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Aerofoil and wing pitching moment coefficient at zero angle of attack due to deployment of leading-edge high-lift devices

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

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

1. NOTATION AND UNITS

		SI	British
A	aspect ratio, $2s/\bar{c}$		
a, b	construction lengths in Sketch 3.2c	m	ft
a_l	theoretical rate of change of lift with leading-edge device deflection, Equation (3.3)	rad^{-1}	rad^{-1}
$(a_1)_0$	basic aerofoil lift-curve slope in incompressible flow	rad^{-1}	rad^{-1}
C_L	lift coefficient; (<i>lift per unit span</i>)/ qc for aerofoil, (<i>lift</i>)/ qS for wing		
C_{L0B}	lift coefficient at zero angle of attack for basic aerofoil		
ΔC_{L0l}	increment in lift coefficient at zero angle of attack due to deployment of leading-edge device on aerofoil, based on c (see Item No. 94027, Derivation 2)		
$\Delta C'_{L0l}$	increment in lift coefficient at zero angle of attack due to deployment of leading-edge device on aerofoil, based on c' , Equation (3.1), $\Delta C_{L0l}(c/c')$, (see Item No. 94027, Derivation 2)		
$[\Delta C'_{L0l}]_1$	contribution to $\Delta C'_{L0l}$ dependent on leading-edge device type and deflection, Equation (3.2)		
$[\Delta C'_{L0l}]_2$	contribution to $\Delta C'_{L0l}$ dependent on leading-edge device type, see Table 3.1		
C_m	pitching moment coefficient; (<i>pitching moment per unit span</i>)/ qc^2 for aerofoil, referenced to $c/4$, (<i>pitching moment</i>)/ $qS\bar{c}$ for wing, referenced to $\bar{c}/4$, see Sketch 1.1		
C_{m0}	C_m for aerofoil at zero lift, see Section 3.2		
C_{m0i}	inviscid value of C_{m0}		
$C_{m\alpha 0B}$	pitching moment coefficient at zero angle of attack for basic aerofoil, based on c^2 and referenced to $c/4$, approximated as C_{m0} , see Section 3.2		
$\Delta C_{m\alpha 0}$	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 (3.12)		

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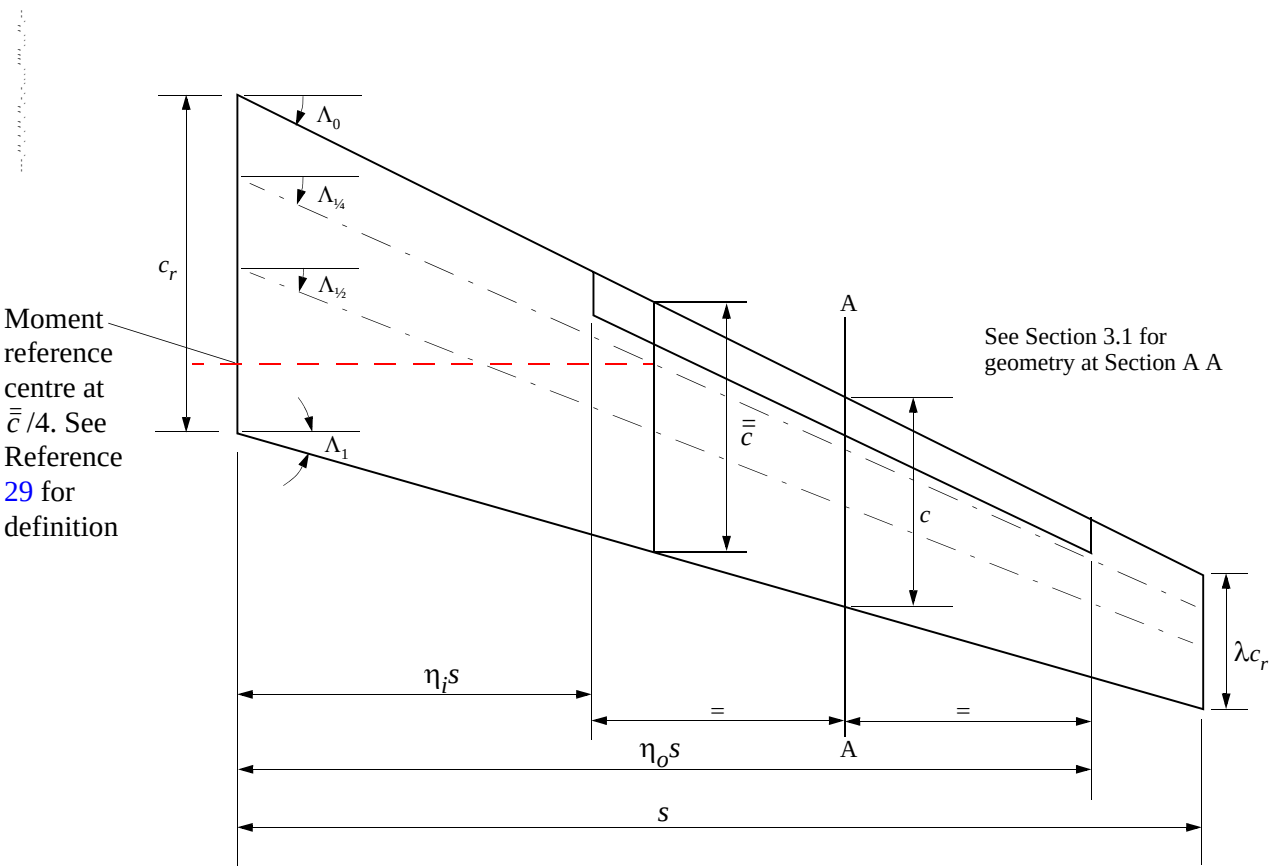
$\Delta C'_{ml\alpha 0}$	increment in pitching moment coefficient at zero angle of attack due to deployment of leading-edge device on aerofoil, based on c'^2 and referenced to $c'/4$, see Equation (3.13)		
$\Delta C_{mlw\alpha 0}$	increment in pitching moment coefficient at zero angle of attack due to deployment of leading-edge device on wing, based on $S\bar{c}$ and referenced to $\bar{c}/4$, see Equation (3.18)		
c	basic (plain) aerofoil chord or wing chord at mid-span of device (<i>i.e.</i> chord with high-lift devices undeployed), see Sketch 1.1	m	ft
c'	extended aerofoil chord, <i>i.e.</i> chord with leading-edge device deployed, see Sketches 3.1 to 3.3	m	ft
$\bar{c}$	wing geometric mean chord	m	ft
$\bar{\bar{c}}$	wing aerodynamic mean chord (see Item No. 76003, Reference 29)	m	ft
c_{el}	effective chord of leading-edge device, see Table 3.1	m	ft
c_l	chord of leading-edge device, see Sketches 3.1 to 3.3	m	ft
c'_l	extended chord of leading-edge device, see Sketches 3.1 to 3.3	m	ft
Δc_l	chord extension due to deployment of leading-edge device, see Sketches 3.1 to 3.3	m	ft
c_r	wing root (centre-line) chord, see Sketch 1.1	m	ft
F	viscous correction factor used in calculation of C_{m0} , see Equation (3.17)		
H_l	height of trailing-edge of slat or Krüger flap above aerofoil chord-line, see Sketches 3.2a to 3.2c and 3.3a to 3.3c	m	ft
h_{2l}	centre of incremental lift at zero angle of attack due to leading-edge device deployment on aerofoil section expressed as fraction of basic aerofoil chord, measured positive aft from 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, see Equation (3.15)		
h'_{2lT}	theoretical value (always negative) on which h'_{2l} is based, see Equation (3.14a) and Figure 1		
K	part-span factor; pitching moment coefficient increment due to part-span leading-edge devices extending symmetrically from wing centre-line divided by pitching moment coefficient increment due to full-span leading-edge devices at same deflection angle, Figure 2		
K_l	leading-edge device type correlation factor, see Table 3.2		

$K_{l\Lambda}$	leading-edge device type correlation factor for wing sweep, see Table 3.2		
K_m	leading-edge device type correlation factor, see Table 3.2		
K_i	value of K corresponding to $\eta = \eta_i$, required in Equation (3.18)		
K_o	value of K corresponding to $\eta = \eta_o$, required in Equation (3.18)		
K_Λ	part-span factor dependent on wing sweep effect, Equation (3.19) and Figures 3a to 3f		
$K_{\Lambda i}$	value of K_Λ corresponding to $\eta = \eta_i$, required in Equation (3.18)		
$K_{\Lambda o}$	value of K_Λ corresponding to $\eta = \eta_o$, required in Equation (3.18)		
K_0	correlation factor in Equation (3.2), dependent on type of leading-edge device, see Table 3.1		
L_l	overlap between trailing edge of deployed slat or vented Krüger flap and fixed aerofoil nose, see Sketch 3.2a or 3.2b	m	ft
M	free-stream Mach number		
p	parameter in Equation (3.19) for K_Λ , see Equation (3.20)		
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_l	chordwise location of undeployed slat trailing edge, see Sketch 3.2a	m	ft
x_n	chordwise location of fixed aerofoil nose, see Sketch 3.2a	m	ft
x_τ	chordwise location of trailing edge of c'_l for deployed Krüger flaps and sealed slats, see Sketches 3.3a to 3.3c	m	ft
z_h	vertical location of hinge for drooped leading edge, see Sketch 3.1	m	ft
α	angle of attack	deg	deg
α_0	angle of attack for zero lift	deg	deg
δ_l, δ_l°	deflection of leading-edge device, positive leading edge down, see Sketches 3.1 to 3.3	rad, deg	rad, deg

ρ_l	leading-edge radius of basic (plain) aerofoil, see Sketches 3.1 to 3.3	m	ft
η	spanwise distance from wing centre-line as fraction of semi-span		
η_i	value of η at inboard limit of leading-edge device, see Sketch 1.1		
η_o	value of η at outboard limit of leading-edge device, see Sketch 1.1		
θ_l	angular parameter related to effective chord of leading-edge device, Equation (3.4)	rad	rad
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, see Sketch 1.1	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 (leading-edge devices undeployed)

2. INTRODUCTION

This Item provides a method to obtain the increment in pitching moment coefficient at zero angle of attack due to deployment of various leading-edge devices at low speeds, either on an aerofoil or on a wing. The devices to be considered are listed in Table 3.1.

For aerofoils, the method predicts the centre of lift position, h_{2l} , due to leading-edge device deployment, based on the thin-aerofoil theory of Derivation 25 and modified to obtain correlation with the experimental data of Derivations 3, 5, 8, 9, 10, 14 and 21. This is combined with the increment in aerofoil lift coefficient, $\Delta C'_{L0l}$, calculated from Item No. 94027 (Derivation 2) to estimate the total pitching moment coefficient increment.

For wings with full-span leading-edge devices, 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 26 and 27 are used as the basis for these factors, with some adjustment to the simple theoretical assumptions. For wings with part-span devices, additional factors are introduced that are dependent on taper ratio, aspect ratio, sweep and spanwise extent of the device.

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. 94027 to determine the lift increment characteristics of the aerofoil/device combination from which to derive the pitching moment coefficient increment. All those parts of Item No. 94027 required in the estimation of $\Delta C'_{L0l}$ are included in this Item, in Section 3.1. It is therefore unnecessary to use Item No. 94027 unless background information is required. Section 3.1 also provides geometric definitions required in the determination of both $\Delta C'_{L0l}$ and h_{2l} .

For wings, the *streamwise* section, leading-edge device geometries and angles at the mid-span of the device are taken to be representative of the wing/device system, see Sketch 1.1. The method again requires the use of Item No. 94027 to determine the lift increment characteristics of the representative section 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 leading-edge devices.

3.1 Determination of $\Delta C'_{L0l}$

The increment in aerofoil lift coefficient at zero angle of attack, based on the extended chord length c' , is given by

$$\Delta C'_{L0l} = [\Delta C'_{L0l}]_1 + [\Delta C'_{L0l}]_2. \quad (3.1)$$

In Equation (3.1) the first term is the main contribution obtained from the theory, and is given by

$$[\Delta C'_{L0l}]_1 = K_0 a_l \delta_l, \quad (3.2)$$

where K_0 is an empirical correlation factor which is dependent upon the type of leading-edge device. The lift slope, a_l , is the theoretical rate of change of lift coefficient with respect to the deflection δ_l , positive nose down, given by thin-plate theory (Reference 25) as

$$a_l = -2(\theta_l - \sin \theta_l) \text{ rad}^{-1} \quad (3.3)$$

where $\theta_l = \cos^{-1}(1 - 2c_{el}/c') \text{ rad}$ (3.4)

and $\sin \theta_l = [1 - (1 - 2c_{el}/c')^2]^{1/2}$, (3.5)

in which c_{el} is the effective chord of the leading-edge device.

Combination of Equations (3.1) to (3.5) gives

$$\Delta C'_{L0l} = -2K_0 \delta_l \left\{ \cos^{-1}(1 - 2c_{el}/c') - [1 - (1 - 2c_{el}/c')^2]^{1/2} \right\} + [\Delta C'_{L0l}]_2, \quad (3.6)$$

in which $[\Delta C'_{L0l}]_2$ is a correction required only for slats and vented Krüger flaps.

The parameters involved in Equation (3.6) take different values according to the type of leading-edge device. Table 3.1 shows the source of the required geometry and definitions or locations whereby the relevant parameters can be determined.

TABLE 3.1 Source of geometry and relevant parameters required for evaluation of Equation (3.6) for various leading-edge devices

Leading-edge devices	Geometry in		Parameters in Equation (3.6)		
	Section	Sketch	c_{el}/c'	K_0	$[\Delta C'_{L0l}]_2$
Plain leading-edge flaps and drooped leading edges	3.1.1	3.1	c'_l/c'	1.0	0
Slats and vented Krüger flaps	3.1.2	3.2	c_l/c'	1.35	0.030
Krüger flaps and sealed slats	3.1.3	3.3	c'_l/c'	1.8	0

In addition to the sketches, Sections 3.1.1 to 3.1.3 contain special comments concerning the geometry and its influence on $\Delta C'_{L0l}$ via the correlation parameters.

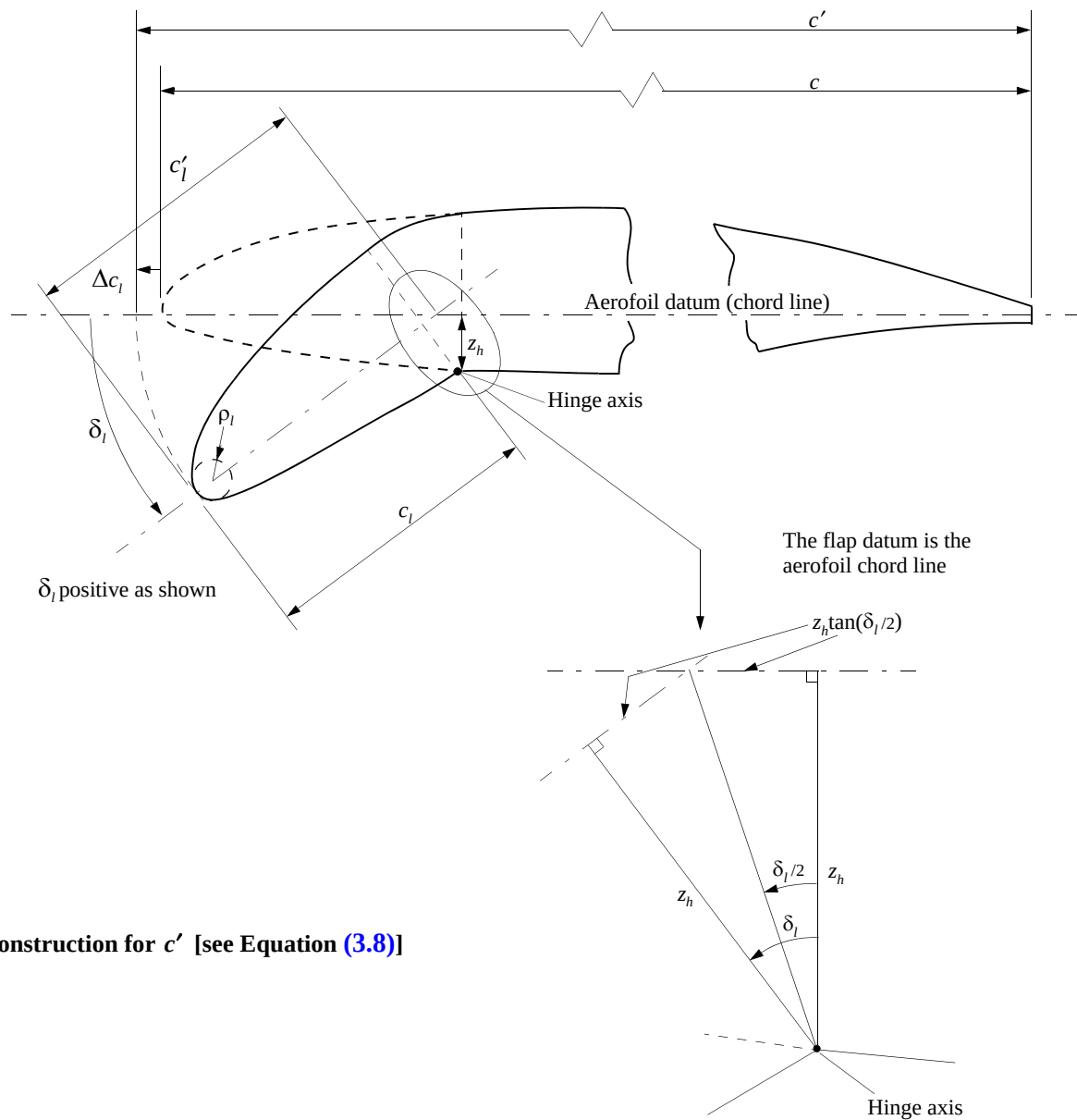
3.1.1 Plain leading-edge flaps and drooped leading edges

Many variations in design are possible for plain leading-edge flows and drooped leading edges. Sketch 3.1 shows the specific case of a device deployed by rotation around a lower-surface hinge, for which

$$c_l' = c_l + z_h \tan(\delta_l/2) \quad (3.7)$$

$$\text{and} \quad c' = c + 2z_h \tan(\delta_l/2). \quad (3.8)$$

The corresponding values of c'_l and c' appropriate to any other arrangement used would have to be determined.



Sketch 3.1 Plain leading-edge flap and drooped leading edge

3.1.2 Slats and vented Krüger flaps

Geometric properties of slats and vented Krüger flaps are shown in Sketches 3.2a, 3.2b and 3.2c.

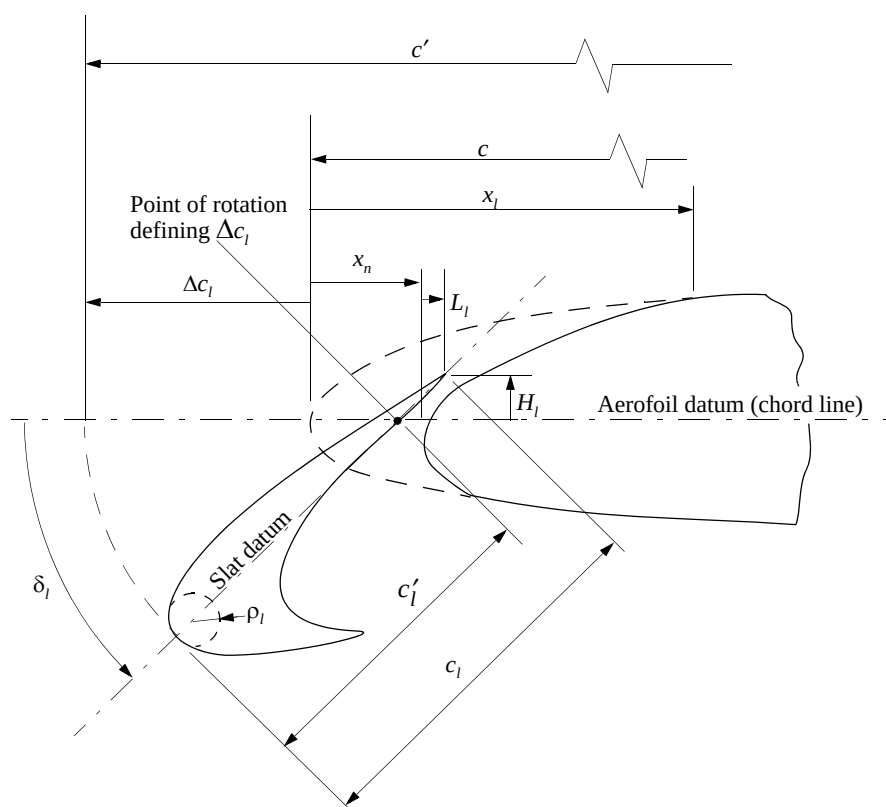
The deflection, δ_l , of both slats and vented Krüger flaps is defined using the angle between the datum chords of the slat (or flap) and the aerofoil. The slat (or flap) datum chord is defined as the line passing through the centre of the leading-edge radius and the slat (or flap) trailing edge. The extended chord, c' , and the chord extension, Δc_l , are defined by rotating the slat (or flap) about the intersection of the slat (or flap) and aerofoil datum chords, as shown in Sketch 3.2c.

In Sketches 3.2a and 3.2b, for a slat and vented Krüger flap

$$c'_l = c_l - H_l \operatorname{cosec} \delta_l. \quad (3.9)$$

For a slat, the geometry in Sketch 3.2a and the construction in Sketch 3.2c give

$$\begin{aligned} c' &= c + \Delta c_l \\ &= c + c_l - x_n - L_l - b \\ &= c + c_l - x_n - L_l - H_l \tan(\delta_l/2). \end{aligned} \quad (3.10a)$$



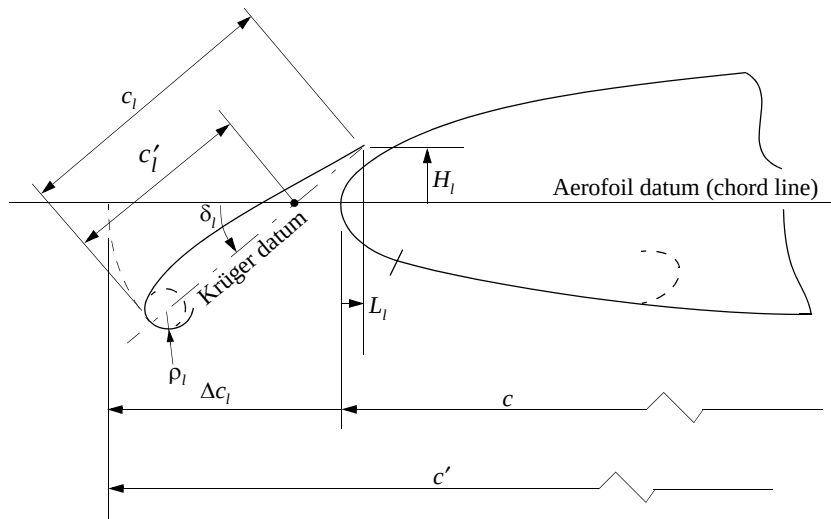
Construction for c' [see Equation (3.10a)]

δ_l , H_l and L_l positive as shown

Sketch 3.2a Slat

For a vented Krüger flap, the geometry in Sketch 3.2b and the construction in Sketch 3.2c give

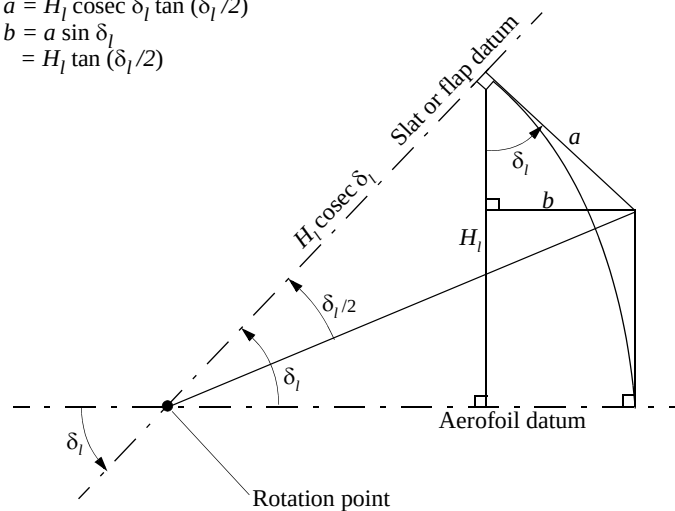
$$\begin{aligned}
 c' &= c + \Delta c_l \\
 &= c + c_l - L_l - b \\
 &= c + c_l - L_l - H_l \tan(\delta_l/2) .
 \end{aligned}
 \tag{3.10b}$$



Construction for c' [see Equation (3.10b)]

Sketch 3.2b Vented Krüger flap

$$\begin{aligned}
 a &= H_l \operatorname{cosec} \delta_l \tan(\delta_l/2) \\
 b &= a \sin \delta_l \\
 &= H_l \tan(\delta_l/2)
 \end{aligned}$$



Sketch 3.2c Rotation of slat and vented Krüger flap