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Aerofoil and wing pitching moment coefficient increment at zero angle of attack due to deployment of leading-edge and trailing-edge high-lift devices in combination at low speed

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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 INCREMENT AT ZERO ANGLE OF ATTACK DUE TO DEPLOYMENT OF LEADING-EDGE AND TRAILING-EDGE HIGH-LIFT DEVICES IN COMBINATION AT LOW SPEEDS

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AEROFOIL AND WING PITCHING MOMENT COEFFICIENT INCREMENT AT ZERO ANGLE OF ATTACK DUE TO DEPLOYMENT OF LEADING-EDGE AND TRAILING-EDGE HIGH-LIFT DEVICES IN COMBINATION AT LOW SPEEDS

1. NOTATION AND UNITS

In order to use this Item, reference may be required to one or more of several Items on the aerodynamic effects of high-lift device deployment. In order to avoid repetition the notation is restricted to those symbols specifically used in the method of this Item. Additional notation required for the evaluation of the examples is included in Section 7.

		SI	British
A	aspect ratio, $2s/\bar{c}$		
a_1	theoretical rate of change of lift coefficient with wing angle of attack	rad^{-1}	rad^{-1}
C_L	lift coefficient; $(\text{lift})/qc$ for aerofoil, $(\text{lift})/qS$ for wing		
C_{L0B}	lift coefficient at zero angle of attack for basic aerofoil, based on c , used in Equation (3.1)		
$\Delta C'_{L0l}$	increment in lift coefficient at zero angle of attack due to deployment of leading-edge device on aerofoil, based on c' , see Equation (3.1) and Item No. 94027		
$\Delta C'_{L0t}$	increment in lift coefficient at zero angle of attack due to deployment of trailing-edge flap on aerofoil, based on c' , see Equation (3.5) and Item Nos 94028 to 94031		
C_m	pitching moment coefficient; $(\text{pitching moment})/qc^2$ for aerofoil, $(\text{pitching moment})/qS\bar{c}$ for wing, referenced to $c/4$ for aerofoil and $\bar{c}/4$ for wing		
$C_{m\alpha 0B}$	pitching moment coefficient at zero angle of attack for basic aerofoil, based on c^2 and referenced to $c/4$, used in Equation (3.1)		
$\Delta C_{ml\alpha 0}$	increment in pitching moment coefficient at zero angle of attack due to deployment of leading-edge device on aerofoil, based on c^2 and referenced to $c/4$, see Equation (3.1)		
$\Delta C'_{ml\alpha 0}$	increment in pitching moment coefficient at zero angle of attack due to deployment of leading-edge device on aerofoil, based on c'^2 and referenced to $c'/4$, see Equation (3.1)		
$\Delta C_{mlt\alpha 0}$	increment in pitching moment coefficient at zero angle of attack due to deployment of leading-edge device in combination with trailing-edge flap on aerofoil, based on c^2 and referenced to $c/4$, see Equation (3.6)		

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$\Delta C_{mltw\alpha 0}$	increment in pitching moment coefficient at zero angle of attack due to deployment of leading-edge device in combination with trailing-edge flap on wing, based on $S\bar{c}$ and referenced to $\bar{c}/4$, see Equation (3.12)		
$\Delta C_{mlw\alpha 0}$	increment in pitching moment coefficient at zero angle of attack due to deployment of leading-edge device on wing, based on $S\bar{c}$ and referenced to $\bar{c}/4$, see Equation (3.13)		
$\Delta C_{mt\alpha 0}$	increment in pitching moment coefficient at zero angle of attack due to deployment of trailing-edge flap on aerofoil, based on c^2 and referenced to $c/4$, see Equation (3.2)		
$\Delta C'_{mt\alpha 0}$	increment in pitching moment coefficient at zero angle of attack due to deployment of trailing-edge flap on aerofoil, based on c'^2 and referenced to $c'/4$, see Equation (3.2)		
$\Delta C_{mtw\alpha 0}$	increment in pitching moment coefficient at zero angle of attack due to deployment of trailing-edge flap on wing, based on $S\bar{c}$ and referenced to $\bar{c}/4$, see Equation (3.11)		
$\Delta C_{mw\alpha 0}$	general increment in pitching moment coefficient at zero angle of attack due to deployment of leading-edge device or trailing-edge flap either separately or in combination on wing, based on $S\bar{c}$ and referenced to $\bar{c}/4$, see Equation (3.9)		
c	basic (plain) aerofoil chord or wing chord at device mid-span, <i>i.e.</i> chord with high-lift devices undeployed	m	ft
c'	extended aerofoil chord, <i>i.e.</i> chord with high-lift devices deployed, see Sketches 3.2 to 3.4	m	ft
$\bar{c}$	wing geometric mean chord	m	ft
$\bar{\bar{c}}$	wing aerodynamic mean chord	m	ft
c_l	chord of leading-edge device, see Item No. 94027	m	ft
Δc_l	chord extension due to deployment of leading-edge device, see Item No. 94027	m	ft
c_t	chord of trailing-edge flap, see Item Nos 94028 to 94031	m	ft
c_{t1}, c_{t2}, c_{t3}	chord of first, second, third element of slotted trailing-edge flap, see Item Nos 94030 and 94031	m	ft
Δc_t	chord extension due to deployment of trailing-edge flap, see Equation (3.7)	m	ft
h'_2	empirical centre of incremental lift at zero angle of attack due to trailing-edge flap angular deflection on aerofoil section expressed as fraction of extended chord, measured positive aft from extended aerofoil quarter-chord position		

h'_{2l}	empirical centre of incremental lift at zero angle of attack due to leading-edge device angular deflection on aerofoil section expressed as fraction of extended chord, measured positive aft from extended aerofoil quarter-chord position		
K	part-span factor; pitching moment coefficient increment due to part-span leading-edge device or part-span trailing-edge flap extending symmetrically from wing centre-line divided by pitching moment coefficient increment due to full-span leading-edge device or trailing-edge flap, respectively, at same deflection angle		
K_f	trailing-edge flap type correlation factor, see Table 3.2		
$K_{f\Lambda}$	trailing-edge flap type correlation factor for wing sweep, see Table 3.2		
K_l	leading-edge device type correlation factor, see Table 3.2		
K_{lt}	correlation factor for combination of leading-edge device and trailing-edge flap on aerofoil, required in Equation (3.8), see Table 3.1		
K_{ltw}	correlation factor for combination of leading-edge device and trailing-edge flap on wing, required in Equation (3.12), see Table 3.3		
$K_{l\Lambda}$	leading-edge device type correlation factor for wing sweep, see Table 3.2		
K_i	value of K corresponding to $\eta = \eta_i$, required in Equations (3.11), (3.12), (3.13), see Table 3.2		
K_o	value of K corresponding to $\eta = \eta_o$, required in Equations (3.11), (3.12), (3.13), see Table 3.2		
K_Λ	part-span factor dependent on wing sweep effect		
$K_{\Lambda i}$	value of K_Λ corresponding to $\eta = \eta_i$, required in Equations (3.11), (3.12), (3.13), see Table 3.2		
$K_{\Lambda o}$	value of K_Λ corresponding to $\eta = \eta_o$, required in Equations (3.11), (3.12), (3.13), see Table 3.2		
M	free-stream Mach number		
q	free-stream kinetic pressure	N/m ²	lbf/ft ²
$R_{\bar{c}}$	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	m	ft

δ_l°	deflection of leading-edge device, positive leading-edge down	deg	deg
η	spanwise distance from wing centre-line as fraction of semi-span		
η_i	value of η at inboard limit of each portion of wing, see Sketch 3.5		
η_o	value of η at outboard limit of each portion of wing, see Sketch 3.5		
Λ_0	wing leading-edge sweep angle	deg	deg
$\Lambda_{1/4}$	wing quarter-chord sweep angle	deg	deg
$\Lambda_{1/2}$	wing half-chord sweep angle	deg	deg
Λ_1	wing trailing-edge sweep angle	deg	deg
λ	wing taper ratio (tip chord/root chord)		

Subscripts

A,B,C,D	used with η_i or η_o for wing portions containing sections A, B, C and D, see Sketch 3.5
$()_l$	denotes leading-edge device, used with part-span factors
$()_{lt}$	denotes presence of both leading-edge and trailing-edge devices, used with part-span factors
$()_t$	denotes trailing-edge flap, used with part-span factors
$()_{expt}$	denotes experimental value
$()_{pred}$	denotes predicted value

2. INTRODUCTION

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

For aerofoils the method predicts the centre of lift positions, due to deployment of a plain flap, split flap or slotted flap in combination with any type of leading-edge device. The prediction is based on the thin-aerofoil theory of Derivation 28 modified to obtain correlation with the experimental data of Derivations 12,13,16,17,19 and 23 to 26. The centres of lift are combined with the increments in aerofoil lift coefficient, calculated from Item Nos 94027 to 94031 (Derivations 2 to 6), to estimate the total pitching moment coefficient increment.

For wings with full-span leading-edge devices and trailing-edge 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 29 and 30 were used as the basis for these factors, with some adjustment to the simple theoretical assumptions. For wings with part-span leading-edge devices and trailing-edge flaps, deployed either separately or in combination, additional factors are introduced that are dependent on taper ratio, aspect ratio, sweep and spanwise extent of the high-lift devices.

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 for a wing.

Reference 36 provides a method for predicting the variation of pitching moment coefficient curve with angle of attack with high-lift devices deployed.

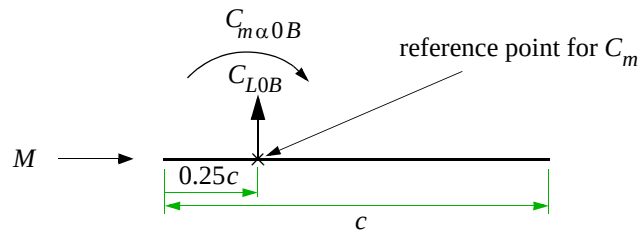
3. DERIVATION OF METHOD

The method relies heavily on the calculation procedures of the Items on lift and pitching moment increments due to independent deployment of leading-edge and trailing-edge devices, included in Derivations 2 to 11. This Section shows how the method was derived for idealised leading-edge and trailing-edge devices on an aerofoil or on a wing and the application for each type of device.

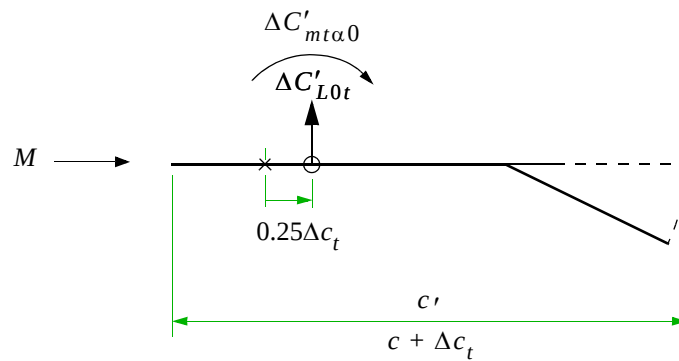
3.1 Centre of Lift Increment due to Leading-edge Device or Trailing-edge Flap Based on c'

The centre of the lift increments at zero angle of attack, h'_{2l} for leading-edge devices and h'_{2t} for trailing-edge flaps, expressed as fractions of the extended chord c' , are calculated in the same way as in the Items on pitching moment increment for individual high-lift devices, Item Nos 98009, 98017, 99004, 99014 and 00029 (Derivations 7 to 11), except that the definition of c' now includes the extensions due to both leading-edge and trailing-edge devices, which are defined for each device in the Items on lift increment, Item Nos 94027 to 94031.

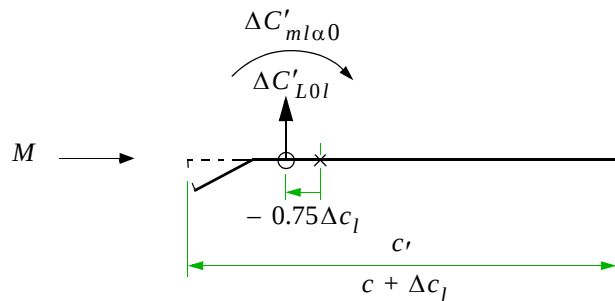
The reference points used for the increments of lift coefficient and pitching moment coefficient based on the extended chord (i.e. the primed values) are shown in Sketches 3.1 to 3.4. In each case the reference point taken is the quarter-chord point of the extended chord, and is marked on each sketch with a '○'. The quarter-chord point of the basic chord is marked on each sketch with a 'X' and is the reference point for the unprimed values of lift coefficient and pitching moment coefficient. The sketches show the distance between the two reference points for each case.



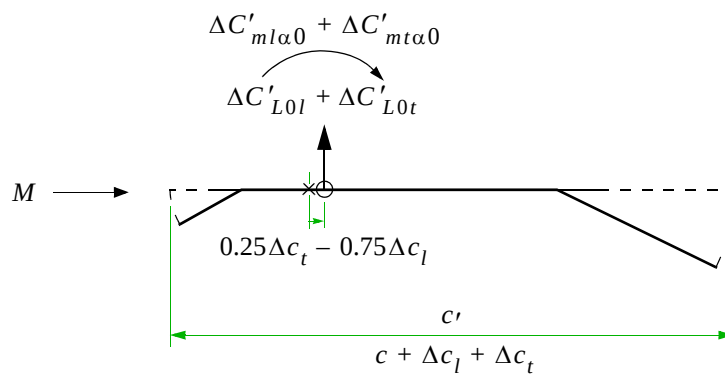
Sketch 3.1 Basic aerofoil



Sketch 3.2 Trailing-edge extension



Sketch 3.3 Leading-edge extension



Sketch 3.4 Leading-edge and trailing-edge extensions

3.2 Aerofoil Pitching Moment Coefficient Increment

For leading-edge devices, from Equation (3.12) of Item No. 00029 (Derivation 11)

$$\begin{aligned}\Delta C_{ml\alpha 0} &= \Delta C'_{ml\alpha 0} (c'/c)^2 + 0.75\Delta C'_{L0l} (c'/c)(c'/c - 1) + 0.75C_{L0B}(c'/c - 1) + C_{m\alpha 0B}(c'/c - 1) \\ &= \Delta C'_{ml\alpha 0} (c'/c)^2 + 0.75\Delta C'_{L0l} (c'/c)\Delta c_l/c + 0.75C_{L0B}\Delta c_l/c + C_{m\alpha 0B}(c'/c - 1). \quad (3.1)\end{aligned}$$

Similarly, for trailing-edge flaps from, for example, Equation (3.1) of Item No. 99014 (Derivation 10)

$$\begin{aligned}\Delta C_{mt\alpha 0} &= \Delta C'_{mt\alpha 0} (c'/c)^2 - \Delta C'_{L0t} (c'/c)(c'/c - 1)/4 - C_{L0B}(c'/c - 1)/4 + C_{m\alpha 0B}(c'/c - 1) \\ &= \Delta C'_{mt\alpha 0} (c'/c)^2 - 0.25\Delta C'_{L0t} (c'/c)\Delta c_t/c - 0.25C_{L0B}\Delta c_t/c + C_{m\alpha 0B}(c'/c - 1). \quad (3.2)\end{aligned}$$

For a leading-edge device deployed in combination with a trailing-edge flap which extends without rotation, a comparison of Sketch 3.3 with Sketch 3.4 shows that the distance between the reference points for the unprimed and the primed values of pitching moment coefficient changes from $-0.75\Delta c_l/c$ to $[0.25\Delta c_l/c - 0.75\Delta c_t/c]$. Therefore, Equation (3.1) becomes

$$\begin{aligned}\Delta C_{ml\alpha 0} &= \Delta C'_{ml\alpha 0} (c'/c)^2 + \Delta C'_{L0l} (c'/c)[0.75\Delta c_l/c - 0.25\Delta c_t/c] \\ &\quad + C_{L0B}[0.75\Delta c_l/c - 0.25\Delta c_t/c] + C_{m\alpha 0B}(c'/c - 1). \quad (3.3)\end{aligned}$$

Similarly, for a trailing-edge flap deployed in combination with a leading-edge device which extends without rotation, a comparison of Sketch 3.2 with Sketch 3.4 shows that the distance between the two reference points changes from $0.25\Delta c_t/c$ to $[0.25\Delta c_t/c - 0.75\Delta c_l/c]$. Therefore, Equation (3.2) becomes

$$\begin{aligned}\Delta C_{mt\alpha 0} &= \Delta C'_{mt\alpha 0} (c'/c)^2 - \Delta C'_{L0t} (c'/c)[0.25\Delta c_t/c - 0.75\Delta c_l/c] \\ &\quad - C_{L0B}[0.25\Delta c_t/c - 0.75\Delta c_l/c] + C_{m\alpha 0B}(c'/c - 1). \quad (3.4)\end{aligned}$$

For consistency with Equation (3.3), Equation (3.4) is better written as

$$\begin{aligned}\Delta C_{mt\alpha 0} &= \Delta C'_{mt\alpha 0} (c'/c)^2 + \Delta C'_{L0t} (c'/c)[0.75\Delta c_l/c - 0.25\Delta c_t/c] \\ &\quad + C_{L0B}[0.75\Delta c_l/c - 0.25\Delta c_t/c] + C_{m\alpha 0B}(c'/c - 1). \quad (3.5)\end{aligned}$$

The general equation for simultaneous deployment of leading-edge and trailing-edge devices results from the combination of Equations (3.3) and (3.5) so that

$$\begin{aligned}\Delta C_{mlt\alpha 0} &= [\Delta C'_{ml\alpha 0} + \Delta C'_{mt\alpha 0}](c'/c)^2 + [\Delta C'_{L0l} + \Delta C'_{L0t}](c'/c)[0.75\Delta c_l/c - 0.25\Delta c_t/c] \\ &\quad + C_{L0B}[0.75\Delta c_l/c - 0.25\Delta c_t/c] + C_{m\alpha 0B}(c'/c - 1), \quad (3.6)\end{aligned}$$

where c' is the extended chord with both devices deployed.

The last two terms involving C_{L0B} and $C_{m\alpha 0B}$, which provide an approximation to the effect of the aerofoil extension without device rotation, are only required once in Equation (3.6).

Sketch 3.4 shows the schematic definition of c' with both leading-edge and trailing-edge devices deployed and it is necessary to refer to Item Nos 94027 to 94031, as shown in Table 3.1, for the detailed definitions which depend on device geometry to evaluate c' in particular cases.

The definition of Δc_l is explicit in the leading-edge device Items. However, the definition of Δc_t is not explicit in every trailing-edge flap Item. A single definition applicable to all trailing-edge flaps can be obtained by the use of

$$\Delta c_t/c = c'/c - \Delta c_l/c - 1. \quad (3.7)$$

In order to allow for some interference effect between the leading-edge and trailing-edge devices a correlation factor K_{lt} has been included in Equation (3.6), which now becomes

$$\begin{aligned} \Delta C_{ml\alpha 0} = & [\Delta C'_{ml\alpha 0} + K_{lt} \Delta C'_{mt\alpha 0}](c'/c)^2 + [\Delta C'_{L0l} + \Delta C'_{L0t}](c'/c)[0.75\Delta c_l/c - 0.25\Delta c_t/c] \\ & + C_{L0B}[0.75\Delta c_l/c - 0.25\Delta c_t/c] + C_{m\alpha 0B}(c'/c - 1). \end{aligned} \quad (3.8)$$

The values of the pitching moment coefficient increments on an aerofoil based on the extended chord, $\Delta C'_{ml\alpha 0}$ and $\Delta C'_{mt\alpha 0}$, are obtained from Item Nos 98009, 98017, 99004, 99014 and 00029 and the values of the lift coefficient increments, $\Delta C'_{L0l}$ and $\Delta C'_{L0t}$, are obtained from Item Nos 94027 to 94031, as shown in Table 3.1. The estimation of aerofoil section lift coefficient and pitching moment coefficient at zero angle of attack, C_{L0B} and $C_{m\alpha 0B}$, requires the use of Item Nos Aero W.01.01.05, 72024, 87001 and 98011 (Derivation 1 and References 31, 33 and 35), as detailed in Item No. 00029.

The correlation factor K_{lt} probably depends on the combination of leading-edge and trailing-edge devices. To the accuracy of the present analysis the type of trailing-edge flap is unimportant and the empirical values in Table 3.1 are appropriate. It should be noted that this correlation factor has been applied to only the moment term since its application to the lift term would imply a different correlation from that developed in the Items on lift coefficient increment for individual trailing-edge flaps. Note that for wings the factor K_{ltw} , with different values, replaces K_{lt} , see Section 3.3.

TABLE 3.1 Values of K_{lt} and sources of data required in evaluation of Equation (3.8)

Device	$c', \Delta C'_{L0l} \text{ or } \Delta C'_{L0t}$		$\Delta C'_{ml\alpha 0} \text{ or } \Delta C'_{mt\alpha 0}$		K_{lt}		
	Item No.	Derivation	Item No.	Derivation	Leading-edge device type		
Leading-edge	94027	2	00029	11	Plain flap or droop	Slat or vented Krüger flap	Krüger flap or sealed slat
Plain flap	94028	3	98017	8	0.95	1.09	0.91
Split flap	94029	4	98009	7	0.95	1.09	0.91
Single-slotted flap	94030	5	99004	9	0.95	1.09	0.91
Double-slotted flap	94031	6	99014	10	0.95	1.09	0.91
Triple-slotted flap	94031	6	99014	10	0.95	1.09	0.91
See also introductory Item on high-lift devices, Item No. 94026 (Reference 34).							

3.3 Wing Pitching Moment Coefficient Increment

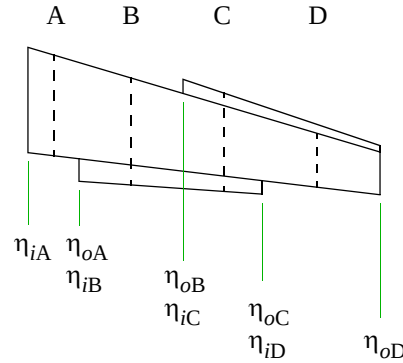
It is evident that a wing can have several different combinations of leading-edge and trailing-edge devices at different spanwise stations. The four possible combinations are shown in Sketch 3.5, where the half-wing is divided into four portions, with representative sections A to D at the mid-span of each portion.

Section A has no high-lift devices

Section B has trailing-edge flaps only

Section C has both leading-edge and trailing-edge devices.

Section D has leading-edge devices only



Sketch 3.5

The incremental pitching moment coefficient for the whole wing is therefore

$$\Delta C_{mw\alpha 0} = \Delta C_{mw\alpha 0A} + \Delta C_{mw\alpha 0B} + \Delta C_{mw\alpha 0C} + \Delta C_{mw\alpha 0D}, \quad (3.9)$$

with the four terms evaluated as in (i) to (iv) below. The calculations in (ii) and (iv) for the wing portions containing sections B and D are identical to those in the Items which deal with the deployment of a single device.

For section C it is impracticable to use the combined form of Equation (3.8) with appropriate three-dimensional wing factors and that equation is therefore rearranged as

$$\begin{aligned} \Delta C_{ml\alpha 0} = & \Delta C'_{ml\alpha 0} (c'/c)^2 + \Delta C'_{L0l} (c'/c) [0.75\Delta c_l/c - 0.25\Delta c_t/c] \\ & + K_{lt} \Delta C'_{mt\alpha 0} (c'/c)^2 + \Delta C'_{L0t} (c'/c) [0.75\Delta c_l/c - 0.25\Delta c_t/c] \\ & + C_{L0B} [0.75\Delta c_l/c - 0.25\Delta c_t/c] + C_{m\alpha 0B} (c'/c - 1), \end{aligned} \quad (3.10)$$

which allows the factors to be applied to the aerofoil section increments.

(i) For the portion of wing with no high-lift devices,

$$\Delta C_{mw\alpha 0A} = 0.$$

(ii) For the portion of wing with only a trailing-edge flap,

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

from Equation (3.11) of Item No. 99014 for example, where the part-span factors K_o , $K_{\Lambda o}$ and K_i , $K_{\Lambda i}$ correspond to values of $\eta = \eta_{oB}$ and η_{iB} .