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Increments in aerofoil lift coefficient at zero angle of attack and in maximum lift coefficient due to deployment of various leading-edge high-lift devices at low speeds

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THE PREPARATION OF THIS DATA ITEM

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INCREMENTS IN AEROFOIL LIFT COEFFICIENT AT ZERO ANGLE OF ATTACK AND IN MAXIMUM LIFT COEFFICIENT DUE TO DEPLOYMENT OF VARIOUS LEADING-EDGE HIGH-LIFT DEVICES AT LOW SPEEDS

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1. NOTATION AND UNITS

		SI	British
a_l	theoretical rate of change of lift coefficient with leading-edge device deflection, Equation (3.3)	rad ⁻¹	rad ⁻¹
a_{ml}	theoretical rate of change of maximum lift coefficient with leading-edge device deflection, Equation (3.9)	rad ⁻¹	rad ⁻¹
C_{Lm}	maximum lift coefficient of aerofoil with high-lift devices deployed, based on c		
C_{L0}	lift coefficient at zero angle of attack for aerofoil with high-lift devices deployed, based on c		
ΔC_{Lml}	increment in maximum lift coefficient due to deployment of leading-edge device, based on c , Equation (3.12)		
$\Delta C'_{Lml}$	increment in maximum lift coefficient due to deployment of leading-edge device, based on c' , Equation (3.8) or (3.10), at datum Reynolds number $R_c = 3.5 \times 10^6$		
ΔC_{L0l}	increment in lift coefficient at zero angle of attack due to deployment of leading-edge device, based on c , Equation (3.7)		
$\Delta C'_{L0l}$	increment in lift coefficient at zero angle of attack due to deployment of leading-edge device, based on c' , Equation (3.6)		
$[\Delta C'_{L0l}]_1$	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 4.1		
c	basic (plain) aerofoil chord (<i>i.e.</i> chord with high-lift devices undeveloped), see Sketch 4.1	m	ft
c'	extended aerofoil chord (<i>i.e.</i> chord with high-lift devices deployed), see Sketch 4.1	m	ft
c_{el}	effective chord of leading-edge device, see Table 4.1	m	ft
c_l	chord of leading-edge device, see Sketches 4.1 and 4.2	m	ft
c'_l	extended chord of leading-edge device, see Sketches 4.1 to 4.3	m	ft

Δc_l	chord extension due to deployment of leading-edge device, see Sketches 4.1 to 4.3	m	ft
F_R	factor for effect of Reynolds number on $\Delta C_{L_{ml}}$, Equation (3.11)		
G_l	slat or vented Krüger gap; distance between device trailing edge and aerofoil surface, normal to aerofoil surface, see Sketch 4.2(a) or 4.2(b)	m	ft
H_l	height of slat or vented Krüger flap trailing edge above aerofoil chord line, see Sketch 4.2(a) or 4.2(b)	m	ft
K_e	correlation factor for overlap of slat trailing edge, Figure 3		
K_g	correlation factor for geometry of leading-edge device, Figures 2a and 2b		
K_l	correlation factor for effect of leading-edge device deflection*, Figures 1a to 1c		
K_0	correlation factor in $[\Delta C'_{L_{0l}}]_1$, dependent on type of leading-edge device, see Table 4.1		
L_l	overlap between deployed slat or vented Krüger flap trailing-edge and fixed aerofoil nose, see Sketch 4.2(a) or 4.2(b)	m	ft
M	free-stream Mach number		
R_c	Reynolds number based on free-stream conditions and aerofoil chord c		
t	maximum thickness of aerofoil	m	ft
x	chordwise distance aft from leading edge of basic (plain) aerofoil	m	ft
x_l	chordwise location of undeveloped slat trailing-edge, see Sketch 4.2(a)	m	ft
x_n	chordwise location of fixed aerofoil nose, see Sketch 4.2(a)	m	ft
x_τ	chordwise location of trailing edge, of c'_l for deployed Krüger flaps and sealed slats, see Sketch 4.3(a) to 4.3(c)	m	ft
z_h	vertical location of hinge for drooped leading edge, see Sketch 4.1	m	ft
$z_{u1.25}$	upper-surface ordinate at $x = 0.0125c$ for basic (plain) aerofoil	m	ft
δ_l, δ_l°	deflection of leading-edge device, see Sketches 4.1 to 4.3	rad, deg	rad, deg

δ_0, δ_0°	datum value of δ_l, δ_l° at which $\Delta C'_{Lml} = 0$, dependent on type of leading-edge device, see Table 4.1	rad, deg	rad, deg
θ_l	angular parameter related to effective chord of leading-edge device, Equation (3.4)	rad	rad
ρ_l	leading-edge radius of basic (plain) aerofoil or leading-edge device	m	ft

Subscripts

()_{expt} denotes experimental value

l denotes leading-edge device

()_{pred} denotes predicted value

Superscript

° denotes angle in degrees

' denotes value based on extended chord

* Plus other deployment effects related to deflection for other than plain leading-edge flap and drooped leading edge, see Sections 4.2 and 4.3.

2. INTRODUCTION

2.1 Scope of the Item

This Item provides semi-empirical methods for estimating the incremental effects on aerofoil lift at zero angle of attack and on maximum lift due to the deployment of various leading-edge high-lift devices at low speeds. The types of leading-edge device considered are plain flaps, drooped leading edges, slats (including sealed slats) and Krüger flaps (including vented Krügers).

Section 3 outlines the background to the development of the methods and provides the resulting equations for the estimation of ΔC_{L0l} , the increment in lift coefficient at zero angle of attack and ΔC_{Lml} , the increment in maximum lift coefficient due to the deployment of a leading-edge device.

Section 4 presents the means whereby particular types of leading-edge device are treated. For easy reference a tabular layout is used to show numerical values or the location of the data required to evaluate the equations for each of the leading-edge devices covered.

Section 5 concerns applicability and accuracy, Section 6 gives the Derivation and Reference and, finally, Section 7 presents a number of detailed examples illustrating the use of the methods.

2.2 Application of Data to Aerofoils with Trailing-edge Flaps

In order to use the data obtained from the present Item in the wider context in which trailing-edge flaps are also used, it is essential to refer to Item No. 94026 (Reference 15). That Item acts as an introduction to, and a link between, the Items in the complete series dealing with the incremental effects of high-lift device deployment on aerofoil lift at zero angle of attack and at its maximum. It describes how the incremental effects are summed and added to the contributions from the basic (*i.e.* plain) aerofoil to give the total lift coefficient values at zero angle of attack, C_{L0} , and at maximum lift, C_{Lm} .

3. LIFT COEFFICIENT INCREMENTS ΔC_{L0l} AND ΔC_{Lml}

First approximations to the lift coefficient increments due to the deployment of leading-edge high-lift devices can be obtained from the theory for an equivalent thin hinged plate with empirical correlation factors to account for the geometry of practical aerofoil high-lift devices. To make some allowance for the effects of chord extension in the theory, the flap chord ratio and the lift coefficient increments are based on the aerofoil extended chord. This approach was used in Derivation 11 and the methods developed for this Item have improved on that approach and applied it to a wider range of leading-edge devices. The resulting methods are as follows.

3.1 Increment in Lift Coefficient at Zero Angle of Attack

The deployment of a leading-edge device gives a (usually small) loss in aerofoil lift at zero angle of attack, determined from

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

The prime symbol (') indicates that the lift coefficient increment is based on the aerofoil extended chord c' .

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, and 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 as

$$a_l = -2(\theta_l - \sin \theta_l) \quad (3.3)$$

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

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

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

Combination of Equations (3.2) to (3.5) gives, in conjunction with Equation (3.1),

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

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

To convert the lift coefficient based on extended chord to one based on basic aerofoil chord, the equation

$$\Delta C_{L0l} = (c'/c)\Delta C'_{L0l} \quad (3.7)$$

is used. The value of ΔC_{L0l} can be taken to be independent of Reynolds number.

The determination of $\Delta C'_{L0l}$ for various types of leading-edge device is given in Section 4.

3.2 Increment in Maximum Lift Coefficient

The increment in maximum lift coefficient is given by

$$\Delta C'_{Lml} = K_e K_g K_l a_{ml} (\delta_l - \delta_0) \quad (3.8)$$

For given flow conditions the empirical correlation factors K_e , K_g and K_l are dependent only upon leading-edge device geometry. In this Item K_e , K_g and K_l have been determined for a datum Reynolds number of $R_c = 3.5 \times 10^6$ (see Section 5). The parameter a_{ml} is the theoretical rate of change of maximum lift coefficient with respect to δ_l , given by thin plate theory as

$$a_{ml} = 2 \sin \theta_l \quad (3.9)$$

in which $\sin \theta_l$ is given by Equation (3.5).

Equation (3.8) can be rewritten, using Equations (3.9) and (3.5), as

$$\Delta C'_{Lml} = 2 K_e K_g K_l (\delta_l - \delta_0) [1 - (1 - 2c_{el}/c')^2]^{1/2}, \quad (3.10)$$

for the datum Reynolds number. The parameter δ_0 is the empirically-derived value of δ_l required to give $\Delta C'_{Lml} = 0$ for slats and vented Krüger flaps.

The magnitude of ΔC_{Lml} is influenced by Reynolds number. Analysis of data in Derivations 10 and 14 showed that if K_e , K_g and K_l were correlated at a datum Reynolds number, taken here as $R_c = 3.5 \times 10^6$, then all the Reynolds number dependence of ΔC_{Lml} could be allowed for through a factor, F_R , given by

$$F_R = 0.153 \log_{10} R_c, \quad (3.11)$$

which is unity at the datum.

Thus

$$\Delta C_{Lml} = F_R (c'/c) \Delta C'_{Lml}. \quad (3.12)$$

The method for the determination of $\Delta C'_{Lml}$ for various types of leading-edge device is given in Section 4.

4. DETERMINATION OF $\Delta C'_{L0l}$ AND $\Delta C'_{Lml}$ FOR A RANGE OF LEADING-EDGE HIGH-LIFT DEVICES

To determine values of $\Delta C'_{L0l}$ and $\Delta C'_{Lml}$, and thence to determine the associated values of ΔC_{L0l} and ΔC_{Lml} , for the various types of leading-edge device, Equations (3.6) and (3.10) are used in conjunction with Equations (3.7) and (3.12). The parameters involved in Equations (3.6) and (3.10) take different values according to the type of leading-edge device, so Table 4.1 is presented to show the source of the required geometry and definitions or locations whereby the relevant parameters can be determined.

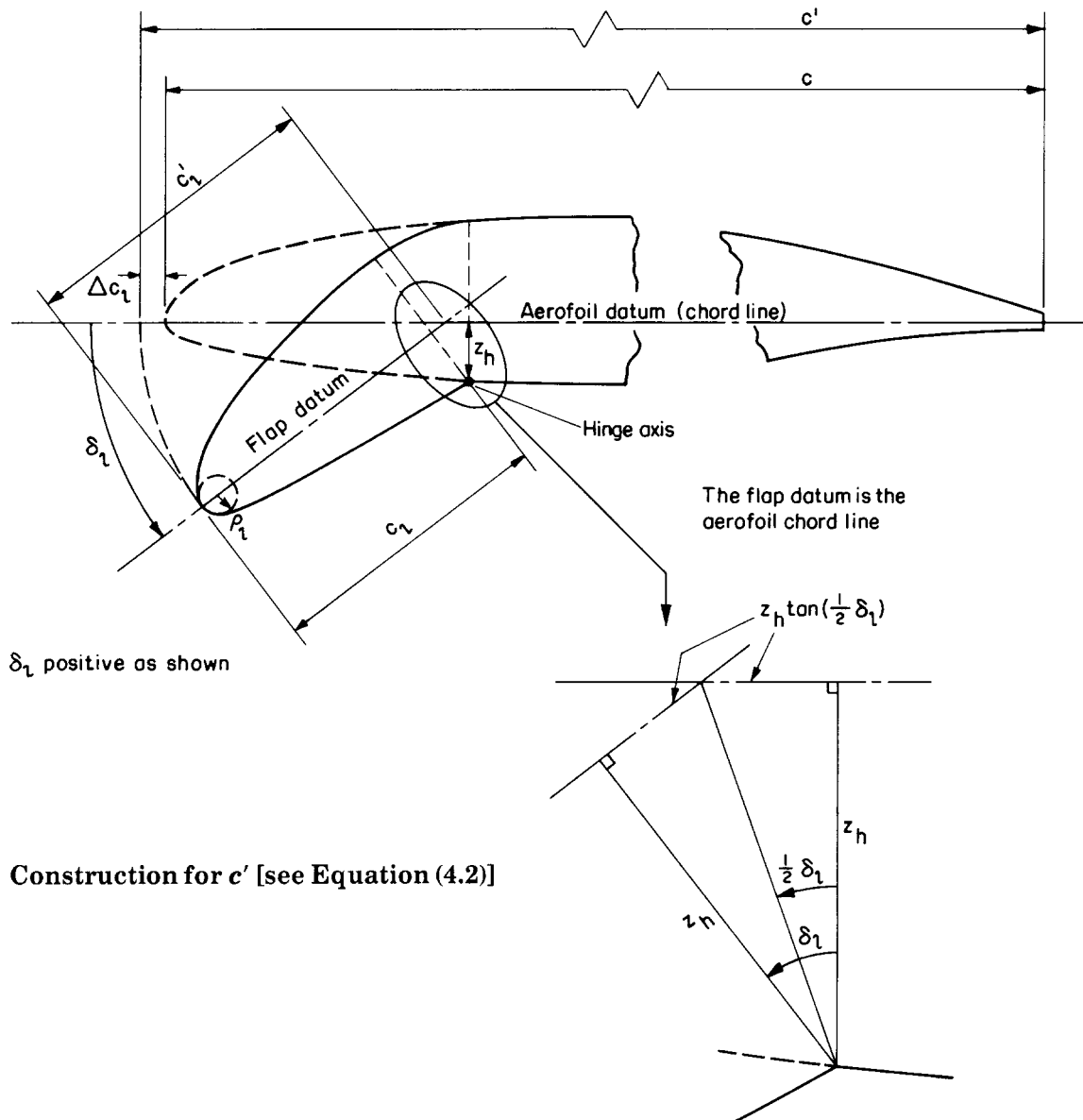
TABLE 4.1 Source of geometry and relevant parameters required for evaluation of Equations (3.6) and (3.10) for various leading-edge devices

Leading-edge device	Geometry in Section	Parameter in Equation (3.6) or (3.10)							
		c_{el}	δ_l	K_0	$[\Delta C'_{L0l}]_2$	K_e	K_g	K_l	δ_0
Plain leading-edge flaps and drooped leading edges	4.1	c'_l	Sketch 4.1	$1/K_l$	0	1.0	Fig. 2a	Fig. 1a	0
Slats and vented Krüger* flaps	4.2	c_l	Sketch 4.2	1.35	0.030	Fig 3 for slats, 1.0 for vented Krügers	Fig. 2b	Fig. 1b	0.25
Krüger* flaps and sealed slats	4.3	c'_l	Sketch 4.3	1.8	0	1.0	Fig. 2a	Fig. 1c	0

* It is **essential** to refer to Section 4.3 for the determination of ΔC_{Lml} for Krüger flaps (vented or unvented) for details of a limitation on Krüger nose geometry.

In addition to the sketches, Sections 4.1 to 4.3 contain special comments concerning the geometry and its influence on $\Delta C'_{L0l}$ or $\Delta C'_{Lml}$ via the correlation parameters.

4.1 Plain Leading-edge Flaps and Drooped Leading Edges



Sketch 4.1 Plain leading-edge flaps and drooped leading edges

From Sketch 4.1,

$$c_l' = c_l + z_h \tan(\delta_l / 2) \quad (4.1)$$

and
$$c' = c + 2z_h \tan(\delta_l / 2). \quad (4.2)$$

Equations (4.1) and (4.2) relate to the specific type of device shown in Sketch 4.1, *i.e.* a device deployed by rotation around a lower-surface hinge. Many variations in design are possible and the corresponding values of c_l' and c' appropriate to any other arrangement used would have to be determined.