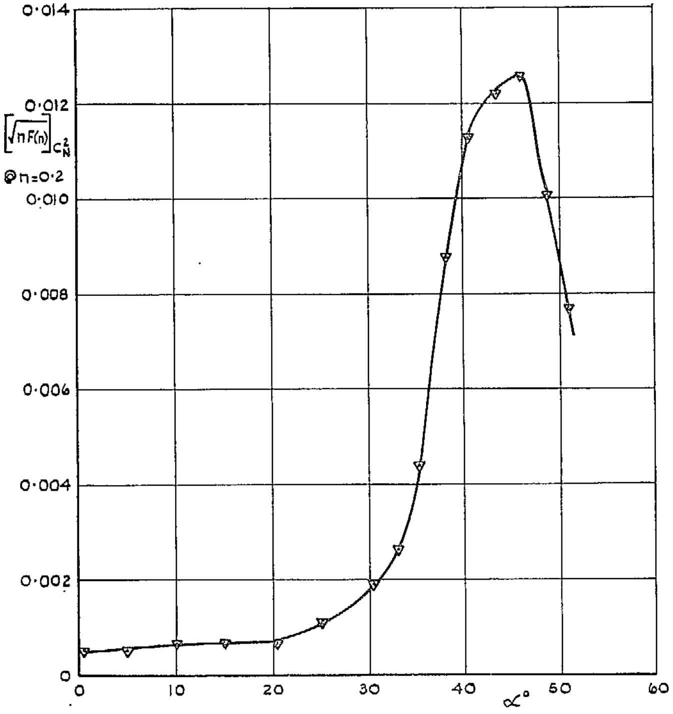


FIG. 6. Low-frequency component of normal-force fluctuation.

$\bar{\bar{c}} = 0 \cdot 652$ feet $\quad V = 80$ ft/sec

(87656) Wt. 65/1418 K.5 8/63 Hw.

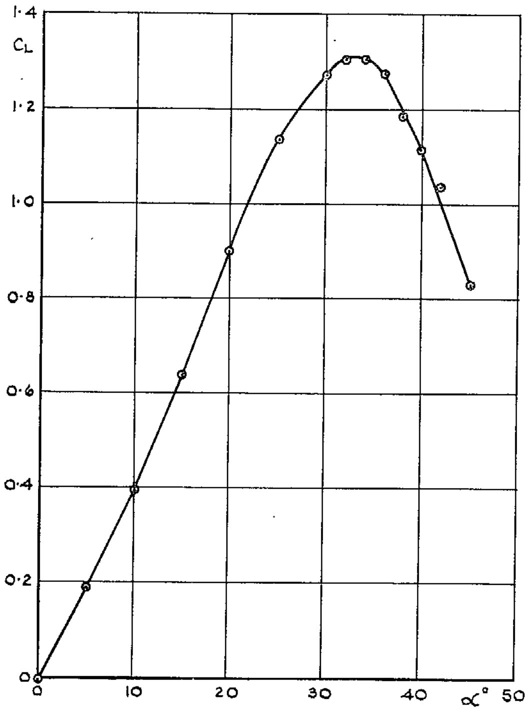
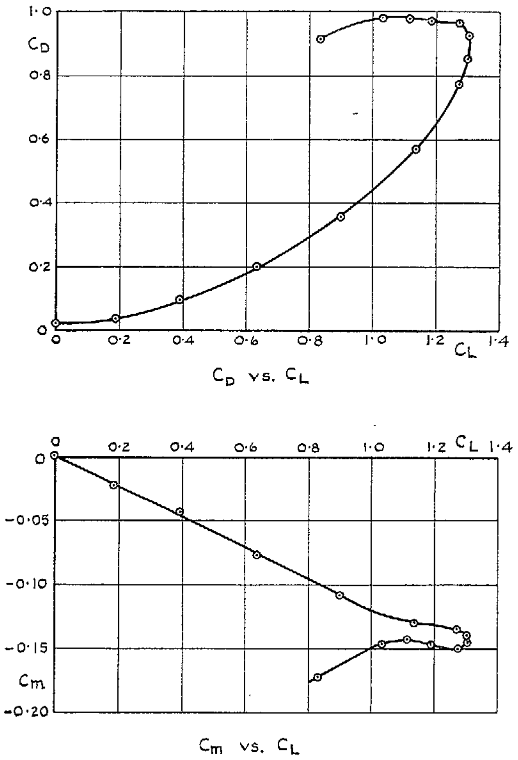


FIG. 7. Wing lift coefficient.



C_m IS BASED ON THE AERODYNAMIC MEAN CHORD $\bar{c}$ AND IS EXPRESSED ABOUT THE QUARTER-CHORD POINT OF THE A.M.C.

FIG. 8. Drag and pitching-moment coefficients.

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