



Increment in wing profile drag coefficient due to the deployment of a single-slotted flap

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INCREMENT IN WING PROFILE DRAG COEFFICIENT DUE TO THE DEPLOYMENT OF A SINGLE-SLOTTED FLAP

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INCREMENT IN WING PROFILE DRAG COEFFICIENT DUE TO THE DEPLOYMENT OF A SINGLE-SLOTTED FLAP

1. NOTATION AND UNITS

		SI	British
A	wing aspect ratio, b^2/S_w		
b	wing span	m	ft
C_D	wing drag coefficient, based on S_w		
C_{DPminB}	minimum profile drag coefficient for basic wing		
ΔC_{DPmin}	increment in minimum value of wing profile drag coefficient due to flap deployment		
C_{DV}	inviscid trailing-vortex drag coefficient		
ΔC_{DV}	component of trailing-vortex drag coefficient due to part-span flap effects		
C_{DviscB}	viscous drag coefficient for basic wing, see Equation (3.9)		
ΔC_{Dvisc}	increment in wing viscous drag coefficient due to flap deployment		
C_L	wing lift coefficient, based on S_w		
C_{Lmax}	maximum value of C_L		
C_{LminB}	value of C_L for basic wing for minimum C_{DviscB} , see Equation (3.9)		
ΔC_{L0t}	increment in wing lift coefficient at zero incidence due to flap deployment		
c	chord of basic aerofoil or section, see Sketch 1.1(i)	m	ft
c'	extended chord of aerofoil or section with flap deployed, see Sketch 1.1(ii) and Equation (3.5)	m	ft
c_{dp}	aerofoil profile drag coefficient, based on c		
c_{dpminB}	minimum value of c_{dp} for basic aerofoil		
Δc_{dpmin}	increment in minimum value of c_{dp} due to flap deployment		
$\Delta c_{dpmin\delta}$	increment in minimum value of c_{dp} due to flap deflection angle		
$c_{dp\alpha 0B}$	value of c_{dp} for basic aerofoil at zero incidence		

$\Delta c_{dp\alpha 0}$	increment in profile drag coefficient due to flap deployment for aerofoil at zero incidence, based on c		
$\Delta c_{dp\alpha 0\delta}$	increment in profile drag coefficient due to flap deflection angle for aerofoil at zero incidence, based on c		
$\Delta c'_{dp\alpha 0\delta}$	increment in profile drag coefficient due to flap deflection angle for aerofoil at zero incidence, based on c' , from Figures 1 and 2		
c_l	aerofoil lift coefficient, based on c		
c_{lminB}	value of c_l for basic aerofoil at $c_{dp} = c_{dpminB}$		
c_{l0B}	lift coefficient of basic aerofoil at zero incidence, based on c		
Δc_{l0t}	increment in c_l due to flap deployment on aerofoil at zero incidence, based on c		
$\Delta c'_{l0t}$	increment in c_l due to flap deployment on aerofoil at zero incidence, based on c'		
c_r	wing root (centre-line) chord	m	ft
c_t	chord of single-slotted flap, see Sketch 1.1(ii)	m	ft
Δc_t	distance from shroud trailing edge to flap nose measured along flap datum, positive as shown in Sketch 1.1(ii); see Equations (3.6) and (3.7)	m	ft
c'_t	extended chord of flap, see Sketch 1.1(ii) and Equation (3.6)	m	ft
$\bar{c}$	mean chord of basic wing, S_w / b	m	ft
K	factor, from ESDU Aero F.02.01.08 (Reference 14), applied to ΔC_{L0t} in calculation of ΔC_{DV} , see Example 2 in Section 7.2		
K_{visc}	wing lift-dependent drag factor, see Equation (3.9)		
k_{visc}	aerofoil lift-dependent drag factor, see Equation (3.1)		
k_w	empirical factor, see Section 3.2		
M	freestream Mach number		
$R_{\bar{c}}$	Reynolds number based on $\bar{c}$		
S_w	wing planform area	m ²	ft ²
s	wing semi-span	m	ft
Δs	inboard flap extension, from ESDU 97003 (Reference 27), for modelling fuselage interference, see Example 2 in Section 7.2	m	ft
V	freestream velocity	m/s	ft/s
x_{cmax}	chordwise position of maximum camber of basic aerofoil or section, positive aft of leading edge, see Sketch 1.1(i)	m	ft

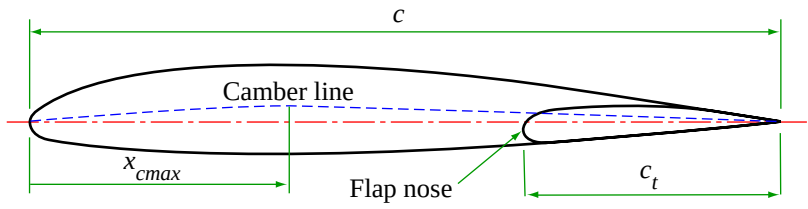
Δx_t	chordwise gap between shroud trailing edge and flap nose, positive as shown in Sketch 1.1(ii); Δx_t is negative if flap nose is forward of shroud trailing edge	m	ft
x_{tr}	chordwise position of boundary-layer transition, measured positive aft from leading edge, mean of upper-surface and lower-surface values	m	ft
x_{ts}	chordwise position of shroud trailing edge, measured positive aft from leading edge, see Sketch 1.1(ii)	m	ft
Δz_t	gap between shroud trailing edge and flap nose measured normal to aerofoil or section datum, positive as shown in Sketch 1.1(ii); Δz_t will be positive for all practical configurations	m	ft
α	angle of incidence, of chord line for basic aerofoil, of root chord (as datum) for wing	deg	deg
δ	$(1 + \delta)$ is lift-dependent drag factor due to trailing-vortex wake for plane, straight-tapered wing, see ESDU 74035 (Reference 16)		
δ_t	flap deflection angle in streamwise plane, see Sketch 1.1(ii)	deg	deg
η	spanwise distance from wing centre-line as fraction of semi-span		
η_B	maximum width of body as fraction of semi-span		
η_i	value of η at inboard limit of flap, see Sketch 1.2		
η_o	value of η at outboard limit of flap, see Sketch 1.2		
$\Lambda_{1/4}$	wing quarter-chord sweep angle, see Sketch 1.2	deg	deg
$\Lambda_{1/4\eta}$	local wing quarter-chord sweep angle	deg	deg
λ	wing taper ratio (tip chord/root chord)		
μ	part-span flap factor in Equation (3.15), from ESDU Aero F.02.01.07 (Reference 13) for straight-tapered wings, as difference of values μ_1 and μ_2 for two inboard flaps extending from $\eta = 0$ to η_o and from $\eta = 0$ to η_i , respectively, see Example 2 in Section 7.2		

Subscripts

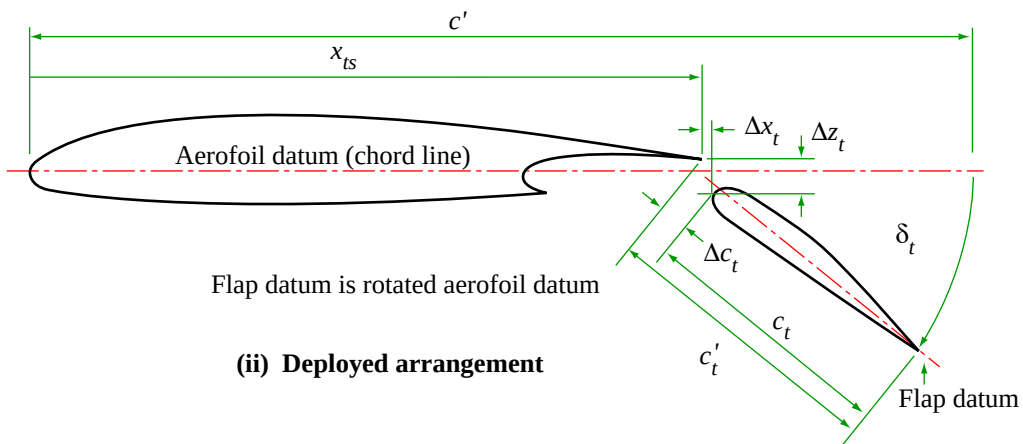
$_{expt}$ as in () $_{expt}$ denotes experimental value

$_{pred}$ as in () $_{pred}$ denotes predicted value

Note 'basic' is used to denote the aerofoil or wing with flap undeployed.

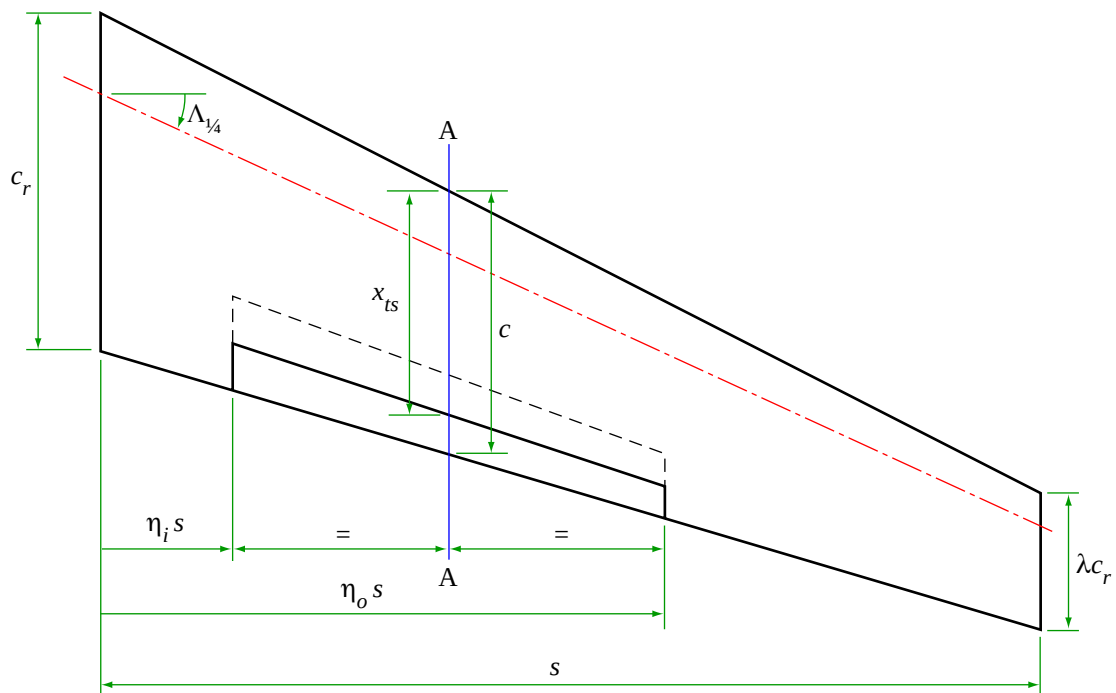


(i) General arrangement



(ii) Deployed arrangement

Sketch 1.1 Aerofoil or section on AA below



Sketch 1.2 Wing notation (flaps undeployed)

2. INTRODUCTION

To construct the low speed drag polar of a wing with a single-slotted trailing-edge flap deployed, it is necessary to add to the profile drag coefficient of the basic wing the increment in profile drag coefficient caused by flap deployment and then add the trailing-vortex drag coefficient for the configuration with flap deployed. This Data Item describes how the profile drag coefficient increment may be estimated for wings of moderate to high aspect ratio ($A \geq 6$) and modest sweep ($\Lambda_{1/4} \leq 30^\circ$). It compares the overall drag polar with experimental data to assess the accuracy of the estimate. The method is described in Section 3. Accuracy and applicability are addressed in Section 4. The Derivation and References are given in Section 6. Two worked examples are given in Section 7.

3. WING PROFILE DRAG COEFFICIENT INCREMENT

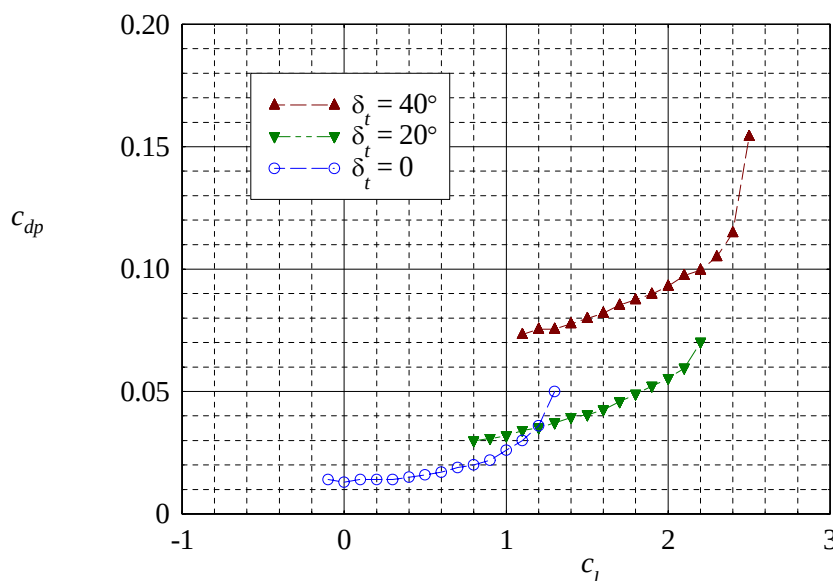
To obtain the increment in profile drag coefficient for a wing due to the deployment of a single-slotted trailing-edge flap, use is made of the work of Torenbeek (Derivation 1) to model the lift-dependent contribution. This is added to a lift-independent increment that is derived by combining a contribution due to flap deflection angle with a contribution that makes an explicit allowance for rearward flap translation.

3.1 Aerofoil Sections

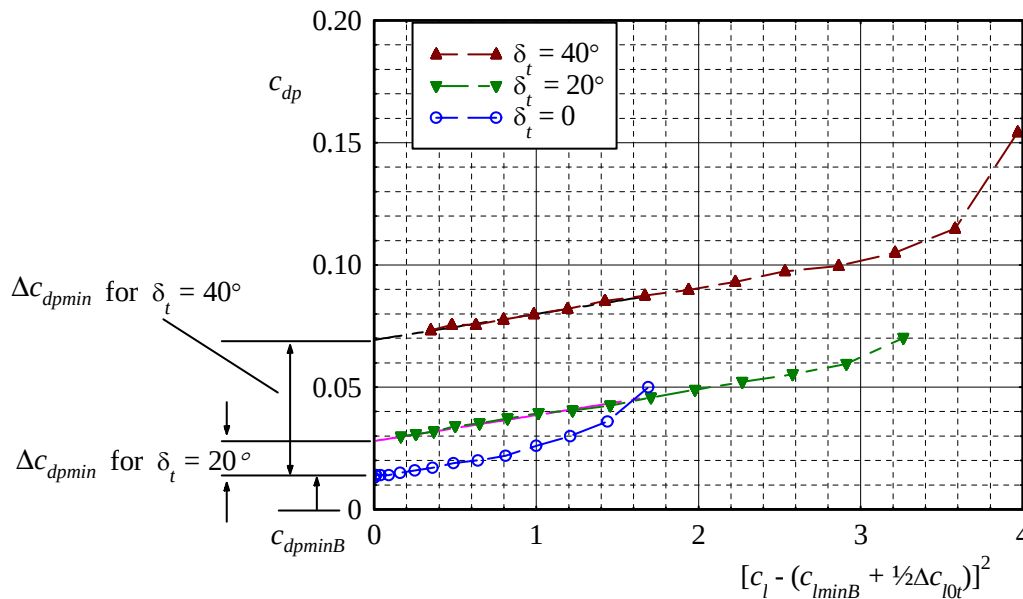
In Derivation 1 the profile drag coefficient of the basic aerofoil, away from proximity to maximum c_l , is expressed as the sum of a minimum value and a quadratic lift-dependent term, so that

$$c_d = c_{d_{pminB}} + k_{visc}(c_l - c_{lminB})^2, \quad (3.1)$$

where $c_{d_{pminB}}$ is the minimum profile drag coefficient of the basic aerofoil, which occurs when the lift coefficient is c_{lminB} . By definition, k_{visc} is the aerofoil lift-dependent drag factor. With flaps deflected to give a zero-incidence lift coefficient increment Δc_{l0t} , it was noted in Derivation 1 that experimental drag coefficients plotted against $[c_l - (c_{lminB} + \frac{1}{2}\Delta c_{l0t})]^2$ as a series of approximately parallel straight lines for a fixed flap deflection angle, until c_l approached maximum c_l . For a typical case, see Sketches 3.1(i) and (ii), which show the original drag polars and their replotted form, respectively.



Sketch 3.1 (i) Illustration of variation of c_{dp} with c_l for basic aerofoil and two flap-deployed cases



Sketch 3.1(ii) Data of Sketch 3.1(i) replotted to investigate quadratic lift dependence

The interpretation of Sketch 3.1(ii) is that deployment of the flap causes a simple translation of the well-formed parabolic part of the basic aerofoil drag polar through an increase in the minimum value of c_{dp} and a shift to higher c_l in the location of the minimum. This allows the drag polar of the aerofoil with flap deployed to be written as

$$c_d = c_{dpminB} + \Delta c_{dpmin} + k_{visc} [c_l - (c_{lminB} + \frac{1}{2} \Delta c_{l0t})]^2 \quad (3.2)$$

The intercepts on the ordinate axis of Sketch 3.1(ii) define the increment in minimum c_{dp} as Δc_{dpmin} , dependent on δ_t . The linearity of the lines shows that $\frac{1}{2} \Delta c_{l0t}$ is a good empirical approximation of the shift in c_l of the polar minimum*. The fact that the lines are nearly parallel establishes that the value of k_{visc} , their slope, is independent of δ_t and the same as the value for the basic aerofoil in Equation (3.1).

For the purposes of analysis and prediction, the increment in the minimum value is divided into a component primarily dependent on flap deflection, but with a secondary dependence on chord extension, and an explicit flap translation term related solely to the chord extension,

so that

$$\Delta c_{dpmin} = \underbrace{\Delta c_{dpmin\delta}}_{\text{due to deflection angle}} + \underbrace{c_{dpminB}[(c'/c) - 1]}_{\text{due to translation only}} \quad (3.3)$$

* See also the comments in Appendix A

Rearward translation of the flap affects $\Delta c_{dpmin\delta}$ and for the purposes of analysis and prediction the extended aerofoil and flap chords c' and c'_t , shown in Sketch 1.1(ii), are introduced and $\Delta c'_{dpmin\delta}$ is correlated as a function of c'_t/c' and δ_t , where

$$\Delta c_{dpmin\delta} = (c' / c) \Delta c'_{dpmin\delta} . \quad (3.4)$$

Note that the generalisation in Equation (3.4) does not remove the need for the inclusion of the explicit translation term in Equation (3.3).

The extended chords are defined, see Sketch 1.1(ii), as

$$c' = x_{ts} + c'_t \quad (3.5)$$

and
$$c'_t = c_t + \Delta c_t . \quad (3.6)$$

The increment Δc_t can be positive or negative. It is the perpendicular distance between two lines drawn normal to the flap datum, one to pass through the flap nose and the other to pass through the shroud trailing edge. When the line through the flap nose is aft of that through the shroud trailing edge, as in Sketch 1.1(ii), Δc_t is positive. If the line through the flap nose is ahead of that through the shroud trailing edge Δc_t is negative. Section 4 of ESDU 87005 also gives the relationship

$$\Delta c_t = \Delta z_t \sin \delta_t + \Delta x_t \cos \delta_t , \quad (3.7)$$

and the values of Δz_t , Δx_t and δ_t will determine Δc_t .

Figures 1 and 2 of this Data Item provide values for $\Delta c'_{dpmin\delta}$ in terms of c'_t/c' and δ_t , for use in Equation (3.4) and thence in Equation (3.3). Figure 1 applies generally when the position of maximum camber of the basic aerofoil is in the range $0.15c \leq x_{cmax} \leq 0.65c$. Figure 2 applies if the position of maximum camber is well aft, $0.70c \leq x_{cmax} \leq 0.80c$, but only if the flap deflection angle is low, $\delta_t \leq 30^\circ$ say. For higher flap deflection angles, $\delta_t \geq 40^\circ$ say, Figure 1 is to be used for aerofoils with aft camber; some tolerance should be allowed in the choice between Figures 1 and 2 for $30^\circ \leq \delta_t \leq 40^\circ$. The origin of Figures 1 and 2, which are based on the data and work underlying the earlier correlations of the profile drag coefficient increment *at zero incidence*, $\Delta c_{dp\alpha 0}$, in ESDU 87005, is described later in Section 4*. See Section 5.2 for a discussion of the range of applicability of Figures 1 and 2; this is particularly important for Figure 2 which is a correlation based on a small number of data.

The explicit translation term in Equation (3.3) is an approximate allowance for the additional profile drag that arises from the increase in surface area when the flap is deployed. The expression in Equation (3.3) is the simple one commonly used, merely the product of the basic aerofoil profile drag coefficient and the increase in chord length as a fraction of c . The method in ESDU 00027 (Reference 29) may be used to calculate c_{dpminB} (given as C_{Dmin} in the notation of ESDU 00027).

3.2 Wings

For a wing in shock-free flow, the method in ESDU 07002 (Reference 32) considers the total drag coefficient of a basic wing as the sum of a viscous drag coefficient C_{DviscB} and an inviscid trailing-vortex drag coefficient C_{DV} , so that

$$C_D = C_{DviscB} + C_{DV} . \quad (3.8)$$

* The method does not require the use of any material in Section 4, which is provided only for reference and completeness.

In ESDU 07002, the viscous drag coefficient is written

$$C_{DviscB} = C_{DPminB} + K_{visc}(C_L - C_{LminB})^2, \quad (3.9)$$

where C_{DPminB} is the minimum profile drag coefficient of the basic wing, occurring at the lift coefficient C_{LminB} , and K_{visc} is the lift-dependent drag factor. Prediction methods for those three parameters are given in ESDU 07002.

With trailing-edge flaps deployed, the wing drag coefficient can be written

$$C_D = C_{DPminB} + \Delta C_{Dvisc} + C_{DV}, \quad (3.10)$$

where ΔC_{Dvisc} is the increase in viscous drag coefficient above the minimum value for the basic wing. Section 5.2 in ESDU 97002 (Reference 26) shows how the inviscid flap-deployed trailing-vortex drag factor C_{DV} may be estimated (see also the worked examples in Section 7).

The form of Equation (3.2) suggests that the drag coefficient of an unswept wing with full-span trailing-edge flaps may be expressed as

$$C_D = C_{DPminB} + \Delta C_{DPmin} + K_{visc}[C_L - (C_{LminB} + \frac{1}{2}\Delta C_{L0t})]^2 + C_{DV}, \quad (3.11)$$

where the lift coefficient increment due to flap deployment, ΔC_{L0t} , can be obtained from the method in ESDU 93019 (Reference 23).

For wings of high aspect ratio and low sweep it is possible to take

$$\Delta C_{DPmin} = k_w \Delta c_{dpmin}, \quad (3.12)$$

with Δc_{dpmin} evaluated using Equation (3.3) for the streamwise wing section at the mid-span of the flapped part of the wing (section AA in Sketch 1.2). The factor k_w is introduced to be determined empirically from a study of wing drag polars.

Experimental data from Derivations 3 to 9 and 11 for straight-tapered, unswept wings with $A \geq 6$ and full-span flaps, were compared with the predictions of Equation (3.11)*. The comparisons suggest that the best overall accuracy of prediction is obtained by setting

$$k_w = 0.9. \quad (3.13)$$

For a swept wing with full-span flaps, the factor $\cos \Lambda_{1/4}$ is introduced so that

$$k_w = 0.9 \cos \Lambda_{1/4}. \quad (3.14)$$

The $\cos \Lambda_{1/4}$ factor is similarly employed, with empirical support, in ESDU 74010, 87024 and 06014 (References 15, 21 and 30), when wing flap profile drag increments are derived from streamwise section data.

* With $C_{DV} = (1 + \delta)C_L^2 / \pi A$, and $1 + \delta$ from ESDU 74035 (Reference 16).

For wings with part-span flaps the correction factor μ is brought in, so that in the most general case

$$k_w = 0.9\mu \cos \Lambda_{1/4} . \quad (3.15)$$

The factor μ is the planform area ratio $s \int_{\eta_i}^{\eta_o} c d\eta / \frac{1}{2}S_w$ where η_i and η_o define the extremities of the part-span flap, see Sketch 1.2.

For straight-tapered wings, the method in ESDU Aero F.02.01.07 (Reference 13) provides μ . An inviscid trailing-vortex drag correction for part-span flaps must of course be included in C_{DV} , see Section 5 of ESDU 97002 (Reference 26) and Example 2 in Section 7.2.

If the wing is cranked, so that the local quarter-chord sweep angle, $\Lambda_{1/4\eta}$, is not constant, or if the flap chord ratios and flap deflection angle vary spanwise, as may be the case if there is more than a single flap panel, then Δc_{dpmin} should be evaluated at a number of spanwise stations and ΔC_{DPmin} obtained by spanwise integration over the flapped part of the wing, taken to extend from η_i to η_o , i.e.

$$\Delta C_{DPmin} = s \int_{\eta_i}^{\eta_o} 0.9 \cos(\Lambda_{1/4\eta}) \Delta c_{dpmin} c d\eta / \frac{1}{2}S_w . \quad (3.16)$$

The method of ESDU 74035 gives the trailing-vortex drag coefficient of wings with no spanwise variation of section camber or twist as

$$C_{DV} = \frac{(1 + \delta)}{\pi A} C_L^2 , \quad (3.17)$$

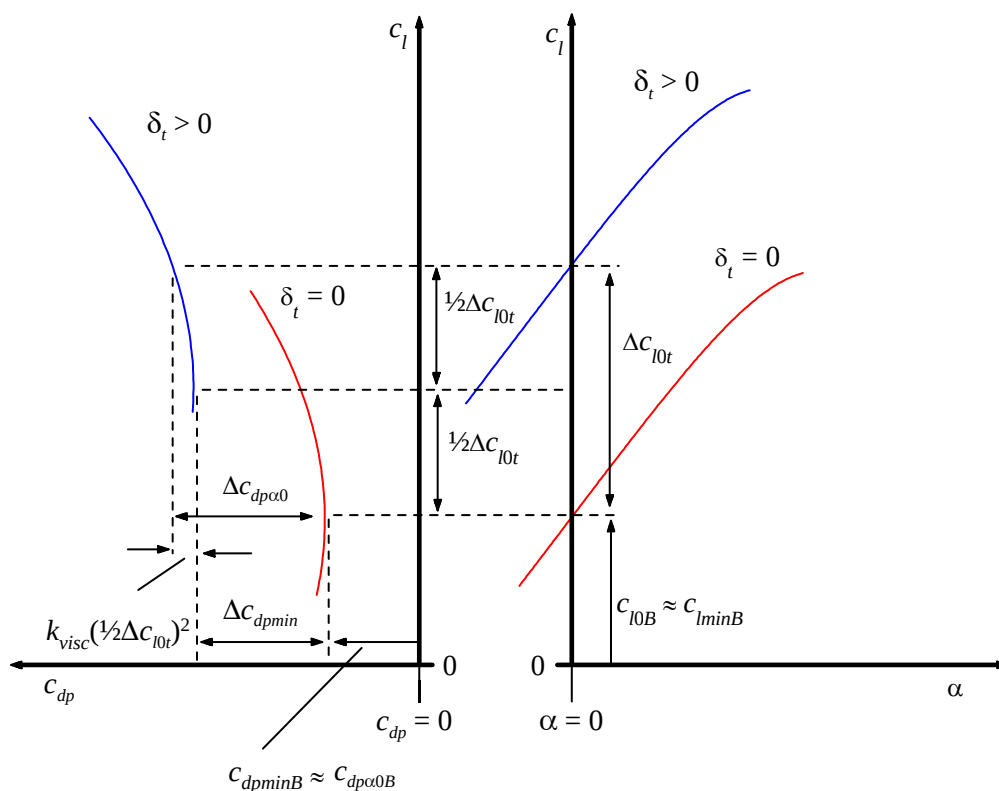
where the factor $(1 + \delta)$ allows for departures from an elliptical spanwise loading due to the shape of the wing planform. Equation (3.17) and the values of $(1 + \delta)$ defined by the wing planform are equally applicable to a wing with full-span flaps deflected, provided that the flap chord ratios and the deflection angle are constant across the span. The main Figures in ESDU 74035 present $(1 + \delta)$ graphically for straight-tapered wings but the way their use may be extended to cranked wings is described in that Data Item.

Part-span flaps give rise to an increment in the trailing-vortex drag coefficient because they cause an additional distortion of the spanwise loading. ESDU Aero F.02.01.08 (Reference 14) gives a method for estimating the increment when the basic wing has an elliptical loading. Other estimation methods may be used if available. For a cranked wing, methods for calculation of the vortex drag coefficient increment based on A , $\Lambda_{1/4}$ and λ may be employed by substituting for those parameters values appropriate to the “equivalent” straight-tapered wing, the geometric construction of which is defined in ESDU 76003 (Reference 17).

A method to allow for fuselage interference effects on flap characteristics is given in ESDU 97003 (Reference 27). With a fuselage present, C_{DPminB} in Equation (3.11) needs to be supplemented by an increment in drag coefficient to provide the value appropriate to the basic wing-fuselage combination and the trailing-vortex drag coefficient also needs to be modified, see Example 2 in Section 7. Appendix A of ESDU 76003 covers the construction of the “equivalent” straight-tapered wing for a wing-fuselage combination if the wing is cranked.

4. ORIGIN OF FIGURES 1 AND 2

At zero incidence, the drag coefficient of the basic aerofoil, $c_{dp\alpha 0B}$, is a good approximation to c_{dpminB} and so the zero incidence lift coefficient, c_{l0B} , is a good estimate of c_{lminB} . On this basis it is possible to relate Δc_{dpmin} to the increment in c_d at zero incidence, $\Delta c_{dp\alpha 0}$, by allowing for the fact that with a flap deployed the profile drag coefficient minimum occurs away from zero incidence, at $c_l = c_{lminB} + \frac{1}{2}\Delta c_{l0t}$ on the basis of Equation (3.2), see Sketch 4.1.



Sketch 4.1 Aerofoil lift and drag coefficients

From the Sketch 4.1, or by substitution of zero incidence values in Equations (3.1) and (3.2),

$$\Delta c_{dpmin} = \Delta c_{dp\alpha 0} - k_{visc} \left(\frac{1}{2} \Delta c_{l0t} \right)^2 . \quad (4.1)$$

If $\Delta c_{dp\alpha 0}$ is treated as the sum of one component due to flap deflection angle and a second due to explicit flap translation

$$\Delta c_{dp\alpha 0} = \Delta c_{dp\alpha 0\delta} + c_{dpminB} [(c' / c) - 1] , \quad (4.2)$$

and Equation (4.1) can be written

$$\Delta c_{dpmin} = \Delta c_{dp\alpha 0\delta} + c_{dpminB} [(c' / c) - 1] - k_{visc} \left(\frac{1}{2} \Delta c_{l0t} \right)^2 . \quad (4.3)$$

Comparison of Equations (3.3) and (4.3) gives

$$\Delta c_{dpmin\delta} = \Delta c_{dp\alpha 0\delta} - k_{visc}(\frac{1}{2}\Delta c_{l0t})^2, \quad (4.4)$$

or with the drag coefficients based on c' ,

$$\Delta c'_{dpmin\delta} = \Delta c'_{dp\alpha 0\delta} - k_{visc}(\frac{1}{2}\Delta c_{l0t})^2(c/c'). \quad (4.5)$$

Typically $\Delta c'_{dpmin\delta}$ is between 5% and 20% smaller than $\Delta c'_{dp\alpha 0\delta}$.

ESDU 87005 provides three Figures that give $\Delta c'_{dp\alpha 0}$ as a function of c'_t/c' and δ_t^* . The correlations are subject to the proviso that, for a given flap deflection angle, flap chord and chord extension, the flap slot gap has been optimised for producing maximum lift coefficient at the stall. The Figures are distinguished from each other by the chordwise position of maximum camber of the basic aerofoil. There is no explicit allowance for rearward translation of the flap.

Figure 2 of ESDU 87005 applies to aerofoils with forward maximum camber ($x_{cmax} \sim 0.15c$). Review of the data used to construct that Figure, which are mainly from early NACA tests, also reveals that there was little or no rearward flap translation ($\sim 0.05c$ for $\delta_t \leq 20^\circ$ and only $\sim 0.1c$ at greater δ_t). The flap translation in these cases was an incidental consequence of opening and optimising the slot rather than a large deliberate chord extension, as for a Fowler-type flap. Moreover, the correlation concentrated on data for $\delta_t \geq 40^\circ$, where the explicit flap translation effect was only a small part of the total drag coefficient increment. The values in Figure 2 of ESDU 87005 therefore closely approximate the angular deflection term $\Delta c'_{dp\alpha 0\delta}$.

The data used to construct Figure 1 of ESDU 87005, which is for $0.20c \leq x_{cmax} \leq 0.65c$, are sparse but are for more modern data and for all δ_t there was a deliberate rearward flap translation, of between $0.13c$ and $0.31c$. If an explicit allowance for flap translation is made separately from the effect of flap deflection angle, then a repetition of the original manipulation of the data that led to Figure 1 of ESDU 87005 produces a correlation that would be adequately represented by Figure 2 of ESDU 87005. Consequently, *Figure 1 of this Data Item* has been produced by making use of Equation (4.5) to adjust Figure 2 of ESDU 87005 and it provides $\Delta c'_{dpmin\delta}$ in the extended range of applicability $0.15c \leq x_{cmax} / c \leq 0.65$.

Figure 3 of ESDU 87005, which applies for aerofoils with aft camber, $0.70c \leq x_{cmax} \leq 0.80c$, is again based on sparse data for flaps with deliberate rearward translation, $\sim 0.13c$ and $\sim 0.25c$ for the two cases covered. It gives a much lower profile drag coefficient increment than the Figures for more forward x_{cmax} . A remanipulation of the original data with explicit allowance for rearward flap translation and use of Equation (4.5) results in *Figure 2 of this Data Item*, which provides $\Delta c'_{dpmin\delta}$ when $0.70c \leq x_{cmax} \leq 0.80c$. However, Figure 2, is only recommended for use if $\delta_t \leq 30^\circ$; for aerofoils with aft camber and $\delta_t \geq 40^\circ$, *Figure 1* is recommended and caution is needed for intermediate δ_t , see Section 5.2.

* ESDU 87005 uses the capitalized notation $\Delta C'_{Dp\alpha 0}$.

5. ACCURACY AND APPLICABILITY

5.1 Accuracy

Sketches 5.1 to 5.17 compare the predicted drag polars for unswept wings with full-span flaps against experimental values from Derivations 3 to 9 and 11. In all these cases the position of maximum camber was in the range $0.15 \leq x_{cmax} / c \leq 0.65$ and $\Delta c'_{dp\alpha 0\delta}$ was taken from Figure 1. Sketches 5.18 to 5.20 show comparisons for the swept wing of Derivation 10; this wing has a section with rearward maximum camber, so predictions with $\Delta c'_{dp\alpha 0\delta}$ taken from Figure 1 and from Figure 2 are both included. It is seen that the use of data from Figure 1 is better at $\delta_t = 40^\circ$, while data from Figure 2 work better at $\delta_t = 10^\circ$ and 25° . It is to be noted that the construction data for Figure 2 did not include cases for $\delta_t > 30^\circ$.

Sketch 5.21 compares the predicted and experimental values of C_D at $C_L = 0.7C_{Lmax}$ and Sketch 5.22 the values at $C_L = 0.9C_{Lmax}$. The agreement is within $\pm 10\%$ in both cases*.

Sketch 5.23 repeats Sketch 5.6 but now includes a prediction obtained by simply combining the vortex drag contribution with C_{DPminB} and a profile drag coefficient increment that is independent of C_L . Such an increment is, for example, provided by ESDU Aero F.02.01.06 (Reference 12) (ΔC_{D0} in the notation of that Data Item), and it would replace the second and third terms of Equation (3.11). This is an approximation that is often made when the means of estimating the lift-dependent contribution are not available. Making an allowance for the lift dependence of the profile drag coefficient gives a noticeably improved modelling of the variation of C_D with C_L .

Sketch 5.24 shows a prediction of the drag polar for a configuration from Derivation 10, where a wing mounted just below mid-height on a circular fuselage of $0.14b$ diameter had flaps extending outboard from the fuselage side to 60% of the wing semi-span. With the inclusion of fuselage-flap interference effects, estimated using the method of ESDU 97003, and a part-span trailing-vortex drag term, obtained by the method in ESDU Aero F.02.01.07, the agreement with experiment is similar to that for full-span flaps on an isolated wing. See also Example 2 in Section 7.2.

5.2 Applicability

The method is applicable in low-speed freestream flow to wings with trailing-edge single-slotted flaps, for wings with aspect ratios of 6 and above and quarter-chord sweep angles up to 30° . For a given flap deflection angle, flap chord and chord extension, the flap slot gap is assumed to be optimised to produce maximum lift coefficient at the stall. The basic wing must satisfy the applicability requirements of ESDU 07002 if the method of that Data Item is used to estimate K_{visc} and C_{LminB} .

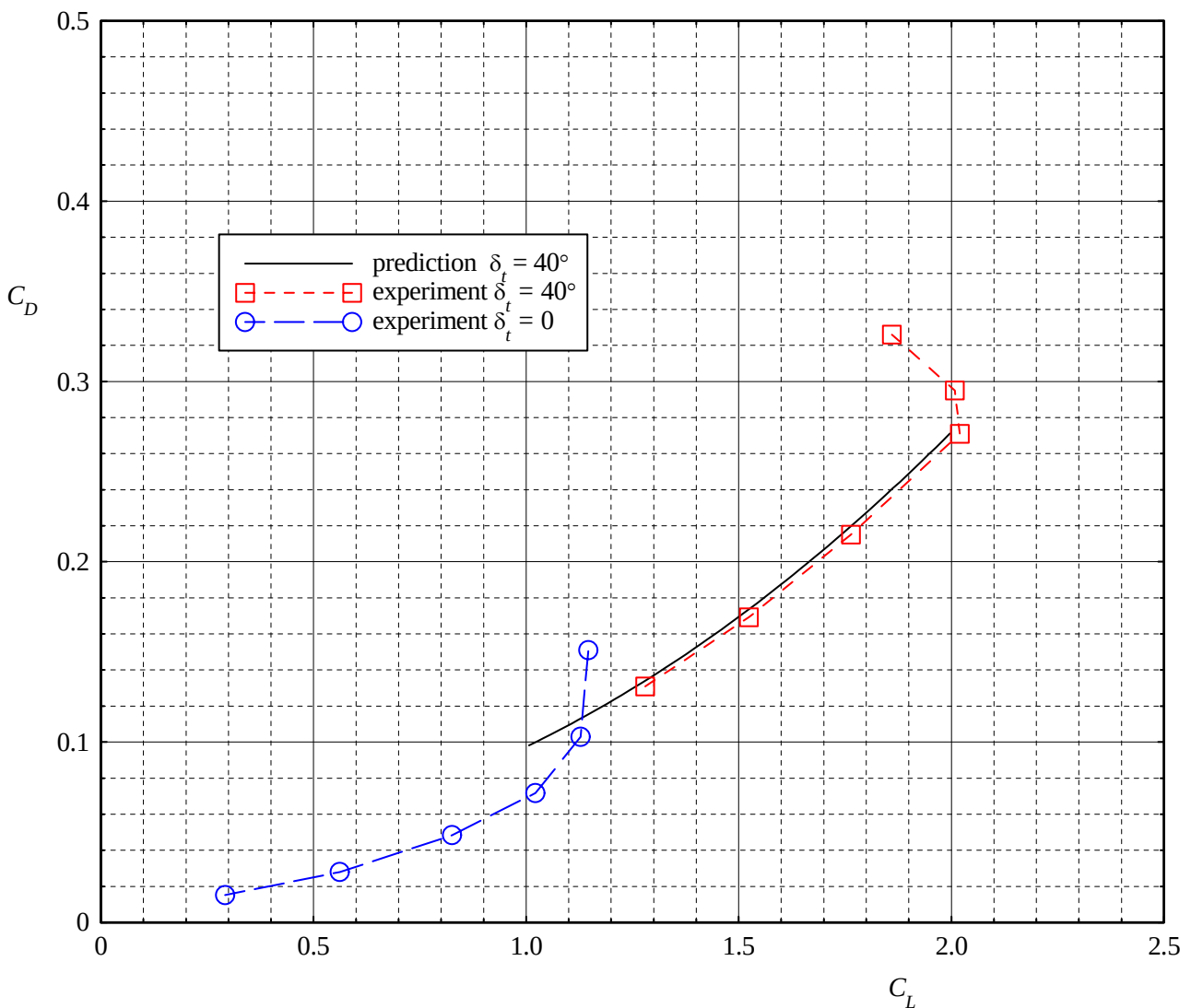
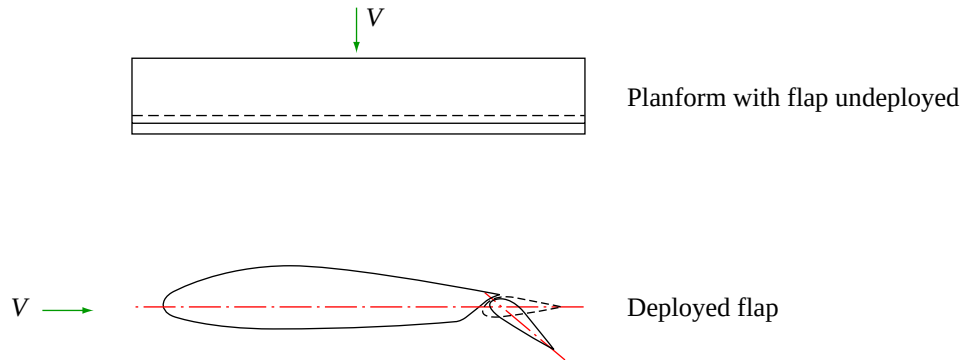
The Reynolds number range of the data used for this Data Item was 0.6×10^6 to 7×10^6 , but most of the aerofoil data leading to Figures 1 and 2 were for Reynolds numbers in the range 2.6×10^6 to 3.5×10^6 ; see ESDU 87005 where it is argued that effects of Reynolds number above this range will be contained within the overall accuracy band ($\pm 0.20\Delta c'_{dp\alpha 0}$) of the correlation in that Data Item. The thickness to chord ratio ranged from 0.09 to 0.21 and the extended flap chord ratio varied from 0.15 to 0.42. Wing aspect ratios were between 6 and 9, with $\Lambda_{1/4}$ up to 28° . The predicted drag polar will not be valid very close to C_{Lmax} , and $0.9C_{Lmax}$ should be used as an upper bound on C_L . An estimate of the value of C_{Lmax} may be made by the method of ESDU 91014 (Reference 22). That method is incorporated in the method of ESDU 96003 (Reference 25), which provides the lift curve for wings with flaps deployed; the method of ESDU 96003 is programmed in ESDUpac A9931 that accompanies ESDU 99031 (Reference 28).

* Derivation 1 gives a prediction method for $\Delta c'_{dpmin}$ that is completely different from that of this Data Item. The use of that method, in modified form, has been studied but provides no advantage in prediction accuracy over the method of this Data Item.

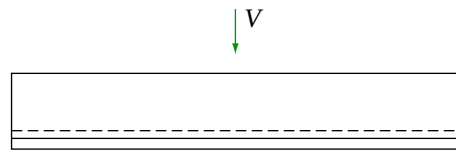
On the basis of the extensive range of data for flap deployment on aerofoils used in the preparation of ESDU 87005 and the more modest range of data for wings studied in the preparation of this Data Item, Figure 1 is recommended for the prediction of $\Delta c'_{dp\alpha 0\delta}$ whenever the basic mid-span section of the flapped part of the wing has a position of maximum camber in the range $0.15c \leq x_{cmax} \leq 0.65c$, for flap deflection angles $0 \leq \delta_t \leq 60^\circ$. On Figure 1, the area enclosed by broken lines indicates where test data were available.

Aft camber

The data for cases where the position of maximum camber is well aft are very few in number. Data for flap deployment on only two aerofoils were considered in ESDU 87005, for $x_{cmax} = 0.70c$ and $0.80c$, with $\delta_t \leq 30^\circ$. Derivation 10 provides a single set of data for flap deployment on a wing, with $x_{cmax} = 0.75c$, as reviewed in Section 5.1 above. On that basis, Figure 2 is tentatively recommended for use when $0.70c \leq x_{cmax} \leq 0.80c$ for $\delta_t \leq 30^\circ$, at least as an illustration of the low profile drag coefficient increments that can occur with aft camber. However, Figure 1 is to be preferred for $\delta_t \geq 40^\circ$ because the data in Sketch 5.20 showed that the low drag increments suggested in Figure 2 would not be maintained at high flap deflection angles. Care as to which Figure should be used is needed for sections with aft camber and deflection angles in the intermediate range, $30^\circ < \delta_t < 40^\circ$, because the values of $\Delta c'_{dp\alpha 0\delta}$ are so much lower in Figure 2 than in Figure 1. On Figure 2 the area enclosed by broken lines emphasises the small range where data were available.



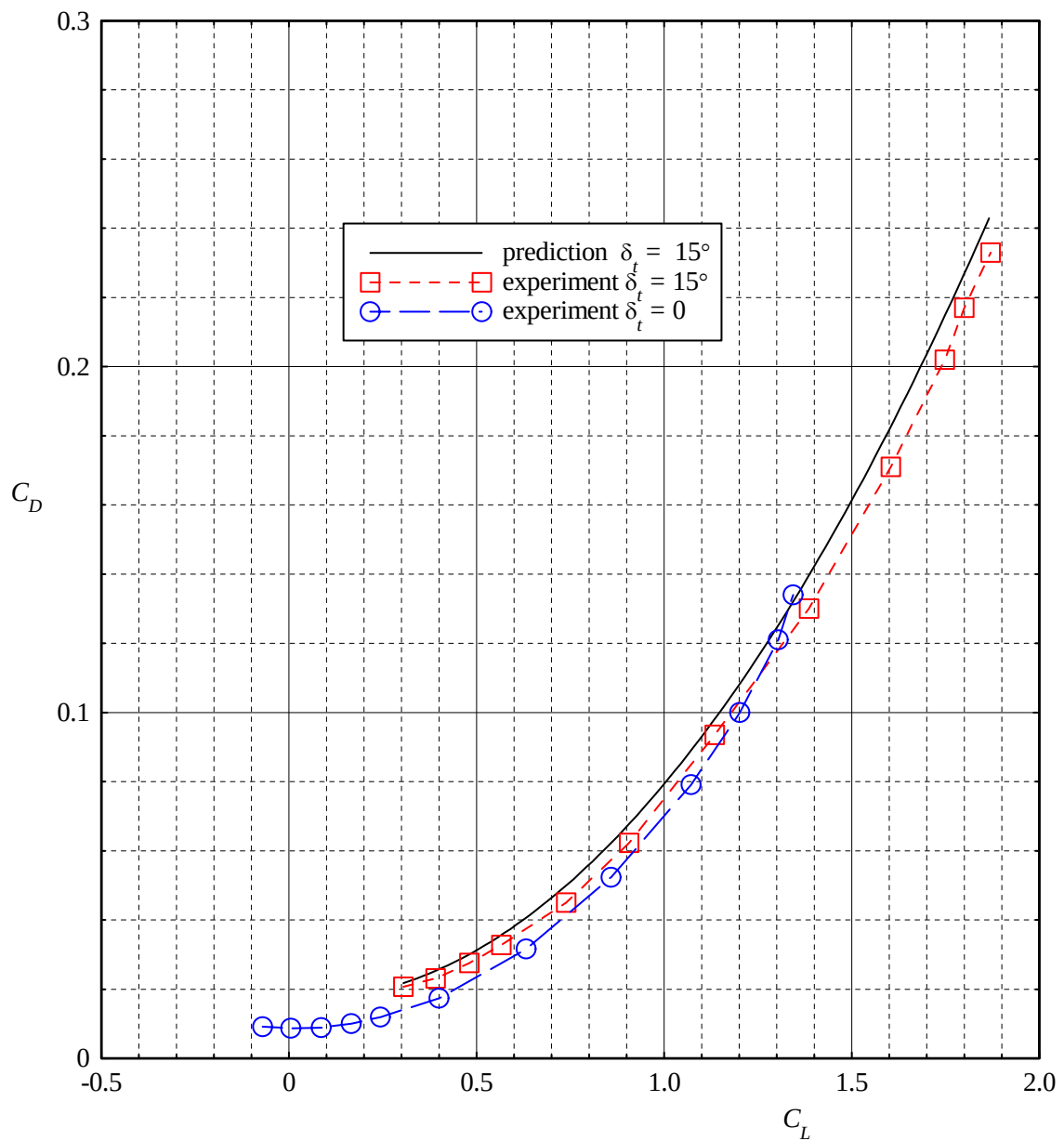
**Sketch 5.1 Drag polars for wing with $A = 6$, $\Lambda_{1/4} = 0$, $\lambda = 1$
and extended chord ratios $c'_t/c' = 0.17$ and $c'/c = 1.03$
(Derivation 5)**



Planform with flap undeployed

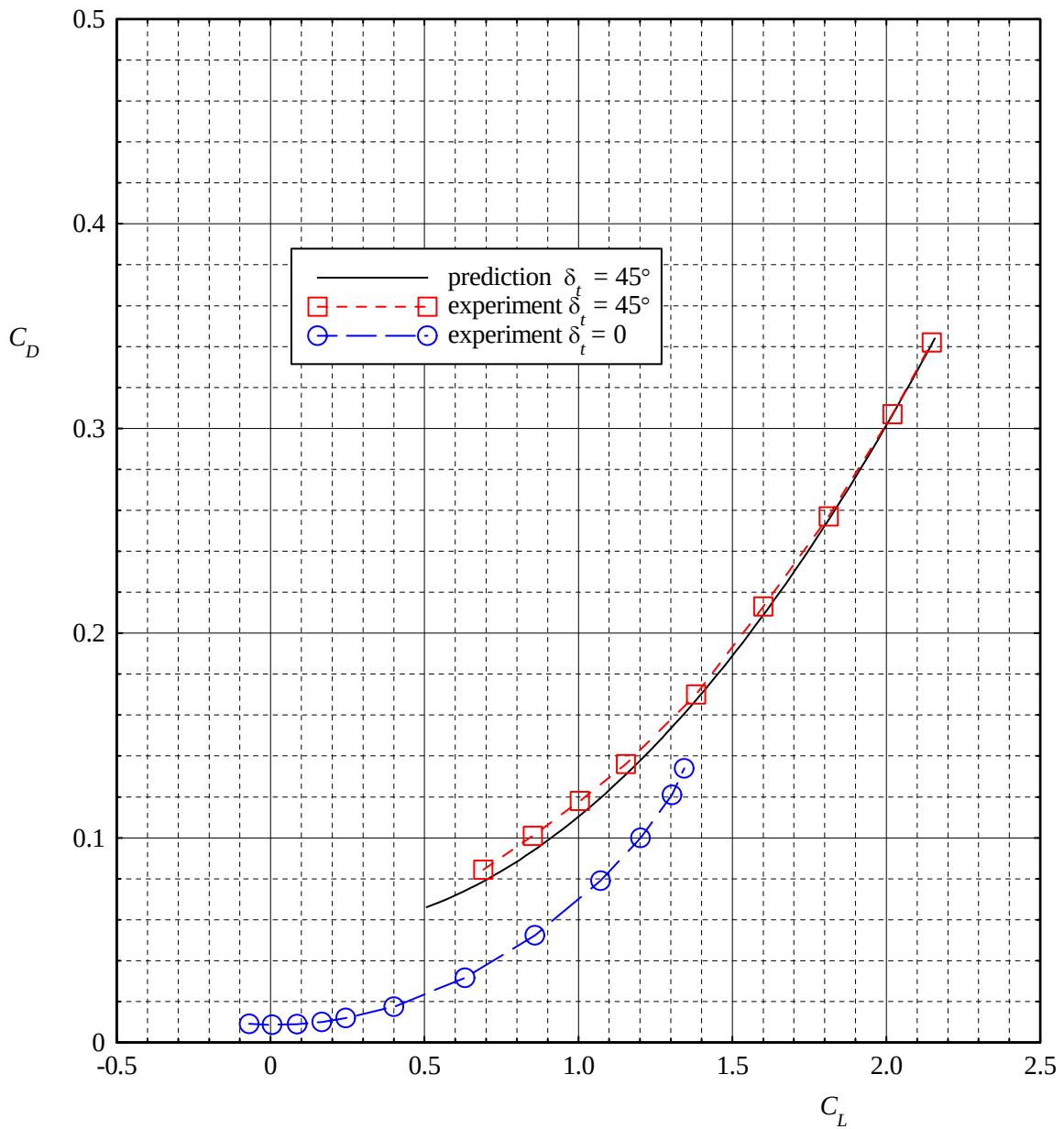
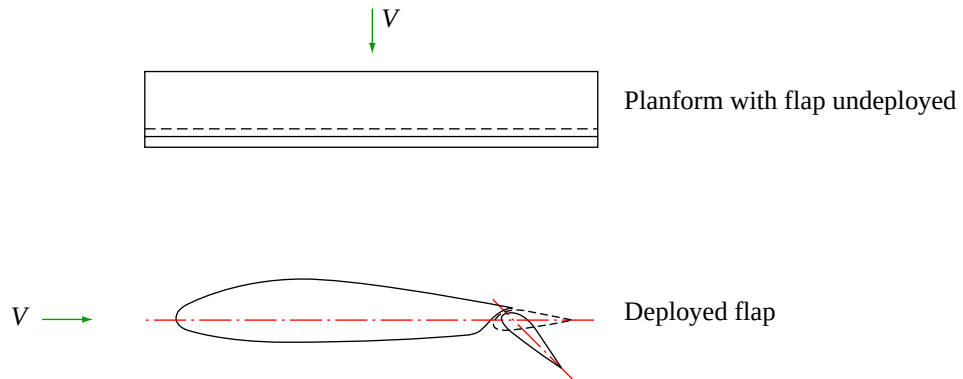


Deployed flap



**Sketch 5.2 Drag polars for wing with $A = 6$, $\Lambda_{1/4} = 0$, $\lambda = 1$
and extended chord ratios $c'_t/c' = 0.16$ and $c'/c = 1.01$**

Derivation 6



Sketch 5.3 Drag polars for wing with $A = 6$, $\Lambda_{1/4} = 0$, $\lambda = 1$

and extended chord ratios $c'_t/c' = 0.19$ and $c'/c = 1.03$

Derivation 6