



Drag of a rectangular planform cavity in a flat plate with a turbulent boundary layer for Mach numbers up to 3. Part III : Effect of doors



Endorsed by
The Royal Aeronautical Society

ESDU DATA ITEMS

Data Items provide validated information in engineering design and analysis for use by, or under the supervision of, professionally qualified engineers. The data are founded on an evaluation of all the relevant information, both published and unpublished, and are invariably supported by original work of ESDU staff engineers or consultants. The whole process is subject to independent review for which crucial support is provided by industrial companies, government research laboratories, universities and others from around the world through the participation of some of their leading experts on ESDU Technical Committees. This process ensures that the results of much valuable work (theoretical, experimental and operational), which may not be widely available or in a readily usable form, can be communicated concisely and accurately to the engineering community.

We are constantly striving to develop new work and review data already issued. Any comments arising out of your use of our data, or any suggestions for new topics or information that might lead to improvements, will help us to provide a better service.

THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Aerodynamics Committee. This Committee first met in 1942 and now has the following membership:

Chairman	
Mr A.J. Wells	— Independent
Vice-Chairman	
Mr P.D. Chappell	— Independent
Members	
Mr K. Bradbrook	— BAE SYSTEMS, Preston
Mr P. Camacho*	— Boeing, Long Beach, CA, USA
Mr O. Coudray	— Airbus France, Toulouse, France
Dr P.C. Dexter	— BAE SYSTEMS, Advanced Technology Centre, Filton, Bristol
Mr J.R.J. Dovey	— Independent
Prof. K.P. Garry	— Cranfield University
Mr D.H. Graham*	— Northrop Grumman Corp., El Segundo, CA, USA
Prof. J.M.R. Graham	— Imperial College, London
Mr M.J. Green	— Independent
Mr J.M. van den Heever*	— Denel Dynamics, South Africa
Dr E.H. Kitchen	— Rolls-Royce Commercial Aero Engines Ltd, Derby
Miss M. Maina	— Aircraft Research Association Ltd
Mr A. Miller	— Airbus UK, Filton, Bristol
Mr E. Totland*	— Saab AB, Linköping, Sweden
Mr J. Tweedie	— Short Brothers plc, Belfast
Mr S.F. Wood	— BAE SYSTEMS, Chadderton.

* Corresponding Member

The construction and subsequent development of the Data Item were undertaken by

Mr P.D. Chappell	— Independent
------------------	---------------

The person with overall responsibility for the work in this subject area is Mr A.J. Clarke, Head of the Aerodynamics Group

DRAG OF A RECTANGULAR PLANFORM CAVITY IN A FLAT PLATE WITH A TURBULENT BOUNDARY LAYER FOR MACH NUMBERS UP TO 3. PART III : EFFECT OF DOORS

CONTENTS

	Page
1. NOTATION AND UNITS	1
2. INTRODUCTION	5
3. DOOR DRAG	6
3.1 General	6
3.2 Prediction of Door Drag	6
3.2.1 Door leading and trailing edges: straight with square edges (Sketch 3.2(a))	10
3.2.1.1 Subsonic flow	10
3.2.1.2 Supersonic flow	13
3.2.2 Door leading and trailing edges: straight with chamfered edges (Sketch 3.2(b))	14
3.2.2.1 Subsonic flow	14
3.2.2.2 Supersonic flow	16
3.2.3 Door leading and trailing edges: sawtooth with chamfered edges (Sketch 3.2(c))	17
3.2.3.1 Subsonic flow	17
3.2.3.2 Supersonic flow	18
3.3 Summary of Door Drag Prediction Components	18
3.4 Total Drag Coefficient due to the Presence of a Rectangular Cavity with Doors Open at 90°	20
3.5 Alleviation of Door Drag	21
4. DERIVATION AND REFERENCES	22
4.1 Derivation	22
4.2 References	22
5. EXAMPLES	23
5.1 Door leading and trailing edges: straight with square edges	24
5.1.1 $M_1 = 0.8$	24
5.1.2 $M_1 = 2.0$	28
5.2 Summary of Results	31
APPENDIX A PRESSURE DRAG DUE TO THE FLAT FRONT FACE OF A TWO-DIMENSIONAL LONG FLAT PLATE	33
A1. NOTATION AND UNITS	33
A2. INTRODUCTION	34

A3.	WAVE DRAG DUE TO THE FLAT FRONT FACE OF A TWO-DIMENSIONAL LONG FLAT PLATE	34
A4.	CONJECTURAL EXTENSION OF THE METHOD OF SECTION A3 TO SUBSONIC SPEEDS	37
A5.	CONCLUSION	38
A6.	DERIVATION	39
	APPENDIX B BASE DRAG OF A TWO-DIMENSIONAL FLAT PLATE WITH A BLUNT TRAILING EDGE AT SUBSONIC SPEEDS	40
B1.	NOTATION AND UNITS	40
B2.	INTRODUCTION	42
B3.	SUBSONIC BASE DRAG DUE TO A BLUNT TRAILING EDGE ON A TWO-DIMENSIONAL FLAT PLATE	43
	B3.1 Development of Prediction Method for Base Drag	47
	B3.1.1 Effect of trailing-edge sweep	50
	B3.1.2 The prediction method	52
B4.	EFFECTS OF THREE-DIMENSIONAL FLOW	54
B5.	CONCLUDING REMARKS	56
B6.	DERIVATION AND REFERENCES	56
	B6.1 Derivation	56
	B6.2 References	57
	APPENDIX C PRESSURE DRAG OF A WEDGE LEADING EDGE ON A TWO-DIMENSIONAL FLAT PLATE UP TO SUPERSONIC SPEEDS	59
C1.	NOTATION AND UNITS	59
C2.	INTRODUCTION	60
C3.	PRESSURE DRAG OF A WEDGE LEADING EDGE ON A TWO-DIMENSIONAL FLAT PLATE UP TO SUPERSONIC SPEEDS	61
	C3.1 Prediction Method	63
	C3.1.1 Subsonic speeds ($\tilde{M}_1 < 0$)	63
	C3.1.2 Supersonic speeds ($\tilde{M}_1 \geq 0$)	65
	C3.2 Solution of Oblique Shock Relations for ζ	69
C4.	CONCLUSIONS	73
C5.	DERIVATION AND REFERENCES	74
	C5.1 Derivation	74
	C5.2 References	74

DRAG OF A RECTANGULAR PLANFORM CAVITY IN A FLAT PLATE WITH A TURBULENT BOUNDARY LAYER FOR MACH NUMBERS UP TO 3. PART III : EFFECT OF DOORS

1. NOTATION AND UNITS

SI British

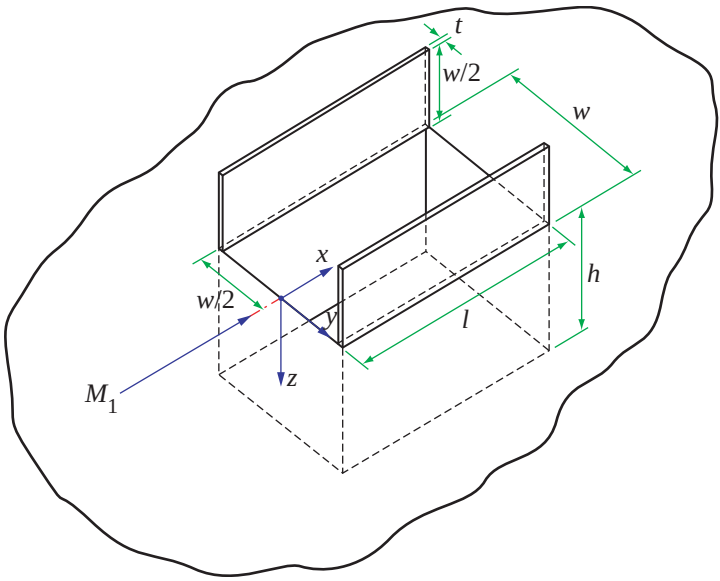
C_D	drag coefficient due to presence of cavity (<i>i.e.</i> net drag), with pair of doors open at 90°, based on planform (floor) area wl and kinetic pressure q_{1m} , see Equation (3.48)
C_{Db}	two-dimensional base drag coefficient of door with unswept trailing edge; (average base drag of door per unit width)/($q_{1m}t$) = (base drag of door)/($q_{1m}t w/2$), Equations (3.7) and (3.21) to (3.24)
C_{Db0}	value of C_{Db} at $M_1 = 0$, Equations (3.9) and (3.10)
C_{Db1}	M_1 -dependent component of C_{Db} in supersonic flow, Equation (3.21)
C_{Db2}	θ -dependent component of C_{Db} in supersonic flow, Equation (3.22)
C_{Dd}	gross drag coefficient for pair of open doors, based on wl and q_{1m} , Equations (3.2), (3.19), (3.26), (3.34), (3.40), (3.45), (3.46) and (3.47)
$(\Delta C_{Dd})_{le}$	increment in C_{Dd} arising from pressure drag due to shaping of door leading edges, based on wl and q_{1m} , see Equation (3.47) and Tables 3.1(a) and 3.2(a)
$(\Delta C_{Dd})_{sf}$	increment in C_{Dd} arising from skin friction, based on wl and q_{1m} , see Equation (3.47) and Tables 3.1(a) and 3.2(a)
$(\Delta C_{Dd})_{te}$	increment in C_{Dd} arising from pressure drag due to shaping of door trailing edges, based on wl and q_{1m} , see Equation (3.47) and Tables 3.1(a) and 3.2(a)
$(\Delta C_{Dd})_1$	increment in C_{Dd} arising from pressure drag due to shaping of door leading and trailing edges, based on S_{ref1} and q_{1m} , see Equations (3.1) and (3.2)
$(\Delta C_{Dd})_2$	increment in C_{Dd} due to skin friction on flat door surfaces, based on S_{ref2} and q_{1m} , see Equations (3.1) and (3.2)
$(\Delta C_{Dd})_3$	increment in C_{Dd} due to boundary-layer effects at door/surface junctions, based on S_{ref3} and q_{1m} , see Equation (3.1)
$(\Delta C_{Dd})_4$	increment in C_{Dd} due to interference effects between vertical door pair, based on S_{ref4} and q_{1m} , see Equation (3.1)

Issued October 2011 – 74 pages

C_{Dff}	two-dimensional subsonic drag coefficient due to unswept flat-faced door leading edge; (average drag due to flat face per unit width)/($q_{1m}t$) = (drag due to flat face)/($q_{1m}t w/2$), see Equation (3.6)		
$C_{D Tot}$	total drag coefficient (<i>i.e.</i> <i>net</i> drag) due to presence of cavity with open doors, based on wl and q_{1m} , Equation (3.48)		
$(C_{D Tot})_{ref}$	total drag coefficient due to presence of cavity with open doors, based on S_{ref} and q_{∞} , Equations (3.49) to (3.51)		
C_{Dwff}	two-dimensional wave drag coefficient due to unswept flat-faced door leading edge; (average wave drag due to flat face per unit width)/($q_{1m}t$) = (wave drag due to flat face)/($q_{1m}t w/2$), see Equation (3.20)		
$C_{D\tau}$	two-dimensional drag coefficient due to chamfered unswept door leading edge; (average drag due to chamfered leading edge per unit width)/($q_{1m}t/\tan \tau$) = (drag due to chamfered leading edge)/[($q_{1m}t/\tan \tau$) $w/2$], Equations (3.35) and (3.38)		
$\tilde{C}_{D\tau}$	reduced drag coefficient, Equation (3.27), see Equations (3.29), (3.30) and (3.36), (3.37)		
C_{Fte}	two-dimensional flat plate mean skin friction coefficient for one side of open door (calculated using $R_x = R_l$), based on S_{ref2} and q_{1m} , Equation (3.13)		
C_f	two-dimensional flat plate local skin friction coefficient in absence of cavity		
C_{fm}	value of C_f at cavity mid-length		
C_{p1}	M_1 -dependent component of base pressure coefficient in supersonic flow, Equation (3.21) or Figure 1a of ESDU W.S.02.03.07 (Derivation 2)		
C_{p2}	θ -dependent component of base pressure coefficient in supersonic flow, Equation (3.22) or Figure 1b of ESDU W.S.02.03.07 (Derivation 2)		
F_{M1}	Mach number factor in Equation (3.7), given by Equation (3.8)		
F_{M1A}	Mach number factor in Equation (3.13), given by Equation (3.14)		
F_{M1B}	Mach number factor in Equation (3.13), given by Equation (3.15)		
F_{sev}	factor in ESDU 00006 (Derivation 7) to account for side-edge vortices		
h	depth of rectangular planform cavity, see Sketch 1.1	m	ft
l	cavity length, see Sketches 1.1 and 3.2	m	ft

M_1	Mach number at edge of boundary layer at cavity mid-length, in absence of cavity		
$\tilde{M}_1$	reduced Mach number, Equation (3.28)		
M_∞	free-stream Mach number		
m_d	drag magnification factor in Equation (3.49)		
n	exponent in Equation (3.13), given by Equation (3.16)		
p_1	static pressure at edge of boundary layer, in absence of cavity	N/m ²	lbf/ft ²
p_{1m}	value of p_1 at cavity mid-length, see Equation (3.38)	N/m ²	lbf/ft ²
p_2	static pressure on wedge leading edge for supersonic upstream flow, see Equation (3.38)	N/m ²	lbf/ft ²
q_1	local kinetic pressure at edge of boundary layer, in absence of cavity	N/m ²	lbf/ft ²
q_{1m}	value of q_1 at cavity mid-length	N/m ²	lbf/ft ²
q_∞	free-stream kinetic pressure	N/m ²	lbf/ft ²
R_l	Reynolds number based on l and R_{1m} , $R_{1m}l$		
R_x	Reynolds number based on x and R_{1m} , $R_{1m}x$		
R_1	local unit Reynolds number based on conditions at edge of boundary layer, in absence of cavity	m ⁻¹	ft ⁻¹
R_{1m}	value of R_1 for cavity mid-length	m ⁻¹	ft ⁻¹
$R_{1\infty}$	free-stream unit Reynolds number	m ⁻¹	ft ⁻¹
S_{ref}	wing reference area	m ²	ft ²
S_{ref1}	reference area for $(\Delta C_{Dd})_1$, Equation (3.4)	m ²	ft ²
$(S_{ref1})_{le}$	value of S_{ref1} for chamfered door leading edge, Equation (3.31)	m ²	ft ²
$(S_{ref1})_{te}$	value of S_{ref1} for chamfered door trailing edge, Equation (3.32)	m ²	ft ²
S_{ref2}	reference area for $(\Delta C_{Dd})_2$, Equation (3.17) for straight door edges, Equation (3.42) for sawtooth door edges	m ²	ft ²
S_{ref3}	reference area for $(\Delta C_{Dd})_3$, see Equation (3.1)	m ²	ft ²
S_{ref4}	reference area for $(\Delta C_{Dd})_4$, see Equation (3.1)	m ²	ft ²
t	door thickness, see Sketches 1.1 and 3.2	m	ft (or in.)
w	width of rectangular planform cavity, see Sketches 1.1 and 3.2	m	ft

x, y, z	cavity coordinates from origin at mid-width of front wall top edge (lip); right-handed orthogonal set with x positive aft and z normal to surface, positive into cavity, as shown in Sketch 1.1	m	ft
γ	ratio of specific heat capacities, taken as 1.4 for air		
δ	thickness of turbulent boundary layer at open door base, Equation (3.11)	m	ft
θ	momentum thickness of turbulent boundary layer at open door base, Equation (3.23)	m	ft
Λ	sawtooth sweep angle, see Sketch 3.2(c)	deg	deg
τ	chamfer angle of door leading or trailing edge, measured in streamwise direction, see Sketches 3.2(b) and 3.2(c)	deg	deg



Sketch 1.1 Cavity/door geometry and coordinate system

2. INTRODUCTION

This Data Item is the third in the series of Items concerned with the prediction of the drag of rectangular planform cavities for Mach numbers up to 3. ESDU 00006 (Part I, Derivation 7) deals with cavities having closed flow, and ESDU 00007 (Part II, Derivation 8) is for cavities having open or transitional flow. Those Items are only applicable to cavities without doors, consequently the present Data Item (Part III) completes the series with the provision of methods for the prediction of the drag of a pair of equal width doors open at 90°, typical of weapons bay applications.

The methods, given in Section 3, use data (where available) from the ESDU Aerodynamics Series, and involve planar doors at subsonic or supersonic speeds. The effects of three types of door leading and trailing edges are considered: straight (*i.e.* unswept) with either square edges, in Section 3.2.1, or chamfered (*i.e.* wedge or chiselled) edges, in Section 3.2.2, or sawtoothed with chamfered edges, in Section 3.2.3. A summary of the door drag prediction components is given in Section 3.3, which also includes tables of the components and references to the relevant prediction equations. The way in which door drag is used in the determination of the total drag coefficient due to the presence of a rectangular cavity with doors open at 90° is given in Section 3.4.

The drag prediction methods for cavity doors in Section 3.2 were developed using wind-tunnel data for flat plates at zero angle of attack in uniform flows. As with the methods for the drag of cavities without doors (ESDU 00006 and ESDU 00007), in order to apply the methods to a practical situation in which a cavity with a pair of doors open at 90° is in a non-uniform flow, an artifice employed in the application of excrescence drag data is used, see ESDU 90029 (Derivation 6). In essence, that involves the use of local flow values for Mach number, unit Reynolds number and kinetic pressure at the edge of the boundary layer at the cavity mid-length location, but in the absence of the cavity, and that is detailed in Section 3.4.

With regard to base drag, ESDU 10017 (Reference 18) provides a guide to the effectiveness of the various types of trailing-edge device used to alleviate the drag of blunt trailing edges. The possible use and appropriateness of such devices for weapons bay doors is discussed in Section 3.5.

In order to gain some appreciation of the effects on drag of the different door leading-edge and trailing-edge geometries, a set of examples based on the cavity in Example 2 of ESDU 00006 at $M_1 = 0.8$ and 2.0 is given in Section 5.

The cavity drags predicted using ESDU 00006 and ESDU 00007 are *net* values, representing the drag due to the *presence* (incremental drag) of the cavity without doors. For that, the drag in the *absence* of the cavity (*i.e.* the skin friction drag of the area of flat plate occupied by the cavity) was accounted for in those Items using, as an approximation, the local skin friction coefficient at the cavity mid-length. Therefore, in order to determine the total incremental drag (*net* drag) due to the cavity with open doors, see Section 3.4, the predicted door drag values given by the methods of Section 3 are *gross* values, which include the skin friction on both sides of the open doors.

As noted earlier, the methods given in Section 3 use available data from the ESDU Aerodynamics Series, but there are three main areas where there are no suitable ESDU data. Those areas concern the pressure drag due to blunt leading edges, blunt trailing edges and chamfered (wedge) leading edges of flat plates at subsonic speeds. Appendix A presents semi-empirical methods for the prediction of the subsonic and supersonic pressure drag due to the blunt leading edge of a two-dimensional flat plate. Although a method for supersonic speeds is already available in the ESDU data (ESDU W.S.02.03.10 – Derivation A3 in Appendix A), a re-evaluation using the pressure data of ESDU W.S.05.03.01 (Derivation A2 in Appendix A) allowed a plausible extension to subsonic speeds. A simple empirical method for the prediction of the subsonic base drag of a two-dimensional flat plate with a blunt trailing edge, with some guidance on the effects of trailing-edge sweep and finite plate width, is given in Appendix B. Appendix C

presents a semi-empirical method for the prediction of the pressure drag due to a wedge leading edge on a two-dimensional flat plate at subsonic and transonic speeds, albeit for laminar flow only. An extension to supersonic speeds using oblique shock wave theory is also included.

3. DOOR DRAG

3.1 General

As they stand, the methods of ESDU 00006 and 00007 relate to the drag of rectangular planform cavities *without doors*, the reason being that no drag data for cavities with doors were available at the time of their preparation, and that is still the situation. Consequently, prediction methods for door drag have been developed using existing ESDU Data Items, together with additional data (Appendices A to C) for those areas in which ESDU data are not currently available. In the use of the methods to predict the drag of cavities *with doors*, the methods of both ESDU 00006 and ESDU 00007 require a slight modification in that when doors are present, no flow is expected over the side walls, and the flow will be constrained to become more nearly two-dimensional. Therefore, $w/h > 7$ should be assumed for ESDU 00006 and $w/h > 4$ should be assumed for ESDU 00007. Furthermore, side-edge vortices, which for closed flow can contribute a significant drag at supersonic speeds, will not be present. Therefore, F_{sev} is set to zero in ESDU 00006. For open or transitional flow, side-edge vortices are less likely and there is some doubt about their presence when the shear layer bridges the cavity. If they are present, the empirical method of ESDU 00007 automatically accounts for them and their effect cannot be separated out.

3.2 Prediction of Door Drag

The wide variety of weapons bay door designs, both in terms of the opening configuration, see Sketch 5.3 in ESDU 08011 (Reference 15), and the important treatment of the leading and trailing edges of the individual door panels, makes the development of a generalised drag prediction method particularly difficult.

For a rectangular planform cavity any longitudinal curvature is usually minor, whereas lateral curvature will depend on the aircraft type. For older designs with a body of circular cross section, like the English Electric Canberra or Boeing B52, the lateral curvature is significant. For the newer designs, especially those with an integrated wing-body, like the Lockheed F117 or the Northrop Grumman B2, the door panels have negligible lateral curvature.

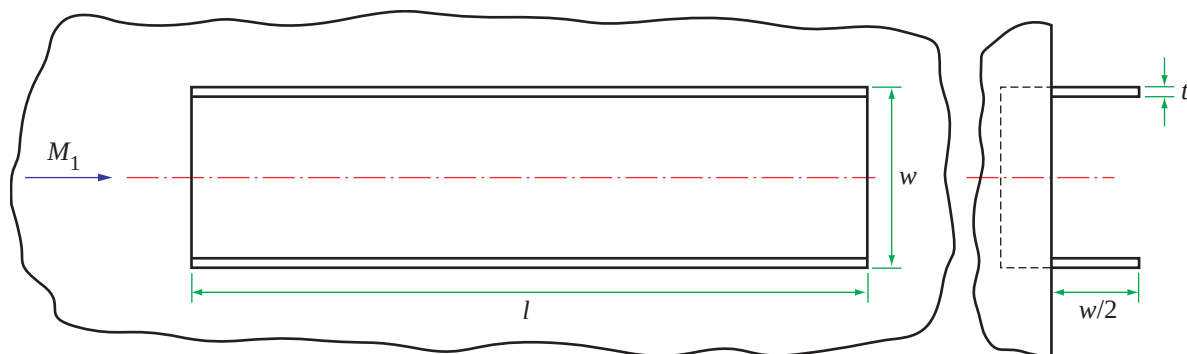
Panel leading and trailing edges in the older designs usually had no special treatment and were left essentially straight and bluff, with no concession to low drag. Even the comparatively modern Rockwell B-1 came into that category, see Sketch 3.21 in ESDU 08012 (Reference 16). The low radar signature (“stealth”) requirement on modern combat aircraft dictates the use of leading and trailing edges that are neither straight nor bluff. The shape usually adopted is that of a sawtooth, see Sketch 3.1.



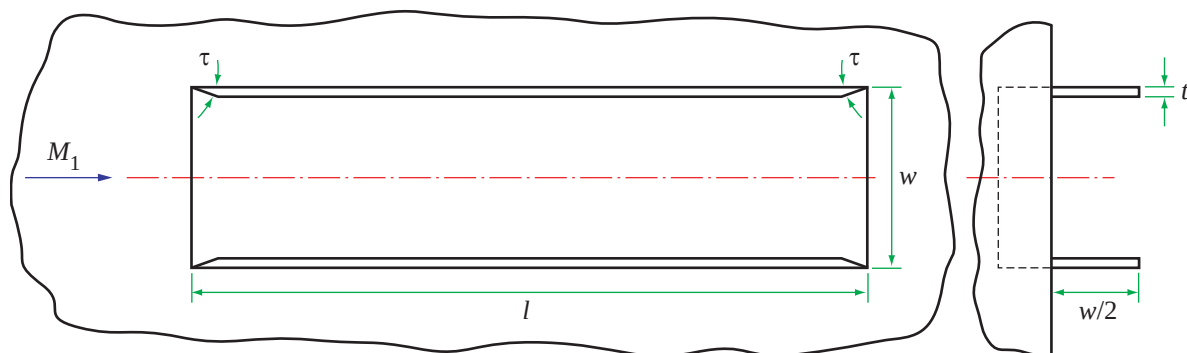
Sketch 3.1 Lockheed Martin F22: Bay doors showing serrated (sawtooth) edges
(Photo © Tom Dowd, Dreamstime.com)

The use of a chamfer, or chisel-edge, on the teeth not only improves “stealth”, but also aids in the reduction of drag, especially wave drag at supersonic speeds.

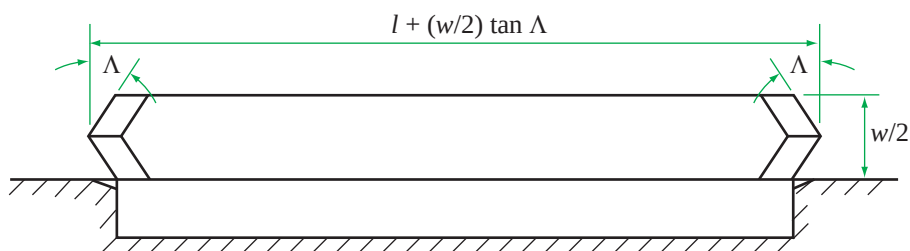
For the purposes of the development of simple door drag prediction methods, idealised construction will be assumed in which the door panels are flat plates with leading edges that are either straight with square (blunt, or flat-faced) or chamfered (wedge, or chiselled) edges, or sawtoothed with chamfered edges. Also, for simplicity, a pair of doors open at 90° will be used. The general arrangements are as shown in Sketch 3.2.



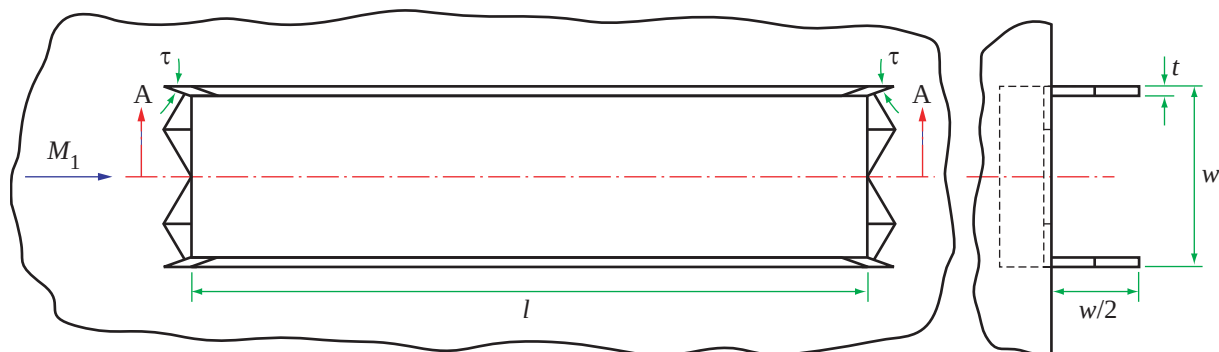
(a) Straight with square edges



(b) Straight with chamfered edges



View on A-A



(c) Sawtoothed with chamfered edges

Sketch 3.2 Door geometry

With the assumption that each door panel is a thin flat plate with different treatment of the leading and trailing edges, as shown in Sketches 3.2(a), 3.2(b) and 3.2(c), an approximate breakdown of the door drag coefficient for the pair of doors, C_{Dd} , consists of four components, as follows.

$$C_{Dd} \approx (\Delta C_{Dd})_1 S_{ref1}/(wl) + (\Delta C_{Dd})_2 S_{ref2}/(wl) + (\Delta C_{Dd})_3 S_{ref3}/(wl) + (\Delta C_{Dd})_4 S_{ref4}/(wl), \quad (3.1)$$

where,

$(\Delta C_{Dd})_1$ = increment in drag coefficient arising from pressure drag due to the shaping of the door leading and trailing edges of the pair of doors,

$(\Delta C_{Dd})_2$ = increment in drag coefficient due to the skin friction on the flat inner and outer surfaces of the pair of doors,

$(\Delta C_{Dd})_3$ = increment in drag coefficient due to boundary-layer effects at the door/surface junctions for the pair of doors

and

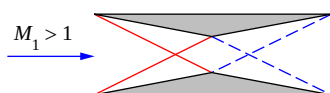
$(\Delta C_{Dd})_4$ = increment in drag coefficient due to interference effects between the vertical door pair.

In Equation (3.1), S_{ref1} to S_{ref4} are the reference areas on which $(\Delta C_{Dd})_1$ to $(\Delta C_{Dd})_4$ are based, and the factors $S_{ref1}/(wl)$ to $S_{ref4}/(wl)$ are used to convert the corresponding drag coefficients to ones based on wl to accord with the definition of C_D for the cavity itself, without doors, as obtained from ESDU 00006 or ESDU 00007.

Before going on to look at the first two terms in Equation (3.1) in more detail, the final two terms will be considered. Equation (3.1) can be simplified by ignoring interference effects between the vertical door pair, so that $(\Delta C_{Dd})_4 = 0$. This is probably a reasonable assumption at subsonic speeds, since biplane theory suggests no interference on drag at zero lift, see ESDU 81023 (Reference 13). The supersonic case is more difficult to assess, even for the simple configuration shown in Sketch 3.2(b) in which the shock and expansion waves would suffer multiple reflections. However, it is likely that the effect on wave drag would be minimal[†] and, unless the shocks reflected from the door inward-facing surfaces induced flow separation, the effect on overall door drag is also likely to be minimal.

The treatment of the boundary-layer effects via $(\Delta C_{Dd})_3$ in Equation (3.1) is a complex problem. In the simplest case, each door is bounded (i) on one side by a horizontal flat surface over which the free-stream flows, generating a turbulent boundary layer with origin upstream of the cavity, and (ii) on the other side by the separated, possibly resonant, shear layer over the cavity, with free-stream flow above it. A simple approach to the problem is obtained by the use of ESDU 84035 (Derivation 5) if it is assumed that the conditions in (i), above, also apply to (ii), so that in effect the cavity has been filled flush with the surrounding surface. That assumption implies an open type of cavity flow (ESDU 00007) in which the separated shear layer bridges the cavity. Open flow is characterised by unsteadiness with resonance, often involving significant vertical shear flow amplitudes, possibly affecting the flow up to, say, a third of the cavity depth

[†] For the special case of the Busemann biplane (Reference 9, see also References 10, 11 and 17, for example) consisting of a pair of half wedges (isosceles triangles with apexes facing) the interference is beneficial in reducing the wave drag of the pair in isolation, attaining a minimum when the leading-edge shocks strike the apexes, as shown below.



above the cavity mouth – in simple terms the effective boundary-layer thickness is periodically increased from the steady state condition. From ESDU 84035 it is found that the effect of the boundary layer on the horizontal surface is to *reduce* the door drag; the thicker the boundary layer, the greater the drag reduction. For all practical door geometries, the ratio of the door width ($w/2$ in Sketch 3.2) to the boundary-layer thickness on the horizontal surface at the door (and cavity) mid-length will be considerably greater than unity, offering a drag reduction of a few percent at most, which is not worth taking account of bearing in mind here the gross assumptions involved, and so it will be assumed that $(\Delta C_{Dd})_3 = 0$.

With the foregoing assumptions, Equation (3.1) can be written as

$$C_{Dd} = (\Delta C_{Dd})_1 \frac{S_{ref1}}{wl} + (\Delta C_{Dd})_2 \frac{S_{ref2}}{wl}, \quad (3.2)$$

where $(\Delta C_{Dd})_1$ and $(\Delta C_{Dd})_2$ are the pressure and skin friction drag contributions for a *pair* of doors.

The above equation represents the *gross* drag of the doors. At first sight it might be thought that the *net* drag, taking account of the door drag in the closed position, would be required. However, that has already been accounted for (using C_{fm}) in the determination of the *net* drag coefficient, C_D , for the cavity in ESDU 00006 and ESDU 00007, as noted in Section 2. For use in those two Data Items C_{fm} is the flat plate local skin friction coefficient at the door mid-length with the doors closed, obtained from the graphical data in ESDU 68020 (Derivation 3) or the curve fit in ESDU 00006. Strictly, the drag of the doors in the closed position should be determined using the values of the flat plate *mean* skin friction coefficient at the closed door leading and trailing edges, but the use of C_{fm} simplifies the procedure, and the error involved is quite small, see Section A3 in Appendix A to ESDU 00006.

The prediction methods for the pressure drag, via $(\Delta C_{Dd})_1$, depend on the particular geometry of the door leading and trailing edges, *i.e.* as in Sketch 3.2(a), 3.2(b) or 3.2(c), and whether the flow is subsonic or supersonic. The turbulent boundary-layer skin friction drag (flat plate), via $(\Delta C_{Dd})_2$, depends only on Mach number and Reynolds number. The prediction methods for the geometries illustrated in Sketches 3.2(a) to 3.2(c) will be considered in Sections 3.2.1 to 3.2.3, respectively, for both subsonic and supersonic flow. All the methods assume two-dimensional flow over the doors. A summary of the door drag prediction components is given in Section 3.3, which also includes tables of the components and references to the relevant prediction equations. The total drag coefficient due to the presence of a rectangular cavity with doors open at 90° is given in Section 3.4.

3.2.1 Door leading and trailing edges: straight with square edges (Sketch 3.2(a))

3.2.1.1 Subsonic flow

There are currently no ESDU data for the pressure drag of flat plates with blunt leading and trailing edges. However, Appendices A and B provide suitable prediction methods for the subsonic pressure drag coefficients of the flat front and rear faces, C_{Dff} and C_{Dbb} respectively, of two-dimensional long flat plates at zero angle of attack.

The pressure drag term in Equation (3.2) is therefore written as

$$(\Delta C_{Dd})_1 \frac{S_{ref1}}{wl} = 2(C_{Dff} + C_{Dbb}) \frac{S_{ref1}}{wl}, \quad (3.3)$$

where $(\Delta C_{Dd})_1$ is the value for a pair of doors and S_{ref1} is the door edge area, given by

$$S_{ref1} = \frac{w}{2}t, \quad (3.4)$$

where the door width is $w/2$ and thickness is t , see Sketches 1.1 and 3.2.

Therefore, Equation (3.3) becomes

$$(\Delta C_{Dd})_1 \frac{S_{ref1}}{wl} = (C_{Dff} + C_{Db}) \frac{t}{l}. \quad (3.5)$$

The value of C_{Dff} , for two-dimensional flow is given by Equation (A4.3) in Appendix A as

$$C_{Dff} = \frac{1.247}{M_1^2} [(1 + 0.2M_1^2)^{3.5} - 1], \text{ for } M_1 \leq 1. \quad (3.6)$$

Equation (3.6) is based on a conjectural extension to subsonic speeds of the method for supersonic speeds, see Appendix A. In effect, it assumes that the average pressure coefficient across the flat face is 0.873 times the stagnation value. A graphical presentation of Equation (3.6) is given in Sketch A4.1 of Appendix A.

The base drag coefficient for two-dimensional flow, C_{Db} , in Equation (3.5) is given in Appendix B as

$$C_{Db} = F_{M1} C_{Db0}, \quad (3.7)$$

where

$$F_{M1} = 1 + 0.438M_1^{2.81}(1 - M_1)^{-0.0409}, \text{ for } M_1 \leq 0.8, \quad (3.8)$$

$$C_{Db0} = 0.6 \left[\sin\left(\frac{\pi t}{11\delta}\right) \right]^{-0.1632 \log_{10}(t/\delta) + 0.4087}, \text{ for } t/\delta \leq 5.5, \quad (3.9)$$

with the argument of sine in radians

and

$$C_{Db0} = 0.6 \text{ for } t/\delta > 5.5. \quad (3.10)$$

The value of t/δ in Equation (3.9) is given in Appendix B as

$$\frac{t}{\delta} = 18.484 \frac{t}{l} (\log_{10} R_l - 2.91). \quad (3.11)$$

From the foregoing it is seen that C_{Db} is given as a function of the boundary-layer thickness, δ , at the door trailing edge, in terms of the door thickness, t , and the Mach number M_1 . Appendix B gives details of the derivation of the method, which is only applicable for $M_1 \leq 0.8$. For $0.8 < M_1 \leq 1$ local shock waves develop which produce somewhat erratic variations of C_{Db} with M_1 . Equation (3.7), using Equations (3.8)

to (3.10), is presented graphically in Sketch B3.7 of Appendix B. Although Equation (3.8) gives plausible values even up to $M_1 = 0.99$, it eventually breaks down at $M_1 = 1$, see Sketch B3.1 in Appendix B which illustrates the likely overly pessimistic base drag prediction over the range $0.8 < M_1 \leq 1$.

On the basis of very few test data, the method for two-dimensional flow is extended in Appendix B to allow for the alleviating effects of finite width on base drag. However, for the present purpose it is suggested that the conservative two-dimensional flow case given by Equations (3.7) to (3.11) be used.

The skin friction drag term in Equation (3.2) is

$$(\Delta C_{Dd})_2 \frac{S_{ref2}}{wl} = 4C_{Fte} \frac{S_{ref2}}{wl}, \quad (3.12)$$

where the factor 4 accounts for the four exposed surfaces of the pair of doors, and C_{Fte} is the two-dimensional flat plate mean skin friction coefficient at the door trailing edge (in the *open* position), given by Equations (4.2) to (4.5) in ESDU 78019 (Derivation 4) as

$$C_{Fte} = \frac{0.455}{F_{M1A} (\log_{10} F_{M1B} R_l)^n}, \quad (3.13)$$

where

$$F_{M1A} = \frac{0.178M_1^2}{[\tan^{-1}(0.4219M_1)]^2}, \quad (3.14)$$

with the inverse tangent evaluated in radians,

$$F_{M1B} = \frac{(1 + 0.178M_1^2)^{-0.702}}{F_{M1A}} \quad (3.15)$$

and

$$n = 2.62105 - 0.0042167 \log_{10}(F_{M1B} R_l). \quad (3.16)$$

Equations (3.13) to (3.16) provide an excellent fit (to within $\pm 0.1\%$) to the curves given in Figure 3 of ESDU 68020 (Derivation 3) with $R_x \equiv R_l$.

In Equation (3.12) S_{ref2} is the surface area of one side of a door, which for the doors in Sketch 3.2(a) is

$$S_{ref2} = \frac{w}{2} l. \quad (3.17)$$

Therefore, Equation (3.12) becomes

$$(\Delta C_{Dd})_2 \frac{S_{ref2}}{wl} = 2C_{Fte}. \quad (3.18)$$

So, with Equations (3.5) and (3.18), Equation (3.2) gives the total gross drag coefficient for the pair of doors as

$$C_{Dd} = C_{Dff} \frac{t}{l} + C_{Db} \frac{t}{l} + 2C_{Fte} \quad (3.19)$$

3.2.1.2 Supersonic flow

In supersonic flow, the variation with M_1 of the wave drag coefficient, C_{Dwff} , due to the flat face of a two-dimensional long flat plate is given, together with similar data for other face profiles, in Figure 1 of ESDU W.S.02.03.10 (Derivation A3 in Appendix A). The data for the flat face were derived from the theory of Maccoll and Codd (Derivation A1). An alternative approach, using pressure distribution data from ESDU W.S.05.03.01 (Derivation A2), is given in Appendix A. That approach gives C_{Dwff} values slightly greater than those in ESDU W.S.02.03.10, and is suggested for use here. Equation (A3.4) in Appendix A gives

$$C_{Dwff} = \frac{1}{0.7M_1^2} \left[0.94 \left(\frac{6}{7M_1^2 - 1} \right)^{2.5} \left(\frac{6M_1^2}{5} \right)^{3.5} - 1 \right], \quad \text{for } M_1 \geq 1, \quad (3.20)$$

which is presented graphically in Sketch A4.1 of Appendix A. The factor 0.94 in Equation (3.20) was derived from an average of the pressure distribution across the flat face.

The base pressure coefficient for an aerofoil section with a blunt (flat-faced) trailing edge in two-dimensional flow is given in ESDU W.S.02.03.07[†] (Derivation 2) as the sum of two components, one (C_{p1} in Figure 1a of ESDU W.S.02.03.07) as a function of M_1 only and the other (C_{p2} in Figure 1b of ESDU W.S.02.03.07) as a function of the ratio of the base thickness (t here) to the boundary-layer momentum thickness at the base (θ). The corresponding base drag coefficient components, C_{Db1} and C_{Db2} , are then simply the base pressure coefficient components with a change of sign (negative to positive). For the present purpose, Figure 1a of ESDU W.S.02.03.07 is well represented (close to reading accuracy) by

$$C_{Db1} = -C_{p1} = 0.691 \times (10)^{-0.247M_1} + 0.409M_1^{-5.23}, \quad \text{for } M_1 \geq 1 \quad (3.21)$$

and Figure 1b is quite well represented (to within ± 0.003) by

$$C_{Db2} = -C_{p2} = -6.87 \left[\log_{10} \left(\frac{t}{\theta} \right) \right]^{-0.00787} + 6.830, \quad \text{for } 3 \leq t/\theta \leq 500. \quad (3.22)$$

So, as for subsonic base drag (Equation (3.9)), a thick boundary layer has an alleviating effect on base drag.

The value of t/θ in Equation (3.22) can be obtained via the relationship $C_{Fte} = 2\theta/l$, so that

$$\frac{t}{\theta} = \frac{2}{C_{Fte}} \frac{t}{l}, \quad (3.23)$$

[†] The method in ESDU W.S.02.03.07 is based on a correlation by Nash (Reference B19 in Appendix B) of a large number of wind-tunnel and flight-test data for aerofoils with small values of thickness/chord. Although it is known that boattails can have a significant alleviating effect on base drag, Nash notes that for the aerofoils used the effect, if any, was small.

with C_{Fte} given by Equations (3.13) to (3.16) or Figure 3 in ESDU 68020.

The total base drag coefficient is then

$$C_{Db} = C_{Db1} + C_{Db2}. \quad (3.24)$$

The first term in Equation (3.2) can now be written as

$$(\Delta C_{Dd})_1 \frac{S_{ref1}}{wl} = 2(C_{Dwff} + C_{Db}) \frac{w/2}{wl} t = (C_{Dwff} + C_{Db}) \frac{t}{l}, \quad (3.25)$$

where C_{Dwff} is given by Equation (3.20) or Sketch A4.1 in Appendix A and C_{Db} is given by Equations (3.21) to (3.24) or Figure 1 of ESDU W.S.02.03.07.

The second term in Equation (3.2) is again evaluated via Equation (3.18) with C_{Fte} given by Equations (3.13) to (3.16), which are applicable to subsonic or supersonic speeds, or Figure 3 of ESDU 68020. Therefore, Equation (3.2) now becomes

$$C_{Dd} = C_{Dwff} \frac{t}{l} + C_{Db} \frac{t}{l} + 2C_{Fte}. \quad (3.26)$$

3.2.2 Door leading and trailing edges: straight with chamfered edges (Sketch 3.2(b))

3.2.2.1 Subsonic flow

There are currently no ESDU data concerning the pressure drag of flat plates with chamfered (or wedge) leading edges for subsonic speeds. Appendix C contains a method developed by Bryson (Derivation C4 in Appendix C) for the surface pressure distribution on wedges with small apex angles ($\tau \leq 10^\circ$). Subsequent integration of the pressure coefficient distributions gave the corresponding two-dimensional pressure drag coefficients, $C_{D\tau}$, for each wedge over the test Mach number range $0.66 \leq M_1 \leq 1.47$. The data were then correlated in terms of reduced drag coefficient, $\tilde{C}_{D\tau}$, against reduced Mach number[†], $\tilde{M}_1$, using the transonic similarity parameters widely used at that time. Later work by Spreiter (Derivation C6 in Appendix C) showed that a modification to the original form of the similarity parameters gave a much improved correlation of the data, especially for supersonic speeds.

The modified similarity parameters are

$$\tilde{C}_{D\tau} = \frac{(\gamma + 1)^{1/3} M_1^{2/3} C_{D\tau}}{(\tan \tau)^{5/3}} = 1.3389 \frac{M_1^{2/3} C_{D\tau}}{(\tan \tau)^{5/3}} \quad \text{with } \gamma = 1.4 \text{ for air,} \quad (3.27)$$

and

$$\tilde{M}_1 = \frac{M_1^{-4/3} (M_1^2 - 1)}{[(\gamma + 1) \tan \tau]^{2/3}} = 0.55786 \frac{M_1^{-4/3} (M_1^2 - 1)}{(\tan \tau)^{2/3}} \quad \text{with } \gamma = 1.4. \quad (3.28)$$

[†] In Derivation C4, Bryson used ξ , common at the time, but $\tilde{M}_1$ has been used here as it is felt to be a more logical companion to $\tilde{C}_{D\tau}$.

The value of $\tilde{M}_1$ is negative for $M_1 < 1$, zero for $M_1 = 1$, and positive for $M_1 > 1$.

In Equation (3.27), $C_{D\tau}$ is based on the axial length of the wedge, $t/\tan \tau$, and is the pressure drag coefficient for the wedge of angle τ , see Sketch 3.2(b).

Sketch C3.3 in Appendix C presents the correlation curve for subsonic speeds, which is given by

$$\tilde{C}_{D\tau} = \frac{0.730 - 0.904\tilde{M}_1 - 0.218\tilde{M}_1^2}{0.481 + 4.33\tilde{M}_1^2}, \quad \text{for } -2.2 \leq \tilde{M}_1 \leq -0.4, \quad (3.29)$$

and

$$\tilde{C}_{D\tau} = 1.7 + 2\tilde{M}_1, \quad \text{for } -0.4 < \tilde{M}_1 < 0. \quad (3.30)$$

For the application to a three-dimensional wedge the reference area for the leading edge is

$$(S_{ref1})_{le} = \frac{w}{2} \frac{t}{\tan \tau}. \quad (3.31)$$

No data have been found for similar wedge trailing edges in subsonic flow. For the idealised geometry of Sketch 3.2(b), the slope discontinuity at the aft shoulder would likely create a problem in practice, leading to flow separation at relatively small values of τ . For a conservative estimate of wedge trailing-edge drag it would be prudent to assume fully separated flow over it. An approximate solution to that case is given by Equations (3.7) to (3.11) of Section 3.2.1.1 for the base drag coefficient, C_{Db} , of a flat rear face.

The reference area for C_{Db} is

$$(S_{ref1})_{te} = \frac{w}{2} t. \quad (3.32)$$

So, the first term in Equation (3.2) is

$$\begin{aligned} (\Delta C_{Dd})_1 \frac{S_{ref1}}{wl} &= 2C_{D\tau} \frac{(w/2)(t/\tan \tau)}{wl} + 2C_{Db} \frac{(w/2)t}{wl} \\ &= \left(\frac{C_{D\tau}}{\tan \tau} + C_{Db} \right) \frac{t}{l}. \end{aligned} \quad (3.33)$$

The second term in Equation (3.2) is again evaluated via Equation (3.18) with C_{Fte} given by Equations (3.13) to (3.16) or Figure 3 of ESDU 68020. Therefore, Equation (3.2) now becomes

$$C_{Dd} = \left(\frac{C_{D\tau}}{\tan \tau} \right) \frac{t}{l} + C_{Db} \frac{t}{l} + 2C_{Fte}. \quad (3.34)$$

The value of $C_{D\tau}/\tan \tau$ is given by a rearrangement of Equation (3.27) as

$$\frac{C_{D\tau}}{\tan \tau} = 0.74688(\tan \tau)^{2/3} M_1^{-2/3} \tilde{C}_{D\tau}, \quad (3.35)$$

where $\tilde{C}_{D\tau}$ is obtained from Equation (3.29) or (3.30) or from Sketch C3.3 in Appendix C.

3.2.2.2 Supersonic flow

As noted in Section 3.2.2.1, Bryson's test data for $C_{D\tau}$ concerning two-dimensional wedges at supersonic speeds up to $M_1 = 1.47$ were well correlated using Spreiter's modified transonic similarity parameters, Equations (3.27) and (3.28), see Appendix C. Sketch C3.5 in that Appendix presents the correlation curve, given by

$$\tilde{C}_{D\tau} = 1.7 + 2\tilde{M}_1, \quad (3.36)$$

for $0 \leq \tilde{M}_1 \leq 0.62$,

and

$$\tilde{C}_{D\tau} = 1.706 + 2.600\tilde{M}_1 - 6.280\tilde{M}_1^2 + 17.49\tilde{M}_1^3 - 17.86\tilde{M}_1^4 + 5.530\tilde{M}_1^5, \quad (3.37)$$

for $0.62 < \tilde{M}_1 \leq 1.2$.

Sketch C3.1 in Appendix C shows that for $0 \leq \tilde{M}_1 \leq 1.2$ the test data relate mainly to cases with a detached bow shock. For $M_1 = 1.2$ the bow shock is marginally attached for τ values up to about 25° , and so for $\tilde{M}_1 > 1.2$ oblique shock wave theory, assuming attached shocks, is appropriate. The simplest method is to use the graphical presentation in Figure 2 of ESDU S.00.03.09 (Derivation 1) to determine p_2/p_{1m} , where p_2 and p_{1m} are the static pressures on the wedge and at the edge of the boundary layer at the cavity mid-length, in the absence of the cavity, respectively. The weak shock solution is required, i.e. the lower of the two values of p_2/p_{1m} for given values of τ and M_1 . (Note that p_{1m} is given as p_1 and τ is given as δ in ESDU S.00.03.09.) The value of $C_{D\tau}/\tan \tau$ is then given by

$$\frac{C_{D\tau}}{\tan \tau} = C_p = \frac{(p_2/p_{1m}) - 1}{0.7M_1^2}. \quad (3.38)$$

Equation (3.38) is used for $\tilde{M}_1 > 1.2$, and a good approximation to the corresponding M_1 is given via Equation (C3.15) in Appendix C as

$$M_1 > 1 + 6.022 \times 10^{-2} \tau - 2.486 \times 10^{-3} \tau^2 + 1.198 \times 10^{-4} \tau^3 - 1.767 \times 10^{-6} \tau^4. \quad (3.39)$$

A plot of the boundary for $\tilde{M}_1 = 1.2$ is given in Sketch C3.6 of Appendix C.

As noted in Appendix C, it is difficult to obtain an accurate value of p_2/p_{1m} (and hence $C_{D\tau}$) from ESDU S.00.03.09, partly because of the likely need to interpolate in τ , but more especially because p_2/p_{1m} , rather than $(p_2/p_{1m}) - 1$, is presented. In spite of that problem, with care the accuracy is probably satisfactory for the present purpose. Greater accuracy in the determination of C_p can be achieved by analytical means using Equations (C3.10) to (C3.14), as discussed in Appendix C.

With regard to the wedge trailing edges in supersonic flow, an assumption of simple-wave flow, see ESDU S.00.03.08 (Reference 12), would provide a thrust component offsetting the drag due to the wedge leading edges. However, fully attached flow over the aft wedges is unlikely for practical wedge angles and

so the conservative case of fully separated flow, *i.e.* effectively blunt trailing edges, will be assumed. For that case the base drag coefficient, C_{Db} , is determined using Equations (3.21) to (3.24) in Section 3.2.1.2. The reference area for C_{Db} is $(S_{ref1})_{te}$, as given by Equation (3.32).

The development of the first and second terms in Equation (3.2) is identical to that leading to Equation (3.34) for subsonic flow in Section 3.2.2.1. Therefore, Equation (3.2) here becomes

$$C_{Dd} = \left(\frac{C_{D\tau}}{\tan \tau} \right) \frac{t}{l} + C_{Db} \frac{t}{l} + 2C_{Fte}, \quad (3.40)$$

where $C_{D\tau}/\tan \tau$ is given by Equation (3.35), in which $\tilde{C}_{D\tau}$ is given by Equation (3.36) or (3.37) for $0 \leq M_1 \leq 1.2$. For $M_1 > 1.2$, $C_{D\tau}/\tan \tau$ is given by Equation (3.38).

3.2.3 Door leading and trailing edges: sawtooth with chamfered edges (Sketch 3.2(c))

3.2.3.1 Subsonic flow

An allowance for the effects of leading-edge and trailing-edge sweep on the first term in Equation (3.2) – which for straight (*i.e.* unswept, $\Lambda = 0$), chamfered edges is given by Equation (3.33) – can be made assuming infinite sheared wing conditions, involving a simple $\cos \Lambda$ factor on the $\Lambda = 0$ case. Such an assumption is consistent with that of two-dimensional conditions in the development of Equation (3.33). Therefore, Equation (3.33) here becomes

$$(\Delta C_{Dd})_1 \frac{S_{ref1}}{wl} = \left(\frac{C_{D\tau}}{\tan \tau} + C_{Db} \right) \frac{t}{l} \cos \Lambda \quad (3.41)$$

in which τ is measured in the streamwise direction, and $C_{D\tau}/\tan \tau$ for chamfered leading edges and C_{Db} for blunt (flat-faced) bases are determined as noted in Section 3.2.2.1. Section 6.1.2 in ESDU 10017 (Reference 18) shows that the small amount of data for sawtoothed trailing edges are in reasonable agreement with the term $C_{Db} \cos \Lambda$ in Equation (3.41).

With regard to the second term in Equation (3.2), from Sketch 3.2(c) S_{ref2} is here given as

$$S_{ref2} = \frac{wl}{2} + \frac{w^2}{8} \tan \Lambda, \quad (3.42)$$

so that

$$\frac{S_{ref2}}{wl} = \frac{1}{2} + \frac{1}{8} \frac{w}{l} \tan \Lambda. \quad (3.43)$$

Therefore, in this case Equation (3.12) becomes

$$(\Delta C_{Dd})_2 \frac{S_{ref2}}{wl} = 4C_{Fte} \left(\frac{1}{2} + \frac{1}{8} \frac{w}{l} \tan \Lambda \right) = 2C_{Fte} \left(1 + \frac{1}{4} \frac{w}{l} \tan \Lambda \right), \quad (3.44)$$

where $4C_{Fte}$ accounts for the two surfaces on each of the two doors, and C_{Fte} is (as in Equation (3.12)) the two-dimensional flat plate mean skin friction coefficient at the door trailing edge, determined from Equations (3.13) to (3.16) or Figure 3 of ESDU 68020. Strictly, the use of R_l here in the calculation of C_{Fte} is imprecise. The sawtooth extensions give a greater length of turbulent boundary layer, varying between l and $l + (w/2)\tan\Lambda$ across the door width, see Sketch 3.2(c). However, for most practical cases the difference in C_{Fte} by assuming $R_x = R_l$ or $R_x = R_{l+(w/2)\tan\Lambda}$ is negligible, and so the slightly conservative case using $R_x = R_l$ is suggested. In most practical cases, the increase in S_{ref2} due to the sawteeth is negligible, but the increased factor in Equation (3.44) is retained for completeness.

With the foregoing, Equation (3.2) becomes

$$C_{Dd} = \left(\frac{C_{D\tau}}{\tan\tau} \right) \frac{t}{l} \cos\Lambda + C_{Db} \frac{t}{l} \cos\Lambda + 2C_{Fte} \left(1 + \frac{1}{4} \frac{w}{l} \tan\Lambda \right). \quad (3.45)$$

3.2.3.2 Supersonic flow

The simplest approach for supersonic flow is to assume that the $\cos\Lambda$ factor applied to the straight (unswept, $\Lambda = 0$) chamfered edge case for the first term in Equation (3.2) for subsonic flow also applies here. However, while some test data were available for subsonic flow to substantiate the reduction in base drag due to the addition of sawteeth, no data for supersonic flow were available. Nevertheless, on the premise that the $\cos\Lambda$ factor can be applied to the combined pressure drag terms in Equation (3.40), then with the addition of the skin friction term in Equation (3.44), Equation (3.2) becomes, as for the subsonic flow case,

$$C_{Dd} = \left(\frac{C_{D\tau}}{\tan\tau} \right) \frac{t}{l} \cos\Lambda + C_{Db} \frac{t}{l} \cos\Lambda + 2C_{Fte} \left(1 + \frac{1}{4} \frac{w}{l} \tan\Lambda \right), \quad (3.46)$$

where $C_{D\tau}/\tan\tau$ is given by Equation (3.35), in which $\tilde{C}_{D\tau}$ is given by Equation (3.36) or (3.37) for $0 \leq M_1 \leq 1.2$. For $M_1 > 1.2$, $C_{D\tau}/\tan\tau$ is given by Equation (3.38).

3.3 Summary of Door Drag Prediction Components

The final prediction equations in Sections 3.2.1 to 3.2.3, which are presented boxed, are all of the same form, comprising three terms. The first two arise from the pressure drags due to the door leading edges (le) and trailing edges (te), while the third term is due to the skin friction drag (sf). Therefore, it is convenient to write the general form of the equations as

$$C_{Dd} = (\Delta C_{Dd})_{le} + (\Delta C_{Dd})_{te} + (\Delta C_{Dd})_{sf}, \quad (3.47)$$

in which the three components relate to the drag terms outlined above.

As an aid to the use of the boxed equations for C_{Dd} in Sections 3.2.1 to 3.2.3, Tables 3.1(a) and 3.2(a) list the three components $(\Delta C_{Dd})_{le}$, $(\Delta C_{Dd})_{te}$ and $(\Delta C_{Dd})_{sf}$ used in the given equation for C_{Dd} at subsonic and supersonic speeds, respectively. The companion Tables 3.1(b) and 3.2(b) give the corresponding equation numbers for the parameters C_{Dff} , C_{Dwff} , $C_{D\tau}/\tan\tau$, C_{Db} and C_{Fte} required in the evaluation of the three components at subsonic and supersonic speeds, respectively.

TABLE 3.1 Subsonic flow

(a) Components of C_{Dd}

Door Configuration Sketch No.	Section No.	C_{Dd} Equation No.	$(\Delta C_{Dd})_{le}$	$(\Delta C_{Dd})_{te}$	$(\Delta C_{Dd})_{sf}$
3.2(a)	3.2.1.1	(3.19)	$C_{Dff} \frac{t}{l}$	$C_{Ddb} \frac{t}{l}$	$2C_{Fte}$
3.2(b)	3.2.2.1	(3.34)	$\left(\frac{C_{D\tau}}{\tan \tau}\right) \frac{t}{l}$	$C_{Ddb} \frac{t}{l}$	$2C_{Fte}$
3.2(c)	3.2.3.1	(3.45)	$\left(\frac{C_{D\tau}}{\tan \tau}\right) \frac{t}{l} \cos \Lambda$	$C_{Ddb} \frac{t}{l} \cos \Lambda$	$2C_{Fte} \left(1 + \frac{1}{4} \frac{w}{l} \tan \Lambda\right)$

(b) Equation numbers for required parameters

Parameter	Equation No.
C_{Dff}	(3.6)
$\frac{C_{D\tau}}{\tan \tau}$	(3.35) with (3.29) or (3.30)
C_{Ddb}	(3.7) to (3.11)
C_{Fte}	(3.13) with (3.14) to (3.16)

TABLE 3.2 Supersonic flow

(a) Components of C_{Dd}

Door Configuration Sketch No.	Section No.	C_{Dd} Equation No.	$(\Delta C_{Dd})_{le}$	$(\Delta C_{Dd})_{te}$	$(\Delta C_{Dd})_{sf}$
3.2(a)	3.2.1.2	(3.26)	$C_{Dwff} \frac{t}{l}$	$C_{Ddb} \frac{t}{l}$	$2C_{Fte}$
3.2(b)	3.2.2.2	(3.40)	$\left(\frac{C_{D\tau}}{\tan \tau}\right) \frac{t}{l}$	$C_{Ddb} \frac{t}{l}$	$2C_{Fte}$
3.2(c)	3.2.3.2	(3.46)	$\left(\frac{C_{D\tau}}{\tan \tau}\right) \frac{t}{l} \cos \Lambda$	$C_{Ddb} \frac{t}{l} \cos \Lambda$	$2C_{Fte} \left(1 + \frac{1}{4} \frac{w}{l} \tan \Lambda\right)$

(b) Equation numbers for required parameters

Parameter	Equation No.
$C_{Dw\ ff}$	(3.20)
$\frac{C_{D\tau}}{\tan \tau}$	(3.35) with (3.36) or (3.37) for $0 \leq \tilde{M}_1 \leq 1.2$; (3.38) for $\tilde{M}_1 > 1.2$
C_{Db}	(3.24) with (3.21) to (3.23)
$C_{F\ te}$	(3.13) with (3.14) to (3.16)

3.4 Total Drag Coefficient due to the Presence of a Rectangular Cavity with Doors Open at 90°

The drag coefficient, C_D , due to the presence of a cavity with the flow constraints due to a pair of doors open at 90°, as shown in Sketches 3.2(a), 3.2(b) and 3.2(c), is determined from ESDU 00006 for closed flow or ESDU 00007 for transitional or open flow, as described in Section 3.1. Therefore, the total drag coefficient due to the presence of a cavity with open doors, $C_{D\ Tot}$, is

$$C_{D\ Tot} = C_D + C_{Dd} , \quad (3.48)$$

with C_{Dd} given by Equation (3.47). Thus $C_{D\ Tot}$ represents the total (net) drag increment due to the cavity with open doors.

The drag prediction methods for cavity doors in Section 3.2 were developed using wind-tunnel data for flat plates at zero angle of attack in uniform flows. In the Introduction (Section 2) it is noted that, as with the methods for the drag of cavities without doors (ESDU 00006 and ESDU 00007), in order to apply the methods to a practical situation in which a cavity with a pair of doors open at 90° is in a non-uniform flow, an artifice previously used in the application of excrescence drag data, see ESDU 90029 (Derivation 6), was also used here. To that end, the door drag coefficient C_{Dd} and all its components, together with all the flow parameters used in the prediction methods, were based on local flow values at the edge of the boundary layer at the cavity mid-length, but in the absence of the cavity. The flow parameters used were therefore M_1 , R_{1m} , p_{1m} and q_{1m} .

The principles in ESDU 90029 give $(C_{D\ Tot})_{ref}$, the value of $C_{D\ Tot}$ from Equation (3.48) based on the wing reference area S_{ref} and free-stream kinetic pressure q_∞ , as

$$(C_{D\ Tot})_{ref} = C_{D\ Tot} \frac{wl}{S_{ref}} m_d = (C_D + C_{Dd}) \frac{wl}{S_{ref}} m_d . \quad (3.49)$$