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**Increments in aerofoil lift coefficient
at zero angle of attack and in maximum lift
coefficient due to deployment of a
single-slotted trailing-edge flap, with or
without a leading-edge high-lift
device, at low speeds**

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Mr A.E. Sewell*	— McDonnell Douglas Corp., Long Beach, Calif., USA
Mr M.R. Smith	— British Aerospace Airbus Ltd, Bristol
Mr J. Tweedie	— Short Brothers plc, Belfast.

* Corresponding Member

The technical work in the assessment of the available information and the construction and subsequent development of the Data Item was carried out under contract by

Mr J.R.J. Dovey.

The person with overall responsibility for the work in this subject area is Mr P.D. Chappell, Head of the Aircraft Aerodynamics Group.

INCREMENTS IN AEROFOIL LIFT COEFFICIENT AT ZERO ANGLE OF ATTACK AND IN MAXIMUM LIFT COEFFICIENT DUE TO DEPLOYMENT OF A SINGLE-SLOTTED TRAILING-EDGE FLAP, WITH OR WITHOUT A LEADING-EDGE HIGH-LIFT DEVICE, AT LOW SPEEDS

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INCREMENTS IN AEROFOIL LIFT COEFFICIENT AT ZERO ANGLE OF ATTACK AND IN MAXIMUM LIFT COEFFICIENT DUE TO DEPLOYMENT OF A SINGLE-SLOTTED TRAILING-EDGE FLAP, WITH OR WITHOUT A LEADING-EDGE HIGH-LIFT DEVICE, AT LOW SPEEDS

1. NOTATION AND UNITS

		SI	British
$(a_1)_0$	basic aerofoil lift-curve slope in incompressible flow	rad^{-1}	rad^{-1}
C_{Lm}	maximum lift coefficient of aerofoil with high-lift devices deployed, based on c		
$(C_{LmB})_d$	maximum lift coefficient of basic aerofoil at datum Reynolds number $R_c = 3.5 \times 10^6$		
C_{L0}	lift coefficient at zero angle of attack for aerofoil with high-lift devices deployed, based on c		
ΔC_{Lm}	increment in maximum lift coefficient due to deployment of high-lift devices, based on c , Equation (3.2)		
ΔC_{Lml}	increment in maximum lift coefficient due to deployment of leading-edge high-lift device, based on c , see Section 5		
ΔC_{Lmt}	increment in maximum lift coefficient due to deployment of trailing-edge flap, based on c , Equation (3.4)		
$\Delta C'_{Lmt}$	increment in maximum lift coefficient due to deployment of single-slotted trailing-edge flap, based on c' , at datum Reynolds number $R_c = 3.5 \times 10^6$, Equation (4.9)		
$(\Delta C'_{Lmt})_0$	component of $\Delta C'_{Lmt}$ independent of flap deflection, Equation (4.6)		
$(\Delta C'_{Lmt})_1$	component of $\Delta C'_{Lmt}$ due to flap deflection, Equation (4.6)		
ΔC_{L0}	increment in lift coefficient at zero angle of attack due to deployment of high-lift devices, based on c , Equation (3.1)		
ΔC_{L0l}	increment in lift coefficient at zero angle of attack due to deployment of leading-edge high-lift device, based on c , see Item No. 94027		
ΔC_{L0t}	increment in lift coefficient at zero angle of attack due to deployment of trailing-edge flap, based on c , Equation (3.3)		
$\Delta C'_{L0t}$	increment in lift coefficient at zero angle of attack due to deployment of single-slotted trailing-edge flap, based on c' , Equation (4.1)		

$\Delta C'_{L1}$	increment in lift coefficient associated with deployment of single-slotted trailing-edge flap on aerofoil with lift-curve slope of 2π , based on c' , Equation (4.1) and Figure 2		
c	basic (plain) aerofoil chord (<i>i.e.</i> chord with high-lift devices undeployed), see Sketch 4.1	m	ft
c'	extended aerofoil chord (<i>i.e.</i> chord with high-lift devices deployed), see Sketch 4.1 and Equation (4.4)	m	ft
c_{t1}	chord of single-slotted trailing-edge flap, see Sketch 4.1	m	ft
c'_{t1}	extended flap chord, see Sketch 4.1 and Equation (4.5)	m	ft
Δc_l	chord extension due to deployment of leading-edge device, see Sketch 4.1	m	ft
Δc_{t1}	increment in chord of single-slotted trailing-edge flap, see Sketch 4.1	m	ft
F_R	factor for effect of Reynolds number on ΔC_{Lml} and ΔC_{Lmt} , see Equation (3.5)		
J_{t1}	correlation factor (efficiency factor) for single-slotted trailing-edge flap, Equation (4.2) or (4.3) or Figure 1		
K_l	correlation factor for effect of leading-edge device deflection, see Section 5		
K_T	correlation factor for effect of basic aerofoil geometry, Figure 3		
K_{t1}	correlation factor for effect of deflection of single-slotted trailing-edge flap, Figure 4		
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 basic aerofoil leading edge	m	ft
x_{ts}	chordwise location of flap-shroud trailing edge, see Sketch 4.1	m	ft
x_{um}	chordwise location of maximum upper-surface ordinate	m	ft
$z_{u1.25}$	upper-surface ordinate at $x = 0.0125c$ for basic aerofoil	m	ft
δ_l, δ_l°	deflection of leading-edge device, see Sketch 4.1	rad, deg	rad, deg
$\delta_{t1}, \delta_{t1}^\circ$	deflection of trailing-edge flap, positive trailing edge down, see Sketch 4.1	rad, deg	rad, deg

ρ_l leading-edge radius of basic aerofoil, see Sketch 4.1 m ft

Subscripts

$()_{expt}$ denotes experimental value

$()_{pred}$ denotes predicted value

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 a single-slotted trailing-edge flap, with or without the deployment of a leading-edge device, at low speeds.

Section 3 summarises the equations relating the contributions to the total lift increments at zero angle of attack and at maximum lift arising from the deployment of leading-edge high-lift devices and trailing-edge flaps. Section 4 presents methods whereby the contributions from single-slotted trailing-edge flaps are obtained. The contribution to the lift increment at zero angle of attack arising from a variety of leading-edge high-lift devices is obtainable from Item No. 94027 (Derivation 26). However, with regard to the lift increment at maximum lift, the situation is hampered by the lack of test data for other than slats in combination with slotted flaps. Nevertheless, Section 5 provides a guide to the use of the data in Item No. 94027 in the present context for the full range of leading-edge high-lift devices covered in that Item.

Section 6 concerns applicability and accuracy, Section 7 gives the Derivation and References and Section 8 presents two detailed examples illustrating the use of the methods.

2.2 Application of Data to Calculation of Total Lift Coefficient Values C_{L0} and C_{Lm}

In order to use the data obtained from the present Item in the wider context in which the total lift coefficient at zero angle of attack, C_{L0} , and at maximum lift, C_{Lm} , are required for an aerofoil with high-lift devices deployed, it is necessary to refer to Item No. 94026 (Reference 29). That Item acts as an introduction to, and a link between, each of 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 on maximum lift. It describes how the incremental effects are summed and added to the contributions from the basic (*i.e.* plain) aerofoil to give the total values C_{L0} and C_{Lm} .

3. LIFT COEFFICIENT INCREMENTS ΔC_{L0} AND ΔC_{Lm}

The increments in the lift coefficient at zero angle of attack, ΔC_{L0} , and at maximum lift, ΔC_{Lm} , due to the deployment of a leading-edge high-lift device and a trailing-edge flap on an aerofoil are given by the sum of the individual increments, *i.e.*

$$\Delta C_{L0} = \Delta C_{L0l} + \Delta C_{L0t} \quad (3.1)$$

$$\text{and} \quad \Delta C_{Lm} = \Delta C_{Lml} + \Delta C_{Lmt} \quad (3.2)$$

The increments in Equations (3.1) and (3.2) are based on the chord, c , of the basic aerofoil.

The values of ΔC_{L0l} and ΔC_{Lml} for various leading-edge devices are obtainable from Item No. 94027. However, see Section 5 with regard to ΔC_{Lml} for use with the present Item.

For correlation purposes it is more convenient to present the right-hand sides of Equations (3.1) and (3.2) in terms of increments based on the extended chord c' . Also, whereas values of ΔC_{L0l} and ΔC_{L0t} can be taken to be independent of Reynolds number, the values of ΔC_{Lml} and ΔC_{Lmt} are influenced by Reynolds number. Thus, for a general trailing-edge flap, Item No. 94028 (Derivation 27) shows that

$$\Delta C_{L0t} = \frac{c'}{c} \Delta C'_{L0t} \quad (3.3)$$

$$\text{and} \quad \Delta C_{Lmt} = F_R \frac{c'}{c} \Delta C'_{Lmt} \quad (3.4)$$

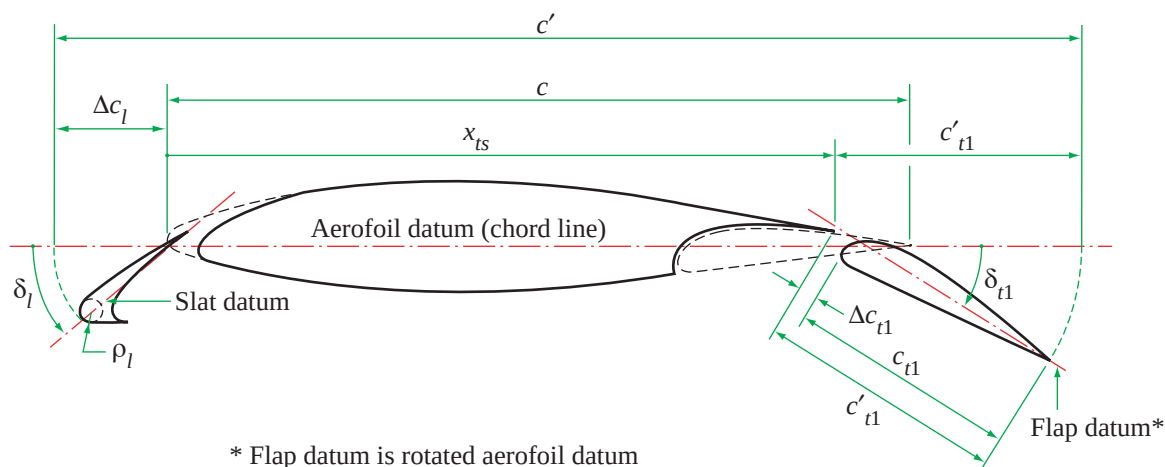
$$\text{where} \quad F_R = 0.153 \log_{10} R_c. \quad (3.5)$$

The value of $\Delta C'_{Lmt}$ in Equation (3.4) is therefore appropriate to the datum Reynolds number $R_c = 3.5 \times 10^6$, for which $F_R = 1$, (see Section 6.1).

The values of $\Delta C'_{L0t}$ and $\Delta C'_{Lmt}$ in Equations (3.3) and (3.4) are determined for single-slotted trailing-edge flaps by the methods of Section 4.

4. LIFT COEFFICIENT INCREMENTS $\Delta C'_{L0t}$ AND $\Delta C'_{Lmt}$

First approximations to the lift coefficient increments due to the deployment of trailing-edge flaps can be obtained from the theory for an equivalent thin hinged plate with empirical correlation factors to account for the geometry of practical aerofoils and flaps. 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 22 and was the basis for the methods developed for plain trailing-edge flaps in Item No. 94028 which was used as a model for the methods given in the present Item for single-slotted trailing-edge flaps, see Sections 4.1 and 4.2. However, some adjustments were required to adapt to the considerable departure from the thin hinged plate basis of the model when applied to a slotted flap, possibly involving large extensions in chord.



Sketch 4.1 Single-slotted trailing-edge flap with typical leading-edge high-lift device (slat)

4.1 Increment in Lift Coefficient at Zero Angle of Attack

The increment in lift coefficient at zero angle of attack due to the deployment of a single-slotted trailing-edge flap is given by

$$\Delta C'_{L0t} = J_{t1} \Delta C'_{L1} (a_1)_0 / 2\pi. \quad (4.1)$$

In this equation J_{t1} is an empirical correlation (or efficiency) factor which is a function of δ_{t1} and is given by

$$J_{t1} = 1.17 [\sin(3.83\delta_{t1}^\circ)]^{1/2} \quad \text{for } 0 \leq \delta_{t1}^\circ \leq 23.5^\circ \quad (4.2)$$

$$\text{and } J_{t1} = 1.17 \quad \text{for } \delta_{t1}^\circ > 23.5^\circ, \quad (4.3)$$

which are plotted in Figure 1.

The flap deflection, δ_{t1} , is seen from Sketch 4.1 to be the angle through which the flap datum* is rotated relative to the stowed flap situation. Thus, for a single-slotted flap δ_{t1} is the angle through which the aerofoil datum is rotated.

The lift coefficient increment, $\Delta C'_{L1}$, associated with the deployment of a single-slotted flap on an aerofoil having a lift-curve slope of 2π , is based on Item No. Flaps 01.01.08 (Derivation 19) and is given in Figure 2 as a function of δ_{t1}° and c'_{t1}/c' . The parameter $\Delta C'_{L1}$, which is based on test data, replaces the value derived from thin plate theory used for plain flaps in Item No. 94028. This was necessary because slot effects are not represented in the simple theory.

The aerofoil extended chord, c' , in Sketch 4.1 is given by

$$c' = \Delta c_l + x_{ts} + c'_{t1} \quad (4.4)$$

The parameter Δc_l is the chord extension due to the deployment of the leading-edge device, obtained for a variety of such devices from Item No. 94027. The quantity x_{ts} is the chordwise location of the trailing-edge of the flap shroud and the extended chord length of the flap, c'_{t1} , is given by

$$c'_{t1} = c_{t1} + \Delta c_{t1}. \quad (4.5)$$

In Sketch 4.1 Δc_{t1} is drawn as having a magnitude sufficiently small to neglect. For those cases in which Δc_{t1} is not small, graphical estimation would be necessary.

The parameter $(a_1)_0$ in Equation (4.1) is the basic aerofoil lift-curve slope in incompressible flow from Item No. Wings 01.01.05 (Derivation 21).

The value of $\Delta C'_{L0t}$ is then used in Equation (3.3) to determine ΔC_{L0t} .

4.2 Increment in Maximum Lift Coefficient

In the development of the method for predicting the increment in maximum lift coefficient it was found necessary to adapt further the thin hinged plate theoretical model to cater for slotted flaps, especially those involving large chord extensions, i.e. Fowler flaps. With such flaps it is possible to obtain significant

* Note that for a single-slotted flap the flap datum is taken as the rotated aerofoil datum, not the flap chord.

increments in maximum lift (with a low drag penalty) by deployment with zero deflection. The increment in maximum lift is then very largely due to chord extension and is related to the basic aerofoil maximum lift. The increment in maximum lift coefficient then consists of two components, one, $(\Delta C'_{Lmt})_0$, independent of flap deflection and the other, $(\Delta C'_{Lmt})_1$, due to the deflection. Thus

$$\Delta C'_{Lmt} = (\Delta C'_{Lmt})_0 + (\Delta C'_{Lmt})_1, \quad (4.6)$$

where

$$(\Delta C'_{Lmt})_0 = (1 - c/c')(C_{LmB})_d \quad (4.7)$$

and

$$(\Delta C'_{Lmt})_1 = K_T K_{t1} J_{t1} \Delta C'_{L1} - (1 - c/c') \sin \delta_{t1} (C_{LmB})_d, \quad (4.8)$$

so that

$$\Delta C'_{Lmt} = (1 - c/c')(1 - \sin \delta_{t1})(C_{LmB})_d + K_T K_{t1} J_{t1} \Delta C'_{L1}. \quad (4.9)$$

In Equation (4.9) $(C_{LmB})_d$ is the maximum lift coefficient for the basic aerofoil at the datum Reynolds number $R_c = 3.5 \times 10^6$, obtained from Item No. 84026 (Derivation 25).

The extended chord, c' , is given by Equations (4.4) and (4.5), J_{t1} is obtained either from Figure 1 or from Equation (4.2) or (4.3) and $\Delta C'_{L1}$ is obtained from Figure 2.

The correlation factor K_T , given in Figure 3, allows for the effect of basic aerofoil geometry via $z_{u1.25}/c$, the dimensionless upper-surface ordinate at $0.0125c$, and x_{um}/c , the dimensionless chordwise location of the maximum upper-surface ordinate. Values of $z_{u1.25}/c$ for a range of NACA sections are given in Item No. 66034 (Reference 28). The correlation factor K_{t1} is given as a function of δ_{t1}° in Figure 4.

Finally, with the value of $\Delta C'_{Lmt}$ obtained from Equation (4.9), ΔC_{Lmt} is evaluated from Equation (3.4) with F_R given by Equation (3.5).

5. EFFECT OF LEADING-EDGE HIGH-LIFT DEVICE

The only leading-edge device for which test data are available for aerofoils with slotted trailing-edge flaps is the slat. With regard to the effect of slat deployment on the lift coefficient at zero angle of attack it was found that the increment determined from Item No. 94027 could be used without modification. That being so, it is anticipated that for ΔC_{L0l} the methods of Item No. 94027 for any leading-edge device may be used in conjunction with the present Item for single-slotted flaps.

Unfortunately, the analysis with regard to maximum lift revealed a more complicated picture. It was found that the optimum slat gap with slotted flaps deployed is larger than for the situation in which the flap is undeployed. The optimum gap is typically within the range $0.02c$ to $0.05c$ with slotted flaps deployed, compared with about $0.01c$ for the flaps undeployed case, for the same range of slat angles. However, only a small variation in ΔC_{Lm} was found within that range, and the test data were used to derive a modified