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Aerofoil and wing pitching moment coefficient at zero angle of attack due to deployment of trailing-edge double-slotted and triple-slotted flaps at low speeds

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item which supersedes, in part, ESDU Aero F.08.01.01 and 02, was monitored and guided by the Aerodynamics Committee. This Committee first met in 1942 and now has the following membership:

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AEROFOIL AND WING PITCHING MOMENT COEFFICIENT AT ZERO ANGLE OF ATTACK DUE TO DEPLOYMENT OF TRAILING-EDGE DOUBLE-SLOTTED OR TRIPLE-SLOTTED FLAPS AT LOW SPEEDS

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AEROFOIL AND WING PITCHING MOMENT COEFFICIENT AT ZERO ANGLE OF ATTACK DUE TO DEPLOYMENT OF TRAILING-EDGE DOUBLE-SLOTTED OR TRIPLE-SLOTTED FLAPS AT LOW SPEEDS

1. NOTATION AND UNITS

		SI	British
A	aspect ratio, $2s/\bar{c}$		
$(a_1)_0$	basic aerofoil lift-curve slope in incompressible flow	rad^{-1}	rad^{-1}
C_L	lift coefficient; (<i>lift</i>)/ qc for aerofoil, (<i>lift</i>)/ qS for wing		
C_{L0B}	lift coefficient at zero angle of attack for basic aerofoil, based on c		
ΔC_{L0t}	increment in lift coefficient at zero angle of attack due to deployment of trailing-edge double-slotted or triple-slotted flap on aerofoil, based on c (see Item No. 94031)		
$\Delta C'_{L0t}$	increment in lift coefficient at zero angle of attack due to deployment of trailing-edge double-slotted or triple-slotted flap on aerofoil, based on c' (see Item No. 94031)		
$\Delta C'_{L1}, \Delta C'_{L2}, \Delta C'_{L3}$	increment in lift coefficient associated with deployment of equivalent first, second, third element of trailing-edge slotted flap on aerofoil with lift-curve slope of 2π , based on c' , Figures 4, 5 and 6 (from Item No. 94031)		
C_m	pitching moment coefficient; (<i>pitching moment</i>)/ qc^2 for aerofoil, (<i>pitching moment</i>)/ $qS\bar{c}$ for wing, referenced to $c/4$ for aerofoil and $\bar{c}/4$ for wing, see Sketch 1.1		
C_{m0}	C_m for aerofoil at zero lift, based on c^2 , see Section 7.1		
C_{m0i}	inviscid value of C_{m0}		
$C_{m\alpha 0B}$	pitching moment coefficient at zero angle of attack for aerofoil, based on c^2 and referenced to $c/4$, approximated as C_{m0} , see Section 7.1		
$\Delta C_{m\alpha 0}$	increment in pitching moment coefficient at zero angle of attack due to deployment of trailing-edge double-slotted or triple-slotted flap on aerofoil, based on c^2 and referenced to $c/4$, see Equation (3.1)		

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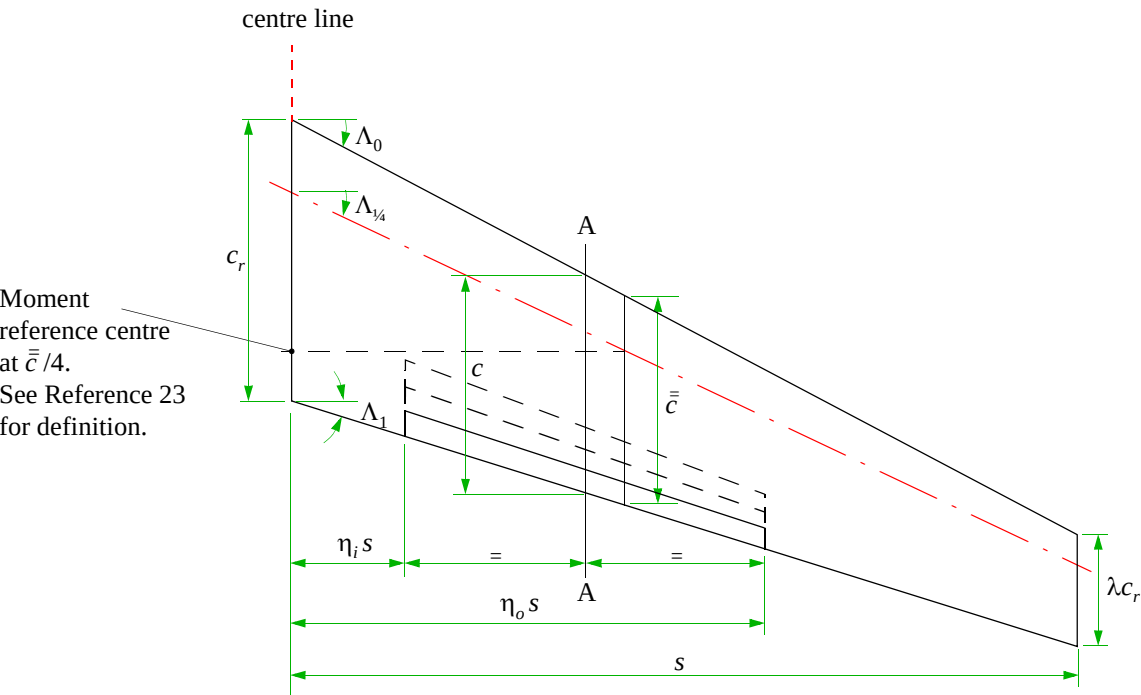
$\Delta C_{mtw\alpha 0}$	increment in pitching moment coefficient at zero angle of attack due to deployment of trailing-edge double-slotted or triple-slotted flap on wing, based on $S\bar{c}$ and referenced to $\bar{c}/4$, see Equation (3.11)		
$\Delta C'_{mt\alpha 0}$	increment in pitching moment coefficient at zero angle of attack due to deployment of trailing-edge double-slotted or triple-slotted flap on aerofoil, based on c'^2 and referenced to $c'/4$, see Equation (3.2)		
c	basic (plain) aerofoil chord or wing chord at flap mid-span (<i>i.e.</i> chord with high-lift devices undeployed), see Sketches 1.1, 1.2 and 1.3	m	ft
c'	extended aerofoil chord, <i>i.e.</i> chord with trailing-edge slotted flap deployed, see Sketches 1.2 and 1.3	m	ft
$\bar{c}$	wing geometric mean chord	m	ft
$\bar{\bar{c}}$	wing aerodynamic mean chord, see Item No. 76003	m	ft
$c_{et1}, c_{et2}, c_{et3}$	equivalent flap chord of first, second, third element of trailing-edge slotted flap, see Sketch 1.2 for double-slotted flap, Sketch 1.3 for triple-slotted flap	m	ft
c_r	wing root (centre-line) chord, see Sketch 1.1	m	ft
c_{t1}, c_{t2}, c_{t3}	chord of first, second, third element of trailing-edge slotted flap, see Sketch 1.2 for double-slotted flap, Sketch 1.3 for triple-slotted flap	m	ft
$\Delta c_{t1}, \Delta c_{t2}, \Delta c_{t3}$	increment in c_{t1}, c_{t2}, c_{t3} , see Sketch 1.2 for double-slotted flap, Sketch 1.3 for triple-slotted flap	m	ft
$c'_{t1}, c'_{t2}, c'_{t3}$	extended chord of first, second, third element of trailing-edge slotted flap, see Sketch 1.2 for double-slotted flap, Sketch 1.3 for triple-slotted flap	m	ft
F	viscous correction factor used in calculation of C_{m0} , see Equation (7.2)		
h_2	centre of incremental lift at zero angle of attack due to trailing-edge slotted flap deployment on aerofoil section expressed as fraction of basic aerofoil chord, measured positive aft from its quarter-chord position		
$h'_{2,1}, h'_{2,2}, h'_{2,3}$	empirical centre of incremental lift at zero angle of attack associated with deployment of equivalent first, second, third element of trailing-edge slotted flap on aerofoil, expressed as fraction of extended chord, measured positive aft from extended aerofoil quarter-chord position, see Equations (3.5), (3.7) and (3.9)		
$h'_{2,1T}, h'_{2,2T}, h'_{2,3T}$	theoretical values on which $h'_{2,1}, h'_{2,2}, h'_{2,3}$ are based, see Equations (3.4), (3.6) and (3.8) and Figure 7		

J_{t1}, J_{t2}, J_{t3}	correlation factor for first, second, third elements of trailing-edge slotted flap, Figures 1, 2 and 3 (from Item No. 94031)		
K	part-span factor; pitching moment coefficient increment due to part-span trailing-edge slotted flaps extending symmetrically from wing centre-line divided by pitching moment coefficient increment due to full-span trailing-edge slotted flaps at same deflection angle, Figure 8		
K_f	flap type correlation factor, (= 1.0)		
$K_{f\Lambda}$	flap type correlation factor for wing sweep, (= 1.0)		
K_i	value of K corresponding to $\eta = \eta_i$, required in Equation (3.11)		
K_o	value of K corresponding to $\eta = \eta_o$, required in Equation (3.11)		
K_Λ	part-span factor dependent on wing sweep effect, Equation (3.14) and Figures 9a to 9f		
$K_{\Lambda i}$	value of K_Λ corresponding to $\eta = \eta_i$, required in Equation (3.11)		
$K_{\Lambda o}$	value of K_Λ corresponding to $\eta = \eta_o$, required in Equation (3.11)		
M	free-stream Mach number		
p	parameter in Equation (3.14) for K_Λ , see Equation (3.15)		
q	free-stream kinetic pressure	N/m ²	lbf/ft ²
R_c	aerofoil Reynolds number, based on free-stream conditions and c		
$R_{\bar{c}}$	wing Reynolds number, based on free-stream conditions and $\bar{c}$		
S	wing planform area, $2s\bar{c}$	m ²	ft ²
s	wing semi-span, see Sketch 1.1	m	ft
t	maximum thickness of aerofoil	m	ft
x_{ts}	chordwise location of flap-shroud trailing edge, see Sketches 1.2 and 1.3	m	ft
z_{um}	maximum upper-surface ordinate of basic aerofoil, see Sketches 1.2 and 1.3	m	ft
$\delta_{t1}^\circ, \delta_{t2}^\circ, \delta_{t3}^\circ$	deflection of first, second, third element of trailing-edge slotted flap, positive trailing-edge down, see Sketch 1.2 for double-slotted flap, Sketch 1.3 for triple-slotted flap	deg	deg
η	spanwise distance from wing centre-line as fraction of semi-span		

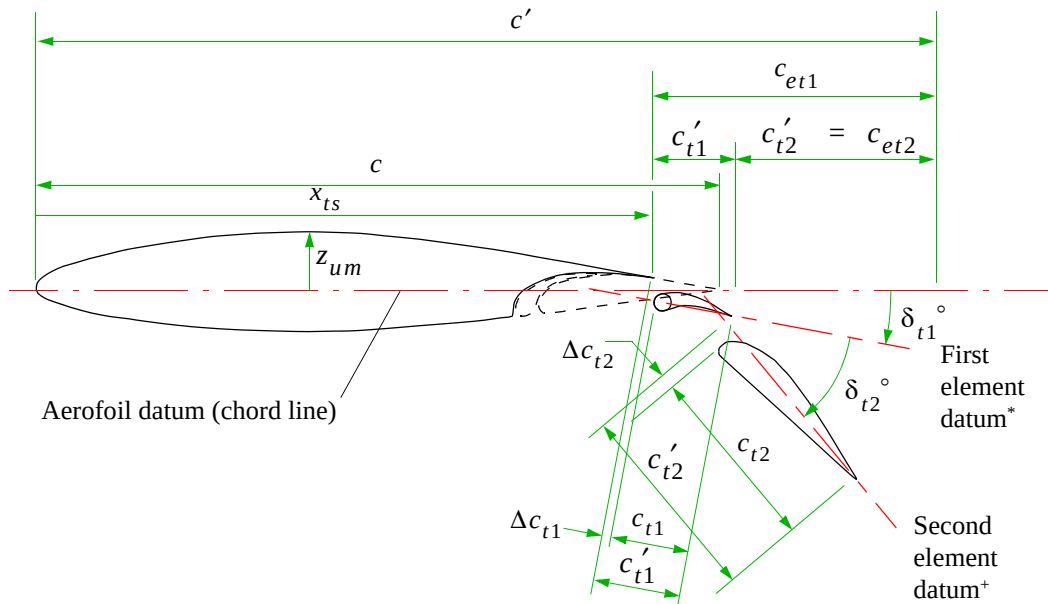
η_i	value of η at inboard limit of flap, see Sketch 1.1		
η_o	value of η at outboard limit of flap, see Sketch 1.1		
Λ_0	wing leading-edge sweep angle, see Sketch 1.1	deg	deg
$\Lambda_{1/4}$	wing quarter-chord sweep angle, see Sketch 1.1	deg	deg
$\Lambda_{1/2}$	wing half-chord sweep angle	deg	deg
Λ_1	wing trailing-edge sweep angle, see Sketch 1.1	deg	deg
λ	wing taper ratio (tip chord/root chord)		

Subscripts

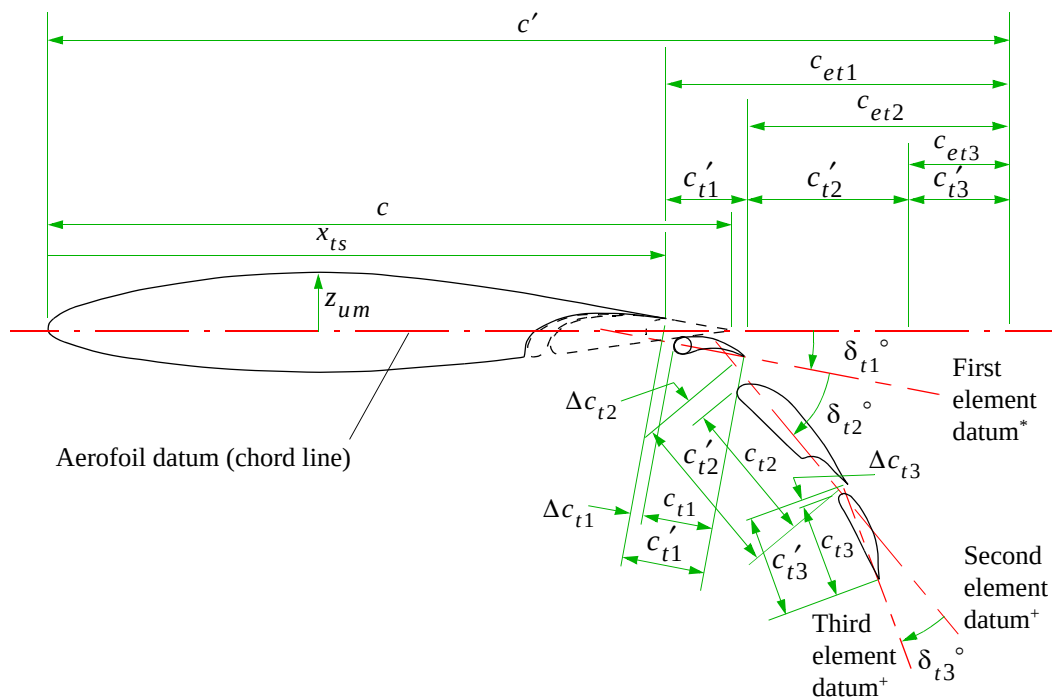
$()_{expt}$	denotes experimental value
$()_{pred}$	denotes predicted value



Sketch 1.1 Wing notation (flaps undeployed)



Sketch 1.2 Deployed double-slotted flap notation (at section AA)



Sketch 1.3 Deployed triple-slotted flap notation (at section AA)

* The deflection of the first flap element, δ_{t1}° , is the angle between the aerofoil datum line (i.e. the aerofoil chord line) and the first element datum line.

The first element datum line is the chord line of the element, defined as the line passing through the centre of the leading-edge radius and the trailing edge.

+ The deflection of the second flap element, δ_{t2}° , is the angle between the first and second element datum lines.

The deflection of the third flap element, δ_{t3}° , is the angle between the second and third element datum lines.

In contrast to the definition of the datum line of the first flap element, the datum lines of the second and third flap elements are the rotated aerofoil datum line considered to be fixed in each element.

2. INTRODUCTION

This Item provides a method to obtain the increment in pitching moment coefficient at zero angle of attack due to deployment of trailing-edge double-slotted or triple-slotted flaps at low speeds, either on an aerofoil or on a wing.

For aerofoils the method predicts the centre of lift position, $h_{2,1}$, $h_{2,2}$ and $h_{2,3}$, due to deployment of each element of a double-slotted or triple-slotted flap, based on the thin-aerofoil theory of Derivation 19 and modified to obtain correlation with the experimental data of Derivations 3, 5, 6, 7, 8, 10, 13, 17 and 18. Each centre of lift position is combined with the increment in aerofoil lift coefficient for the corresponding element calculated from Item No. 94031 (Derivation 2) to estimate the total pitching moment coefficient increment. When applied to a multi-element flap, thin-aerofoil theory represents each element as an 'equivalent' single-element flap (of chord c_{et1} etc., see Sketches 1.2 and 1.3), and their moment contributions are summed.

For wings with full-span flaps, factors, dependent on planform geometry, are applied to the pitching moment coefficient increment on a section that is representative of the wing, to allow for three-dimensional effects. Derivations 20 and 21 are used as the basis for these factors, with some adjustment to the simple theoretical assumptions. For wings with part-span flaps, additional factors are introduced that are dependent on taper ratio, aspect ratio, sweep and spanwise extent of the flap.

Section 3 describes the prediction method and Section 4 discusses Mach number and Reynolds number effects. The applicability and accuracy of the method are addressed in Section 5. The Derivation and References are given in Section 6. Section 7 provides worked examples illustrating the use of the Item for an aerofoil and a wing.

3. PREDICTION METHOD

The method for aerofoils requires the use of Item No. 94031 to determine the lift increment characteristics of the aerofoil/flap combination from which to derive the pitching moment coefficient increment.

For wings, the *streamwise* section, flap geometries and angles at the mid-span of the flap panel are taken to be representative of the wing/flap system, see Sketches 1.1, 1.2 and 1.3. The method again requires the use of Item No. 94031 to determine the lift increment characteristics of the representative section/flap combination from which to derive the section pitching moment coefficient increment. By this means the effects of spanwise variation are averaged out. Empirical corrections allow for the effects of wing planform geometry and the spanwise extent of the flaps.

3.1 Aerofoil Pitching Moment Coefficient Increment $\Delta C_{m\alpha 0}$

The increment in pitching moment coefficient at zero angle of attack, due to deployment of a double-slotted or triple-slotted flap on an aerofoil, is obtained from

$$\Delta C_{m\alpha 0} = \Delta C'_{m\alpha 0}(c'/c)^2 - \Delta C'_{L0t}(c'/c)(c'/c - 1)/4 - C_{L0B}(c'/c - 1)/4 + C_{m\alpha 0B}(c'/c - 1). \quad (3.1)$$

Here, $\Delta C'_{m\alpha 0}$ is the increment in pitching moment coefficient at zero angle of attack due to deployment of a double-slotted or triple-slotted flap on an aerofoil, based on the extended chord, and is evaluated as

$$\Delta C'_{m\alpha 0} = -[J_{t1}\Delta C'_{L1}h'_{2,1} + J_{t2}\Delta C'_{L2}h'_{2,2} + J_{t3}\Delta C'_{L3}h'_{2,3}](a_1)_0/2\pi, \quad (3.2)$$

and $\Delta C'_{L0t}$ is the increment in lift coefficient at zero angle of attack due to deployment of a double-slotted or triple-slotted flap on an aerofoil, based on the extended chord, and is evaluated as

$$\Delta C'_{L0t} = [J_{t1}\Delta C'_{L1} + J_{t2}\Delta C'_{L2} + J_{t3}\Delta C'_{L3}](a_1)_0/2\pi, \quad (3.3)$$

where J_{t1} , J_{t2} , J_{t3} , $\Delta C'_{L1}$, $\Delta C'_{L2}$ and $\Delta C'_{L3}$ are given in Figures 1 to 6 respectively, reproduced from Item No. 94031. The basic aerofoil lift-curve slope, $(a_1)_0$, in incompressible flow, may be obtained from Item No. Wings 01.01.05 (Derivation 1) and the flap deflection angles, δ_{t1}° , δ_{t2}° and δ_{t3}° , are in degrees. The formulae for J_{t1} , J_{t2} and J_{t3} are included on Figures 1 to 3.

The centre of the lift increment due to the first flap element at zero angle of attack, $h'_{2,1}$, is expressed as a fraction of the extended chord and measured positive aft from the quarter-chord point of the extended aerofoil chord. It is derived empirically from its theoretical value in Derivation 19 for a hinged plate on a thin aerofoil and adjusted to allow for chord extension by replacing c_{t1}/c with c_{et1}/c' to give

$$h'_{2,1T} = \frac{0.25[1 - (2c_{et1}/c' - 1)^2]^{1/2}[1 - (2c_{et1}/c' - 1)]}{\left\{ \pi - \cos^{-1}(2c_{et1}/c' - 1) + [1 - (2c_{et1}/c' - 1)^2]^{1/2} \right\}}. \quad (3.4)$$

An incremental adjustment to obtain correlation with experimental data gives

$$h'_{2,1} = h'_{2,1T} - 4(z_{um}/c)^{1.5}(x_{ts}/c - 1), \quad (3.5)$$

where x_{ts}/c is the chordwise location of the flap-shroud trailing edge as a fraction of the basic aerofoil chord and z_{um}/c is the ratio of the maximum upper-surface ordinate to the aerofoil chord, see Sketches 1.2 and 1.3.

Following the model of Equation (3.4), the theoretically derived centre of the lift increment due to the second flap element at zero angle of attack is

$$h'_{2,2T} = \frac{0.25[1 - (2c_{et2}/c' - 1)^2]^{1/2}[1 - (2c_{et2}/c' - 1)]}{\left\{ \pi - \cos^{-1}(2c_{et2}/c' - 1) + [1 - (2c_{et2}/c' - 1)^2]^{1/2} \right\}}. \quad (3.6)$$

No adjustment is required to obtain correlation with experimental data, so that

$$h'_{2,2} = h'_{2,2T}. \quad (3.7)$$

Similarly, for the third flap element

$$h'_{2,3T} = \frac{0.25[1 - (2c_{et3}/c' - 1)^2]^{1/2}[1 - (2c_{et3}/c' - 1)]}{\left\{ \pi - \cos^{-1}(2c_{et3}/c' - 1) + [1 - (2c_{et3}/c' - 1)^2]^{1/2} \right\}}, \quad (3.8)$$

where again no adjustment is required to obtain correlation with experimental data, so that

$$h'_{2,3} = h'_{2,3T} . \quad (3.9)$$

Values of $h'_{2,1T}$, $h'_{2,2T}$ and $h'_{2,3T}$, determined respectively from Equations (3.4), (3.6) and (3.8), are given in Figure 7 as a function of c_{et1}/c' , c_{et2}/c' and c_{et3}/c' .

The final terms in Equation (3.1) involving C_{L0B} and $C_{m\alpha 0B}$, the lift and pitching moment coefficients at zero angle of attack for the basic aerofoil, provide an approximation to the effect of extension of the aerofoil without flap angular rotation. (Note that the term involving $C_{m\alpha 0B}$ is always small compared to the first two terms in Equation (3.1) and it is sufficient to use C_{m0} in place of $C_{m\alpha 0B}$, see Section 7.1). The method must not be used to obtain pitching moment increments due to extension without rotation of at least one of the slotted flap elements, since the values due to extension alone are critically dependent on detailed geometry not accounted for in the method. As shown in Table 5.1, the minimum validated combined flap deflection angle for double-slotted flaps is $|\delta_{t1}^\circ| + \delta_{t2}^\circ = 20^\circ$.

The centre of incremental lift at zero angle of attack due to flap deployment, expressed as a fraction of the basic aerofoil chord and referred to its quarter-chord position, is obtained from

$$h_2 = \frac{-\Delta C_{m\alpha 0}}{\Delta C'_{L0t} (c'/c)} . \quad (3.10)$$

3.2 Wing Pitching Moment Coefficient Increment $\Delta C_{mtw\alpha 0}$

For a wing at zero angle of attack the increment in pitching moment coefficient due to slotted flap deployment is

$$\Delta C_{mtw\alpha 0} = K_f (K_o - K_i) \Delta C_{m\alpha 0} + K_{f\Lambda} (K_{\Lambda o} - K_{\Lambda i}) (A/2) \Delta C'_{L0t} (c'/c) \tan \Lambda_{1/4} , \quad (3.11)$$

where A is the wing aspect ratio, $\Lambda_{1/4}$ is the wing quarter-chord sweep angle, and $\Delta C'_{L0t}$ and $\Delta C_{m\alpha 0}$ are now calculated from Equations (3.3) and (3.1), respectively, for the representative streamwise section of the wing, taken at flap mid-span.

The part-span factors K_i and K_o are obtained from Figure 8 as functions of wing taper ratio and the inboard and outboard limits of the flap, $\eta = \eta_i$ and η_o , respectively.

The flap-type correlation factors for double-slotted and triple-slotted flaps have been derived from the data of Derivations 4, 9, 11, 12 and 14 to be

$$K_f = 1.0 \quad (3.12)$$

and $K_{f\Lambda} = 1.0 . \quad (3.13)$

The part-span wing-sweep factors, $K_{\Lambda i}$ and $K_{\Lambda o}$, are obtained for slotted flaps from Figures 9a to 9f as functions of the extended chord ratio, c'/c , and the inboard and outboard limits of the flap, $\eta = \eta_i$ and η_o respectively, for a range of values of wing taper ratio. Note that for all cases with a full-span flap or an unswept quarter-chord line the second term in Equation (3.11) has a value of zero.

The data for K_Λ given in Figures 9a to 9f for $\lambda = 0, 0.1, 0.2, 0.4, 0.6$ and 1 were obtained from Derivation 20 for extended flaps in the form

$$K_\Lambda = \frac{-3(1+\lambda)}{4(1+\lambda+\lambda^2)} \left\{ \left[0.5\eta^2 - 0.333(1-\lambda)\eta^3 \right] \left[(c'/c)(1-p) + p \right] - \left[0.5 - 0.333(1-\lambda) \right] p \right\}, \quad (3.14)$$

where λ is the wing taper ratio

$$\text{and } p = \frac{(c'/c)[\eta - 0.5(1-\lambda)\eta^2]}{0.5(1+\lambda) - [\eta - 0.5(1-\lambda)\eta^2](1-c'/c)}. \quad (3.15)$$

4. EFFECTS OF MACH NUMBER AND REYNOLDS NUMBER

4.1 Mach Number Effects

High local Mach numbers will occur at low free-stream Mach number as a result of high angle deployment of slotted flaps. Significant Mach number effects will occur at free-stream Mach numbers greater than about 0.2, at large values of δ_{t1}° , δ_{t2}° and δ_{t3}° and at progressively smaller values of these angles as Mach number is increased. None of the data considered for this Item was for a Mach number greater than 0.2.

4.2 Reynolds Number Effects

Values of $\Delta C_{mt\alpha 0}$ and $\Delta C_{mtw\alpha 0}$ are derived with an aerofoil lift-curve slope, $(a_1)_0$ (obtained from Item No. Wings 01.01.05), which is dependent on Reynolds number. For the data used in the derivation of this Item no additional effect of Reynolds number on $\Delta C_{mt\alpha 0}$ or $\Delta C_{mtw\alpha 0}$ was found over the ranges of Reynolds number shown in Tables 5.1 and 5.2.

5. APPLICABILITY AND ACCURACY

5.1 Applicability

5.1.1 Aerofoils

The method given in this Item for estimating the position of the centre of the lift increment and the increment in pitching moment coefficient at zero angle of attack due to deployment of a trailing-edge double-slotted or triple-slotted flap applies only to aerofoils without the deployment of a leading-edge device.

Table 5.1 summarises the parameter ranges covered by the experimental data, obtained from Derivations 3, 5, 6, 7, 8, 10, 13, 17 and 18, correlated by Equations (3.5), (3.7) and (3.9).