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Pitching moment curve of wings with leading-edge and trailing-edge high-lift devices deployed at low speeds

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Aerodynamics Committee. This Committee first met in 1942 and now has the following membership:

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PITCHING MOMENT CURVE OF WINGS WITH LEADING-EDGE AND TRAILING-EDGE HIGH-LIFT DEVICES DEPLOYED AT LOW SPEEDS

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PITCHING MOMENT CURVE OF WINGS WITH LEADING-EDGE AND TRAILING-EDGE HIGH-LIFT DEVICES DEPLOYED AT LOW SPEEDS

1. NOTATION AND UNITS

In order to use this Item, reference may be required to one or more of several Data Items on the aerodynamics of high-lift device deployment. In order to avoid repetition the notation is restricted to those symbols specially used in the method of this Item and the examples in Section 7.

		SI	British
A	aspect ratio, $2s/\bar{c}$		
a_1	basic wing lift-curve slope, see Item No. 70011	rad^{-1}	rad^{-1}
Δa_1	increment in lift-curve slope due to high-lift device deployment	rad^{-1}	rad^{-1}
C_L	lift coefficient; $(\text{lift})/qS$ for wing, $(\text{lift})/qc$ for aerofoil		
C_L^*	lift coefficient at which lift curve starts to depart from that defined by Equation (4.19) in Item No. 96003		
C_{L0B}	aerofoil lift coefficient at zero angle of attack with high-lift devices undeployed (<i>i.e.</i> 'basic aerofoil')		
ΔC_{L0}	increment in aerofoil lift coefficient due to deployment of high-lift devices at zero angle of attack		
C_{L0Bw}	wing lift coefficient at zero angle of attack with high-lift devices undeployed (<i>i.e.</i> 'basic wing'), see Sketch 4.1		
C_{L0w}	wing lift coefficient at zero angle of attack with high-lift devices deployed, $C_{L0Bw} + \Delta C_{L0w}$, see Sketch 4.1		
ΔC_{L0w}	increment in wing lift coefficient due to deployment of high-lift devices at zero angle of attack, see Sketch 4.1		
$C_{L(\alpha)}$	lift coefficient due to angle of attack, α , from value at $\alpha = 0$		
C_{Lmaxw}	wing maximum lift coefficient with high-lift devices deployed		
C_m	aerofoil pitching moment coefficient at angle of attack, Equation (4.6), $(\text{pitching moment})/qc^2$, referenced to $c/4$, positive nose up		
ΔC_m	increment in aerofoil pitching moment coefficient due to angle of attack from value at $\alpha = 0$, see Sketch 4.7		

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C_{mw}	wing pitching moment coefficient at angle of attack, Equation (4.20), (<i>pitching moment</i>)/ $qS\bar{c}$, referenced to $\bar{c}/4$, positive nose up		
ΔC_{mw}	increment in wing pitching moment coefficient due to angle of attack from value at $\alpha = 0$, see Equation (4.21)		
$C_{mw\alpha 0}$	wing pitching moment coefficient at zero angle of attack with high-lift devices deployed, $C_{mw\alpha 0B} + \Delta C_{mw\alpha 0}$		
$C_{mw\alpha 0B}$	wing pitching moment coefficient at zero angle of attack with high-lift devices undeployed (<i>i.e.</i> 'basic wing'), see Sketch 4.2		
$\Delta C_{mw\alpha 0}$	increment in wing pitching moment coefficient at zero angle of attack due to deployment of leading-edge device or trailing-edge flap either separately or in combination		
$C_{m\alpha 0}$	aerofoil pitching moment coefficient at zero angle of attack with high-lift devices deployed, $C_{m\alpha 0B} + \Delta C_{m\alpha 0}$		
$C_{m\alpha 0B}$	aerofoil pitching moment coefficient at zero angle of attack with high-lift devices undeployed, see Sketch 4.7		
$\Delta C_{m\alpha 0}$	increment in aerofoil pitching moment coefficient at zero angle of attack due to deployment of leading-edge device or trailing-edge flap either separately or in combination		
c	chord of wing at device mid-span or of aerofoil with high-lift devices undeployed	m	ft
c'	extended chord, <i>i.e.</i> chord with high-lift devices deployed	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_l'	extended chord of leading-edge device, see Item No. 94027	m	ft
Δc_l^*	effective chord extension due to deployment of leading-edge device, see Table 4.1, used in Equations (4.15) and (4.19)	m	ft
c_t	chord of plain or split trailing-edge flap, see Item Nos 94028 and 94029	m	ft

$c_{et1}, c_{et2}, c_{et3}$	equivalent flap chord of first, second, third element of slotted trailing-edge flap, see Item No. 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
$c'_{t1}, c'_{t2}, c'_{t3}$	extended 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 Table 4.2, used in Equations (4.17) and (4.19)	m	ft
Δc_{t1}	increment in chord of single-slotted trailing-edge flap, see Sketch 4.1 of Item No. 94030, $c'_{t1} = c_{t1} + \Delta c_{t1}$	m	ft
h_0	aerodynamic centre of aerofoil, taken through zero angle of attack, expressed as fraction of c , measured positive aft from $c/4$		
Δh_0	change in h_0 for aerofoil due to deployment of high-lift devices, measured positive aft		
h_{0w}	aerodynamic centre of wing, taken through zero angle of attack, expressed as fraction of $\bar{c}$, measured positive aft from $\bar{c}/4$		
Δh_{0w}	change in h_{0w} for wing due to deployment of high-lift devices, measured positive aft		
h_1	effective centre of lift due to angle of attack for aerofoil, expressed as fraction of c , measured positive aft from $c/4$, see Section 4.3		
Δh_1	change in h_1 for aerofoil due to angle of attack with high-lift devices deployed, measured positive aft, Equations (4.13), (4.15), (4.17) and (4.19)		
h_{1w}	effective centre of lift due to angle of attack for wing, expressed as fraction of $\bar{c}$, measured positive aft from $\bar{c}/4$, see Section 4.4		
Δh_{1w}	change in h_{1w} for wing due to angle of attack with high-lift devices deployed, measured positive aft		
K_h	part-span factor for devices extending symmetrically from wing centre-line, defined in Equation (4.29) and obtained from Figure 2, applied to sectional ('full span') value of Δh_1 for devices at same deflection angle		
K_{hi}	value of K_h corresponding to $\eta = \eta_i$, required in Equations (4.25), (4.26), (4.27) and (4.28)		
K_{ho}	value of K_h corresponding $\eta = \eta_o$, required in Equations (4.25), (4.26), (4.27) and (4.28)		

$K_{h\Lambda}$	part-span factor dependent on wing sweep effect for devices extending symmetrically from wing centre-line, defined in Equation (4.30) and obtained from Figures 3a to 3e		
$K_{h\Lambda i}$	value of $K_{h\Lambda}$ corresponding to $\eta = \eta_i$, required in Equations (4.26), (4.27) and (4.28)		
$K_{h\Lambda o}$	value of $K_{h\Lambda}$ corresponding to $\eta = \eta_o$, required in Equations (4.26), (4.27) and (4.28)		
K_R	correlation function defined in Equation (4.9) and obtained from Figure 1, see Section 4.3		
$K_{\delta l}$	factor on c_l' in Equations (4.15) and (4.17), see Table 4.1		
$K_{\delta t}$	factor on c_t in Equations (4.17) and (4.19); see Table 4.3 for values of $K_{\delta t} c_t$ according to flap type		
L_l	overlap between deployed slat or vented Krüger flap trailing-edge and fixed section nose, see Sketch 4.2 of Item No. 94027	m	ft
M	free-stream Mach number		
q	free-stream kinetic pressure	N/m ²	lbf/ft ²
R	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	m	ft
t	aerofoil maximum thickness	m	ft
x	chordwise distance aft from wing apex	m	ft
$\bar{x}_{1/4}$	chordwise distance of $\bar{c}/4$ aft from wing apex, see Item No. 76003 (Reference 31)	m	ft
x_{ts}	chordwise position of flap-shroud trailing edge aft of section leading edge	m	ft
α	angle of attack	rad, deg	rad, deg
α^*	angle of attack for C_L^*	rad, deg	rad, deg
Δ_t	composite flap angle factor used in Equations (4.16) and (4.19), see Table 4.2	rad, deg	rad, deg

δ_l	deflection of leading-edge device, measured in streamwise plane, see Item No. 94027	rad, deg	rad, deg
δ_t	deflection of plain or split trailing-edge flap measured in streamwise plane, see Item Nos 94028 and 94029	rad, deg	rad, deg
$\delta_{t1}, \delta_{t2}, \delta_{t3}$	deflection of first, second, third element of slotted trailing-edge flap relative to datum of preceding element, measured in streamwise plane, see Sketches 4.1 of Item Nos 94030 and 94031	rad, deg	rad, 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 4.9		
η_o	value of η at outboard limit of each portion of wing, see Sketch 4.9		
Λ_0	wing leading-edge sweep angle	deg	deg
$\Lambda_{1/4}$	wing quarter-chord sweep angle	deg	deg
λ	wing taper ratio (tip chord/root chord)		

Subscripts

A, B, C, D	used with Δh_1 and η_i or η_o for wing portions A, B, C and D, see Sketch 4.9
w	denotes value for wing
$()_{\text{expt}}$	denotes experimental value
$()_{\text{pred}}$	denotes predicted value
l, t, lt	used with ΔC_{L0} , Δh_0 , h_1 and Δh_1 , to denote leading-edge, trailing-edge or combined leading-edge and trailing-edge device deployment, respectively

2. INTRODUCTION

This Data Item provides an empirical method for predicting the non-linear pitching moment curve for wings with leading-edge devices and/or trailing-edge flaps deployed symmetrically at low speeds. In the application of the method a number of other Items may be required, and these are listed in Section 3.

The method, detailed in Section 4, has been validated for wings with part-span or full-span split flaps, plain flaps, single-slotted and double-slotted flaps, plain leading-edge flaps, Krüger flaps and slats. Lack of test data prevents evaluation for triple-slotted flaps but the method is expected to apply. The same method has been found to apply to aerofoils with high-lift devices, supporting its applicability to high aspect ratio unswept wings.

Section 5 addresses applicability and accuracy, Section 6 gives the Derivation and Section 7 presents a detailed worked example illustrating the use of the method.

In this Item the term 'basic' is used to denote a wing or aerofoil with devices undeployed. The change of pitching moment due to angle of attack with high-lift devices deployed, may be obtained by combining the lift calculated by the method of Item No. 96003 (Reference 33) with a centre of lift which has a non-linear movement with angle of attack. The methods used to estimate the variation of centre of lift due to angle of attack are presented in this Item. It should be noted that some experimental data for wings with leading-edge devices show marked non-linearity at low angle of attack, probably due to flow breakdown associated with excessive leading-edge device deployment angles. The method does not cater for the prediction of these characteristics since high-lift device deployment at low angle of attack is of little relevance. The method does not apply beyond the angle of attack for which flow breakdown effects become significant, and therefore does not address the pitch break characteristics as C_{Lmax} is approached. Further information on restriction of the use of the method is included in Section 5.

3. REQUIRED DATA ITEMS

The following Items are required for the calculation of the increment in wing pitching moment coefficient, ΔC_{mw} , due to angle of attack from $\alpha = 0$. The list includes those Items from which required geometry definitions may be obtained.

<i>Data Item No.</i>	<i>Derivation No.</i>	<i>To Determine</i>
70011	29	Aerodynamic centre position of basic wing.
72024	30	Aerodynamic centre and $C_{m\alpha 0B}$ for basic aerofoil.
76003	31	Basic wing planform geometry.
94027	1	Section geometry with leading-edge devices.
94028	2	Section geometry with plain trailing-edge flaps.
94029	3	Section geometry with split trailing-edge flaps.
94030	4	Section geometry with single-slotted trailing-edge flaps.
94031	5	Section geometry with double-slotted or triple-slotted trailing-edge flaps.
96003	33	Lift curve of wing with high-lift devices deployed.

The following additional Items are required for the calculation of the wing pitching moment coefficient at zero angle of attack, with devices deployed, so that the total pitching moment of the wing at any angle of attack may be calculated.

<i>Data Item No.</i>	<i>Derivation No.</i>	<i>To Determine</i>
87001	32	$C_{mw\alpha 0B}$ for basic wing with camber and twist.
98009	6	$\Delta C_{mw\alpha 0}$ for trailing-edge split flaps.
98017	7	$\Delta C_{mw\alpha 0}$ for trailing-edge plain flaps.
99004	8	$\Delta C_{mw\alpha 0}$ for trailing-edge single-slotted flaps.
99014	9	$\Delta C_{mw\alpha 0}$ for trailing-edge double-slotted and triple-slotted flaps.
00029	10	$\Delta C_{mw\alpha 0}$ for leading-edge high-lift devices.
01013	11	$\Delta C_{mw\alpha 0}$ for leading-edge and trailing-edge high-lift devices in combination.

Note that Item No. 87001 provides the pitching moment coefficient at zero lift and this must be converted to the zero incidence value. See worked example.

4. METHOD

The method was derived by initially considering linear characteristics and idealised leading-edge and trailing-edge devices. Corrections were then developed to incorporate non-linear effects and to allow application to practical device types.

With high-lift devices deployed, the main parameters that can influence the pitching moment curve of a section in two-dimensional flow are the device element angles, the section shape, the change of chord length due to device deployment, the device type and effect of lap and gap size, the Reynolds number and Mach number. The additional parameters that influence the pitching moment curve in three-dimensional flow are the wing planform geometry, (aspect ratio, taper ratio and sweep), and the spanwise extent of the devices. Only the most influential parameters are required for the method presented in this Item.

4.1 Description of Pitching Moment Curve – Linear Characteristics

Sketches 4.1 and 4.2 show the typical variation of lift coefficient and of pitching moment coefficient with angle of attack for a wing and a wing with high-lift devices deployed, assuming linear characteristics.

The lift at any angle of attack, α , may be described by the equation

$$C_L = C_{L0Bw} + \Delta C_{L0w} + (a_1 + \Delta a_1)\alpha, \quad (4.1)$$

where

C_{L0Bw} is the lift coefficient at zero angle of attack with high-lift devices undeployed,

ΔC_{L0w} is the lift coefficient increment at zero angle of attack due to deployment of high-lift devices,

a_1 is the wing lift-curve slope, and

Δa_1 is the increment in lift-curve slope, due to deployment of high-lift devices.

The pitching moment at any angle of attack is

$$\begin{aligned} C_{mw} &= C_{mw\alpha0} - (a_1 + \Delta a_1)(h_{0w} + \Delta h_{0w})\alpha \\ &= C_{mw\alpha0B} + \Delta C_{mw\alpha0} - (a_1 + \Delta a_1)(h_{0w} + \Delta h_{0w})\alpha, \end{aligned} \quad (4.2)$$

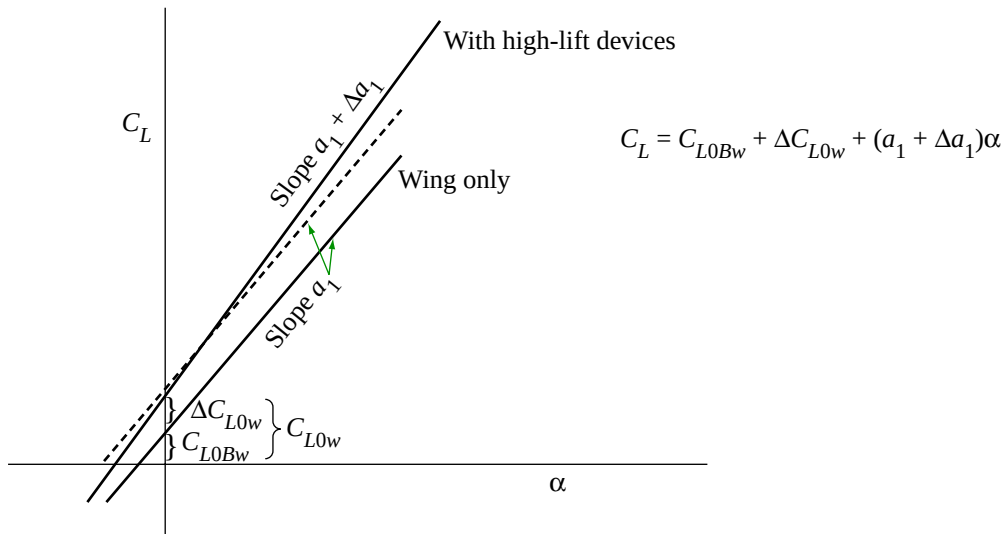
where

$C_{mw\alpha0B}$ is the pitching moment coefficient of the wing at zero angle of attack with high-lift devices undeployed,

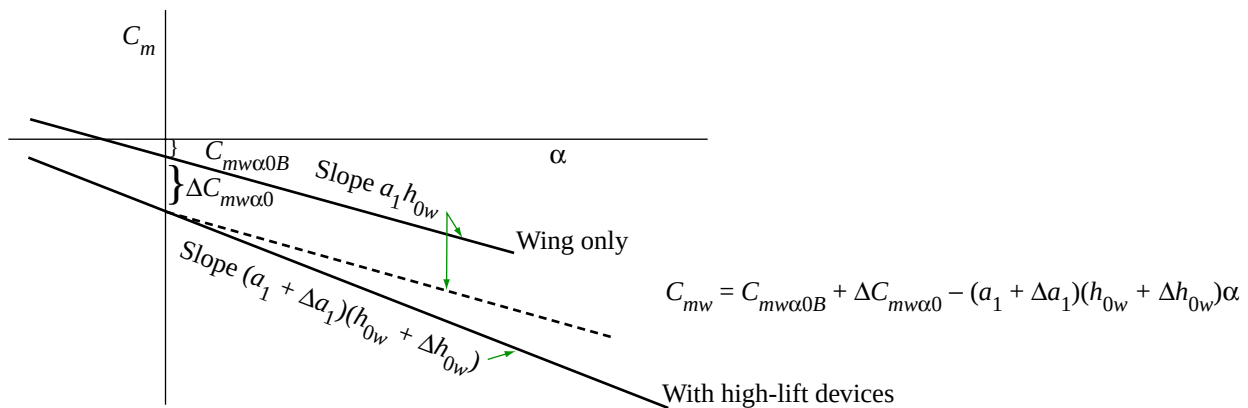
$\Delta C_{mw\alpha0}$ is the pitching moment coefficient increment at zero angle of attack due to deployment of high-lift devices,

h_{0w} is the aerodynamic centre of the wing, taken through zero angle of attack, and

Δh_{0w} is the change of the aerodynamic centre due to deployment of high-lift devices, positive for aft movement.



Sketch 4.1 Wing lift variation with angle of attack for linear characteristics



Sketch 4.2 Wing pitching moment variation with angle of attack for linear characteristics

4.2 Aerodynamic Centre Shift due to Leading-edge or Trailing-edge Device on a Wing Section in Two-dimensional Flow

Sketches 4.3 to 4.6 show the quarter-chord positions of the basic and extended chords resulting from high-lift device deployment on a section. In each sketch the quarter-chord point of the extended chord is marked by 'O'. The quarter-chord point of the basic chord is marked on each sketch by 'X'. The sketches show the distance between the two quarter-chord points for each case. Ignoring any non-linear behaviour, the change of aerodynamic centre due only to the chord extension resulting from deployment of a high-lift device will be closely approximated by the change of position of the quarter-chord point, so that for a trailing-edge flap

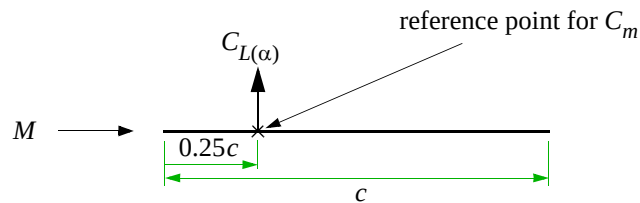
$$\Delta h_{0t} = 0.25 \Delta c_t / c, \quad (4.3)$$

for a leading-edge device

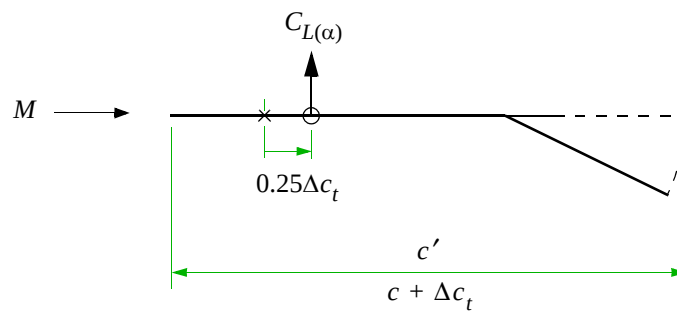
$$\Delta h_{0l} = -0.75\Delta c_l/c \quad (4.4)$$

and for the combination of a leading-edge device and a trailing-edge flap

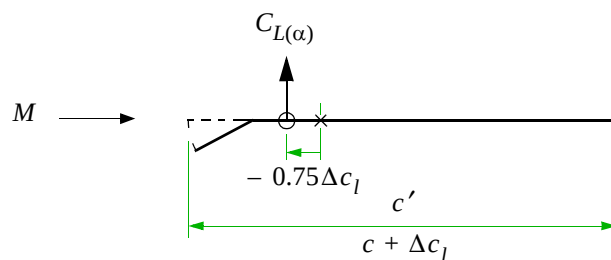
$$\Delta h_{0lt} = 0.25\Delta c_t/c - 0.75\Delta c_l/c. \quad (4.5)$$



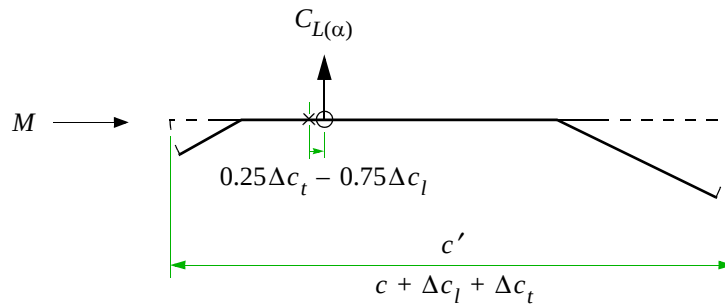
Sketch 4.3 Basic section



Sketch 4.4 Trailing-edge extension



Sketch 4.5 Leading-edge extension



Sketch 4.6 Leading-edge and trailing-edge extensions

4.3 Non-linear Behaviour for a Wing Section

There are two sources of non-linear behaviour which change the aerodynamic centre shift compared with that outlined in Section 4.2. The first of these results from the shortening of the high-lift device planform chord due to its rotation angle.

The second is associated with a progressive shift forward of the centre of lift as angle of attack is increased. This is probably caused by progressive reduction of the effectiveness of the rear part of the wing section, perhaps due to thickening of the boundary layer as angle of attack or flap angle are increased, prior to flow separation. The effect is most pronounced with large combinations of angle of attack and flap angle and at low Reynolds number. For a wing without high-lift devices this effect is small enough to be ignored, but the characteristic can dominate the estimate of the centre of lift at large angle of attack and/or large flap deflection angle, to such an extent, that for cases which might instinctively have been assumed to be stabilising, the net result can be destabilising.

Sketch 4.7 shows the effect of non-linear behaviour on the variation of section pitching moment coefficient with angle of attack, and the necessary equations to define the curve. The most notable difference compared to Equation (4.2) is the introduction of an effective centre of lift, h_1 , which applies to the total change of lift due to angle of attack, from the value at $\alpha = 0$ to the value at α , so that

$$C_m = C_{m\alpha 0} + \Delta C_m = C_{m\alpha 0B} + \Delta C_{m\alpha 0} + \Delta C_m, \quad (4.6)$$

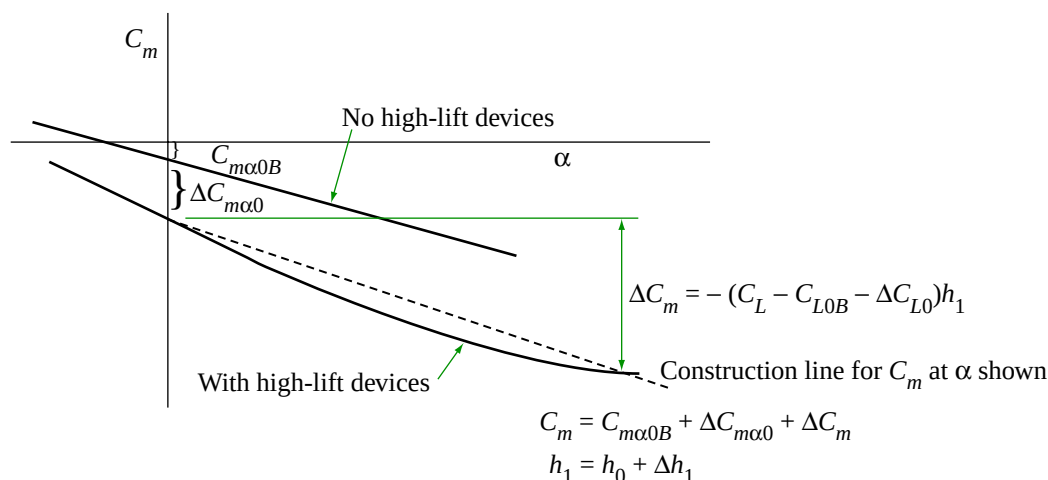
$$\text{where} \quad \Delta C_m = - (C_L - C_{L0B} - \Delta C_{L0}) h_1, \quad (4.7)$$

$$\text{with} \quad h_1 = h_0 + \Delta h_1, \quad (4.8)$$

and

h_0 is the aerodynamic centre with high-lift devices undeployed, taken through $\alpha = 0$, and

Δh_1 is the change of the centre of lift due to angle of attack with high-lift devices deployed.



Sketch 4.7 Section pitching moment variation with angle of attack for non-linear characteristics

The evaluation of Δh_1 , depends on details of the high-lift system and always involves the empirical parameter K_R , obtained from Figure 1 as a function of Reynolds number, based on $\bar{c}$, and leading-edge sweep, and given by

$$K_R = -\left[0.07 - 0.0235(R_{\bar{c}} \times 10^{-6})^{0.5} (\tan \Lambda_0)^{0.5}\right]. \quad (4.9)$$

Note that if evaluation of Equation (4.9) results in a positive value it must be replaced by zero, as indicated in Figure 1.

For a basic wing section

$$\Delta C_{m\alpha 0} = 0 \quad (4.10)$$

and $\Delta C_{L0} = 0, \quad (4.11)$

so that Equations (4.6) to (4.8) give

$$C_m = C_{m\alpha 0B} - (C_L - C_{L0B})(h_0 + \Delta h_1) \quad (4.12)$$

and $\Delta h_1 = K_R[\alpha]^{1.4}, \quad (4.13)$

where α is in radians.

For a wing section with a leading-edge device

$$C_m = C_{m\alpha 0B} + \Delta C_{m\alpha 0} - (C_L - C_{L0B} - \Delta C_{L0I})(h_0 + \Delta h_1) \quad (4.14)$$

and $\Delta h_1 = \Delta h_{1I} = -0.75(\Delta c_l^* - K_{\delta I} c_l')/c + K_R(c'/c)[\alpha]^{1.4}. \quad (4.15)$

See Table 4.1 for Δc_l^* and $K_{\delta I} c_l'$ according to device type.

For a wing section with a trailing-edge flap

$$C_m = C_{m\alpha 0B} + \Delta C_{m\alpha 0} - (C_L - C_{L0B} - \Delta C_{L0t})(h_0 + \Delta h_1) \quad (4.16)$$

and
$$\Delta h_1 = \Delta h_{1t} = 0.25(\Delta c_t - K_{\delta t} c_t)/c + K_R(c'/c)[\alpha + 3.6(\Delta_t)]^{1.4}. \quad (4.17)$$

See Table 4.2 for Δ_t and Δc_t and Table 4.3 for $K_{\delta t} c_t$ according to flap type.

For a wing section with a leading-edge device and a trailing-edge flap

$$C_m = C_{m\alpha 0B} + \Delta C_{m\alpha 0} - (C_L - C_{L0B} - \Delta C_{L0lt})(h_0 + \Delta h_1) \quad (4.18)$$

and

$$\Delta h_1 = \Delta h_{1lt} = 0.25(\Delta c_t - K_{\delta t} c_t)/c - 0.75(\Delta c_l^* - K_{\delta l} c_l')/c + K_R(c'/c)[\alpha + 3.6(\Delta_t)]^{1.4}. \quad (4.19)$$

See Tables 4.1, 4.2 and 4.3 for device parameters.

TABLE 4.1

<i>Device Type</i>	Δc_l^*	$K_{\delta_l} c_l'$
All, except slat with negative L_l or vented Krüger with negative L_l	Δc_l	$(1 - \cos \delta_l) c_l'$
Slat with negative L_l or vented Krüger with negative L_l	$\Delta c_l + 0.7 L_l$	
The distance L_l is defined in Sketch 4.2 of Item No. 94027 as the overlap between the slat or vented Krüger flap trailing edge and the fixed section nose. Negative L_l implies no overlap. The angle δ_l is the deflection and c_l' the extended chord of the leading-edge device, see Item No. 94027.		

TABLE 4.2

Flap Type	Δ_t	Δc_t	Item No.
plain	δ_t	0	94028
split	0	0	94029
single-slotted	$\delta_{t1} c'_{t1}/c'$	$x_{ts} + c'_{t1} - c$	94030
double-slotted	$\delta_{t1} c_{et1}/c' + \delta_{t2} c_{et2}/c'$	$x_{ts} + c'_{t1} + c'_{t2} - c$	94031
triple-slotted	$\delta_{t1} c_{et1}/c' + \delta_{t2} c_{et2}/c' + \delta_{t3} c_{et3}/c'$	$x_{ts} + c'_{t1} + c'_{t2} + c'_{t3} - c$	94031
The angles δ_t , δ_{t1} , δ_{t2} and δ_{t3} are measured in radians.			