



ESDU 91014

Issued August 1991
With Amendment A
August 1995

Maximum lift of wings with trailing-edge flaps at low speeds

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MAXIMUM LIFT OF WINGS WITH TRAILING-EDGE FLAPS AT LOW SPEEDS

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MAXIMUM LIFT OF WINGS WITH TRAILING-EDGE FLAPS AT LOW SPEEDS

1. NOTATION AND UNITS

		SI	British
A	aspect ratio, $2s/\bar{c}$		
C_L	lift coefficient; (lift per unit span)/ qc for aerofoil, (lift)/ qS for wing		
C_{LL}	wing local lift coefficient; (lift per unit span)/ qc		
C_{LLp}	peak (<i>i.e.</i> maximum) value of C_{LL}		
C_{Lmax}	wing maximum lift coefficient		
C_{LmaxB}	wing maximum lift coefficient with high-lift devices undeployed (<i>i.e.</i> "basic" wing)		
C_{Lm}	aerofoil section maximum lift coefficient		
ΔC_{Lmaxt}	increment in wing maximum lift coefficient due to deployment of trailing-edge flaps		
ΔC_{Lmt}	increment in aerofoil section maximum lift coefficient due to deployment of trailing-edge flap, based on c		
$\Delta C'_{Lmt}$	increment in aerofoil section maximum lift coefficient due to deployment of trailing-edge flap, based on c'		
c	wing local chord, see Sketch 1.1; basic aerofoil section chord	m	ft
c'	wing extended local chord	m	ft
c_p	wing chord at spanwise location of peak loading due to incidence, see Sketch 1.1	m	ft
c_r	wing root (centre-line) chord	m	ft
c_t	chord of trailing-edge flap	m	ft
$\bar{c}$	wing geometric mean chord	m	ft
$\bar{\bar{c}}$	wing aerodynamic mean chord	m	ft
F_R	factor for effect of Reynolds number on ΔC_{Lmaxt} , see Equation (6.6)		
K_f	correlation factor dependent on flap type, see Section 6.2		

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$K_{\Lambda t}$	correlation factor for wing sweep, see Equation (6.7)		
M	free-stream Mach number		
q	free-stream kinetic pressure	N/m ²	lbf/ft ²
R_c	Reynolds number based on free-stream conditions and c		
$R_{\bar{c}}$	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	maximum thickness of aerofoil	m	ft
z_{cm}	maximum height of camber line of basic aerofoil (see Item No. 94029)	m	ft
z_{lm}	lower-surface ordinate of basic aerofoil for which distance from chord line is maximum (see Item No. 94029)	m	ft
$z_{u1.25}$	upper-surface ordinate of basic aerofoil at 1.25% chord (see Item Nos 94029, 94030, 94031)	m	ft
β	compressibility parameter, $(1 - M^2)^{1/2}$		
δ_t, δ_t°	deflection angle of trailing-edge flap, measured streamwise (see Item Nos 94028, 94029)	rad, deg	rad, deg
$\delta_{tj}, \delta_{tj}^\circ$	deflection angle of element j of trailing-edge flap relative to datum of preceding element, measured streamwise (see Item Nos 94030, 94031)	rad, deg	rad, deg
ζ_p	leading-edge shape parameter for section normal to leading edge at $\eta = \eta_p, (z_{u1.25}/c)_p \sec \Lambda_0$		
η	spanwise distance from wing centre-line as fraction of semi-span		
η_i	value of η at inboard limit of flap		
η_o	value of η at outboard limit of flap		
η_p	value of η for μ_p		
$\bar{\eta}$	spanwise centre of pressure position for loading due to incidence (see Item No. 83040)		
κ	wing taper parameter in Item No. 83040; $\int_0^1 (c/\bar{c})\eta d\eta$, giving $(1 + 2\lambda)/[3(1 + \lambda)]$ for straight-tapered wing		
Λ_h	flap hinge-line sweep angle (see Section 6.3)	deg	deg

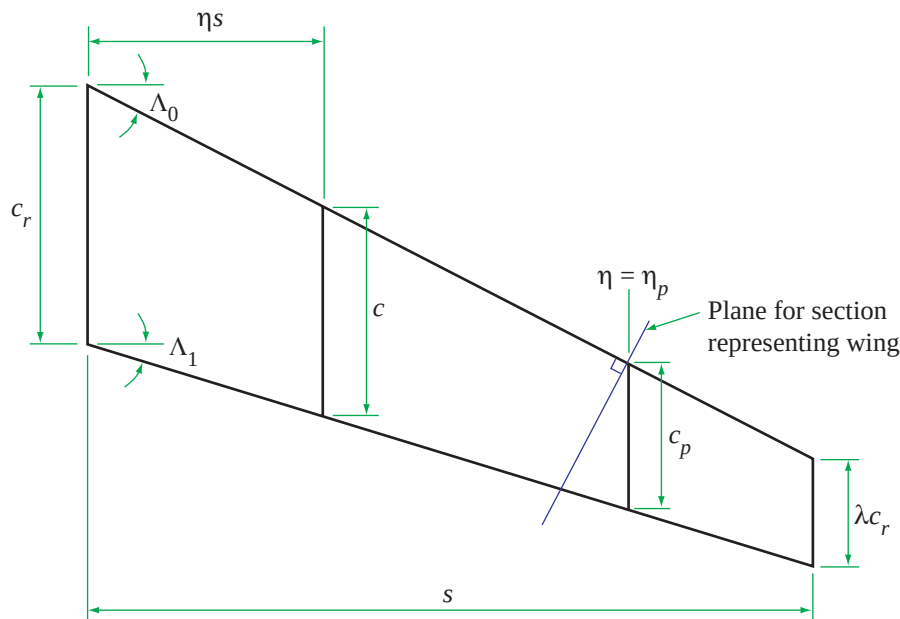
Λ_0	wing leading-edge sweep angle, see Sketch 1.1	deg	deg
$\Lambda_{1/4}$	wing quarter-chord sweep angle	deg	deg
$\Lambda_{1/2}$	wing mid-chord sweep angle	deg	deg
Λ_1	wing trailing-edge sweep angle, see Sketch 1.1	deg	deg
λ	wing taper ratio, (tip chord)/(root chord)		
μ	normalised local lift coefficient, C_{LL}/C_L		
μ_p	peak (<i>i.e.</i> maximum) value of μ		
ρ_l	aerofoil leading-edge radius	m	ft
Φ	part-span factor; lift coefficient increment due to part-span flaps extending symmetrically from wing centre-line divided by lift coefficient increment due to full-span flaps at same flap setting and wing angle of attack		
Φ_i	value of Φ corresponding to η_i , Figure 3a or 3b		
Φ_o	value of Φ corresponding to η_o , Figure 3a or 3b		
ϕ_t°	angle between basic aerofoil datum chord at trailing edge and upper surface, projected if necessary (see Item No. 94028)	deg	deg

Subscripts

p	denotes value for section at η_p
$()_{\text{expt}}$	denotes experimental value
$()_{\text{pred}}$	denotes predicted value

Superscript

$^\circ$	denotes angle in degrees
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Sketch 1.1 Wing notation

2. INTRODUCTION

In this Item the increment in maximum lift coefficient due to the deployment of trailing-edge flaps on a wing is derived from the increment in maximum lift coefficient due to deployment of a trailing-edge flap on an aerofoil section representative of the wing. For wings with full-span high-lift devices the three-dimensional effects are similar to those for a plain wing (*i.e.* a wing with or without camber or twist but without deployment of manoeuvre or high-lift devices such as leading-edge or trailing-edge flaps); separation usually starts near the most highly loaded spanwise station and spreads rapidly with increasing incidence. For this reason the basic concepts with regard to the importance of the spanwise loading and the relevance of the most highly loaded section used in Item No. 89034 (Derivation 5) are maintained in this Item.

Item No. 84026 (Derivation 4) provides a method for the prediction of the maximum lift coefficient of aerofoils. Item Nos 94026 to 94031 (Derivations 6 to 11) provide methods for the prediction of the increment in the maximum lift coefficient of aerofoils due to the deployment of leading-edge or trailing-edge high-lift devices. Item No. 89034 provides a method for the prediction of the maximum lift coefficient of plain, cambered and twisted wings which utilises the aerofoil section data of Item No. 84026. This Item extends the scope of Item No. 89034 to provide the increment in maximum lift coefficient of wings due to the deployment of trailing-edge devices. The maximum lift coefficient of wings with trailing-edge high-lift devices deployed can therefore be obtained by the use of this Item in combination with Item No. 89034.

For subsonic speeds, the increment in maximum lift coefficient due to the deployment of trailing-edge flaps on a high aspect ratio wing is, to a first approximation, determined by the increment in the maximum lift coefficient due to the flaps on the aerofoil section. The main parameters which influence the increment in maximum lift coefficient due to flaps on an aerofoil section are the change in chord length due to trailing-edge flap deployment, aerofoil section geometry, the effective chord of the flap, the type of flap, Reynolds number and Mach number. For flaps on wings, additional parameters influence the maximum lift coefficient, in particular aspect ratio, taper ratio, sweep and spanwise extent of the flap. The estimation of the effects of leading-edge device deployment, without and with deployed trailing-edge flaps, is dealt with in Item No. 92031 (Reference 35).

3. REQUIRED DATA ITEMS

The ESDU Data Items that may be required in the use of this Item are:

<i>Data Item No.</i>	<i>Derivation No.</i>	<i>For Determination of</i>
76003	2	Various geometrical relationships for wings.
83040	3	Spanwise centre of pressure location.
84026	4	Aerofoil maximum lift coefficient for $M \approx 0$.
89034	5	Maximum lift coefficient of plain wings at subsonic speeds.

Increment in aerofoil maximum lift coefficient due to deployment of:

94028	8	plain trailing-edge flaps,
94029	9	trailing-edge split flaps,
94030	10	single-slotted trailing-edge flaps,
94031	11	double-slotted and triple-slotted trailing-edge flaps.

4. SCOPE OF THE ITEM

The method of obtaining the maximum lift coefficient increment of the wing due to a trailing-edge flap, ΔC_{Lmax} , involves the evaluation of the increment, $\Delta C'_{Lmt}$, due to the deployment of the flap on the aerofoil section at the spanwise location of the peak loading due to incidence. The value of $\Delta C'_{Lmt}$, obtained from any of Item Nos 94028 to 94031, is then factored to allow for the effects of aspect ratio, taper and sweep and part-span effects. It has been found that similar factors apply for all types of trailing-edge flap. The method can therefore be used for all those trailing-edge flaps considered in Item Nos 94028 to 94031, which comprise plain, split, single-, double- and triple-slotted flaps. Although data used in the derivation of this Item did not include triple-slotted flaps it is believed that the method will be equally applicable.

The ranges of geometrical and flow parameters for the experimental data from which the correlation factors have been derived are given in Table 7.1.

5. EFFECTS OF MACH NUMBER AND REYNOLDS NUMBER

5.1 Mach Number Effects

High local Mach numbers will occur at low free-stream Mach number as a result of the deployment of high-lift devices. Mach number effects will occur at free-stream Mach numbers greater than about 0.2, depending on detailed section geometry. None of the data considered for this Item was for a Mach number greater than 0.25.

5.2 Reynolds Number Effects

Reynolds number effects for aerofoils are allowed for in the prediction of $\Delta C'_{Lmt}$ in Item Nos 94028 to 94031. For the data used in the derivation of this Item no additional effects of Reynolds number on ΔC_{Lmax} were found. However, it should be noted that in wind-tunnel tests with slotted flaps at very low Reynolds

number ($R_{\bar{c}} < 0.6 \times 10^6$, say) the relatively thicker boundary layer reduces the effectiveness of the slot, thus reducing ΔC_{Lmax} . If estimates are required for single-slotted flaps at such low Reynolds numbers, the use of plain flap data may yield a more representative result.

The effects of Reynolds number on C_{LmaxB} , the maximum lift coefficient of the basic wing with no high-lift devices deployed, are dealt with in Item No. 89034.

6. PREDICTION METHOD

6.1 Derivation of Method

Reports considered in the development of the method include work by Young, Roshko, McRae and Sanders (Derivations 24, 27, 28 and 29). The main effects of aspect ratio, taper ratio and the effects of sweep on the spanwise loading are allowed for by the concepts used in Item No. 89034.

The part of the method of Item No. 89034 that is applicable to a plain wing with little or no sweep, where the effects of outboard flow of the boundary layer may be neglected, requires the spanwise variation of the local lift coefficient, C_{LL} , and a comparison of this with the spanwise variation of C_{Lm} , the maximum lift coefficient of the aerofoil section. For the incidence at which the peak local lift coefficient, C_{LLp} matches the local section maximum lift coefficient, C_{Lm} , the distribution of $C_{LL}c/\bar{c}$ is obtained and integrated to obtain the value of the maximum lift coefficient of the wing, C_{Lmax} . This concept is extended here to apply to a wing with a full-span trailing-edge flap and therefore the increment in C_{Lmax} due to the flap.

The same simplifying assumptions as those used in Item No. 89034 have been made to reduce the complex procedure outlined above to the calculation for only the most highly loaded spanwise station. The spanwise position, η_p , of the most highly loaded section for loading due to incidence and the corresponding normalised lift coefficient, μ_p , are shown in Figures 1 and 2 which are taken from Item No. 89034. These Figures are in terms of taper ratio, λ , and the spanwise centre of pressure location, $\bar{\eta}$, corresponding to the spanwise loading due to incidence, obtainable from Item No. 83040.

For wings with part-span flaps the procedure outlined above would need to account for the change in spanwise loading distribution due the deployment of the part-span flap. Item No. 74012 (Derivation 1) includes part-span effects, derived from a combination of theory and wind-tunnel data, for the increment in lift at a constant incidence. This has been found to be an adequate representation of part-span effects on ΔC_{Lmax} for plain and split flaps and is therefore incorporated in this Item. However, for slotted flaps the part-span effects on ΔC_{Lmax} are somewhat different and have been derived by correlation of data from Derivations 13, 15, 31 and 32.

The effects of wing sweep have been derived from an analysis of data from Derivations 14, 16, 19, 22, 23, 25, 26, 31 and 32 and require the use of geometrical characteristics for the section normal to the leading-edge at the spanwise location of maximum loading due to incidence (see Sketch 1.1), flap angle measured normal to the hinge-line and a sweep correlation factor, $K_{\Delta t}$.

Equation (3.5) in Item No. 94028 and Equation (3.4) in Item Nos 94029 to 94031 give the general expression for the increment in maximum lift coefficient due the deployment of a trailing-edge flap on an aerofoil for the datum Reynolds number based on chord c of 3.5×10^6 as