



ESDU 94026

Issued December 1994

With Amendment A

July 1995

Supersedes in part

ESDU 85033

Introduction to the estimation of the lift coefficients at zero angle of attack and at maximum lift for aerofoils with high-lift devices at low speeds

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THE PREPARATION OF THIS DATA ITEM

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INTRODUCTION TO THE ESTIMATION OF THE LIFT COEFFICIENTS AT ZERO ANGLE OF ATTACK AND AT MAXIMUM LIFT FOR AEROFOILS WITH HIGH-LIFT DEVICES AT LOW SPEEDS

CONTENTS

	Page
1. NOTATION AND UNITS	1
2. INTRODUCTION	2
3. LIFT DEVELOPMENT UP TO THE STALL	2
3.1 Stall of Basic Aerofoil	3
3.1.1 Data Item	4
3.2 Effects of Deploying High-Lift Devices	4
3.2.1 Data Items	7
4. PROCEDURE FOR ESTIMATING C_{L0} AND C_{Lm}	9
5. APPLICABILITY AND ACCURACY	11
5.1 Applicability	11
5.2 Accuracy	11
6. REFERENCES	13
7. EXAMPLES	14
7.1 Example 1	14
7.2 Example 2	15

INTRODUCTION TO THE ESTIMATION OF THE LIFT COEFFICIENTS AT ZERO ANGLE OF ATTACK AND AT MAXIMUM LIFT FOR AEROFOILS WITH HIGH-LIFT DEVICES AT LOW SPEEDS

1. NOTATION AND UNITS

The notation given here is restricted to that required for this Item, with the exception of Section 7. For some of the notation in that Section and for the complete notation required in the use of the individual Items referred to herein, reference should be made to the appropriate Items (*i.e.* References 6 and 8 to 12).

SI British

C_L	lift coefficient, based on c		
C_{Lm}	maximum lift coefficient of aerofoil with high-lift devices deployed, based on c		
C_{LmB}	maximum lift coefficient of basic aerofoil, based on c		
C_{L0}	lift coefficient at zero angle of attack for aerofoil with high-lift devices deployed, based on c		
C_{L0B}	lift coefficient at zero angle of attack for basic aerofoil, based on c		
ΔC_{Lm}	increment in maximum lift coefficient due to deployment of high-lift devices, based on c		
ΔC_{Lml}	increment in maximum lift coefficient due to deployment of leading-edge high-lift device, based on c		
ΔC_{Lmt}	increment in maximum lift coefficient due to deployment of trailing-edge flap, based on c		
ΔC_{L0}	increment in lift coefficient at zero angle of attack due to deployment of high-lift devices, based on c		
ΔC_{L0l}	increment in lift coefficient at zero angle of attack due to deployment of leading-edge high-lift device, based on c		
ΔC_{L0t}	increment in lift coefficient at zero angle of attack due to deployment of trailing-edge flap, based on c		
c	basic aerofoil chord (<i>i.e.</i> chord with high-lift devices undeployed)	m	ft
c'	extended aerofoil chord (<i>i.e.</i> chord with high-lift devices deployed)	m	ft
t	maximum thickness of aerofoil	m	ft

Issued December 1994
With Amendment A, July 1995 – 19 pages

α angle of attack of basic aerofoil chord line relative to free stream rad rad

Subscripts

$()_{expt}$ denotes experimental value

$()_{pred}$ denotes predicted value

2. INTRODUCTION

This Item provides an introduction to aerofoil lift and the effects of high-lift device deployment at low speeds. It centres in particular on the effects on the lift coefficient at zero angle of attack, C_{L0} , and on the maximum lift coefficient, C_{Lm} . The Item acts as an introduction to, and a link between, the Item (Reference 6) for the basic aerofoil* and the Items (References 8 to 12) in the complete series dealing with the incremental effects, ΔC_{L0} and ΔC_{Lm} , of high-lift device deployment. The Item also describes how the incremental effects on C_{L0B} and C_{LmB} for the basic (*i.e.* plain) aerofoil are used to give the total values C_{L0} and C_{Lm} .

Section 3 describes the lift development on basic aerofoils up to the stall and briefly discusses the various stall categories. It goes on to consider the effects of high-lift device deployment on aerofoil lift characteristics, with particular reference to the zero angle of attack and maximum lift cases.

Section 4 describes the procedure whereby the contributions obtained from References 6 and 8 to 12 are used to estimate the total values C_{L0} and C_{Lm} . A guide to the location of the information for the basic aerofoil and each of the high-lift devices is presented in tabular form.

Section 5 provides a discussion of the applicability and an assessment of the overall accuracy of the methods given for C_{L0} and C_{Lm} . Section 6 gives the References and Section 7 gives two examples. The first example provides a typical illustration of the calculation procedure. Due to a lack of experimental data none of the Data Items specifically treats the practical case of a tabbed-Fowler flap. Consequently, a second example has been included to show how the methods of Reference 11 for a single-slotted flap and Reference 9 for a plain flap may be combined, using the principles established for double-element flaps in Reference 12, to treat the case of a tabbed-Fowler flap.

3. LIFT DEVELOPMENT UP TO THE STALL

At low speeds the two-dimensional flow over an aerofoil, with high-lift devices undeployed, normally remains attached at small angles of attack and the increase of lift coefficient with angle of attack is effectively linear. At a certain angle of attack, dependent on the section geometry and the free-stream conditions, flow separation starts. Further increase in angle of attack causes progressive growth of the separated region and reduction in the slope of the lift curve until a maximum lift coefficient, C_{LmB} , is reached, and the aerofoil stalls. At still higher angles of attack, the lift is reduced, perhaps catastrophically. The main types of stall are discussed briefly in Section 3.1.

* The term "basic aerofoil" refers to an aerofoil with high-lift devices undeployed; it is synonymous with the term "plain aerofoil" that is sometimes used.

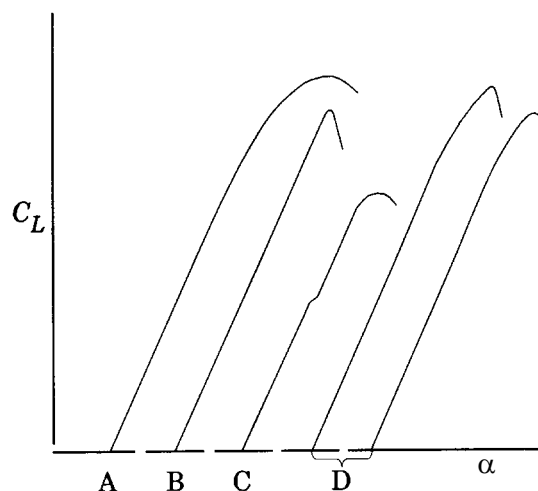
The deployment of high-lift devices affects the lift curve of an aerofoil through changes in the lift coefficient at zero angle of attack, in the point and nature of departure from the near-linear characteristic at low angles of attack and in the maximum lift coefficient. Leading-edge and trailing-edge devices affect lift on an aerofoil in two-dimensional flow in different ways.

The major effect of a leading-edge device is to delay the onset of leading-edge separation, thus increasing the lift attainable before the stall. The major effect of a trailing-edge device on the other hand is to increase the camber of the aerofoil with a consequent increase in lift at a given angle of attack. The use of properly designed slots between the elements of a trailing-edge device further enhances the maximum lift attainable. Typical lift curves associated with various high-lift devices are considered in Section 3.2.

Although the free-stream flow past an aerofoil with high-lift devices deployed may be low-speed, the local flow around a leading-edge slat, for example, can attain supersonic velocities. Compressibility effects can therefore be important.

3.1 Stall of Basic Aerofoil

There are various types of stall related to where flow separations occur on the aerofoil. Four distinct types of stall are identified, having typical lift versus angle of attack curves of the type shown in Sketch 3.1, see Item No. 66034 (Reference 1).



Sketch 3.1 Aerofoil stall classification

Type A: Trailing-edge stall

Trailing-edge stall is due to separation moving forward from the trailing edge as angle of attack increases. This is typical of thick aerofoils (thickness-chord ratio $t/c = 0.15$, say) having a well-rounded suction peak and moderate adverse pressure gradient. A rounded maximum to the lift curve is probable.

Type B: Leading-edge stall

On moderately thin sections, the laminar boundary layer may separate at a particular angle of attack with re-attachment of the shear layer enclosing a “short” bubble followed by a turbulent boundary layer. At a critical angle of attack, less than that at which the flow would break down at the trailing edge, the bubble bursts, giving a sudden fall in lift coefficient. This is typical of sections having t/c between about 0.06 and 0.09.

Type C: Thin aerofoil stall

On very thin sections after initial laminar separation with re-attachment occurring further downstream, a “long” bubble is formed which extends with increasing angle of attack. The lift curve has a discontinuous slope when the bubble first forms, which is followed by a rounded maximum when the bubble has reached the trailing-edge, with subsequent detachment and loss of lift. This is typical of sections having t/c below 0.05, say.

Type D: Combined stall

Here, both laminar separation at the leading edge and turbulent separation at the trailing edge occur before C_{LmB} is reached. The lift curves vary in character and two possibilities, characterised by a sharp or rounded maximum, are depicted in Sketch 3.1. This type of stall is the least common and a typical value of t/c is 0.12.

Fuller details of the nature of these types of stall and the effects on aerofoil characteristics are given in References 1 to 3.

3.1.1 Data Item

It has proved possible to define empirical relationships for estimating the maximum lift coefficient, C_{LmB} , in terms of specified geometric characteristics of the aerofoil, Reynolds number and Mach number for smooth or rough surfaces, see Item No. 84026 (Reference 6). A method for estimating the lift coefficient at zero angle of attack, C_{L0B} , is also included.

3.2 Effects of Deploying High-Lift Devices

The rise of C_L between C_{L0} and C_{Lm} is dependent on the stall characteristics. The effects of deploying plain leading-edge and trailing-edge flaps may, in the first instance, be interpreted partly as those of modified camber. These will produce small decrements in the lift coefficient at zero angle of attack for leading-edge flaps, but major increments for trailing-edge flaps. The increment in lift coefficient between zero angle of attack and maximum lift can also change significantly from that for the basic aerofoil. For example, many high-lift systems comprise two or more elements with chord extensions and slots between the elements in the deflected settings. Although the resultant changes in lift coefficient at zero angle of attack for such systems are significant, the effects on the lift coefficient increment between zero angle of attack and maximum lift due to the complex flow around the multiple elements can predominate. Furthermore, boundary layer separation may occur on any element, thus adding to the complexity. The number of independent parameters is so large in such cases that the complete correlation of test data is not practical. Fortunately, it is possible to simplify the problem by making independent estimates of the effects of each element in turn and summing the results, as described in Reference 4.

Sketch 3.2 shows the lift curves of a particular aerofoil without and with typical high-lift devices, such as those illustrated in Sketch 3.3. The lift coefficient, C_L , is referred to the chord of the basic aerofoil and the increased slopes for the multi-element devices are primarily due to chord extensions. The angle of attack, α , is defined as that of the undeflected part of the aerofoil. Brief outlines of the dominant physical processes affecting the lift curves are given below, but for a more extensive discussion see References 5 and 7.

Leading-edge devices (Sketch 3.3a) reduce the lift coefficient at zero angle of attack due to the negative camber near the nose; the consequent reduction in peak suction allows a significant increase in the angle of attack at which leading-edge separation occurs, thus increasing the maximum lift coefficient. Such devices have a comparatively small effect on trailing-edge flow conditions.

The slot of a slotted leading-edge flap (slat or vented Krüger flap, Sketch 3.3a(iii)) provides a means of

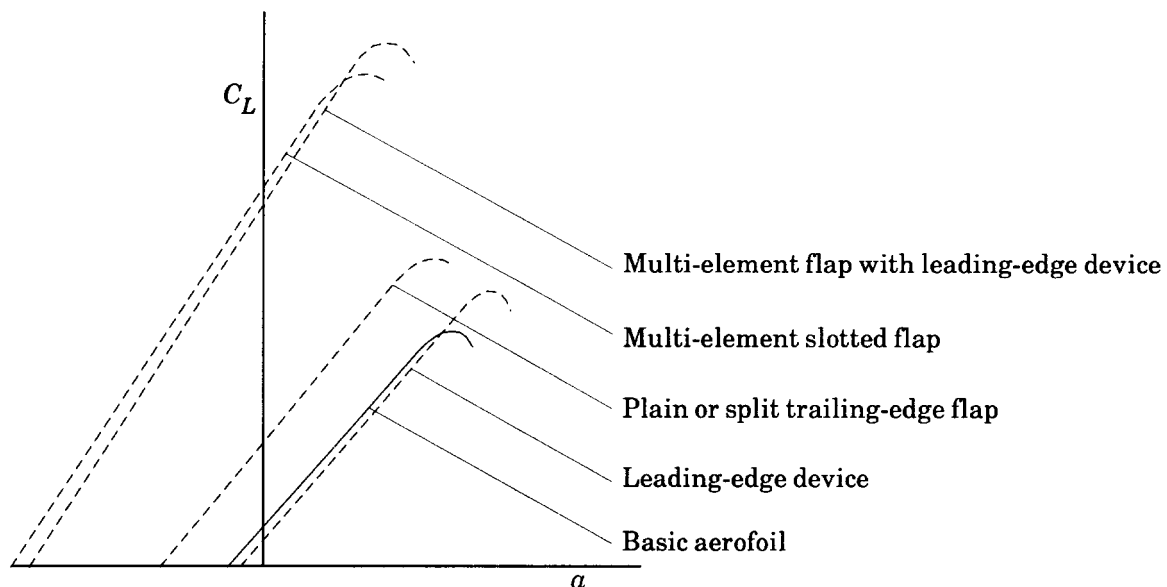
reducing the pressure gradient on the forward part of the main aerofoil section, thus allowing a higher angle of attack to be achieved before separation occurs in this region. If there is a chord extension there is a further rise in maximum lift coefficient.

Plain trailing-edge flaps (Sketch 3.3b) achieve higher maximum lift coefficients largely due to the camber effect which increases the lift coefficient at zero angle of attack. For large flap deflections the upper-surface suction has a maximum at the hinge line as well as at the leading edge. So the adverse pressure gradient over much of the aerofoil is reduced while over the flap it is greatly increased. As a result flow separation occurs over the flap at moderate deflections, but does not pass upstream of the hinge until much higher deflections are reached. Lift due to flap deflection continues to increase at a reduced rate, reaching a maximum just before separation moves ahead of the flap or the flow breaks down at the leading edge.

Deflection of a split flap (Sketch 3.3c) creates a region of low pressure behind the flap which depresses the aerofoil trailing-edge pressure. As a result a less adverse pressure gradient is created over the rear upper surface of the aerofoil, thus delaying the onset of trailing-edge separation and increasing the maximum lift coefficient. Therefore, separation may occur first at the leading edge of the aerofoil, in which case the lift would fall more sharply from the maximum.

Slotted trailing-edge flaps (Sketch 3.3d) develop considerably more maximum lift than plain flaps because the flow through the slot gives rise to a number of beneficial effects (see References 5 and 7). Fowler flaps (Sketch 3.3e) behave in a similar fashion to simple slotted flaps but develop more lift due to their greater chord extensions. Multi-element systems can employ a combination of the two types, although a wholly Fowler system is more efficient (Sketch 3.3e (iv), for example).

With a combination of leading-edge and trailing-edge devices (Sketch 3.3f), the highest practical values of C_{Lm} for mechanical systems are achievable as indicated in Sketch 3.2. The leading-edge device has essentially similar incremental effects whether or not the trailing-edge device is deflected.



Sketch 3.2 Typical lift curves