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Lift curve of wings with high-lift devices deployed at low speeds

**Associated software: ESDUpacs A9931, B9931
See ESDU 99031**

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THE PREPARATION OF THIS DATA ITEM

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LIFT CURVE OF WINGS WITH HIGH-LIFT DEVICES DEPLOYED AT LOW SPEEDS

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LIFT CURVE OF WINGS WITH HIGH-LIFT DEVICES DEPLOYED AT LOW SPEEDS

1. NOTATION AND UNITS

		<i>SI</i>	<i>British</i>
A	wing aspect ratio, $2s/\bar{c}$		
a_1	basic wing lift-curve slope (see Item No. 70011)	rad^{-1}	rad^{-1}
a_1^*	wing lift-curve slope, $dC_L/d\alpha$, at $\alpha = \alpha^*$ with high-lift devices deployed	rad^{-1}	rad^{-1}
C_L	wing lift coefficient, lift/ qc for aerofoil, lift/ qS for wing		
C_L^*	lift coefficient at which lift curve starts to depart from that defined by Equation (4.19) (see Sketch 4.1 and Section 4.4)		
C_{LmB}	aerofoil maximum lift coefficient		
C_{LmaxB}	wing maximum lift coefficient with high-lift devices undeployed (<i>i.e.</i> “basic” wing)		
C_{Lmaxw}	wing maximum lift coefficient with high-lift devices deployed, see Sketch 4.1		
ΔC_{Lmaxl}	increment in wing maximum lift coefficient due to deployment of leading-edge devices		
$\Delta C_{Lmax t}$	increment in wing maximum lift coefficient due to deployment of trailing-edge flaps		
C_{L0B}	aerofoil lift coefficient at zero angle of attack with high-lift devices undeployed (<i>i.e.</i> “basic aerofoil”)		
C_{L0Bw}	wing lift coefficient at zero angle of attack with high-lift devices undeployed (<i>i.e.</i> “basic” wing)		
C_{L0w}	wing lift coefficient at zero angle of attack with high-lift devices deployed, see Sketch 4.1		
ΔC_{L0l}	increment in aerofoil lift coefficient at zero angle of attack due to deployment of leading-edge devices		
ΔC_{L0t}	increment in aerofoil lift coefficient at zero angle of attack due to deployment of trailing-edge flaps		
ΔC_{L0lw}	increment in wing lift coefficient at zero angle of attack due to deployment of leading-edge devices		

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ΔC_{L0tw}	increment in wing lift coefficient at zero angle of attack due to deployment of trailing-edge flaps		
c	chord of basic aerofoil chosen to be representative of wing, <i>i.e.</i> chord at mid-span of high-lift device panel	m	ft
c'	extended aerofoil chord, <i>i.e.</i> chord with high-lift device deployed	m	ft
c''	effective aerofoil chord with high-lift devices deployed (see Equation (4.7))	m	ft
$\bar{c}$	wing geometric mean chord	m	ft
$\bar{\bar{c}}$	wing aerodynamic mean chord	m	ft
c_l	chord of leading-edge device (see Item No. 94027)	m	ft
c_t	chord of trailing-edge flap (plain or split)	m	ft
c_{ti}	chord of trailing-edge flap element i (see for example Sketches 4.1 of Item Nos 94030 and 94031)	m	ft
c'_{ti}	extended chord of trailing-edge flap element i (see for example Sketches 4.1 of Item Nos 94030 and 94031)	m	ft
Δc_l	chord extension due to deployment of leading-edge device (see Sketches 4.1 to 4.3 of Item No. 94027)	m	ft
Δc_t	chord extension due to deployment of trailing-edge flap (see Equations (4.14) to (4.18))	m	ft
i	integer denoting element of trailing-edge flap ($i = 1$ to 3)		
K_δ	factor on c_t used in definition of c'' for trailing-edge flap (see Equations (4.8) to (4.12))		
M	free-stream Mach number		
N	power in Equation (4.5) to allow for Reynolds number effect on lift curve (see Figure 1)		
p	factor and power used in Equation (4.22) to define shape of lift curve between C_L^* and C_{Lmaxw}		
q	free-stream kinetic pressure	N/m ²	lbf/ft ²
$R_{\bar{\bar{c}}}$	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
x_{ts}	chordwise position of shroud trailing-edge (see Sketch 4.1 of Item Nos 94030 and 94031)	m	ft

α	angle of attack	rad, deg	rad, deg
α^*	angle of attack for C_L^* (see Sketch 4.1 and Section 4.4)	rad, deg	rad, deg
α_{CLmaxw}	angle of attack for C_{Lmaxw} (see Sketch 4.1)	rad, deg	rad, deg
α_{0B}	angle of attack for zero lift of basic wing	rad, deg	rad, deg
α_{0w}	angle of attack for zero lift of wing with high-lift devices deployed (see Sketch 4.1)	rad, deg	rad, deg
δ_l	deflection of leading-edge device measured streamwise (see Item No. 94027)	deg	deg
δ_t	deflection of trailing-edge flap measured streamwise (see Item Nos 94028 and 94029)	deg	deg
δ_{ti}	deflection of element i of trailing-edge flap relative to datum of preceding element, measured streamwise (see for example Sketches 4.1 of Item Nos 94030 and 94031)	deg	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		
$\bar{\eta}$	spanwise centre of pressure position for loading due to angle of attack (see Item No. 83040)		
Λ_0	wing leading-edge sweep angle	deg	deg
$\Lambda_{1/4}$	wing quarter-chord sweep angle	deg	deg
λ	wing taper ratio, ratio of tip chord to centre-line chord		
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 (see Figure 2)		
Φ_i, Φ_o	value of Φ corresponding to $\eta = \eta_{it}, \eta_{ot}$		
Ψ	part-span factor; lift coefficient increment due to part-span leading-edge device extending symmetrically from wing centre-line divided by lift coefficient increment due to full-span leading-edge device at same setting and wing angle of attack (see Figure 2)		
Ψ_i, Ψ_o	value of Ψ corresponding to $\eta = \eta_{il}, \eta_{ol}$		

2. INTRODUCTION

This Item provides an empirical method for predicting the non-linear lift curve up to and including maximum lift for wings with high-lift devices deployed at low speeds. In the application of the method a number of other Data Items may be required, and these are listed in Section 3.

The method, detailed in Section 4, has been validated for wings with part-span or full-span split flaps, plain flaps, single-slotted and double-slotted flaps, plain leading-edge flaps, Krüger flaps and slats. Lack of test data prevents evaluation for triple-slotted flaps but the method is expected to apply. The same method has also been found to apply to aerofoils with high-lift devices, confirming its applicability to high aspect ratio wings.

Section 5 addresses applicability and accuracy, Section 6 gives the Derivation and Section 7 presents a detailed worked example illustrating the use of the method. The method has been programmed in Item No. 96003 (Reference 32) for wings and wing body combinations.

In this Item the term “basic” is used to denote a wing or aerofoil without high-lift devices deployed.

3. REQUIRED DATA ITEMS

<i>Data Item No.</i>	<i>Derivation No.</i>	<i>To Determine:</i>
70011	1	Basic wing lift-curve slope.
76003	2	Basic wing planform geometry.
83040	3	Basic wing spanwise centre of pressure location.
84026	4	C_{L0B} and C_{LmB} for aerofoils*.
87031	5	α_{0B} for wings.
89034	6	C_{LmaxB} for wings.
91014	7	$\Delta C_{Lmax t}$ for trailing-edge flaps on wings.
92031	8	$\Delta C_{Lmax l}$ for leading-edge devices with and without trailing-edge flaps deployed on wings.
93019	9	ΔC_{L0tw} for single-slotted flaps on wings.
94027	10	ΔC_{L0l} and ΔC_{Lml} for leading-edge devices on aerofoils.
94028	11	ΔC_{L0t} and ΔC_{Lmt} for plain trailing-edge flaps on aerofoils.
94029	12	ΔC_{L0t} and ΔC_{Lmt} for split trailing-edge flaps on aerofoils.
94030	13	ΔC_{L0t} and ΔC_{Lmt} for single-slotted trailing-edge flaps on aerofoils.
94031	14	ΔC_{L0t} and ΔC_{Lmt} for double-slotted or triple-slotted trailing-edge flaps on aerofoils.
95021	15	ΔC_{L0tw} for double-slotted or triple-slotted flaps on wings.
96032	16	ΔC_{L0lw} for leading-edge devices on wings.
97009	17	ΔC_{L0tw} for split flaps on wings.
97011	18	ΔC_{L0tw} for plain flaps on wings.

* As stated in Item No. 84026, the methods of Item Nos 72024, 97020 and 98011 (References 29, 30 and 31), taken together, allow a more accurate evaluation of C_{L0B} . However, the difference in prediction is small in magnitude and of little consequence in the evaluation of the wing lift-curve.

4. METHOD

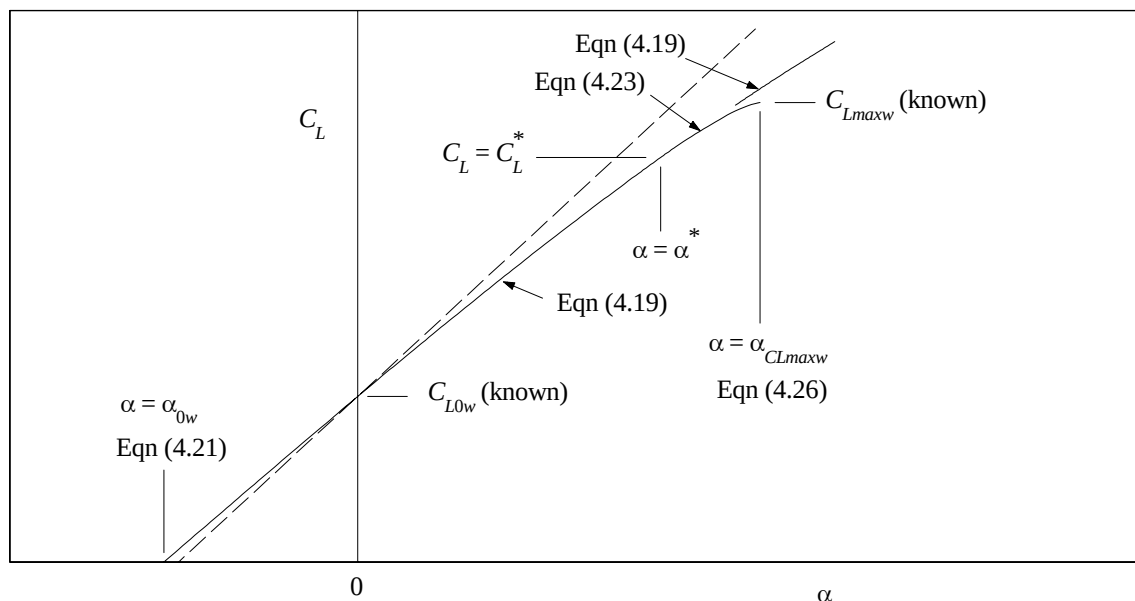
4.1 Lift Curve with High-lift Devices Deployed

The low-speed lift curve of a basic wing of moderate to high aspect ratio or of an aerofoil section is often considered to be linear up to just before the stall. Observation of available test data broadly confirms this, but for wings and aerofoil sections with high-lift devices deployed a very clear progressive reduction in lift slope with increasing angle of attack is observed.

For a two-dimensional aerofoil section with high-lift devices deployed the main parameters that can influence the development of the lift curve, and especially its behaviour as the maximum lift is approached, are the device element angles, the aerofoil shape, the change of aerofoil chord length due to device deployment, the device type and effect of lap and gap size, the Reynolds number and Mach number. For devices on wings the additional parameters that influence the lift curve are the wing planform geometry (aspect ratio, taper ratio and sweep), and the spanwise extent of the device. Since no clear trends could be detected from the available data for many of these parameters the method presented here only requires the use of the most important ones. The method is presented for wings but has also been validated in the limiting case of two-dimensional flow, and may therefore be used with confidence for wings of high aspect ratio.

In the development of the prediction method attempts were made to consider the likely behaviour of each component and the effect of device deflection and of angle of attack for each component. This resulted in a complicated breakdown with many terms and associated assumptions. Limited comparisons using this approach gave some improvement on the linear method but were not as good as those using the method presented here.

The lift curve is evaluated in two separate parts, as shown in Sketch 4.1. The first part provides an estimate for the lift curve through zero angle of attack, and up to the lift coefficient at which the effects of flow breakdown start to become significant. The second part extends the estimation of the lift curve up to maximum lift, and includes the prediction of the angle of attack for maximum lift.



Sketch 4.1

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4.2 Lift Curve through Zero Angle of Attack

For a linear assumption the lift coefficient C_L at angle of attack α for a basic wing is

$$C_L = C_{L0Bw} + a_1 \alpha \quad (4.1)$$

with α in radians. Equation (4.1) may also be expressed as

$$C_L = a_1(\alpha - \alpha_{0B}) \quad (4.2)$$

where a_1 is the basic wing lift-curve slope from Item No. 70011 (Derivation 1) and α_{0B} is its zero-lift angle from Item No. 87031 (Derivation 5).

For a wing with a full-span high-lift device deployed the linear assumption gives

$$C_L = C_{L0w} + a_1(c''/c)\alpha, \quad (4.3)$$

where c'' is an empirically deduced effective chord.

To define α_{0w} , Equation (4.3) is expressed as

$$C_L = a_1(c''/c)(\alpha - \alpha_{0w}). \quad (4.4)$$

From observation of the experimental data as angle of attack is increased the progressive curvature is well described by use of a cosine term starting from the angle for zero lift, so that Equation (4.4) is replaced by

$$C_L = a_1(c''/c)(\alpha - \alpha_{0w})\cos^N(\alpha - \alpha_{0w}) \quad (4.5)$$

where α_{0w} now has to be determined, to be consistent with the equation for C_{L0w} given by

$$C_{L0w} = -a_1(c''/c)\alpha_{0w}\cos^N(-\alpha_{0w}). \quad (4.6)$$

The power N accounts for the observed effect of Reynolds number on the non-linear behaviour and has been derived from the available data. It may be obtained from Figure 1.

From correlation of the data it is apparent that the effective chord c'' with high-lift devices deployed is different from the extended chord c' used in other Data Items on flap effects because of a reduced importance of flap extension for certain types of trailing-edge flap for which a planform-projected chord is more appropriate. Thus, whereas $c' = c + \Delta c_l + \Delta c_t$,

$$c'' = c' - K_\delta c_t = c + \Delta c_l + \Delta c_t - K_\delta c_t \quad (4.7)$$

where Δc_l is defined in Item No. 94027 (Derivation 10) for leading-edge devices and Δc_t is defined in Item Nos 94028 to 94031 (Derivations 11 to 14) for plain, split, single-slotted, double-slotted and triple-slotted flaps.