



ESDU 92031

Issued November 1992

With Amendment A

November 1995

Maximum lift of wings with leading-edge devices and trailing-edge flaps deployed

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MAXIMUM LIFT OF WINGS WITH LEADING-EDGE DEVICES AND TRAILING-EDGE FLAPS DEPLOYED

CONTENTS

	Page
1. NOTATION AND UNITS	1
2. INTRODUCTION	5
3. REQUIRED DATA ITEMS	6
4. SCOPE OF ITEM	6
5. EFFECTS OF MACH NUMBER AND REYNOLDS NUMBER	7
5.1 Mach Number Effects	7
5.2 Reynolds Number Effects	7
6. PREDICTION METHOD	7
6.1 General Expression	8
6.2 Unswept Wings	8
6.3 Swept Wings	9
7. APPLICABILITY AND ACCURACY	10
7.1 Applicability	10
7.2 Accuracy	10
8. DERIVATION AND REFERENCES	16
8.1 Derivation	16
8.1.1 ESDU Data Items	16
8.1.2 Wind-tunnel test reports	17
8.2 References	18
9. EXAMPLES	18
9.1 Example 1	18
9.2 Example 2	23

MAXIMUM LIFT OF WINGS WITH LEADING-EDGE DEVICES AND TRAILING-EDGE FLAPS DEPLOYED

1. NOTATION AND UNITS

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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_{Lm}	aerofoil section maximum lift coefficient		
C_{Lmax}	wing maximum lift coefficient		
C_{LmaxB}	wing maximum lift coefficient with high-lift devices undeployed (<i>i.e.</i> "basic" wing)		
ΔC_{Lm}	increment in aerofoil section maximum lift coefficient due to deployment of high-lift devices		
ΔC_{Lmaxl}	increment in wing maximum lift coefficient due to deployment of leading-edge devices		
ΔC_{Lmaxt}	increment in wing maximum lift coefficient due to deployment of trailing-edge flaps		
ΔC_{Lml}	increment in aerofoil section maximum lift coefficient due to deployment of leading-edge device, based on c ; datum value for Reynolds number of 3.5×10^6		
$\Delta C'_{Lml}$	increment in aerofoil section maximum lift coefficient due to deployment of leading-edge device, based on c' ; datum value for Reynolds number of 3.5×10^6		
c	wing local chord, see Sketch 1.1; basic aerofoil section chord	m	ft
c'	wing extended local chord	m	ft
c_{el}	effective chord of leading-edge device (see Table 4.1 of Item No. 94027)	m	ft
c_l	chord of leading-edge device (see Sketches 4.1 and 4.2 of Item No. 94027)	m	ft

Issued November 1992
With Amendment A, November 1995 - 27 pages

Δc_l	chord extension due to deployment of leading-edge device (see Sketches 4.1 to 4.3 of Item No. 94027)	m	ft
c'_l	extended chord of leading-edge device (see Sketches 4.1 to 4.3 of Item No. 94027)	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
Δc_t	increment in flap chord	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 $\Delta C_{L_{max}}$, see Equation (6.5) or (6.7)	m	ft
G_l	gap between trailing edge of deployed slat or vented Krüger flap and aerofoil surface, measured normal to aerofoil surface (see Sketches 4.2(a) and 4.2(b) of Item No. 94027)	m	ft
H_l	height of trailing edge of leading-edge device above basic aerofoil chord line (see Sketches 4.2 and 4.3 of Item No. 94027)	m	ft
K_e	correlation factor for overlap of slat trailing edge (Figure 3 of Item No. 94027)		
K_g	correlation factor for geometry of leading-edge device (Figures 2a and 2b of Item No. 94027)		
K_l	correlation factor for effect of leading-edge device deflection (Figures 1a to 1c of Item No. 94027, Figure 5 of Item No. 94030 and Figure 10 of Item No. 94031)		
$K_{\Lambda l}$	correlation factor for wing sweep, see Section 6.3		
L_l	overlap between trailing edge of deployed slat or vented Krüger flap and fixed aerofoil nose (see Sketches 4.2(a) and 4.2(b) of Item No. 94027)	m	ft
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 $\bar{\bar{c}}$		

S	wing planform area, $2s\bar{c}$	m^2	ft^2
s	wing semi-span	m	ft
t	maximum thickness of aerofoil	m	ft
x_l	chordwise location of undeployed slat trailing-edge (see Sketch 4.2(a) of Item No. 94027)	m	ft
x_n	chordwise position of fixed aerofoil nose (see Sketch 4.2(a) of Item No. 94027)	m	ft
β	compressibility parameter, $(1 - M^2)^{1/2}$		
δ_l, δ_l°	deflection angle of leading-edge device, measured streamwise (see Sketches 4.1 to 4.3 of Item No. 94027)	rad, deg	rad, deg
δ_t, δ_t°	deflection angle of trailing-edge flap, measured streamwise (see Sketch 4.1 of Item Nos 94028 and 94029)	rad, deg	rad, deg
η	spanwise distance from wing centre-line as fraction of semi-span		
η_{il}, η_{it}	value of η at inboard limit of leading-edge device, trailing-edge flap		
η_{ol}, η_{ot}	value of η at outboard limit of leading-edge device, trailing-edge 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_{hl}	leading-edge device hinge-line sweep angle	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		

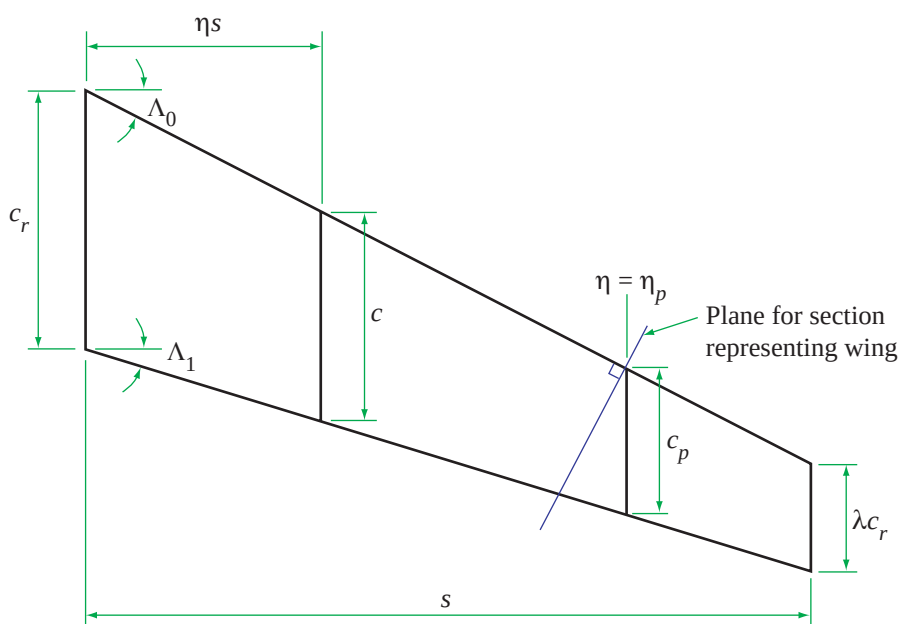
ρ_l	aerofoil leading-edge radius	m	ft
ϕ_t°	angle between basic aerofoil datum chord at trailing edge and upper surface, projected if necessary (see Sketch 4.1 of Item No. 94028)	deg	deg
ψ_i	part-span factor; lift coefficient increment due to part-span leading-edge device extending symmetrically from η_{il} out to wing tip, divided by lift coefficient increment due to full-span leading-edge device at same setting and wing angle of attack		

Subscripts

l	denotes value for leading-edge device
m	denotes aerofoil value of maximum lift
max	denotes wing value of maximum lift
p	denotes value for section at η_p
t	denotes value for trailing-edge flap
$()_{expt}$	denotes experimental value
$()_{pred}$	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 leading-edge devices on a wing is derived from the increment in maximum lift coefficient due to a leading-edge device 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 used in Item No. 89034 (Derivation 4), with regard to the importance of the spanwise loading and the relevance of the most highly loaded section, are maintained in this Item.

The methods for the prediction of aerofoil section maximum lift coefficient, C_{Lm} , and the increment to it, ΔC_{Lm} , due to deployment of leading-edge devices and trailing-edge flaps are presented respectively in Item No. 84026 (Derivation 3) and Item Nos 94026 to 94031 (Derivations 6 to 11).

The methods for the prediction of wing maximum lift coefficient, C_{LmaxB} , for a plain cambered and twisted wing, and the incremental wing maximum lift coefficient, ΔC_{Lmax} , due to deployment of trailing-edge flaps are presented respectively in Item No. 89034 and Item No. 91014 (Derivation 5). Those methods utilise the aerofoil section data of Item No. 84026 and Item Nos 94026 and 94028 to 94031.

The method of the present Item extends the scope of this series of Items by using the aerofoil section data of Item No. 94027 in the prediction of ΔC_{Lmax} , the increment in maximum lift coefficient of a wing due to the deployment of leading-edge devices. The maximum lift coefficient, ΔC_{Lmax} , of wings with leading-edge 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 leading-edge devices on a high aspect ratio wing with no sweep is, to a first approximation, determined by the increment in the maximum lift coefficient due to the leading-edge high-lift devices on the aerofoil section. The main parameters which influence the increment in maximum lift coefficient due to leading-edge devices on an aerofoil section are the type of device, the effective chord, the change in chord length due to leading-edge device deployment, aerofoil section geometry, Reynolds number and Mach number. For leading-edge high-lift devices on wings additional parameters influence the increment in maximum lift coefficient, in particular aspect ratio, taper ratio, sweep and spanwise extent of the device and the presence of a trailing-edge flap. This Item has been developed in conjunction with Item No. 91014 to provide an estimation of the effects of leading-edge devices and trailing-edge flaps in combination.

Leading-edge devices are deployed on unswept wings and wings of moderate sweep ($\Lambda_0 \leq 35^\circ$) primarily so as to increase the maximum lift. Leading-edge devices work by reducing the suction on the upper surface near the leading edge of the wing, to allow an increase in angle of attack before the wing stalls. A more detailed explanation is given in Item No. 94026 and in Reference 27. In general the increased lift cannot be utilised to improve airfield performance because the resulting aircraft attitude would exceed the tail scrape angle. For this reason, for maximum lift, leading-edge devices are invariably used in combination with trailing-edge flaps. For wings of greater sweep, leading-edge devices are often used on their own or in combination with trailing-edge devices to allow greater angles of attack to be attained before outer wing flow breakdown occurs, thus alleviating premature pitch-up or wing-drop and allowing the use of greater lift coefficients. Another use is to increase the available lift before wing buffet occurs.

Experimental data for incremental maximum lift due to leading-edge devices alone are less systematic than for trailing-edge flaps. In the preparation of this Item it has been found that when it is used in combination with Item No. 91014 for trailing-edge flaps there is some improvement in the accuracy of prediction. The method is therefore best suited to the prediction of the increment in maximum lift coefficient due to leading-edge devices on wings with trailing-edge flaps also deployed.

3. REQUIRED DATA ITEMS

Other 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	1	Various geometrical relationships for wings.
83040	2	Spanwise centre of pressure location.
84026	3	Aerofoil maximum lift coefficient for $M \approx 0$.
89034	4	Maximum lift coefficient of plain wings at subsonic speeds.
91014	5	Maximum lift coefficient of wings with trailing-edge flaps at low speeds.
		Increment in aerofoil maximum lift coefficient due to deployment of:
94027	7	leading-edge devices,
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 ITEM

The method of obtaining the maximum lift coefficient increment of the wing due to a leading-edge device, ΔC_{Lmaxl} , involves the evaluation of the increment $\Delta C'_{Lml}$, due to the deployment of the leading-edge device on the aerofoil section at the spanwise location of the peak loading due to incidence. The value of $\Delta C'_{Lml}$, obtained from Item No. 94027, is then factored to allow for the effects of aspect ratio, taper ratio, sweep and part-span effects. It is recommended that similar factors be applied to all leading-edge devices. The method can therefore be used for all those leading-edge devices considered in Item No. 94027, namely plain flaps, drooped leading edges, slats (including sealed slats) and Krüger flaps (including vented Krügers). The method also applies to the increment in maximum lift coefficient due to the deployment of a leading-edge device on a wing which has a trailing-edge device deployed, including any of those considered in Item No. 91014, namely, plain, split, single-, double- and triple-slotted flaps. 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. The method is only suitable for leading-edge devices that extend to the wing tip.

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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 and leading-edge device geometry. None of the data considered for this Item was for a Mach number greater than 0.25. Reference 29 provides background information on the effects of Mach number but insufficient data were available from which to derive a comprehensive prediction method suitable for higher Mach numbers.

5.2 Reynolds Number Effects

Reynolds number effects are allowed for via the prediction of $\Delta C'_{Lml}$ in Item No. 94027. From the data used in the derivation of this Item no additional effects of Reynolds number were found. Reference 29 gives more detailed information on Reynolds number effects for some specific cases.

6. PREDICTION METHOD

Reports considered in the development of the method include Derivations 18, 19, 20, 22 and Reference 26. The main effects of aspect ratio, taper ratio and sweep on the spanwise loading are allowed for by the concepts used in Item No. 89034.

From Item No. 89034 for a plain wing with little or no sweep, where the effects of outboard flow of the boundary layer may be neglected, it is necessary to establish the spanwise variation of C_{LL} and to compare 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 $C_{LL}/\bar{c}$ must be obtained and integrated to obtain the value of the maximum lift coefficient of the wing, C_{Lmax} . This concept is extended to apply to a wing with a full-span leading-edge device and hence for the increment in C_{Lmax} due to the device.

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 for loading due to incidence. The spanwise position, η_p , of this station 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, from Item No. 83040 (Derivation 2).

For wings with part-span leading-edge devices ΔC_{Lmaxl} is dependent on their spanwise location. Figure 3 is based on an analysis of data from Derivation 13, but there were insufficient data for a full determination of part-span effects. In the absence of more relevant information this may be used as a guide to part-span effects for cases where the leading-edge device extends to the wing tip. Maximum lift increments can be very much reduced if the outboard end of the leading-edge device is inboard of the wing tip, especially on swept wings where increments may be reduced to the order of 50% of their full-span value, even for η_{ol} greater than 0.9.

The effects of wing sweep have been derived from analysis of data from Derivations 13 to 15 and 23 to 25 and include 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), Reynolds number effects relating to the Reynolds number normal to the leading-edge, leading-edge device angles taken streamwise and a sweep correlation factor $K_{\Delta l}$.