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Calculation of the Influence of a Body on the Position of the Aerodynamic Centre of Aircraft with Swept-back Wings

By

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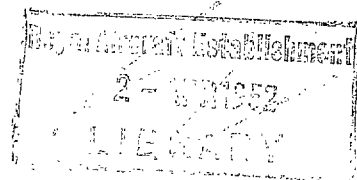
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MINISTRY OF SUPPLY

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Summary.—From systematic three-component measurements of wing-body combinations with swept wings it has been found that the movement of the aerodynamic centre due to the influence of the body is greater for a swept forward than for a straight wing and less for a sweptback wing. The forward shift of the aerodynamic centre due to the body for normal wing body combinations is about $0 \cdot 06c$ for a straight wing, about $0 \cdot 12c$ for a 30 degrees swept forward, but about zero for a 45 degrees sweptback wing.

A simple theoretical method is given for calculating this movement of the aerodynamic centre due to the influence of the body, and it is shown that the agreement with experimental results is quite good.

1. *Introduction.*—For combinations of bodies and wings without sweepback (*i.e.,* straight wings) the influence of the body gives a forward movement of the aerodynamic centre of about 5 to 8 per cent. of the mean chord. This movement of the aerodynamic centre can be calculated in a simple manner using Multhopp's method.[4] The agreement with experiment is good as is shown by systematic measurements made by E. Möller and H. Trienes.[12]

For wing-body combinations with sweptback wings this movement of the aerodynamic centre depends very much on the angle of sweepback. For a sweptforward wing the forward movement of the aerodynamic centre is greater than for a straight wing; for a sweptback wing it is less. For large angles of sweepback $(\Lambda \geqslant 45 \text{ deg})$ there may even be a backwards movement of the aerodynamic centre. This means that for a sweptforward wing, the unstable contribution of the body to the stability in pitch is much greater, but for a sweptback wing is much less than for a straight wing.

This change in the longitudinal stability of an aircraft with a sweptback wing, can be calculated approximately in a simple manner.

1

2. Symbols

b wing span, measured normally to the plane of symmetry of the aircraft

$s = b/2$ semi-span

S area of plan form of wing

$A = b^2/S$, aspect ratio

$c(y)$ wing chord, measured parallel to the plane of symmetry

c_r wing chord at the wing root

c_t wing chord at the wing tip

$z = c_t/c_r$, taper ratio of the wing

$\bar{\bar{c}} = \dfrac{2}{S} \displaystyle\int_{y=0}^{s} c^2(y) dy$, aerodynamic mean chord

$\bar{c} = S/b$, standard mean chord

$\bar{x} = \dfrac{2}{S} \displaystyle\int_{0}^{s} c(y) \, x \, dy$, distance of mean quarter-chord point aft of root quarter-chord (*see* Fig. 2)

$\varLambda$ angle of sweepback of quarter-chord line

l_B length of the body

b_{Bm} maximum width of body

e^* distance of mean quarter-chord point behind nose of body (*see* Figs. 6a and 6b)

e distance of root quarter-chord point behind nose of body (*see* Fig. 6c)

$\varGamma$ circulation

c_L local lift coefficient

L total lift

C_L $L/\frac{1}{2}\rho V^2 S$ total lift coefficient

C_M $M/\frac{1}{2}\rho V^2 S \, \bar{\bar{c}}$ pitching-moment coefficient about lateral axis through wing mean quarter-chord point

α angle of attack, in free stream direction

β local angle of attack of axis of body

V free stream velocity

ε downwash angle

$\varDelta h_N$ forward movement of the aerodynamic centre

2

3. *Physical Basis.*—Under normal flying conditions the front part of the body of a wing body combination has a considerable amount of lift ΔL_B which comes from the upwash in front of the wing (Fig. 1). The rear part of the body has a small amount of negative lift. Both forces give a nose-up pitching moment about the lateral axis through the mean quarter-chord point of the wing. This moment gives a forward movement of the aerodynamic centre due to the influence of the body which gives rise to an additional unstable pitching moment.

On the other hand the spanwise load distribution of the wing is reduced to a certain extent by the influence of the body, near the wing-body junction. This loss of lift $-\Delta L_W$ is of the same order of magnitude as the lift on the front part of the body. The centre of this loss of lift is approximately at the root quarter-chord point of the wing $(c_r/4)$.

The lift on the front part of the body $+\Delta L_B$ and the loss of lift of the wing $-\Delta L_W$ together give an additional pitching moment and hence a movement of the aerodynamic centre which depends on the angle of sweepback of the wing.

3.1. *Straight Wings* (quarter-chord line straight, no sweepback).—In this case the mean quarter-chord point of the wing is at the root quarter-chord point, and the loss of lift $-\Delta L_W$ does not give a pitching moment relative to this axis. The whole additional pitching moment due to the influence of the body comes from the lift on the front part of the body $+\Delta L_B$, and is nose up. This influence of the body gives a forward movement of the aerodynamic centre of an amount equal to about 5 to 8 per cent. of the mean chord for normal combinations.

3.2. *Sweptback Wings.*—The mean quarter-chord point in this case is behind the root quarter-chord point of the wing and the force $-\Delta L_W$ gives a nose-down pitching moment which has the opposite sign from the nose-up moment due to $+\Delta L_B$. It depends on the angle of sweep-back which of these two moments will dominate. It is clear, therefore, that the additional pitching moment due to the influence of the body, *e.g.*, the forward movement of the aerodynamic centre, is smaller for a sweptback wing than for a straight wing.

3.3. *Sweptforward Wings.*—In this case the mean quarter-chord point of the wing is in front of the root quarter-chord point. The loss of lift therefore gives a nose-up pitching moment which has the same sign as the pitching moment from $+\Delta L_B$ which is also nose up. Hence, in this case the total additional pitching moment due to the influence of the body is greater than for a straight wing.

Since the major part of the lift on the body comes from the portion in front of the wing, the movement of the aerodynamic centre due to the body will depend mainly on the distance of the wing behind the nose of the body.

As the pitching moments are referred to an axis through the wing mean quarter-chord point the distance of this point behind the nose of the body (length e^*, Fig. 6a) has been chosen to fix the position of the wing relative to the body.

The theoretical calculation of the influence of the body just mentioned is done in two steps: firstly by calculating the pitching moment from the loss of lift on the wing, and secondly that from the lift on the body. The details of the calculations are given in an unpublished report by H. Münz.[1]

4. *Calculation of the Pitching Moment due to the Reduction of Lift on the Wing.*—In order to get the pitching moment due to the reduction of lift on the wing, the change in the spanwise load distribution of the wing due to the influence of the body has to be calculated first. The amount of lift lost due to the body is larger for a low wing than for a high wing combination. The experimental results of L. Lochmann[5] for a mid-wing combination are given in Fig. 3. It should be noted that the reduction of lift occurs only in the immediate neighbourhood of the body.

3

The load distribution can be calculated with an accuracy good enough for the present purpose by using Multhopp's method[2], but assuming a diminution of the lift slope from $(dC_L/d\alpha)\infty = 2\pi$ to $(dC_L/d\alpha)\infty = 0\cdot3 \times 2\pi$ over that part of the span covered by the body (Fig. 3). The factor $0\cdot3$ was found to fit for a mid-wing; it might be smaller for a low-wing and larger for a high-wing combination.

This method of calculating the influence of the body on the lift distribution is rather rough, and may be about 10 per cent in error.

With this span load lift distribution for the wing, one can obtain the pitching moment about the lateral axis through the mean quarter-chord point (Fig. 2). The pitching moment for a strip at a distance y from the centre-line of the wing, with its quarter-chord point at a distance x from the y axis through the mean quarter-chord point is

$$dM = x \cdot dL = (\bar{y} - y) \cdot \tan \Lambda \cdot dL.$$

Also

$$dL = c_L \cdot q \cdot c(y) \, dy,$$

and therefore

$$dM = q \tan \Lambda \cdot c_L \cdot c(y) \, (\bar{y} - y) \, dy.$$

Hence the pitching moment of the wing alone is

$$M_W = 2q \tan \Lambda \int_{y=0}^{s} (c_L)_W \, c(y) \, (\bar{y} - y) \, dy \quad .. \qquad .. \qquad .. \qquad .. \qquad (1)$$

and the moment of the wing with body interference (*i.e.*, allowing for the reduction in spanwise lift distribution) is

$$M_{BW} = 2q \tan \Lambda \int_{y=0}^{s} (c_L)_{BW} \, c(y) \, (\bar{y} - y) \, dy. \qquad .. \qquad .. \qquad .. \qquad (2)$$

From the difference between these two moments $(\Delta M)_{BW} = M_{BW} - M_W$ we can deduce the forward movement of the aerodynamic centre $(\Delta h_N)_{BW}$ due to the local loss of lift from the equation:

$$(\Delta M)_{BW} = (\Delta h_N)_{BW} \cdot L_W \qquad .. \qquad .. \qquad .. \qquad .. \qquad .. \qquad .. \qquad (3)$$

where $L_W = C_{LW} \, q \, S$ is the lift of the wing alone.

From equations (1), (2), (3) we have

$$\left(\frac{\Delta h_N}{\bar{\bar{c}}}\right)_{BW} = \frac{A}{2} \tan \Lambda \frac{1}{C_{LW}} \int_{\eta=0}^{1} [(c_L)_{BW} - (c_L)_W] \frac{c(\eta)}{\bar{\bar{c}}} (\bar{\eta} - \eta) \, d\eta \qquad .. \qquad .. \qquad (4)$$

Here $\eta = y/s$; $\bar{\eta} = \bar{y}/s$ and $\bar{\bar{c}}$ is the aerodynamic mean chord (see list of symbols).

Equation (4) can be easily evaluated, if the spanwise lift distributions of the wing alone and of the wing and body are known. It is sufficient to calculate the span load lift distribution for the straight wing (without sweepback), for only the difference $(c_L)_{BW} - (c_L)_W$ is needed, and the error involved will disappear to a first approximation. The extent of the movement of the aerodynamic centre obtained from equation (4) depends mainly on the planform of the wing and the ratio of the body width to the wing span, but not on the distance of the wing from the nose of the body. The results of evaluating equation (4) for three tapered wings of aspect ratio $A = 5$ are given in Table 1. The lift slopes of the wings and of the wing-body combinations are also included.

4

TABLE 1.

Movement of the aerodynamics centre due to the loss of wing lift caused by the body.
Width of body : wing span $= 1 : 7$.

$$\left(\frac{dC_L}{d\alpha}\right)_\infty = 0\cdot3 \times 2\pi \quad \text{across the width of the body.}$$

$z = \dfrac{c_t}{c_r}$	$\left(\dfrac{dC_L}{d\alpha}\right)_W$	$\left(\dfrac{dC_L}{d\alpha}\right)_{BW}$	$-\left(\dfrac{\Delta h_N}{\bar{\bar{c}}}\right)_{BW}$
0·2	4·50	3·97	0·065 tan Λ
0·6	4·32	3·75	0·098 tan Λ
1·0	4·28	3·65	0·105 tan Λ

N.B.

For $z = 0\cdot2$, $\bar{\bar{c}} = 1\cdot148\bar{c}$;

$z = 0\cdot6$, $\bar{\bar{c}} = 1\cdot021\bar{c}$;

$z = 1\cdot0$, $\bar{\bar{c}} = \bar{c}$.

5. *Calculation of the Pitching Moment due to the Lift on the Body.*—The nose up pitching moment due to the lift on the front part of the body and to the (small) negative lift on the rear part of the body is a pure moment and for this reason is independent of the position of the axis. It can be calculated by using Multhopp's method[4] and is

$$\frac{1}{q}\frac{dM_B{}^*}{d\alpha} = \frac{\pi}{2}\int_{x=-l_B}^{x=0} b_B{}^2(x)\frac{d\beta}{d\alpha}\,dx \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (5)$$

where l_B is the total length of the body, $b_B(x)$ the local width of the body and $\beta(x)$ the local angle of incidence of the body axis (Fig. 4). The origin is assumed to be in the nose of the body. As before, expressing the change of pitching moment by a movement of the aerodynamic centre: $M_B{}^* = (\Delta h_N{}^*)_B\,L_W$ and substituting $L_W = \dfrac{dC_{LW}}{d\alpha}\cdot\Delta\alpha\,q\,S$ one obtains:

$$\left(\frac{\Delta h_N{}^*}{\bar{\bar{c}}}\right)_B = \frac{\pi}{2}\frac{A}{\dfrac{dC_{LW}}{d\alpha}}\int_{x=-l_B\delta}^{0}\frac{b_B{}^2(x)}{b^2}\frac{d\beta}{d\alpha}\,d\left(\frac{x}{\bar{\bar{c}}}\right). \quad \cdots \quad \cdots \quad \cdots \quad (6)$$

In evaluating this equation the main work consists in calculating the angle of incidence β of the body axis. There is upwash in front of the wing and downwash behind the wing. Taking the downwash as positive we have

$$\frac{d\beta}{d\alpha} = 1 - \frac{d\varepsilon}{d\alpha}.$$

Along the chord of the wing the flow is completely guided; and therefore in this region $d\beta/d\alpha = 0$. For wings without sweepback the downwash at the rear end of the body can be calculated from Ref. 3, taking a linear distribution of $d\beta/d\alpha$, from $d\beta/d\alpha = 0$ at the trailing edge of the wing to the value at the rear end of the body.

5

The major part of the integral (6) comes from the upwash in front of the wing. For the straight wing Multhopp[2] has given a method of calculation which works on the lifting line theory. For the wing with sweepback this method can be modified in a simple manner by replacing the wing by a sweptback horseshoe vortex (Fig. 5). For calculating the upwash and downwash on the body axis this approximation is assumed to be good enough. The values of $d\beta/d\alpha$ calculated in this way are given in Fig. 5 for several angles of sweepback. These calculations were made on the basis of a lifting line theory. The results may be improved by using the lifting surface theory.

As an example of the method the position of the aerodynamic centre has been calculated for the wing-body combinations shown in Fig. 6. These wings were chosed as they have already been tested experimentally and so provide a direct comparison between theory and measurements (*see* section 5). The wings are of aspect ratio $A = 5$, taper ratios $z = c_t/c_r = 1\cdot0$; $0\cdot6$; $0\cdot2$ and angles of sweepback $\Lambda = -30$ deg, 0 deg, $+30$ deg, $+45$ deg. The body is an ellipsoid of revolution of axis ratio 1:7. The length of the body is equal to the span of the wing. The position of the wing relative to the body is given by $e/l_B = 0\cdot3$ and $e^*/l_B = 0\cdot4$ (*see* Fig. 6). Table 2 gives the movement of the aerodynamic centre for these wings calculated by means of equation (6).

TABLE 2

Forward movement of the aerodynamic centre due to the lift on the body for tapered wings with different angles of sweepback (see Fig. 6)

Angle of sweepback Λ (degrees)	$e^*/l_B = 0\cdot4$		$e/l_B = 0\cdot3$
	$\left(\dfrac{\Delta h_N{}^*}{\bar{\bar{c}}}\right)_B$ $z = 1\cdot0$	$\left(\dfrac{\Delta h_N{}^*}{\bar{\bar{c}}}\right)_B$ $z = 0\cdot2$	$\left(\dfrac{\Delta h_N{}^*}{\bar{\bar{c}}}\right)_B$ $z = 1\cdot0$
-30	$0\cdot1112$	$0\cdot0714$	$0\cdot0837$
0	$0\cdot0807$	$0\cdot0530$	$0\cdot071$
$+30$	$0\cdot0604$	$0\cdot0432$	$0\cdot0623$
$+45$	$0\cdot0510$	$0\cdot0385$	$0\cdot0523$

N.B.   For $z = 0\cdot2$, $\bar{\bar{c}} = 1\cdot148\bar{c}$;

$z = 1\cdot0$, $\bar{\bar{c}} = \bar{c}$.

Finally the total movement of the aerodynamic centre due to the influence of the body is obtained by adding the values of $(\Delta h_N/\bar{\bar{c}})$ and $(\Delta h_N{}^*/\bar{\bar{c}})$ from Table 1 and Table 2

$$\left(\frac{\Delta h_N}{\bar{\bar{c}}}\right)_B = \left(\frac{\Delta h_N}{\bar{\bar{c}}}\right)_{BW} + \left(\frac{\Delta h_N{}^*}{\bar{\bar{c}}}\right)_B \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (7)$$

The values calculated in this way are given in Table 3 and plotted against the angle of sweepback in Fig. 8.

TABLE 3

Total forward movement of the aerodynamic centre due to the influence of the body for tapered wings with various angles of sweepback (see Fig. 8).

Angle of sweepback A (degrees)	$e^*/l_B = 0.4$		$e/l_B = 0.3$
	$\left(\dfrac{\Delta h_N}{\bar{\bar{c}}}\right)_B$ $z = 1.0$	$\left(\dfrac{\Delta h_N}{\bar{\bar{c}}}\right)_B$ $z = 0.2$	$\left(\dfrac{\Delta h_N}{\bar{\bar{c}}}\right)_B$ $z = 1.0$
$-$ 30 deg.	0.1717	0.1049	0.1443
0 deg.	0.0807	0.0530	0.0710
$+$ 30 deg.	-0.0001	0.0057	0.0020
$+$ 45 deg.	-0.0540	-0.0260	-0.0527

N.B.   For $z = 0.2$, $\bar{\bar{c}} = 1.148\bar{c}$;

$z = 1.0$, $\bar{\bar{c}} = \bar{c}$.

6. *Comparison of Theory and Measurement.*—The results of systematic three-component measurements on the above wing-body combinations are given in three reports by E. Möller.[6,7] The first and third reports deal with wings of constant chord with four angles of sweepback $A = -$ 30 deg, 0 deg, $+$ 30 deg, $+$ 45 deg, the second report deals with tapered wings with the same angles of sweepback. The body was the same in all cases, *i.e.*, an ellipsoid of revolution of axis ratio 1 : 7. A mid-wing combination was used throughout. Further details may be seen from Fig. 6. The tests on the plain wings (no body) were made at an earlier date by W. Jacobs and the results are given in Refs. 9, 10 and 11. From these two sets of measurements the forward movement of the aero-dynamic centre is evaluated by means of the equation

$$\left(\frac{\Delta h_N}{\bar{\bar{c}}}\right)_B = A \left(\frac{dC_M}{dC_L}\right)_B = \left(\frac{dC_M}{dC_L}\right)_{B+W} - \left(\frac{dC_M}{dC_L}\right)_W \qquad .. \qquad .. \qquad .. \qquad (8)$$

where $(dC_M/dC_L)_{B+W}$ is the slope of the pitching-moment curve for the wing-body combination and $(dC_M/dC_L)_W$ that of the wing alone. Fig. 7 gives the pitching-moment curves for the wing-body combinations shown in Fig. 6b. These show very clearly that the difference between the values of dC_M/dC_L for the wing alone and the wing-body combination decreases rapidly with increasing angle of sweepback.

The movement of the aerodynamic centre due to the influence of the body, evaluated from these and other measurements, is shown compared with the theoretical results in Fig. 8. The agreement is on the whole quite good. The difference between the measured and calculated values of the movement of the aerodynamic centre is never more than 3 per cent of the mean chord, and over the most practical range of angle of sweepback (*i.e.*, between $A = 0$ deg and $A = +$ 45 deg), the agreement is even better. In view of the very approximate nature of the theory this agreement is surprisingly good.

7

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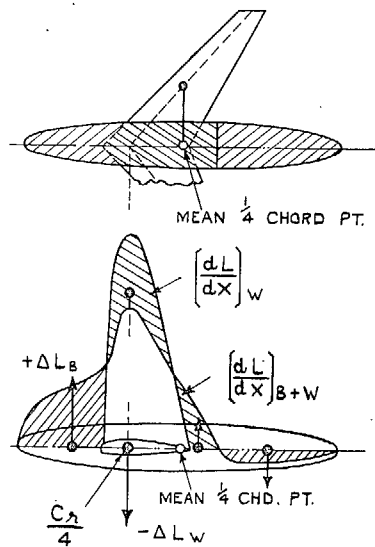
CONTRIBUTION TO NOSE-UP PITCHING MOMENT

CONTRIBUTION TO NOSE-DOWN PITCHING MOMENT
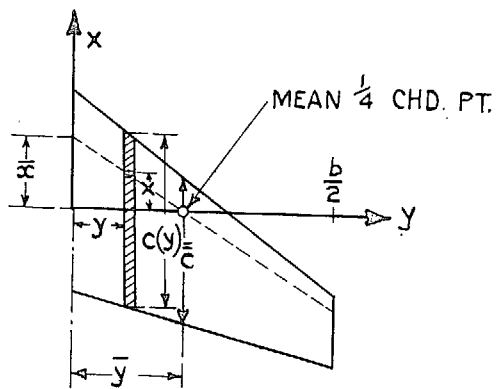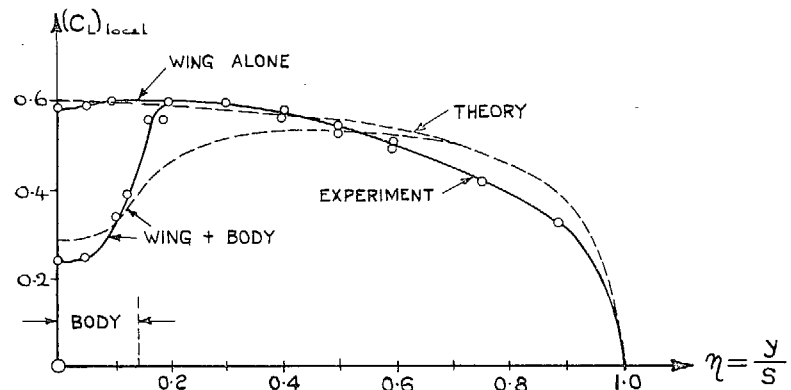
FIG. 1. Lift distribution for a
wing-body combination.

FIG. 3. Span loading distributions for a mid-wing combination.
Rectangular wing $A = 5$; $\bar{C}_L = 0\cdot56$.

FIG. 2. Typical wing planform
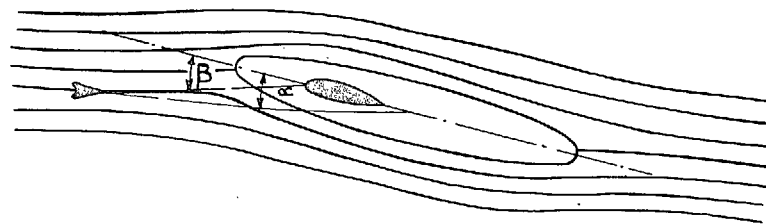showing notation used.

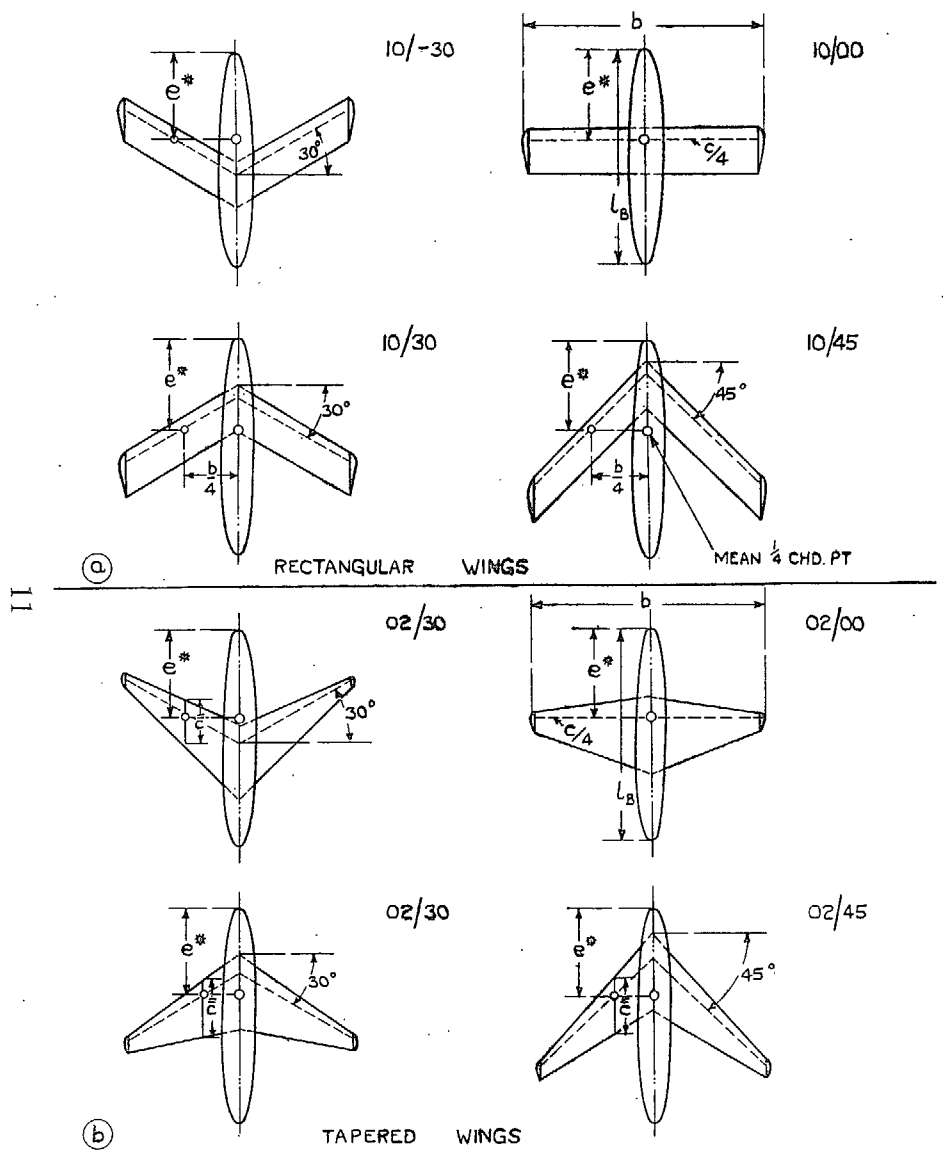FIG. 4. Cross-sectional view in ' XZ ' plain showing local
incidence of body axis.

$$\frac{d\beta}{d\alpha} = 1 - \frac{C_L'}{2\pi A}\left[1 - \frac{\sqrt{(\xi_1 + \tan\Lambda)^2 + 1} - \frac{\xi_1}{|\xi_1|}\tan\Lambda}{\xi_1}\right]$$

WHERE $C_L' = \frac{dC_L}{d\alpha}$

$\Gamma = \frac{1}{2}\frac{vb}{A}C_L'\alpha$

$1 - \frac{C_L'}{\pi A} = 0.73$

$A = 5$

$\frac{d\beta}{d\alpha}$

$\Lambda = -30°$

$0°$

$30°$

$45°$

$\Lambda = 30°$ $0°$

$+30°$

$45°$

$\xi_1 = \frac{X_1}{S}$

−1·2   −0·8   −0·4   0   0·4   0·8   1·2

−2·4   −1·6   0·8
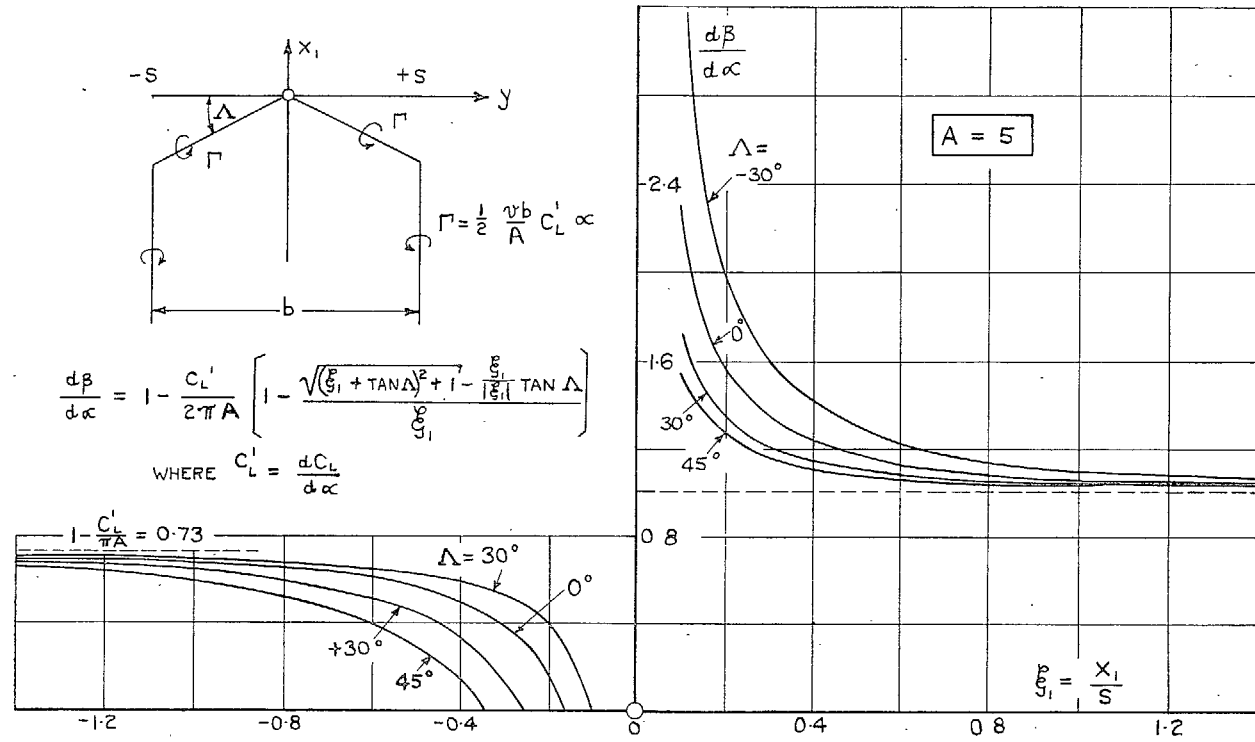
FIG. 5.   Curves of upwash and downwash on the axis of symmetry of a sweptback horseshoe vortex.

FIG. 6. Rectangular and tapered wings $e^*/l_B = 0\cdot4$. $b = 0\cdot75m$.
Body thickness ratio 1: 7. $l_B = 0\cdot75m$.

FIG. 6 (cont.). Rectangular wings. $e/l_B = 0\cdot3$. $b = 0\cdot75m$.
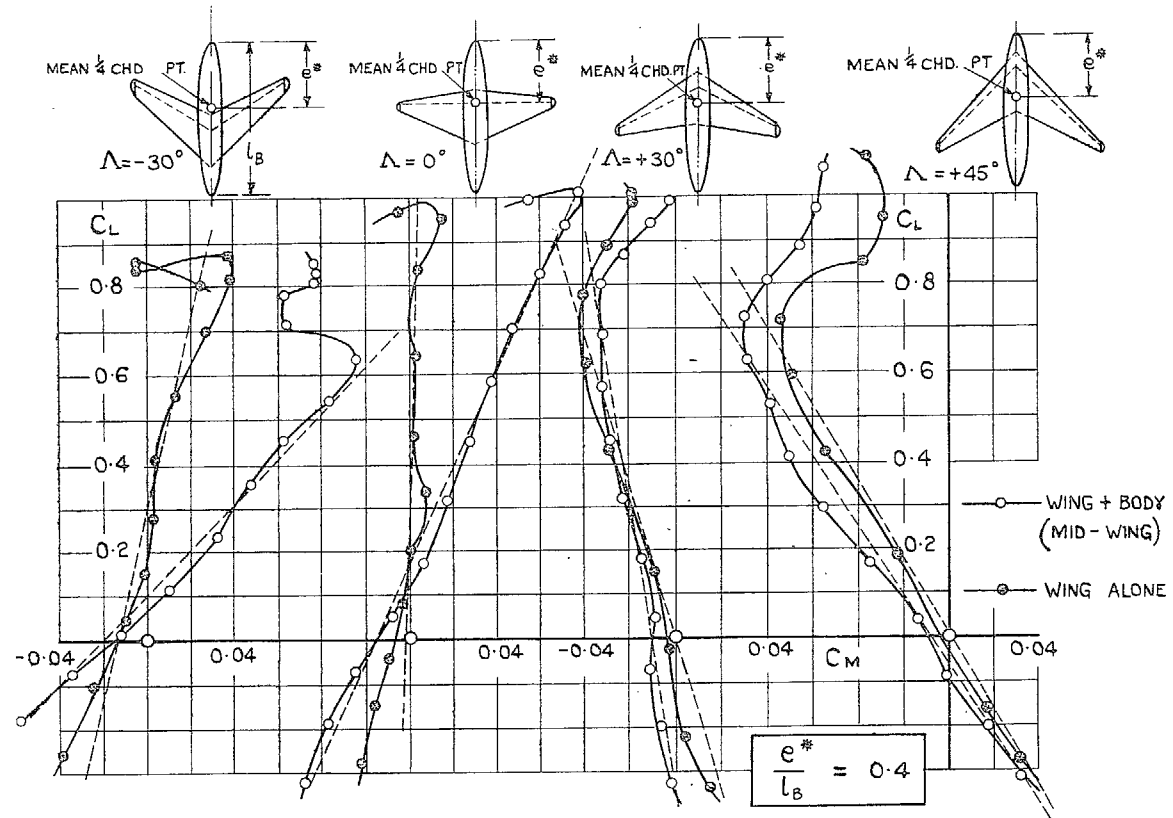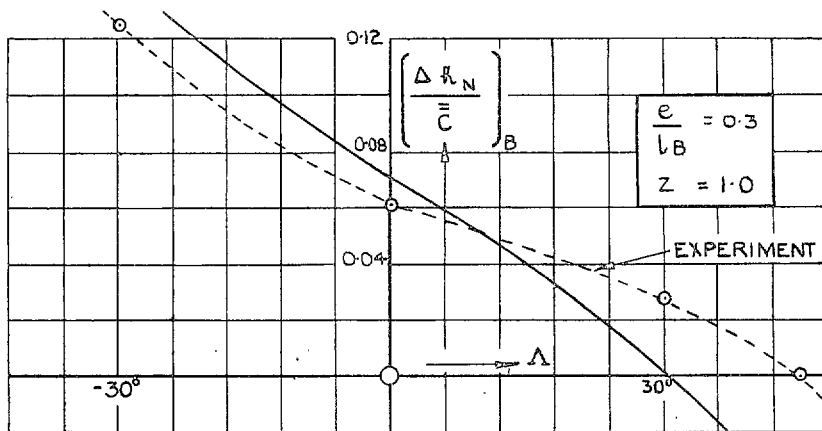Body thickness ratio 1: 7. $l_B = 0\cdot75m$.
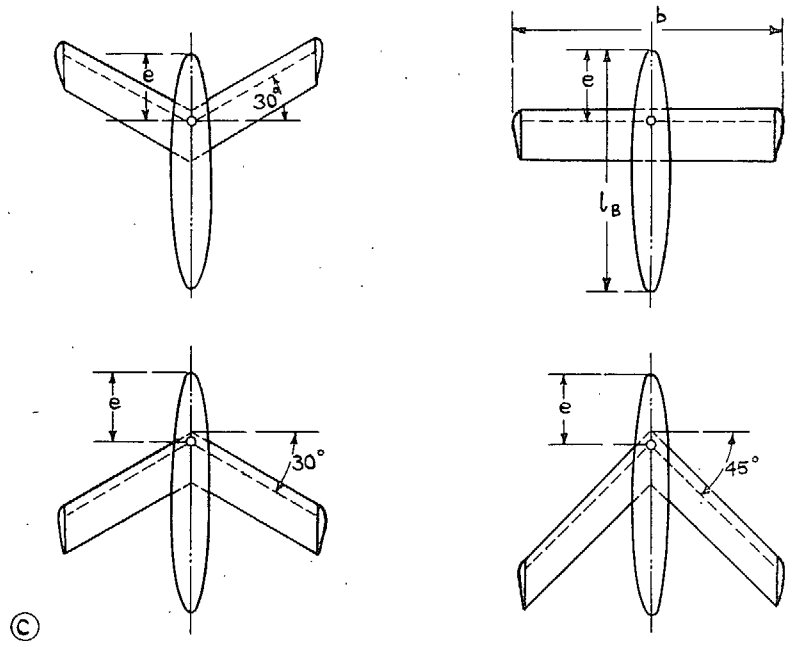
FIG. 7.   Pitching moment curves for the wing planforms shown in Fig. 6b.
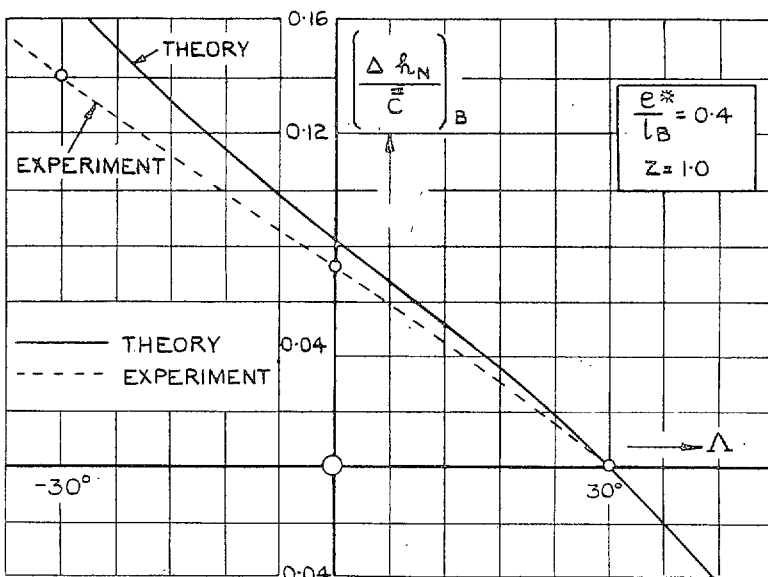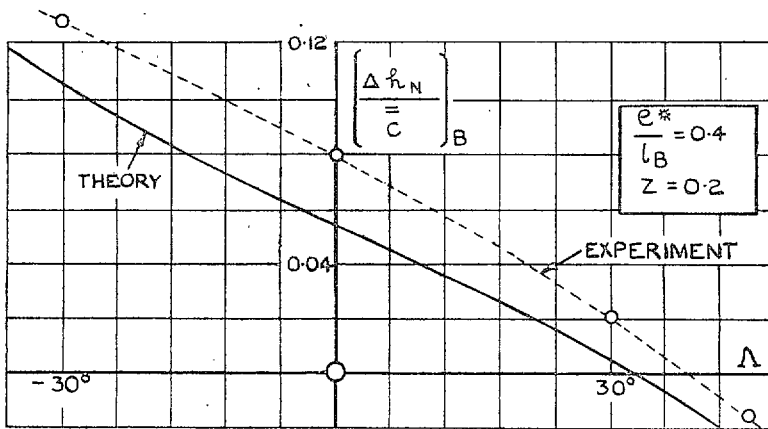
FIG. 8. Forward movement of the aerodynamic centre due to the addition of a body on sweptforward and sweptback wings.

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