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Examples of excrescence drag prediction for typical wing components of a subsonic transport aircraft at the cruise condition

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Mr A.E. Sewell*	— McDonnell Douglas, Long Beach, Calif., USA
Mr M.R. Smith	— British Aerospace Airbus Ltd, Bristol.

* Corresponding Member

The technical work in the assessment of the available information and the construction and subsequent development of the Data Item was undertaken by

Mr P.D. Chappell — Head of Aircraft Aerodynamics Group.

EXAMPLES OF EXCRESCENCE DRAG PREDICTION FOR TYPICAL WING COMPONENTS ON A SUBSONIC TRANSPORT AIRCRAFT AT THE CRUISE CONDITION

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EXAMPLES OF EXCRESCENCE DRAG PREDICTION FOR TYPICAL WING COMPONENTS ON A SUBSONIC TRANSPORT AIRCRAFT AT THE CRUISE CONDITION

1. NOTATION AND UNITS

In this Item, and in the Examples in particular, wherever possible the notation is that of the Items concerning excrescence drag and is not usually repeated. Additional notation introduced in the present Item is defined below, split for convenience into that for the main text and the separate Examples.

1.1 Main Text

		<i>SI</i>	<i>British</i>
A	wing aspect ratio, $4s^2/S_{ref}$		
A_{ref}	reference area for excrescence	m ²	ft ²
C_D	excrescence drag coefficient based on q_∞ and S_{ref}		
C_{Dfp}	excrescence drag coefficient obtained from Data Items, based on q_1 and A_{ref}		
C_{Dwing}	total value of C_D for wing		
C_L	wing lift coefficient		
c	local wing chord, see Equations (4.1) to (4.4)	m	ft
c_c	centre-line chord of wing, see Sketch 4.2	m	ft
c_k	chord at trailing-edge kink, see Sketch 4.2	m	ft
c_r	root (centre-line) chord of basic trapezoidal planform, see Sketch 4.2	m	ft
c_t	wing tip chord, see Sketch 4.2	m	ft
$\bar{c}$	mean chord of basic trapezoidal planform, $\frac{1}{2}(c_t + c_r)$	m	ft
M	Mach number		
q_1	local kinetic pressure at edge of boundary layer, $\frac{1}{2}\rho_1 u_1^2$	N/m ²	lbf/ft ²
q_∞	free-stream kinetic pressure, $\frac{1}{2}\rho_\infty u_\infty^2$	N/m ²	lbf/ft ²
$R_{\bar{c}}$	Reynolds number based on free-stream flow parameters and $\bar{c}$		

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R_1	unit Reynolds number based on local flow parameters at edge of boundary layer	m^{-1}	ft^{-1}
R_∞	unit Reynolds number based on free-stream flow parameters	m^{-1}	ft^{-1}
S_{ref}	wing reference area, area of basic trapezoidal planform, $s(c_t + c_r)$	m^2	ft^2
s	wing semi-span, see Sketch 4.2	m	ft
T	static temperature	K	K
u	velocity	m/s	ft/s
x	chordwise distance measured locally from wing leading-edge	m	ft
η	spanwise distance from wing root as fraction of semi-span		
η_k	value of η for trailing-edge kink, see Sketch 4.2	m	ft
Λ_0	leading-edge sweep angle, see Sketch 4.2	deg	deg
$\Lambda_{1/4}$	quarter-chord line sweep angle for basic trapezoidal planform	deg	deg
Λ_1	trailing-edge sweep angle for basic trapezoidal planform, see Sketch 4.2	deg	deg
λ	taper ratio of basic trapezoidal planform, $c_t + c_r$		
ρ	density of air	kg/m^3	$slug/ft^3$
<i>Subscripts</i>			
1	denotes local value at edge of boundary layer		
∞	denotes free-stream value		

1.2 EXAMPLES A, a

C_{D0}, C_{D90} drag coefficient for step or groove aligned with ($\beta = 0$), or normal to ($\beta = 90^\circ$) flow, based on q_1 and face area, Lh , for step or planform area, Lt , for groove

1.3 EXAMPLES B, b

Subscripts

(fore-end) denotes value at forward end of step

SF denotes value relating to skin friction drag

1.4 EXAMPLES C, c

a, b	number of linear groove segments used to approximate circular arcs generated by (r_1, θ_1) , (r_2, θ_2) , see Sketch C.2		
m	general linear groove segment identifier		
p	peripheral length of access panel generated by circular arcs (r_1, θ_1) , (r_2, θ_2) , see Equation (C.2.3)	m	ft
p'	peripheral length of access panel defined by polygonal approximation, see Equation (C.2.2)	m	ft
r	radius	m	ft
r_1, r_2	radii used to define access panel periphery, see Sketch C.2	m	ft
L	length of linear groove segment	m	ft
β_0	groove inclination for access panel with unswept major axis, see Sketch C.2	deg	deg
β_{m0}	value of β_0 for groove segment m	deg	deg
θ_1, θ_2	angles used to define access panel periphery, see Sketch C.2	deg	deg
Λ_n	sweep of access panel major axis	deg	deg

1.5 EXAMPLES D, d

No additional notation

1.6 EXAMPLES E, e

No additional notation

1.7 EXAMPLES F, f

C_{D90}	drag coefficient for trapezoidal-section groove normal ($\beta = 90^\circ$) to flow, based on q_1 and face area, Lh
C_{D90F}	drag coefficient for forward-facing step normal to flow, based on q_1 and face area, Lh
C_{D90R}	drag coefficient for rearward-facing step normal to flow, based on q_1 and face area, Lh
<i>Subscripts</i>	
i, o	relating to inboard, outboard control gap

2. INTRODUCTION

This Item illustrates the practical use of those excrescence drag Data Items, see Table 2.1, that are particularly pertinent to the types of excrescence commonly found on wings.

TABLE 2.1 Excrescence drag Data Items applicable to wings

Derivation No.	Data Item No.	To Determine
2	68020	Flat plate local and mean skin friction.
3	74036	Drag due to circular cavities.
4	75028	Drag due to grooves, including flow inclination effect.
5	75031	Drag due to steps.
8	90029	Drag for the excrescence on the aircraft, see Equations (3.1) and (3.2).
9	91028	Drag magnification factor and local flow parameters.
10	92039	Drag due to control gaps and deep slots.

In order to illustrate the application (Section 3) of the excrescence drag Items applicable to wings the case of a subsonic transport aircraft in the cruise condition has been chosen, and the excrescence drag arising from a number of wing components (controls, removable panels *etc.*) is calculated (Section 4).

Each component is the subject of a separate example and the various contributions to the excrescence drag of the component are calculated and itemised for two calculation cases. Calculation Case (i) deals with an ideal situation in which there are no avoidable surface mismatches or sealing problems, and Calculation Case (ii) deals with the effects of possible surface mismatches or poor sealing. The itemised drag contributions for each component are used to highlight those areas of detail design and installation that are likely to contribute most to avoidable drag. Conclusions from the calculations are summarised in Section 5.

3. APPLICATION OF EXCRESCENCE DRAG DATA ITEMS

The application of the excrescence drag Data Items to the prediction of the excrescence drag of an aircraft component is discussed in some detail in the Introductory Item, No. 90029 (Derivation 8). Equation (3.1) of that Item relates the drag coefficient, C_D , due to an excrescence on an aircraft to the drag coefficient, C_{Dfp} , of an idealised approximation to that excrescence obtained from wind-tunnel tests with the excrescence mounted on a flat plate*, *i.e.*

$$C_D = C_{Dfp} m_d \frac{A_{ref}}{S_{ref}} K. \quad (3.1)$$

In Equation (3.1) C_D is based on free-stream kinetic pressure, q_∞ , and aircraft wing reference area S_{ref} , and C_{Dfp} (obtained from the Data Items) is based on kinetic pressure, q_1 , at the edge of the boundary layer at the excrescence location and a reference area, A_{ref} , for the excrescence. The drag magnification factor, m_d , allows for differences attributable to non-uniform pressure distribution on the aircraft compared to the uniform pressure distribution of the wind-tunnel tests. Finally, K is a factor intended to allow for any differences between the geometry and orientation of the excrescence as tested in the wind-tunnel and as located on the aircraft. If it is reasonable to assume that there are no significant differences then K can

* Note that in the notation of the Data Items themselves the excrescence drag coefficient is given as C_D ($\equiv C_{Dfp}$, as used here).

be taken to be unity. For most of the Examples in this Item such an assumption is felt to be justified, so that Equation (3.1) becomes

$$C_D = C_{Dfp} m_d \frac{A_{ref}}{S_{ref}}. \quad (3.2)$$

However, some situations in the Examples require the adaptation of a Data Item method, which implies the use of a value of $K \neq 1$, although this is not specifically identified, see Sections D.2.2 and F.2.2.

4. EXCRESCENCE DRAG OF TYPICAL WING COMPONENTS

In order to illustrate the use of the Items listed in Table 2.1 of Section 2 the case of a subsonic transport aircraft in the cruise is used. For that aircraft the excrescence drag of a number of typical wing components is calculated using predictions of C_{Dfp} from the Items in conjunction with Equation (3.2).

4.1 The Wing Examples

Sketches 4.1a and 4.1b give the general arrangement of the upper and lower surface respectively of the wing chosen for the Examples. The layout and location of the control surfaces together with some other wing components are shown. Of the many components illustrated, six have been selected for detailed excrescence drag consideration; they are indicated on the sketches as

- | | |
|-------------------------|-------------------------|
| (a) Slat panel No. 1 | (d) Aileron |
| (b) Spoiler panel No. 2 | (e) Undercarriage door |
| (c) Access panel No. 20 | (f) Outboard flap panel |

Each of the components (a) to (f) is considered as a separate example, and these illustrations follow Section 6. Two calculation cases are considered for each component:

- Calculation Case (i): The main calculation case; an ideal situation in which there are airtight seals and no avoidable surface mismatches (Examples A to F).
- Calculation Case (ii): The subsidiary calculation case; a possible situation in which surface mismatch or poor sealing occurs (Examples a to f).

Examples A to F employ a largely common format. Detailed sketches of the component provide all the dimensions necessary for the excrescence drag calculations and also illustrate the methods of sealing. In each Example there follows an introduction listing those features of the geometry contributing towards the excrescence drag. Another section deals with the calculation methods to be used and, where necessary, outlines the ways in which either the methods of the Data Items or the geometry of the component itself need to be adapted to provide an appropriate solution. A final section deals with the calculations themselves. Detailed calculations are given only for one feature of the component; the complete calculations are summarised in tabular form. The final table itemises the excrescence drag contribution arising from each feature considered. The major contributions are briefly reviewed, together with some consideration, if possible, of means whereby they might be reduced.

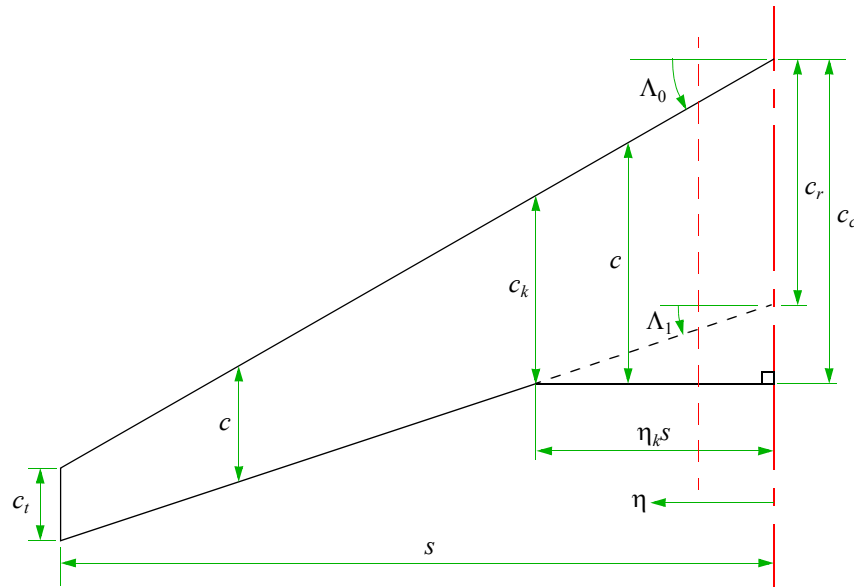
The subsidiary Examples a to f follow a similar pattern and conclude with the penalties arising from the surface mismatches or poor sealing.

Finally, it should be noted that, since all the wing components considered have counterparts on the opposite half-wing, the calculated excrescence drag would need to be doubled for the aircraft.



4.1.1 Wing planform geometry

The wing planform consists of a basic trapezium with the addition of an inboard triangular trailing-edge extension, as shown in Sketch 4.2.



Sketch 4.2 Planform geometry

For the purposes of the Examples a number of geometrical parameters for the wing are required. With reference to Sketch 4.2 the local wing chord, c , is determined from one of two equations, dependent upon the value of η . Thus,

for $\eta < \eta_k$

$$c = c_r[1 - \eta(1 - \lambda)] + s(\eta_k - \eta)\tan\Lambda_1 \quad (4.1)$$

and for $\eta \geq \eta_k$

$$c = c_r[1 - \eta(1 - \lambda)] \quad (4.2)$$

For the example:

A	$=$	9.2	η_k	$=$	0.33
λ	$=$	0.28	s	$=$	23 m
Λ_0	$=$	29.71°	c_r	$=$	7.813 m
$\Lambda_{1/4}$	$=$	27.00°	c_t	$=$	2.188 m
Λ_1	$=$	18.06°	$\bar{c}$	$=$	5 m

Therefore, with the relevant values, Equations (4.1) and (4.2) become,

for $\eta < 0.33$

$$c = 10.288 - 13.125\eta \text{ m} \quad (4.3)$$

and for $\eta \geq 0.33$

$$c = 7.813 - 5.625\eta \text{ m} . \quad (4.4)$$

These equations give $c_c = 10.288 \text{ m}$ (for $\eta = 0$) and $c_k = 5.957 \text{ m}$ (for $\eta = \eta_k = 0.33$).

The value of S_{ref} is here taken as the area of the basic trapezoidal planform, *i.e.*

$$\begin{aligned} S_{ref} &= s(c_t + c_r) \\ &= 23 (2.188 + 7.813) \\ &= 230 \text{ m}^2 . \end{aligned}$$

4.1.2 Flow conditions in cruise

Free-stream conditions

The aircraft cruises at a Mach number, M , of 0.8 at 10500 m (34449 ft), which from Item No. 77021 (Derivation 6) for ISA (International Standard Atmosphere) conditions, gives a unit Reynolds number $R_\infty = 6.406 \times 10^6$ per metre and so $R_{\bar{c}} = 3.20 \times 10^7$.

The wing lift coefficient, C_L , is 0.45.

Local flow conditions

The chordwise pressure distribution for the wing at a number of spanwise stations was available from wind-tunnel tests. For the excrescence drag calculations the variation of the local flow parameters M_1 , u_1/u_∞ , T_1/T_∞ and ρ_1/ρ_∞ , together with the drag magnification factor, m_d , are required over the exposed wing planform. Item No. 90029 (Derivation 8) points out that the only available method for obtaining m_d relates to two-dimensional flow, but suggests that its application to three-dimensional flow for excrescences fully immersed in the boundary layer, as in the Examples of this Item, is acceptable. Item No. 91028 (Derivation 9), together with its associated program, ESDUpac A9128, provides a means of calculating the variation of m_d over an aerofoil assuming a knowledge of the pressure distribution only. The method also provides the variation of the aforementioned local flow parameters.

ESDUpac A9128 has been used in conjunction with the given pressure distributions to provide chordwise variations of the local flow parameters and m_d on the upper and lower surfaces for a range of values of η across the span. Plots against x/c and η in the region of the wing component of interest are given for each of the Examples A to F.

It is important to note that the flow parameters M_1 , u_1/u_∞ etc. relate to the true local flow, which is not necessarily streamwise. For simplicity in the calculations, however, it has been assumed that the local flow is streamwise. For the wing under consideration, local flow directions would not be expected to deviate from the free-stream direction by more than about 10° , even in the worst case, *i.e.* near the leading edge of the upper surface where maximum suction is coupled with the most highly swept isobar.

A knowledge of the local flow conditions enables the Reynolds number, R_x , based on local flow values at the edge of the boundary layer and chordwise distance from the wing leading edge to be obtained from

$$R_x = R_1 x \quad (4.5)$$

where

$$R_1 = R_\infty \frac{(u_1/u_\infty)(\rho_1/\rho_\infty)}{(T_1/T_\infty)^{0.8}} \text{ per unit length} \quad (4.6)$$

in which R_1 is unit Reynolds number based on flow parameters at the edge of the boundary layer and $R_\infty = 6.406 \times 10^6$ per metre at cruise. In Equation (4.6) dynamic viscosity is taken to be proportional to (static temperature)^{0.8}, as in Appendix A of Derivation 4 for example.

Obviously, by means of R_1 any other Reynolds number based on local values can be obtained. For example,

$$R_h = R_1 h \quad (4.7)$$

and

$$R_d = R_1 d, \quad (4.8)$$

where h is step height or groove depth and d is cavity diameter.

5. CONCLUDING REMARKS

5.1 General

The results of the calculations for Examples A to F can be taken to be reasonably typical of the minimum level of excrescence drag coefficients to be expected from such wing components on a modern subsonic transport aircraft in cruising flight. They are probably close to the minimum for the simple reason that a good standard of design has been assumed, in which the seals are airtight and there are no avoidable surface mismatches. It is also implicitly assumed that the surface finish is aerodynamically smooth and is free from other imperfections such as waviness. In practice such a standard is difficult to achieve, but is a necessary aim. An impression of the possible penalties of poor design, installation or maintenance is given in the subsidiary Examples a to f.

5.2 Assessment of the Calculation Methods

The Data Item methods are approximate and were derived from wind-tunnel data on excrescences in turbulent boundary layers only. Their application to excrescences near to the wing leading edge might therefore be considered to be somewhat suspect. However, even though continually improving wing designs, using modern construction materials and methods, are providing the potential for ever greater extents of laminar flow, the realisation of the full potential in practice is unlikely, given the presence of spanwise grooves and slots near to the leading edge associated with high-lift devices such as slats or Krüger flaps.

The necessary approximations in the development of the excrescence drag prediction Items themselves can be taken to justify simplifications made to shorten the time required in their application. A considerable proportion of the calculation time is devoted to the determination of the necessary local flow conditions for the excrescence drag-producing feature; generally, the larger the feature, the more the detail that is required. For example, in the case of a streamwise groove with closed ends, sets of flow parameters are required at each end and at the mid-length point of the groove. Depending on the length of the groove and its location it is conceivable that the changes in the flow variables along the length are such that a single set might be taken to represent the groove as a whole. While this principle was applied in some of the more obvious situations in the Examples, there were others where, with hindsight, it could also have been applied. There is sometimes, therefore, a certain inconsistency in approach throughout the examples in this and other matters. However, these inconsistencies did not affect the way in which the Items were used, neither did they significantly affect the results.

In practice, each situation has to be treated on its merits. Indeed, in the calculation of the excrescence drag of a complete aircraft it might not be justifiable to employ the level of detail used in the examples of this Item in every case. As part of the overall excrescence drag assessment, a Data Item in the Performance Series (Reference 11) provides a rapid means of determining a range of excrescence drag values within which that for a given aircraft might be expected to lie. That Item also provides similar information concerning some of the major contributions to the overall value.

5.3 Principal Conclusions from the Examples

An inspection of the summary tables for each of the Examples A to F and their associated subsidiaries a to f reveals important guidelines in the design for minimum excrescence drag.

While almost any surface discontinuity will lead to a drag penalty, some types of discontinuity are, obviously, inherently worse than others in this respect, forming a natural hierarchy for drag guideline purposes. For example, a rearward-facing step of given length and height, normal to a flow of known conditions, will typically exhibit a drag about half that of its forward-facing counterpart. As a comparison, an open-ended groove of the same length and with a square section of the same depth and width as the step height, has about $1/20^{\text{th}}$ of the forward-facing step drag when normal to the flow and only about $1/40^{\text{th}}$ of it when aligned with the flow. Thus steps, especially forward-facing ones, offer very serious drag penalties by comparison with grooves and are anathema to good design. Even grooves, especially when normal to the flow, can lead to very significant drag penalties, particularly for long lengths, even with small width and depth. The Examples also show that deep slots (depth/width ≥ 3) normal to the flow can be a source of serious drag penalty and are best faired over, leaving shallow grooves at worst.

The Examples also illustrate the profound effect that the location of the component on the wing can have on its excrescence drag, via the drag magnification factor, m_d . In the Examples m_d can attain values of nearly 3 on the upper surface and up to 1.3 on the lower surface. Clearly, therefore, if there were no constraint on the location of a component it would make sense to locate it in an area where m_d is low.

Finally, it is of interest to summarise the calculated excrescence drag coefficients for each of the wing components (a) to (f) and to present the drag coefficients as a percentage of a plausible total excrescence drag value for the wing, assuming reasonably good design, taken here as $C_{D\text{wing}} = 6 \times 10^{-4}$, see Table 5.1 below.

TABLE 5.1 Summary of calculated excrescence drag coefficients for the Examples

Wing component	Calculation Case (i) (Examples A to F)		Calculation Case (ii) (Examples a to f)	
	$C_D(\times 10^4)$	$C_D/C_{Dwing}(\%)$	$C_D(\times 10^4)$	$C_D/C_{Dwing}(\%)$
(a) Slat panel No. 1	0.08881	1.48	0.14354	2.39
(b) Spoiler panel No. 2	0.02606	0.43	0.03644	0.61
(c) Access panel No. 20	0.00440	0.07	0.00977	0.16
(d) Aileron	0.02876	0.48	0.06050	1.01
(e) Undercarriage door	0.02406	0.40	0.04960	0.83
(f) Outboard flap panel	0.13323	2.22	0.15913	2.70

The slat panel No. 1, which has roughly the same wetted area as the aileron, has more than treble the drag of the aileron, principally due to the high m_d value in the former case. Access panel No. 20 has the lowest drag of any of the components considered, but it is of considerable significance because there are 56 such panels for the aircraft. Examples D, d and F, f highlight the consequences of inadequate sealing which, if present, would have aggravated the penalties of excrescence drag from the other four wing components.

6. DERIVATION AND REFERENCES

6.1 Derivation

The Derivation lists selected sources of information that have been used in the preparation of this Item.

1. WIEGHARDT, K. Erhöhung des turbulenten Riebungswiderstandes durch Oberflächenstörungen.
ZWB ForschBer, 1563, 1942. (Translation available as "Increase of the turbulent frictional resistance caused by surface irregularities", MAP R&T 103, 1946.)
2. ESDU The compressible two-dimensional turbulent boundary layer, both with and without heat transfer, on a smooth flat plate, with application to wedges, cylinders and cones.
ESDU 68020, 1968.
3. ESDU Drag due to a circular cavity in a flat plate with a turbulent boundary layer at subsonic, transonic and supersonic speeds.
ESDU 74036, 1974.
4. ESDU Drag due to grooves in a flat plate with a turbulent boundary layer, at subsonic and supersonic speeds.
ESDU 75028, 1975.
5. ESDU Drag due to two-dimensional steps and ridges immersed in a turbulent boundary layer for Mach numbers up to 3.
ESDU 75031, 1975.
6. ESDU Properties of a standard atmosphere.
ESDU 77021, 1977.
7. AGARD Aircraft Excrescence Drag.
AGARDograph AG264, 1981.
8. ESDU An introduction to aircraft excrescence drag.
ESDU 90029, 1990.
9. ESDU Simplified method for the prediction of aerofoil excrescence drag magnification factor for turbulent boundary layers at subcritical Mach numbers.
ESDU 91028, 1991.
10. ESDU Drag due to gaps round undeflected trailing-edge controls and flaps at subsonic speeds.
ESDU 92039, 1992.

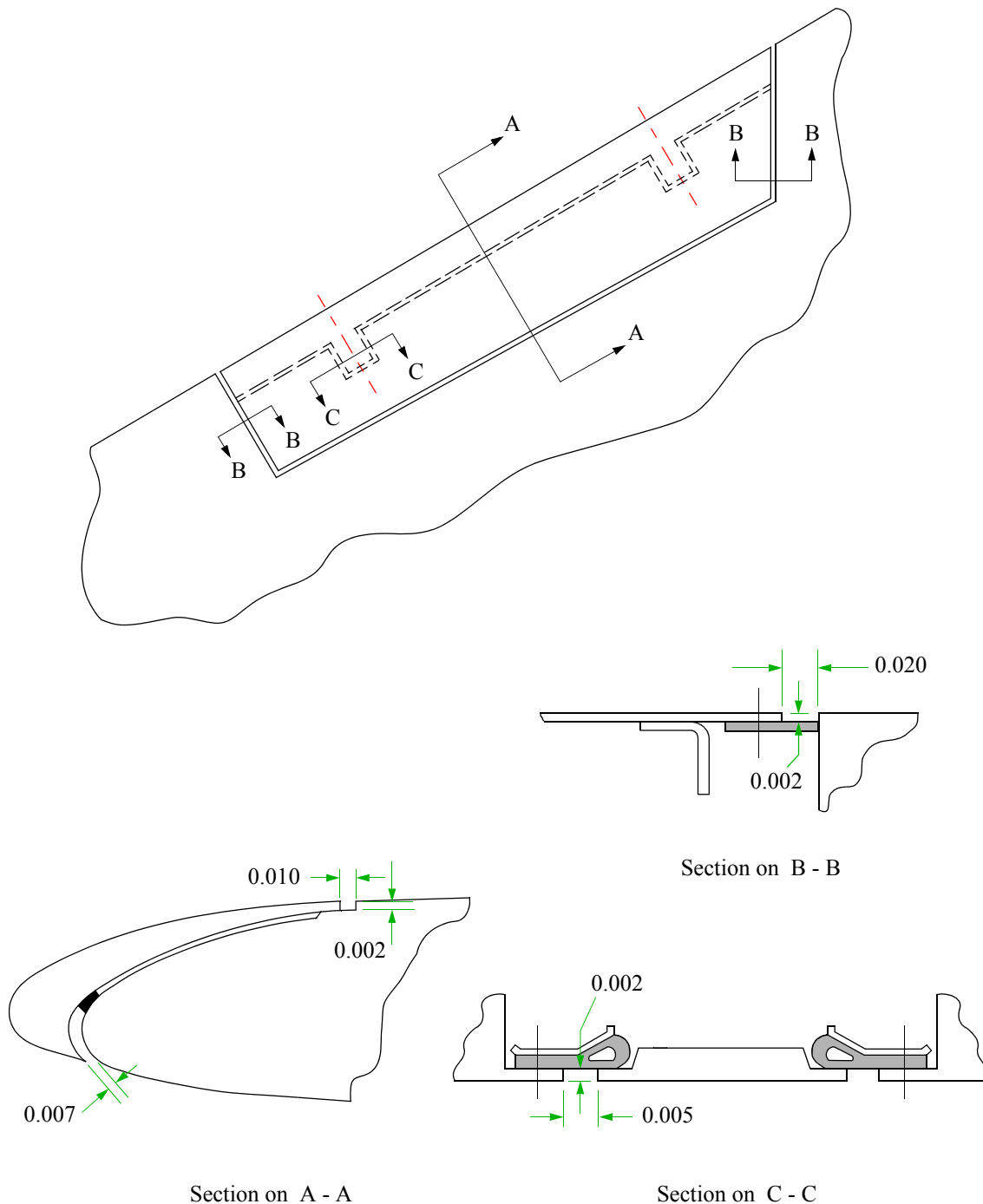
6.2 References

The References given are sources of information supplementary to that given in this Item.

11. ESDU Excrescence drag levels for a wide range of aircraft. ESDU 94044, 1994. (In the Performance Series.)

EXAMPLE A: SLAT PANEL No. 1 (Calculation Case (i))

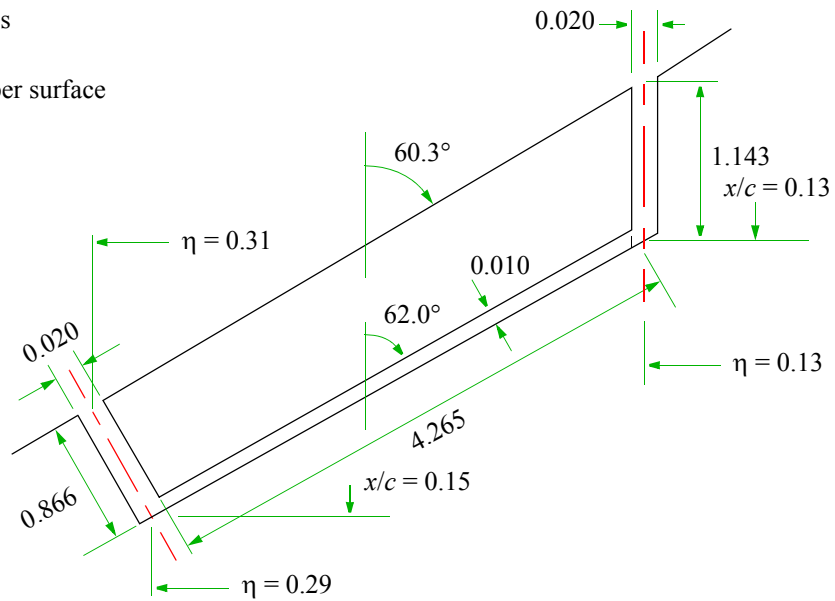
All lengths in metres



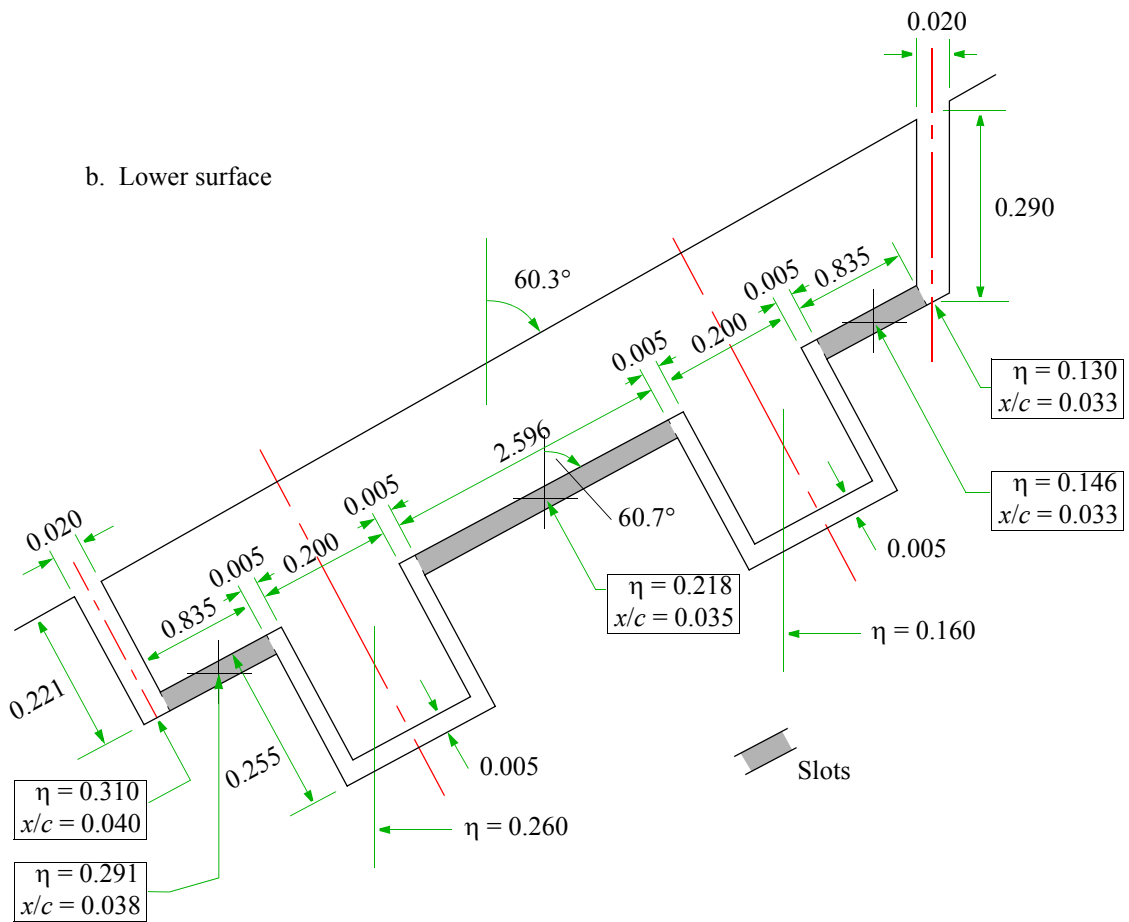
Sketch A.1 General arrangement

All lengths in metres

a. Upper surface



b. Lower surface



Sketch A.2 Detailed geometry

A.1 Introduction

Sketches A.1 and A.2 give the general arrangement and detailed geometry respectively of the slat panel inboard of the engine pylon station, *i.e.* slat panel No. 1. The slat panel is operated by means of two rotary drives, hydraulically powered. The drive arrangement necessitates rectangular apertures in the lower surface of the fixed wing structure. When the panel is stowed fairing plates seal the apertures using P-section seals. The slat trailing-edge contact aids sealing by means of light downward pressure due to flexure. This is coupled with a P-section seal at the nose of the fixed wing structure to ensure good sealing against the large pressure difference between the upper and lower surfaces near the wing leading edge. The panel extremities are sealed by means of adjustable blade seals abutting the fixed structure. The geometry of those features that are considered to contribute to the excrescence drag of the panel when correctly rigged is detailed in the sketches. The present example, for Calculation Case (i), deals with this situation. Example a, for Calculation Case (ii), considers the effect of poor rigging. From the point of view of the calculations the features contributing to excrescence drag can be approximated by shallow rectangular section grooves and deep slots, identified as follows.

A.1.1 Upper surface

- a. A longitudinal (streamwise) groove at the inboard extremity and a longitudinal groove normal to the leading edge at the outboard extremity. The grooves have an open forward end at the wing leading edge and a closed aft end.
- b. A lateral (spanwise) groove at the slat trailing edge.

A.1.2 Lower surface

- a. Longitudinal grooves at the panel extremities corresponding to those on the upper surface. Both ends of the grooves are open.
- b. Three deep lateral (spanwise) slots at the slat heel.
- c. Peripheral grooves round the two slat drive fairing plates. Each plate has two longitudinal grooves, closed fore and aft, normal to the wing leading edge and one lateral groove parallel to the leading edge.

A.2 Method of Calculation

The grooves are dealt with using Item No. 75028, with modifications for open-ended streamwise grooves. The method of that Item also requires the use of Item Nos 68020 and 75031. The deep slots are dealt with using Item No. 92039. The general principles involved in the treatment of the features listed in Sections A.1.1 and A.1.2 are as follows.

A.2.1 Longitudinal grooves from the leading edge (*i.e.* a in Sections A.1.1 and A.1.2)

The groove formed at each extremity of the panel is treated as two grooves, open at the leading edge, split between the upper and lower surfaces. For simplicity, the groove length in each case is determined from the wing planform geometry and ignores the increase in length associated with the true wing surface. The error is likely to be only a few per cent.

The method of Item No. 75028 for streamwise grooves assumes that the groove is sufficiently far downstream of the origin of the turbulent boundary layer for the skin friction of the groove side walls to be determined by the local skin friction coefficient, C_f . In the present case the turbulent boundary layer is assumed to originate from the wing leading edge ($x = 0$) and so the use of the mean skin friction coefficient, C_F , is necessary to determine C_{DSF} in Item No. 75028. With this change, and for a groove with an open forward end, Equations (4.1) and (4.3) of Item No. 75028 become

$$C_{D0} = C_{DSF} + FC_{D(aft-end)} \quad (\text{A.2.1})$$

$$\text{and} \quad C_{DSF} = C_F \frac{h}{t} \left(2 - 5 \frac{h}{L} \right) \text{ for } L/h > 10. \quad (\text{A.2.2})$$

For a groove with both ends open

$$C_{D0} = C_{DSF} = 2C_F \frac{h}{t}. \quad (\text{A.2.3})$$

In Equation (A.2.1) $C_{D(aft-end)}$ is determined from Figure 1 of Item No. 75031 for a forward-facing step with M_1 , R_x , C_f and R_h having been obtained from local flow conditions at the groove aft-end. Note that $C_{D(aft-end)}$ is based on groove planform area, Lt , and not step area, ht , and that the minor alleviating effect of step sweep is ignored in its calculation. In Equations (A.2.2) and (A.2.3) C_F is determined from Item No. 68020 also with R_x and M_1 having been obtained for local flow conditions at the aft end of the groove.

For the inboard groove, $C_{Dfp} = C_{D0}$ from Item No. 75028.

For the outboard groove, which is oblique to the airflow, both C_{D0} (from Equation (A.2.1)) and C_{D90} (from Item No. 75028) need to be calculated. For C_{D90} the flow conditions relating to the aft end of the groove are again utilised.

Then, from Equation (5.1) of Item No. 75028

$$C_{Dfp} = C_{D0} - (C_{D90} - C_{D0}) \sin^3(1.5\beta) \quad \text{for } 0 < \beta < 60^\circ. \quad (\text{A.2.4})$$

In the determination of an appropriate drag magnification factor, m_d , to apply to the overall groove drag coefficient, C_{Dfp} determined from the Items, to calculate C_D from Equation (3.2), a value appropriate to the aft-end is used, together with $A_{ref} = Lt$ for grooves.

A.2.2 Longitudinal grooves away from the leading edge (i.e. c in the Section A.1.2)

As noted in Section A.2.1, Item No. 75028 is set up to deal with longitudinal grooves, with ends fore and aft, far removed from the origin of the turbulent boundary layer. So, for the grooves to each side of the slat drive fairing plates the method is directly applicable. The appropriate local flow conditions are required at the ends and mid-length point of the groove and for that purpose a mean value of η is assumed for each pair of longitudinal grooves associated with a slat drive fairing plate.

A.2.3 Lateral (spanwise) grooves (*i.e.* b in Section A.1.1 and c in Section A.1.2)

Spanwise grooves are treated using Item No. 75028. The spanwise grooves for the slat panel are oblique to the free-stream flow with $\beta > 60^\circ$. Equation (5.1) of Item No. 75028 shows that they should be treated as normal to the flow, with Equation (3.1) of that Item being appropriate, *i.e.*

$$C_{Dfp} = C_{D90} = (\Phi - \Psi)C_f. \quad (\text{A.2.5})$$

In the determination of Φ , Ψ and C_f values of M_1 , R_x and R_h are required. For simplicity, it is convenient to use values of these parameters appropriate to the mid-length point of the groove. The value of M_d to be used in Equation (3.2) also applies to that point and $A_{ref} = Lt$.

A.2.4 Lateral slots (*i.e.* b in Section A.1.2)

The three deep lateral slots at the slat heel are treated using Item No. 92039. In that Item the drag coefficient increment due to a deep (depth/width ≥ 3) sealed slot ahead of a trailing-edge control is given as

$$\Delta C_{Ds} = 0.05 \quad (\text{A.2.6})$$

based on free-stream kinetic pressure and gap planform area $w_s l$, where w_s is the average of the control gaps on the upper and lower surfaces, *i.e.*

$$w_s = \frac{1}{2}(w_{su} + w_{sl}). \quad (\text{A.2.7})$$

For the present purpose it will be assumed that the method can be applied to the more forward located slots at the slat heel, so that

$$C_D = \Delta C_{Ds} \frac{A_{ref}}{S_{ref}} \quad (\text{A.2.8})$$

$$\text{in which } A_{ref} = \frac{w_{sl}}{2} \Sigma l \quad (\text{A.2.9})$$

where w_{sl} is the slot width and Σl is the sum of the slot lengths.

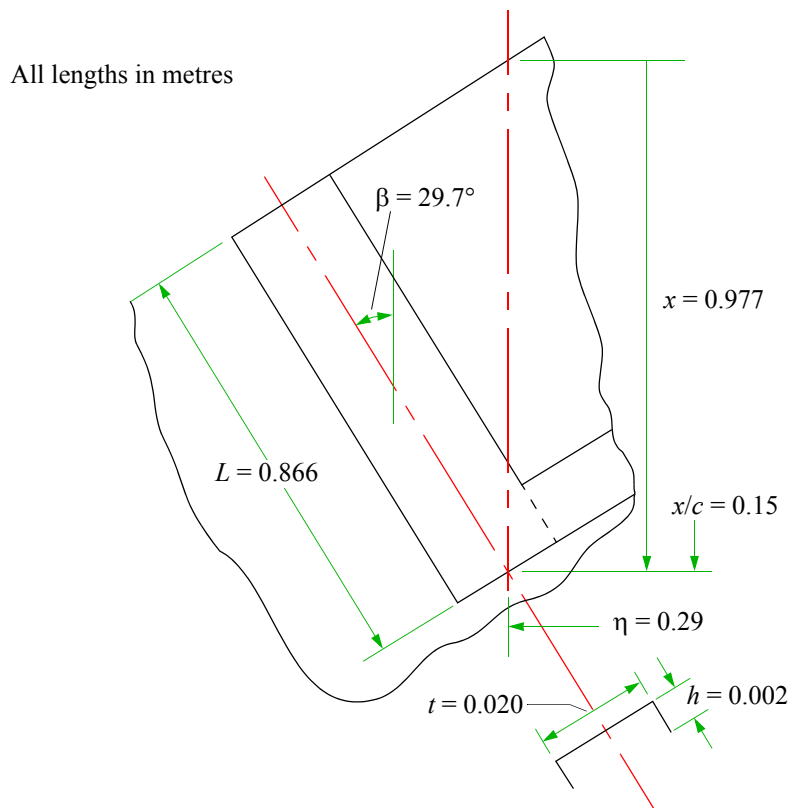
A.3 Local Flow Conditions and Drag Magnification Factor

The variations of the local flow parameters M_1 , u_1/u_∞ , T_1/T_∞ and ρ_1/ρ_∞ , together with the excrescence drag magnification factor, m_d , over the upper and lower surfaces in the region of the inboard slat panel are shown in Figures A.1a to A.1e. Linear interpolation in x/c is satisfactory. With the use of these Figures the values of R_x and R_h can be obtained from Equations (4.5), (4.6) and (4.7).

A.4 Calculations

A detailed calculation will be given for one feature only, the outboard longitudinal groove on the upper surface. The complete calculations are summarised in Table A.4.1.

A.4.1 Calculations for the outboard longitudinal groove on the upper surface



Sketch A.3 Groove geometry

For $\beta = 0$, from Equations (A.2.1) and (A.2.2)

$$C_{D0} = C_{DSF} + FC_{D(aft-end)}$$

where

$$C_{DSF} = C_F \frac{h}{t} \left(2 - 5 \frac{h}{L} \right).$$

In order to calculate C_F the flow conditions at the aft end of the groove are required. So, from Figure A.1a to A.1e for $x/c = 0.15$ and $\eta = 0.29$, $M_1 = 1275$, $u_1/u_\infty = 1.468$, $T_1/T_\infty = 0.85$, $\rho_1/\rho_\infty = 0.668$ and $m_d = 2.70$.

From Equations (4.5) and (4.6) with $R_\infty = 6.406 \times 10^6$ per metre and $x = 0.997$ m

$$R_x = R_1 x$$

in which

$$R_1 = 6.406 \times 10^6 \times \frac{1.468 \times 0.668}{(0.85)^{0.8}}$$

$$= 7.154 \times 10^6 \text{ per metre,}$$

so that

$$R_x = 7.154 \times 10^6 \times 0.997$$

$$= 7.13 \times 10^6.$$

From Figure 3 of Item No. 68020 for $M_1 = 1.275$ and $R_x = 7.13 \times 10^6$,

$$C_F = 0.00279$$

so that from Equation (A.2.2) with L , t and h values from Sketch A.3

$$\begin{aligned} C_{DSF} &= 0.00279 \times \frac{0.002}{0.02} \left(2 - 5 \times \frac{0.002}{0.866} \right) \\ &= 5.55 \times 10^{-4}. \end{aligned}$$

For the aft-end step, from Equations (4.6) and (4.7)

$$\begin{aligned} R_h &= R_1 h = 7.154 \times 10^6 \times 0.002 \\ &= 1.43 \times 10^4. \end{aligned}$$

From Figure 2 of Item No. 68020 for $M_1 = 1.275$ and $R_x = 7.13 \times 10^6$

$$C_f = 0.0023.$$

From Figure 1 of Item No. 75031 for $\log_{10} R_h = 4.16$, $M_1 = 1.275$ and $C_f = 0.0023$,

$$P = 100 \text{ and } Q = 25.$$

$$\begin{aligned} \text{Thus } C_{D(aft-end)} &= (P + Q) C_f \times \frac{ht}{Lt} \\ &= (100 + 25) \times 0.0023 \times \frac{0.002 \times 0.020}{0.866 \times 0.020} \\ &= 6.64 \times 10^{-4}. \end{aligned}$$

Also, Figure 3 of Item No. 75028, for $t/h = 0.02/0.002 = 10$, gives

$$F = 1.$$

Therefore, from Equation (A.2.1),

$$\begin{aligned} C_{D0} &= 5.55 \times 10^{-4} + 1 \times 6.64 \times 10^{-4} \\ &= 1.22 \times 10^{-3}. \end{aligned}$$

For $\beta = 90^\circ$, Equation (3.1) of Item No. 75028 is used.

The local flow conditions at $\eta = 29$, $x/c = 0.15$ gave $M_1 = 1.275$, $C_f = 0.0023$ and $\log_{10} R_h = 4.16$.

Figures 1 and 2 of Item No. 75028 give, with these values,

$$\Phi = 7.53, \Psi = 3.67.$$

Therefore, from Equation (3.1) of Item No. 75028,

$$\begin{aligned} C_{D90} &= (\Phi - \Psi)C_f = (7.53 - 3.67) \times 0.0023 \\ &= 8.88 \times 10^{-3}. \end{aligned}$$

Finally, for $\beta = 29.7^\circ$, Equation (5.1) of Item No. 75028 gives

$$\begin{aligned} C_{Dfp} &= C_{D0} - (C_{D0} - C_{D90})\sin^3(1.5\beta) \\ &= 1.22 \times 10^{-3} - (1.22 \times 10^{-3} - 8.88 \times 10^{-3})\sin^3(1.5 \times 29.7^\circ) \\ &= 3.86 \times 10^{-3}. \end{aligned}$$

(Note that a flow angle change of 30° trebles the drag of the streamwise ($\beta = 0$) groove.)

This is now converted to a value for the aircraft based on aircraft reference area and free-stream kinetic pressure via Equation (3.2), *i.e.*

$$C_D = C_{Dfp} m_d A_{ref} / S_{ref}$$

in which m_d is taken as 2.70 (for the aft-end of the groove), $A_{ref} = Lt$ and $S_{ref} = 230 \text{ m}^2$, giving

$$\begin{aligned} C_D &= 3.86 \times 10^{-3} \times 2.70 \times \frac{0.866 \times 0.02}{230} \\ &= 0.00785 \times 10^{-4}. \end{aligned}$$

(Note that the drag of the groove in a “flat plate” is nearly trebled due to drag magnification effects.)

A.4.2 Summary of calculations

The complete calculations are summarised in the following tables.

TABLE A.4.1a Longitudinal grooves

No.	Location	L (m)	t (m)	h (m)	$A_{ref}(= Lt)$ (m^2)	β (deg)
1.	Slat panel inboard end (upper surface)	1.143	0.020	0.002	0.02286	0
2.	Slat panel inboard end (lower surface)	0.290	0.020	0.002	0.00580	0
3.	Slat panel outboard end (upper surface)	0.866	0.020	0.002	0.01732	29.7
4.	Slat panel outboard end (lower surface)	0.221	0.020	0.002	0.00442	29.7
5.	Inboard slat drive fairing plate (inner or outer groove)	0.255	0.005	0.002	0.00128	29.7
6.	Outboard slat drive fairing plate (inner or outer groove)	0.255	0.005	0.002	0.00128	29.7

TABLE A.4.1a (continued)

No.	Mid-length				Aft-end					
	η	x/c	M_1	R_x ($\times 10^{-6}$)	η	x/c	M_1	R_x ($\times 10^{-6}$)	R_h ($\times 10^{-4}$)	m_d
1.	—	—	—	—	0.13	0.13	1.155	8.06	1.41	1.95
2.	—	—	—	—	0.13	0.033	0.77	1.82	—	0.46
3.	—	—	—	—	0.29	0.15	1.275	7.13	1.43	2.70
4.	—	—	—	—	0.31	0.04	0.74	1.36	1.23	0.44
5.	0.16	0.05	0.80	2.68	0.16	0.070	0.815	3.6	1.29	0.65
6.	0.27	0.055	0.80	2.68	0.27	0.080	0.83	3.32	1.30	0.70

No.	Forward-end				
	η	x/c	M_1	R_x ($\times 10^{-6}$)	R_h ($\times 10^{-6}$)
5.	0.16	0.034	0.79	1.77	1.27
6.	0.27	0.037	0.75	1.57	1.24

No.	C_{D0} ($\times 10^3$)	C_{D90} ($\times 10^3$)	C_{Dfp} ($\times 10^3$)	C_D ($\times 10^4$)
1.	1.00	8.88	1.00	0.00193
2.	0.75	—	0.75	0.00009
3.	1.22	8.88	3.86	0.00785
4.	0.79	13.13	0.79	0.00043
5.	4.84	11.22	7.09	0.00026
6.	4.87	11.19	7.10	0.00028

TABLE A.4.1b Lateral grooves

No.	Location	L (m)	t (m)	h (m)	$A_{ref}(=Lt)$ (m ²)	β (deg)
1.	Slat panel trailing edge	4.265	0.010	0.002	0.04265	62.0
2.	Inboard slat drive fairing plate trailing edge	0.200	0.005	0.002	0.00100	60.3
3.	Outboard slat drive fairing plate trailing edge	0.200	0.005	0.002	0.00100	60.3

No.	Mid-length						C_{D90}	C_D
	η	x/c	M_1	R_x ($\times 10^{-6}$)	R_x ($\times 10^{-4}$)	m_d	C_{Dfp} ($\times 10^3$)	($\times 10^4$)
1.	0.21	0.14	1.300	7.67	1.45	2.76	8.65	0.04429
2.	0.16	0.070	0.815	3.6	1.29	0.65	11.22	0.00032
3.	0.27	0.080	0.835	3.6	1.30	0.73	11.22	0.00036

TABLE A.4.1c Slat heel slots

Σl (m)	w_{sl} (m)	w_s (m)	$A_{ref}(=w_s \Sigma l)$ (m ²)	ΔC_{Ds}	C_D ($\times 10^4$)
4.266	0.007	0.0035	0.01493	0.05	0.03246

TABLE A.4.2 Summary of excrescence drag contributions for slat panel No. 1

Upper Surface:	$C_D (\times 10^4)$
Inboard longitudinal groove	0.00193
Outboard longitudinal groove	0.00785
Trailing-edge groove	0.04429
Total for upper surface	<u>0.05407</u>
Lower Surface:	
Inboard longitudinal groove	0.00009
Outboard longitudinal groove	0.00043
Slat heel slots	0.03246
Slat drive fairing plates:	
longitudinal grooves	0.00108
lateral grooves	0.00068
Total for lower surface	<u>0.03474</u>
Total for slat panel No. 1	<u>0.08881</u>

For this panel the major contributions (86%) to the drag arise from the upper surface trailing-edge groove and the slat heel slots. The example illustrates the importance of minimising these effects by, say, minimising the upper surface trailing-edge groove width and/or chamfering the downwind face of the groove and the possible addition of fairing blades across the slat heel slots.