

ESTIMATION OF AIRFRAME DRAG BY SUMMATION OF COMPONENTS: PRINCIPLES AND EXAMPLES

1. NOTATION AND UNITS

There is no subdivision of aircraft drag or drag coefficient for which a single set of terms or notation exists. This is true generally and within the many drag-related ESDU Data Items. Since the present Item is intended to deal with the overall estimation of drag and its relationship to other Items (and other sources) some general principles have been adopted.

For convenience, most of the text and many of the equations *in this Data Item* are expressed in terms of drag rather than drag coefficient so as to simplify the notation used.

Capital letter subscripts to drag, D , indicate a drag contribution related to a particular flow mechanism.

Lower case word subscripts (or abbreviations) to drag, D , indicate a drag contribution due to a particular airframe component or flight condition.

Notation used once only in any of Tables 6.2 to 6.10 is defined there and not included here.

		SI	British
A	aspect ratio, b^2/S		
a	speed of sound	m/s	ft/s
b	wing span	m	ft
C_D	drag coefficient, D/qS		
C_{D_F}	drag coefficient due to skin friction, D_F/qS		
$C_{D_{min}}$	minimum value of C_D at given value of M		
C_{D_P}	profile drag coefficient, D_P/qS		
$C_{D_{PR}}$	pressure drag coefficient, D_{PR}/qS		
$C_{D_{TV}}$	trailing vortex drag coefficient, D_{TV}/qS		
C_{D_V}	viscous drag coefficient, D_V/qS		
C_{D_W}	wave drag coefficient, D_W/qS		
C_F	flat plate mean skin friction coefficient		

C_{F_e}	equivalent skin friction coefficient, = (aeroplane drag component independent of lift)/ qS_{wet}		
C_f	flat plate local skin friction coefficient		
C_L	lift coefficient, L/qS		
$C_{L_{crit}}$	“critical” value of C_L in “dual parabolic” representation of drag polar		
C_p	pressure coefficient (= $(p_{local}-p)/q$)		
c	chord of aerofoil or of wing at spanwise station η	m	ft
$\bar{c}$	wing geometric mean chord	m	ft
D	drag	N	lbf
$D_{asym \ thr}$	drag due to thrust asymmetry	N	lbf
D_F	drag due to skin friction	N	lbf
D_i	lift-dependent component of drag	N	lbf
D_P	profile drag	N	lbf
D_{P_n}	profile drag of strip normal to wing sweep line	N	lbf
D_{P_s}	profile drag of streamwise strip of wing	N	lbf
D_{PR}	pressure drag	N	lbf
D_{stores}	stores drag (<i>e.g.</i> fuel tanks, weapons)	N	lbf
D_{TV}	trailing vortex drag	N	lbf
D_{trim}	longitudinal trim drag	N	lbf
D_{uc}	undercarriage drag	N	lbf
D_V	viscous drag	N	lbf
D_W	wave drag	N	lbf
D_0	component of drag independent of lift	N	lbf
d	maximum diameter of body (or of equivalent axisymmetric body) of aircraft or of component indicated by subscript	m	ft
e	efficiency factor		

f	denotes function of form, $f[\dots]$		
g	acceleration due to gravity	m/s^2	ft/s^2
j	denotes j th strip of wing or other aerodynamic surface		
K, K_1, K_2	lift-dependent drag factors		
L	lift	N	lbf
l	characteristic length	m	ft
M	Mach number, V/a		
mfr	intake mass flow ratio		
N	number of chordwise strips used to represent wing between root and tip		
p	static (ambient) pressure in free stream	N/m^2	lbf/ft^2
p_{local}	local surface pressure on airframe	N/m^2	lbf/ft^2
q	kinetic pressure, $\rho V^2/2$ (identical to dynamic pressure in incompressible flow)	N/m^2	lbf/ft^2
Re	Reynolds number, $\rho V l / \mu$		
S	wing reference area	m^2	ft^2
S_{wet}	wetted area of aircraft or component indicated by subscript	m^2	ft^2
t	maximum thickness of aerofoil or wing	m	ft
V	true airspeed	m/s	ft/s
x, y, z	coordinates, parallel to aircraft body axis system but with origin chosen to suite the particular topic	m	ft
Δ	denotes an increment in the affixed parameter		
$(1 + \delta)$	lift dependent drag factor due to wing trailing vortices (Reference 26)		
η	non-dimensional spanwise coordinate, $y/(b/2)$		
Λ	sweep of wing	deg	deg
Λ_e	equivalent sweep angle of wing, see Table 6.9	deg	deg
λ	form factor		
μ	dynamic viscosity	N s/m^2	lbf s/ft^2
ρ	density of air	kg/m^3	slug/ft^3

Subscripts

D	denotes drag-rise condition
$datum$	denotes datum value of parameter
j	denotes value for j th strip of wing or other aerodynamic surface
min	denotes minimum value
n	denotes quantity defined in plane containing equivalent two-dimensional aerofoil (see Section 3.3.2.1)
s	denotes quantity defined in streamwise plane parallel to (wing) plane of symmetry
$tail$	denotes tail
$trim$	denotes (longitudinal) trimmed condition
wb	denotes value for wing-body combination
ΔC_L	denotes change in a parameter due to change, ΔC_L , in C_L
ΔM	denotes change in a parameter due to change, ΔM , in M
ΔRe	denotes change in a parameter due to change, ΔRe , in Re
$\frac{1}{4}, \frac{1}{2}$	denotes values at wing quarter chord and half chord locations
0	denotes (i) conditions at sea level in ISA (ii) drag component independent of lift

2. INTRODUCTION

Most airframe drag estimation methods* rely on the summation of contributions due to particular airframe components or flow mechanisms. Examples of several schemes are given and one of these (Table 6.5) presents the basis of the drag estimation method of Reference 49.

Section 3 itemises contributions to overall airframe drag that should, ideally, be considered – although with some procedures two or more of those items are coalesced. Section 4 reviews the practicalities of making these estimates and Table 6.11 lists the ESDU data available.

An introduction to the *representation* of airframe drag for performance calculations is given in Data Item No. 81026 (Reference 32) together with examples of individual aircraft drag characteristics.

The examples of drag estimation schemes considered here in Tables 6.2 to 6.10 range from the relatively simple to those that require at least some usage of CFD techniques. The former tend to be the oldest and probably the most amenable to use at an early stage in design where limited geometric information is available. The latter are more representative of drag estimation procedures in current use wherever CFD techniques are the mainstay of (wing) aerodynamic design. The further that a project proceeds to wind-tunnel and, eventually, flight testing, the more likely the process of drag prediction and correlation will involve a mixture of all available techniques*.

* This Item does not address the following

- (1) The derivation of whole-airframe drag from the adjustment of wind-tunnel measurements to full scale.
- (2) The estimation of drag from the use of CFD simulation of the complete airframe.

3. REFERENCE SCHEME FOR DRAG CONTRIBUTIONS

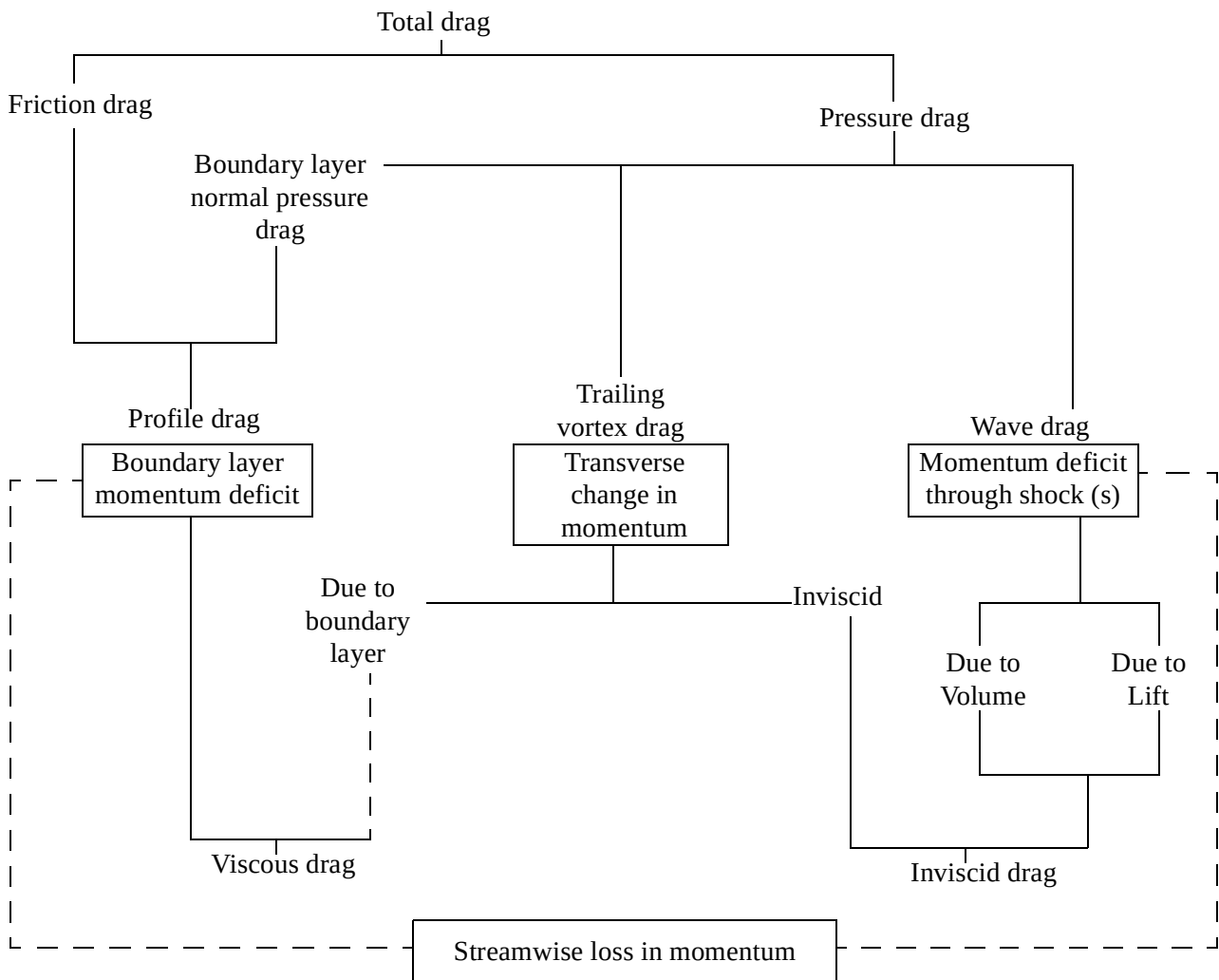
A recurrent problem with drag estimation/analysis procedures is the number of ways of subdividing the total drag, the level of detail to which the various contributions to drag are addressed and the nomenclature/notation used.

Sketch 3.1 shows how drag can be subdivided in several ways. In particular, it shows the interaction between schemes based on fluid-flow principles and those based on the principle of conservation of momentum.

All drag estimation methods can be related to Sketch 3.1, but there are many ways of further subdividing the drag and of predicting individual terms – especially when airframe components are considered separately.

This Data Item presents, in summary form, several existing drag estimation methods so as to illustrate, by example, the range of techniques and levels of sophistication that exist. To provide a common format for those Examples, a Reference Scheme and associated Notation is presented as Table 6.1. Subsequently, Tables 6.2 to 6.10 give the individual examples.

Sections 3.1 to 3.9 provide commentaries on the individual items in the Reference Scheme. Note that some of the Examples in Tables 6.2 to 6.10 do not consider the whole airframe. In other cases two (or more) items of the Reference Scheme may be coalesced into a single drag contribution.



Sketch 3.1 Relationship Between Drag, Drag Components And Momentum Changes

3.1 Total Drag

The Reference Scheme of Table 6.1 is presented in terms of contributions to total drag, D , rather than to the total drag coefficient, C_D . This simplifies the notation and acknowledges that some contributions are not best represented by parameters which include the aircraft reference area.

For each of the examples in Tables 6.2 to 6.10 the notation column remains the same as in the Reference Scheme. The summary of the method given in each Table reflects the terminology of that method but, where symbols are required, uses those of the Reference Scheme wherever possible.

3.2 Datum Conditions for Airframe Drag

The purpose of datum conditions in a drag estimation method is to allow the complete calculation to be performed at those conditions while incremental adjustments are used to generate estimates away from the datum. The use of computational procedures might be thought to render such an approach unnecessary but even here it can be advantageous. For example, it permits the use of data of high quality but limited extent in the region of the datum conditions while accepting that the adjustments to off-datum conditions might be less well founded. The approach is useful also in describing methods (as here) and in identifying the source of small changes in estimated drag for different flight conditions.

If used, the datum conditions consist of some combination of values of C_L , M , Re .

Datum lift coefficient: The traditional approach to profile drag estimation puts $C_{Ldatum} = 0$. However, when considered in terms of airframe aerodynamics, this is not a condition of particular significance and for many aircraft is not a realistic flight condition. Consequently, some methods are formulated around values of C_{Ldatum} (and M_{datum} , see below) which correspond to some optimum feature of aerofoil and/or wing aerodynamics.

Datum Mach number: The desire to simplify skin-friction calculations (by using a single value of Reynolds number) might lead to M_{datum} being taken as a cruise value. Alternatively, a value might be selected at which no wave drag would occur at any flight conditions. A further option is to use datum values of C_L and M which correspond to some optimum feature of aerofoil and/or wing aerodynamics. Examples are combinations of C_L and M which correspond to

- (i) a wing design point (see Reference 47 for review of these),
- (ii) maximum value of ML/D (Table 6.5 provides an example),
- (iii) the drag-rise condition for some specified standard of wing/aerofoil design (Table 6.9 provides an example).

Datum Reynolds number: Skin-friction calculations can be simplified by taking nominal values of C_F at a single datum value of Reynolds number for each airframe component. Adjustments to other conditions can then be made by a simple factor – as illustrated in Addenda B and D of Reference 32. The datum might be taken as a cruise condition or to correspond with other datum conditions.

3.3 Profile Drag

Profile drag is generally regarded as the drag arising due to the presence of the boundary layer on any object moving through a fluid – see Sketch 3.1. This definition allows for the variation in profile drag with lift coefficient (or angle of attack) due to the effect on the boundary layer of changes in the surface pressure distribution. For some estimation procedures the term has come to include the contribution due to wave drag at subsonic speeds. Methods in use for major airframe components, especially wings, are considered in Sections 3.3.1 to 3.3.3. General remarks regarding the contributions due to excrescences, interferences and propulsion systems are given in Sections 3.3.4 to 3.3.6.

3.3.1 Use of flat plate skin friction and form factors

For attached flow on smooth and uniformly rough surfaces, the traditional approach to profile drag estimation is to divide the airframe into a convenient set of j components, say, and to evaluate the sum of their drag contributions as

$$D_p = \sum_{j=1}^N [D_p]_j = q \sum_{j=1}^N [S_{wet} \times C_F \times \lambda]_j. \quad (3.1)$$

Thus, for each airframe component it is necessary to estimate a value for:

- S_{wet} the wetted area of the component,
- C_F the flat plate mean skin friction coefficient, estimated at a Reynolds number based on an appropriate streamwise dimension,
- λ the “form factor” for the component, *i.e.* the ratio of the drag to the drag of a flat plate with the same Reynolds number and transition position.

In using Equation (3.1) systematic errors can be avoided if it is ensured that values of C_F and S_{wet} are based on the same skin friction law and wetted area definition as was used in the derivation of the values of λ . For example, is the “flat plate” area the true surface area of the component or (for a wing, tail, pylon *etc.*) simply twice the planform area? If the latter approach is used, then the effects on surface area of thickness and of dihedral/anhdral are omitted from the calculation.

For some airframe components the use of single values of C_F and λ (even if they are “equivalent” ones) is overly simplistic; in the case of wings and other lifting surfaces this restriction leads to the use of the “strip” methods introduced in Section 3.3.2.

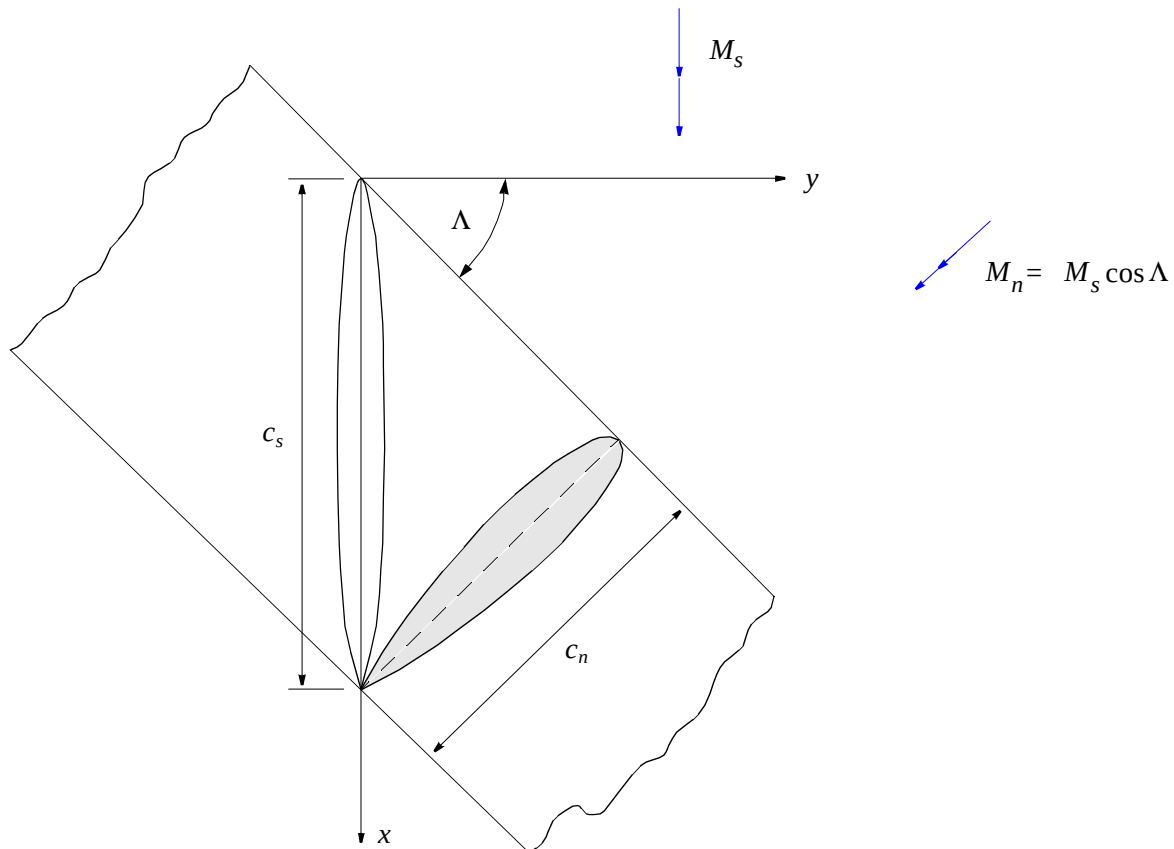
3.3.2 Profile drag estimation using strip methods and simple sweep rules

Strip methods, taken together with the simple sweep rules for an infinite swept wing, provide a means of using two-dimensional aerofoil data to predict profile drag of wings. The approach adopted here is to provide a review of the sweep rules in Section 3.3.2.1 and to give general guidance on the use of strip methods in Section 3.3.2.2. Particular applications are mentioned in Tables 6.3, 6.5, 6.8, 6.9.

3.3.2.1 Simple sweep rules

This section is adapted from Section 5 of Reference 40.

On an unswept wing the flow departs from a two-dimensional character only close to the wing tips, where the formation of tip vortices causes three-dimensional features in the boundary layer and external flow. Wings of moderate sweep (about 30 degrees, say) and high aspect ratios typical of most modern transport aircraft, are often designed so that the flow (except in regions near the roots and tips) is of a quasi-two-dimensional nature, in the sense that it varies only slowly across the span. In these 'mid-semi-span' regions the idealised concept of an 'infinite yawed wing' is a useful starting point, which relates the swept-wing flow to an equivalent two-dimensional flow over a transformed aerofoil section, taken normal to the leading edge of the actual wing, see Sketch 3.2.



Sketch 3.2 Illustration of transformed aerofoil

Following the notation illustrated in Sketch 3.2 and using “s” to denote streamwise conditions and “n” to denote equivalent-two-dimensional conditions, the following relationships may be derived.

From geometric considerations

$$c_n = c_s \cos \Lambda,$$

$$z_n = z_s,$$

so
$$\left(\frac{z}{c}\right)_n = \left(\frac{z}{c}\right)_s \sec \Lambda \quad (3.2)$$

and
$$\left(\frac{t}{c}\right)_n = \left(\frac{t}{c}\right)_s \sec \Lambda. \quad (3.3)$$

From the aerodynamics of the two flow cases,

$$M_n = M_s \cos \Lambda, \quad (3.4)$$

$$V_n = V_s \cos \Lambda. \quad (3.5)$$

Since, for an infinite wing, the pressure perturbations, $(p_{local} - p)$, are the same in the two flow cases, as are p and ρ , it follows that

$$\frac{(p_{local} - p)}{\frac{1}{2}\rho V_n^2} = \frac{(p_{local} - p) \sec^2 \Lambda}{\frac{1}{2}\rho V_s^2}$$

or
$$[C_p]_n = [C_p]_s \sec^2 \Lambda. \quad (3.6)$$

Since values of lift coefficient are obtained by integration of the values of C_p around the aerofoil, it follows from Equation (3.6) that the lift coefficients of the two flows are related by

$$[C_L]_n = [C_L]_s \sec^2 \Lambda \quad (3.7)$$

while, because of Equations (3.2) and (3.3), the pressure drag coefficients are related by

$$[C_{D_{PR}}]_n = [C_{D_{PR}}]_s \sec^3 \Lambda. \quad (3.8)$$

These equations are strictly true only for inviscid flow – no such simple relationships are valid for the viscous drag, particularly when the boundary layers are turbulent – but they are still useful as a general overall guide. In particular, since wave drag is a mainly inviscid phenomenon, the wave drag coefficients are related by

$$[C_{D_w}]_n = [C_{D_w}]_s \sec^3 \Lambda. \quad (3.9)$$

Thus the flow on a swept wing of sweep angle Λ may be compared with the flow on an equivalent aerofoil which is thicker (factor, $\sec \Lambda$), at a higher lift coefficient (factor, $\sec^2 \Lambda$) and at a lower free-stream Mach number (factor, $\cos \Lambda$). (The beneficial effect of sweep is due to the fact that the last of these three factors generally easily outweighs the adverse effects of the other two. In particular, the appearance of shock waves, and their consequent adverse effects on the development of drag and separation, is progressively delayed as the sweep angle is increased.)

3.3.2.2 Strip methods

The principle is that profile drag of a swept tapered wing is estimated by dividing the wing into a number (j , say) of strips – both “streamwise” (subscript “s”) and “normal” (subscript “n”) to the wing sweep line, however defined. For each strip it is assumed that the geometry (chord, thickness, sweep) and flow conditions are constant, or effectively so.

For the required conditions of Mach number, M , and wing lift coefficient, C_L , spanwise loading data are used to determine the lift coefficient, $C_{L_{s,j}}$, for each strip. For this purpose the condition $C_L = 0$ represents a trivial case while the simplest procedure with $C_L \neq 0$ is to assume an elliptical spanwise variation of loading and hence of $C_{L_{s,j}}$.

Geometry and flow conditions for the equivalent two-dimensional aerofoil sections are derived as follows.

Equations (3.2) and (3.3) give the co-ordinates and thickness, $[z/c]_{n,j}$ and $[t/c]_{n,j}$,

Equation (3.4) gives the Mach number $M_{n,j}$,

Equation (3.7) gives the lift coefficient $C_{L_{n,j}}$.

Ideally, values of pressure drag coefficient are obtained for the transformed aerofoil and flow conditions for each strip and converted into an estimate of wing profile drag using Equation (3.8) and the summation,

$$D_P = q \sum_{j=1}^N S_j [C_{D_{F_s}} + C_{D_{P_{R_n}}} \cos^3 \Lambda]_j. \quad (3.10)$$

In Equation (3.10) $C_{D_{F_s,j}}$ is evaluated for *streamwise* flow conditions. The need to select several values of Λ arises in the examples of Tables 6.3, 6.4, 6.8 and 6.9. In Table 6.3 the value of $\Lambda_{1/4}$ for the wing is used. In Table 6.4 the method of Reference 6 calls for the use of Λ values for each percentage chord line in deriving co-ordinates of the equivalent two-dimensional sections. Table 6.8 suggests the use of either $\Lambda_{1/4}$ or $\Lambda_{1/2}$ for the wing. Table 6.9 makes use of the values of an effective sweep angle, Λ_e , derived and presented in Data Item No. 72027 (Reference 25). Other forms of Equation (3.10) may have to be used – depending on the type of aerofoil data available. In the most general case, with values of aerofoil profile and wave drag coefficients given separately,

$$D_P = q \sum_{j=1}^N S_j [C_{D_{F_s}} + [C_{D_{W_n}} + (C_{D_{P_n}} - C_{D_{F_s}})] \cos^3 \Lambda]_j. \quad (3.11)$$

In the simplest case, where there is no wave drag and aerofoil profile drag is expressed in terms of form factors (see Section 3.3.1), Equation (3.11) becomes

$$D_P = q \sum_{j=1}^N S_j C_{F_{s,j}} [1 + (\lambda_n - 1) \cos^3 \Lambda]_j. \quad (3.12)$$

Again, in Equations (3.11) and (3.12) values of $C_{D_{F_{s,j}}}$ and $C_{F_{s,j}}$ are determined based on streamwise flow conditions.