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Drag of axisymmetric cowls at zero incidence for subsonic Mach numbers

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DRAG OF AXISYMMETRIC COWLS AT ZERO INCIDENCE FOR SUBSONIC MACH NUMBERS

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DRAG OF AXISYMMETRIC COWLS AT ZERO INCIDENCE FOR SUBSONIC MACH NUMBERS

1. NOTATION AND UNITS

		<i>SI</i>	<i>British</i>
A	streamtube cross-sectional area	m^2	ft^2
A_S	cowl surface (wetted) area	m^2	ft^2
C_D	cowl total drag coefficient based on cowl maximum cross-sectional area, (total drag)/(free-stream kinetic pressure $\times A_m$)		
C_{DF}	cowl friction drag coefficient based on cowl maximum cross-sectional area, $C_F A_S / A_m$		
C_{Dp}	cowl profile drag coefficient based on cowl maximum cross-sectional area, (profile drag)/(free-stream kinetic pressure $\times A_m$)		
C_F	flat plate mean skin friction coefficient based on surface area		
C_S	surface area coefficient, ratio of surface area of cowl component to surface area of enclosing cylinder (not including ends)		
$C_{\phi pre}$	pre-entry force coefficient based on cowl cross-sectional area at intake plane, (pre-entry force)/(free-stream kinetic pressure $\times A_i$)		
D	cowl local diameter	m	ft
K_0, K	factors used in evaluating λ_0 in Equation (3.1)		
K_1	factor used in evaluating λ_1 in Equation (3.2)		
K_2	factor used in evaluating λ_2 in Equation (3.5)		
K_3, K_4	factors used in evaluating $\Delta\lambda$ in Equation (3.4)		
K_5	factor used in evaluating λ_3 in Equation (3.3)		
K_6, K_7, K_8	factors used in evaluating ΔC_{Ds} in Equation (4.2)		
K_9	factor used in evaluating ΔC_{Ds} in Equation (4.3)		
K_{10}	factor used in evaluating M_{DR} in Equation (5.3)		

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K_{11}	factor used in evaluating ΔC_{Dw} in Equation (5.6)		
L	length of cowl component	m	ft
M	Mach number		
M_{Df}	drag-rise Mach number for forebody followed by long cylindrical section		
M'_{Df}	drag-rise Mach number used in evaluating M_{Df} in Equations (5.1) and (5.2)		
M_{DR}	drag-rise Mach number for complete cowl		
P	local total pressure	N/m ²	lbf/ft ²
p	local static pressure	N/m ²	lbf/ft ²
R_a	initial radius of curvature of cowl afterbody (see Sketch 2.2)	m	ft
Re	Reynolds number based on cowl length		
R_f	initial radius of curvature of cowl forebody (see Sketch 2.2)	m	ft
S	factor used in evaluating $(A_0/A_i)_{crit}$		
ΔC_{Ds}	spillage drag coefficient increment		
ΔC_{Dw}	wave drag coefficient increment		
ΔM_{Df}	drag-rise Mach number increment due to afterbody/forebody interference		
λ	normalised profile drag parameter (the form factor), C_{Dp}/C_{DF}		
λ_0	form factor for forebody		
λ_1	form factor for forebody followed by cylindrical section		
λ_2	form factor for complete cowl with cylindrical midbody		
λ_3	form factor for complete cowl with no midbody		
ρ	ratio of forebody leading-edge radius to that of equivalent NACA 1-series forebody		
θ	streamforce on inside of streamtube, positive in upstream direction	N	lbf
ϕ	streamforce on outside of streamtube, positive in downstream direction	N	lbf

ϕ_a	afterbody force (see Sketch 2.1)	N	lbf
ϕ_f	forebody force (see Sketch 2.1)	N	lbf
$\phi_{post}, \theta_{post}$	post-exit force (see Sketch 2.1)	N	lbf
ϕ_{pre}, θ_{pre}	pre-entry force (see Sketch 2.1)	N	lbf

Subscripts

a	relating to cowl afterbody
c	relating to cowl midbody (cylindrical section)
$crit$	denotes critical value
DR	denotes value at drag-rise Mach number
e	denotes value for nozzle exit plane (see Sketch 2.1)
f	relating to cowl forebody
fR	relating specifically to cowl forebody with increased leading-edge radius relative to equivalent NACA 1-series forebody
i	denotes value for intake entry plane (see Sketch 2.1)
m	denotes value at maximum cowl cross-section
t	relating to total cowl value
0	denotes value at plane far upstream (see Sketch 2.1)
∞	denotes value at plane far downstream (see Sketch 2.1)

2. INTRODUCTION

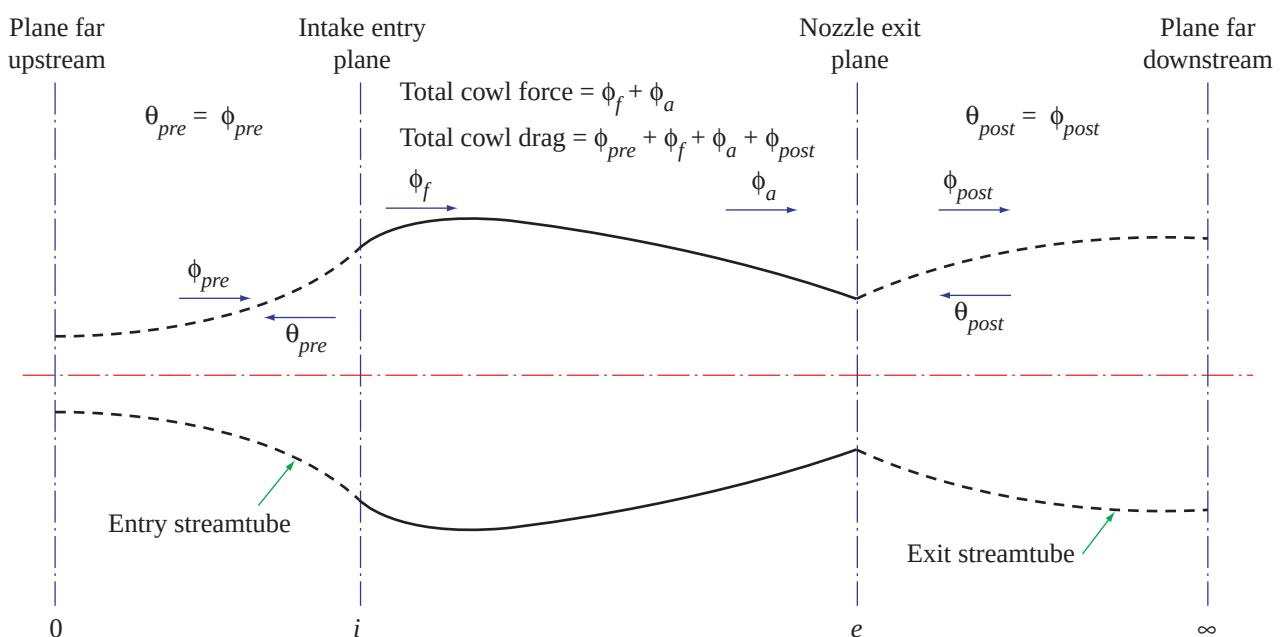
2.1 Thrust and Drag Accounting

In order to estimate aircraft performance accurately it is necessary that all thrust and drag components be defined and properly accounted. This is particularly important for the propulsion system where drag components will be dependent on the engine operating conditions.

Some of the forces involved in the accounting system for a single stream nacelle are shown in Sketch 2.1. The approach used herein is based on that given in Chapter 2 of Reference 23 which gives a comprehensive and detailed treatment of thrust and drag accounting of both single stream and double stream nacelles. For a detailed understanding of thrust and drag accounting, avoiding inconsistencies in definition of forces, the user is referred to Reference 23. It is important that the definitions of thrust and drag are compatible and the recommendations of Reference 23 ensure that this is so.

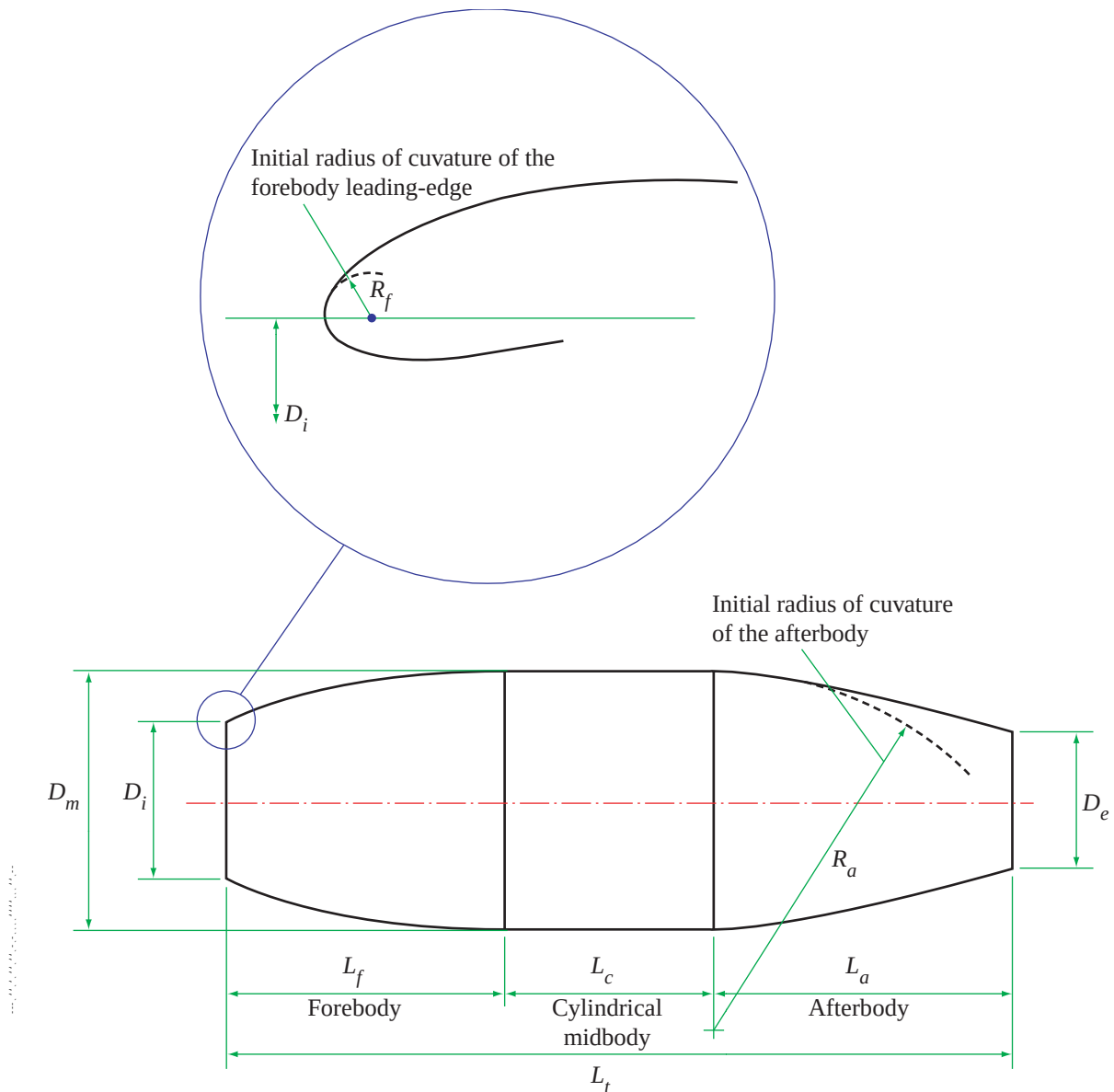
The breakdown of the forces associated with a propulsion system into “thrust” and “drag” is to some extent arbitrary. The accounting system in this Item adopts the concept of entry and exit streamtubes, bounding the flow passing through the complete engine (see Sketch 2.1). Then the cowl drag is defined as the summation of forces acting on the external surface of the cowl and on the outside of the entry and exit streamtubes, whilst the thrust is defined as the summation of the forces acting on the inside. For the case of a double stream nacelle the gas-generator afterbody and plug forces are assumed to be included in the thrust accounting. In this system the entry and exit streamtubes are assumed to extend from far upstream, and to far downstream, respectively.

In the use of any thrust and drag accounting system the distinction between the force on part of the cowl and the drag of that part of the cowl should be understood. In subsonic potential flow the net force on a non-lifting body is zero. Thus, for the forebody in Sketch 2.1, the pre-entry force (ϕ_{pre}), which is equal to the stream force change between the far upstream (0) and intake (i) planes, is exactly balanced by the forebody force, ϕ_f (i.e. for potential flow the forebody drag = $\phi_{pre} + \phi_f = 0$). In real flow, viscous effects result in only a partial cancellation. Thus, in viscous flow, the drag of the forebody is represented by the difference in the real and the potential flow forebody forces. The potential flow forebody force (equal to ϕ_{pre}) is calculable given the intake entry and free-stream conditions and can be estimated using Reference 24.



Notes: ϕ is taken as positive in the downstream direction
 ϕ_f is usually negative, i.e. acts in the upstream direction
 ϕ_{pre} is usually positive, i.e. acts in the downstream direction
 ϕ_a and ϕ_{post} can be either positive or negative, depending on geometry and flow conditions

Sketch 2.1 Illustration of forces associated with a single stream nacelle



Sketch 2.2 Definition of cowl geometry

Although a similar situation exists for the afterbody, where in potential flow the afterbody force (ϕ_a) is equal to the post-exit force (ϕ_{post}), it is not possible to evaluate the post-exit force because of entrainment effects between the jet and external flows. However, for the special case when the propulsion nozzle flow is fully expanded (*i.e.* when the local static pressure on the cowl external surface at the exit plane and the jet exit static pressure are both equal to the free-stream static pressure) the post-exit force is zero. In practice the most convenient approximation to this special case is a reference condition for which the jet exit and free-stream pressures are equal, although, in general, the local static pressure will differ from the free-stream value and will be a function of the afterbody geometry and the free-stream Mach number. In many thrust and drag accounting systems this reference condition is taken as a datum to which jet effects, obtained from detailed model tests, are added. Because of the problems associated with evaluating ϕ_{post} the cowl drag coefficients presented in this Item are applicable to this reference condition.

2.2 Scope and Application of the Data Item

This Item presents a method for estimating the drag of axisymmetric cowls with sharp trailing-edges at zero incidence and at subsonic free-stream Mach numbers. The cowl is represented by a forebody and afterbody which may be separated by a cylindrical mid-body (see Sketch 2.2). The drag estimation procedure outlined in the following sections reflects the changes in cowl flow characteristics that occur as engine mass flow and freestream Mach number are varied. When applying this procedure the user should follow the flow chart given in Figure 10. Details of a computer program for the method are given in Appendix A.

2.2.1 Cowl drag and flow characteristics

For attached flow and at free-stream Mach numbers for which the external flow is shock free the cowl drag coefficient is given by the summation of the friction and pressure drag coefficients (known as the profile drag coefficient). The profile drag coefficient is, for convenience, presented herein as a form factor, λ , in which the drag coefficient is normalised with respect to the mean skin friction drag coefficient of a flat plate with the same Reynolds number (based on total cowl length), and free-stream Mach number as the cowl. The form factors are given for the case of boundary-layer transition at the cowl leading-edge and, for the reasons given in Section 2.1, are applicable for the datum jet conditions appropriate to a fully expanded nozzle. The form factors are presented in Section 3 as a function of cowl geometry and intake mass flow ratio. The range of geometric parameters which have been used in deriving the form factors are listed in Table 9.1.

A reduction in intake flow area ratio, at a given free-stream Mach number, results in an increase in the pre-entry force (ϕ_{pre}) as given in Reference 24. Since, as outlined in Section 2.1, in potential flow $\phi_f = -\phi_{pre}$ the reduction in mass flow results in the forebody suction becoming larger as the forebody force (ϕ_f) increases in magnitude in an attempt to balance the pre-entry force (ϕ_{pre}). Thus, the forebody force is usually negative and acts in a forward direction. The resulting increases in pressure gradients around the cowl lip give rise to thickening boundary layers and increased profile drag until, ultimately, the boundary layer separates. Beyond this condition the magnitude of the forebody force falls rapidly, relative to the pre-entry force, and a rapid rise in drag ($= \phi_{pre} + \phi_f$) occurs. This rapid rise in drag is referred to as spillage drag. Data for estimating the spillage drag coefficient and the critical flow area ratio below which it occurs are given in Section 4. The critical flow area ratio is given as a function of a cowl leading-edge radius parameter and the spillage drag coefficient as a function of the increment in flow area ratio below the critical value.

As the free-stream Mach number increases shock waves form on the external surface of the cowl due to the acceleration of the flow around the forebody. Ultimately, the shocks become strong enough to cause a drag increase, which is referred to here as the wave drag. Data for estimating the wave drag coefficient and the Mach number at which its onset occurs (known as the drag-rise Mach number) are given in Section 5. The drag-rise Mach number is given as a function of a forebody fineness parameter and the wave drag coefficient as a function of the free-stream and drag-rise Mach numbers and the forebody area ratio A_i/A_m .

The forebody geometries for which measured data have been used to establish the spillage and wave drag characteristics are listed in Table 9.2.

In deriving spillage and wave drag coefficients from measured data a simple approach has been used. For spillage characteristics, data at constant Mach number were considered and spillage drag was assumed to be the rapid increase in drag that occurred as the intake flow area ratio was reduced through some critical value. Similarly, for wave drag characteristics, data at constant intake flow area ratio were considered and

wave drag was assumed to be the rapid increase in drag that occurred as the free-stream Mach number was increased above a critical value. It should be noted that for some cowl geometries and flow conditions a reduction in flow area ratio (A_0/A_i) may result in the formation of shock waves before the pressure gradients just downstream from the cowl leading-edge are sufficiently severe to cause the flow to separate. Also, for an increase in Mach number that results in the formation of a shock wave, any further increase in Mach number may result in a flow separation at the foot of the shock and a decrease in shock strength and ultimately a complete collapse of the supercritical flow. It is clear that for such complex flows what is termed "spillage drag" may contain a drag component due to shock waves and similarly what is termed "wave drag" may contain a component due to flow separation. However, it is impossible to give a strict breakdown of drag for such flows and the simple procedure referred to above is considered adequate for most practical applications.

The critical flow area ratio indicates the conditions at which flow separation occurs and, as with other separation onset conditions, it is considered likely that these will be sensitive to Reynolds number. However, experimental data are available only for Reynolds numbers of about 2×10^6 (based on maximum cowl diameter) and do not permit a Reynolds number effect to be quantified. Full-scale Reynolds numbers will, in most cases, be greater than those of the tests. It is therefore thought that at higher Reynolds numbers the spillage drag rise will occur at a lower value of A_0/A_i than that predicted by this Item.

2.2.2 Cowl forebody shapes

The selection of cowl geometry, particularly the forebody shape, is often a compromise to satisfy different requirements. In particular, the high Mach number cruise and low-speed engine-out requirements are conflicting. To minimise wave drag at high Mach number requires a long, thin cowl but this would raise the critical flow area ratio because the cowl lip would be too sharp. Similarly, a short, fat cowl would have good low-speed spillage drag characteristics but would have poor performance at high Mach number because the high suction near the maximum diameter location would lead to the early formation of shock waves.

The only family of forebody shapes that has been extensively tested such that charts can be produced to aid the selection procedure are the NACA 1-series shapes defined in Derivation 1. These forebody shapes form the basis of many cowl designs although it should be noted that the development of modern methods for calculating the supercritical flow over complete cowls should result in cowl shapes giving improved cowl performance. For example, one attempt at improving cowl design is presented in Derivation 18 and indicates that by increasing the leading-edge radius the low-speed characteristics of the NACA 1-series cowls can be improved, while retaining the high-speed characteristics.

Therefore, the charts presented in this Item for spillage drag characteristics are based on the extensive test data for NACA 1-series forebody shapes plus an incremental improvement in low-speed performance resulting from the use of increased forebody leading-edge radius based on the results of Derivation 18. However, it should be noted that the range of geometries for which measured data are available for increased leading-edge radius forebodies is limited (see Table 9.2b).

Thus, the NACA 1-series charts can be regarded as a performance level which is proven and readily obtainable while the incremental low-speed performance can be regarded as a design aim that can be achieved with an increased leading-edge radius while retaining the NACA 1-series high-speed performance by careful design of the forebody profile. For the NACA 1-series shapes the forebody geometry is known (given in Derivation 1) but for the increased leading-edge radius shapes the forebody profile has to be determined by detailed design using modern theoretical methods.

2.3 Estimation of Total Cowl Drag Coefficient

The drag components that contribute to the total cowl drag vary with inlet mass flow, free-stream Mach number and Reynolds number. For most practical applications the conditions of most interest are the low-speed engine failed (low intake mass flow) case and the high-speed cruise (high intake mass flow) case.

For the low-speed case the cowl drag is given by the profile drag plus any spillage drag that is incurred. For the high-speed case the cowl drag is given by the profile drag plus any wave drag that is incurred. For the combination of low intake mass flow and high cruise Mach number, which is not likely to be encountered in practice, the cowl drag is given by the profile drag plus any wave and spillage drags.

The procedure for the estimation of cowl drag is outlined below and allows for these different combinations of drag components.

2.3.1 Estimation of critical flow area ratio and drag-rise Mach number

The first step in the calculation procedure is to calculate the values of the critical flow area ratio, $(A_0/A_i)_{crit}$, and the drag-rise Mach number, M_{DR} , from Sections 4 and 5. These parameters determine the valid range of the profile drag estimation method and also determine the calculation procedure to be used (see Figure 10).

For flow area ratios below the critical value a spillage drag coefficient is added to the profile drag coefficient evaluated at $(A_0/A_i)_{crit}$. Similarly, for free-stream Mach numbers (M_0) above the drag-rise value (M_{DR}) a wave drag coefficient is added to the profile drag coefficient evaluated at M_{DR} .

2.3.2 Cowl drag coefficients for Mach numbers below the drag-rise value ($M_0 \leq M_{DR}$)

The drag coefficient is given by:

- (i) for $(A_0/A_i) \geq (A_0/A_i)_{crit}$

$$C_D = C_{Dp}, \quad (2.1)$$

- (ii) for $(A_0/A_i) < (A_0/A_i)_{crit}$

$$C_D = C_{Dpcrit} + \Delta C_{Ds}. \quad (2.2)$$

In Equations (2.1) and (2.2) all drag coefficients are based on the cowl maximum cross-sectional area and

C_{Dp} is the cowl profile drag coefficient obtained from Section 3.3,
 C_{Dpcrit} is the cowl profile drag coefficient at the critical value of (A_0/A_i) , with $(A_0/A_i)_{crit}$ obtained from Section 4,
 and ΔC_{Ds} is the spillage drag coefficient obtained from Section 4.

2.3.3 Cowl drag coefficients for Mach numbers above the drag-rise value ($M_0 > M_{DR}$) and for $(A_0/A_i) \geq (A_0/A_i)_{crit}$

The drag coefficient is given by:

$$C_D = C_{DpDR} + \Delta C_{Dw} \quad (2.3)$$

where C_{DpDR} is the profile drag coefficient estimated, at the drag-rise Mach number and for the required value of (A_0/A_i) , from Section 3.3
and ΔC_{Dw} the wave drag coefficient increment obtained from Section 5.

2.3.4 Cowl drag coefficients for Mach numbers above the drag-rise value ($M_0 > M_{DR}$) and for $(A_0/A_i) < (A_0/A_i)_{crit}$

For the combination of high Mach number and low flow area ratio, an approximate method of estimating the drag is given by,

$$C_D = (C_{Dpcrit})_{DR} + \Delta C_{Ds} + \Delta C_{Dw} \quad (2.4)$$

where $(C_{Dpcrit})_{DR}$ is the profile drag coefficient evaluated at $(A_0/A_i)_{crit}$ and at the drag-rise Mach number (M_{DR}),
 ΔC_{Ds} is the spillage drag coefficient evaluated from Section 4 as a function of $\Delta(A_0/A_i)$ and M_0 ,
and ΔC_{Dw} the wave drag coefficient obtained from Section 5.

3. COWL PROFILE DRAG COEFFICIENTS

3.1 The Drag Calculation Method

The profile drag coefficients have been calculated by using measured pressure distributions and cowl geometry as input to a boundary-layer computer program and relating profile drag to the momentum deficit far downstream. The boundary-layer procedure used was the entrainment history method due to Horton⁷, transformed to compressible flow by use of Spence's⁷ transformation. For the calculation of profile drag the Squire and Young wake correction was used with the Cook⁸ extension for compressible flow.

The cowl pressure distributions used have been obtained from Derivations 1, 6, 9, 12, 14 and 18 for forebodies and from Derivations 10, 11 and 13 for afterbodies. Most of the pressure distributions have been obtained for forebodies and afterbodies followed or preceded by, respectively, a long cylindrical section. Practical cowl designs will be such that the forebody and afterbody will be separated by only a small cylindrical section. In order to allow for interference between the forebody and afterbody, measured data presented in Derivations 15, 16 and 17 have been used to define the shape of the forebody and afterbody pressure carry-over downstream and upstream of the forebody-cylinder and cylinder-afterbody junctions, respectively.

It has been found that, approximately, the pressures carry over for a distance of one cowl maximum diameter and decay in proportion to the distance squared. Derivation 17 also confirms that the afterbody and forebody pressure distributions obtained from tests on the components in isolation can be superimposed to give a close approximation to the pressure distribution measured for a complete cowl.

3.2 Estimation of the Cowl Form Factor

3.2.1 General

The cowl form factor is estimated in stages. First the forebody value is determined, then a form factor increment due to the afterbody is added with, finally, an allowance for the effect of any cylindrical midbody incorporated in the cowl. The cowl geometry is as defined in Sketch 2.2.

The form factors are for turbulent flow with transition assumed to occur at the cowl leading-edge. The assumption regarding transition at the leading edge may, on the one hand, result in a slight overestimate of the drag if any laminar flow exists but on the other hand a slight underestimate may result at low intake mass flow ratio where, as revealed by measured data presented in Derivation 3, the flow stagnation line can be on the inside of the cowl lip, downstream of the intake entry plane.

It is also assumed that the internal lip shape has no effect on the cowl drag characteristics even though some effect might have been expected since, as noted above, the stagnation line can be on the internal surface.

However, this assumption is supported by tests, reported in Derivation 5, and carried out with contraction ratio (intake inlet area / minimum internal area) varying from 1.035 to 1.35, which did not reveal any significant effect on the cowl drag characteristics.

3.2.2 Form factor for the forebody

The form factor (λ_0) for the forebody is given by

$$\lambda_0 = \frac{1}{K_0} \left\{ 1 + 0.33K \left[\frac{1 - (D_i/D_m)}{L_f/D_m} \right] \right\}^{1.667} \quad (3.1)$$

where K is given in Figure 1a as a function of the forebody area ratio (A_m/A_i) and the flow area ratio (A_0/A_i)

and K_0 is given in Figure 1b as a function of forebody diameter ratio (D_i/D_m) and forebody fineness ratio (L_f/D_m).

The form of Equation (3.1) was obtained from use of correlating parameters developed in Derivation 5 by the use of simple one-dimensional incompressible flow theory.

The form factors given by Equation (3.1) are applicable to NACA 1-series forebodies and to forebodies with increased leading-edge radius compared to the NACA 1-series shapes. However, it should be noted that because the form factor is the ratio of profile drag to skin friction drag the profile drag is slightly greater for the increased leading-edge radius forebodies because of their larger wetted areas.

3.2.3 Form factor for cowl with no cylindrical midbody

The contribution of the afterbody to the cowl drag coefficient is calculated as a form factor increment ($\Delta\lambda$) relative to that for the enclosing cylinder. Thus the form factor increment is added to that estimated for the forebody followed by a cylinder of length equal to the afterbody (λ_1). This form factor is given by

$$\lambda_1 = 1 + K_1(\lambda_0 - 1) \quad (3.2)^*$$

* Note that this equation and the form factor λ_1 apply to the case often encountered in a wind-tunnel where a forebody followed by a cylindrical portion are tested alone. In this particular case $L_a / (L_f + L_a)$ is to be interpreted as $L_c / (L_f + L_c)$ and the complete "cowl" form factor is λ_1 .

where λ_0 is the form factor for the forebody given by Equation (3.1)

and K_1 is given in Figure 2a as a function of L_f/D_m and $L_a/(L_f + L_a)$.

The form factor for the afterbody/forebody combination is then given by

$$\lambda_3 = (\lambda_1 + \Delta\lambda)[1 + K_5(\lambda_0 - 1)(D_m - D_e)/L_a] \quad (3.3)$$

where K_5 is given in Figure 3c as a function of the free-stream (M_0) and drag-rise (M_{DR}) Mach numbers.

The parameter $\Delta\lambda$ is the increment in form factor due to the afterbody relative to that of the enclosing cylinder and is given by

$$\Delta\lambda = K_3 K_4 C_{Sa} \quad (3.4)$$

where K_3 is given in Figure 3a as a function of

$$\left[\frac{1 - (D_e/D_m)}{L_a/D_m} \right] / \left(\frac{L_f + L_a}{D_m} \right),$$

K_4 is given in Figure 3b as a function of λ_0

and C_{Sa} is the ratio of the afterbody wetted area to that of the enclosing cylinder. For the particular case of circular-arc afterbodies C_{sa} is obtained from Figure 4b.

3.2.4 Form factor for cowl with a cylindrical midbody

The complete cowl form factor is given by

$$\lambda_2 = 1 + K_2(\lambda_3 - 1) \quad (3.5)$$

where λ_3 is the cowl form factor for a zero cylindrical midbody length given by Equation (3.3)

and K_2 is given in Figure 2b as a function of L_c/L_t , where $L_t = L_f + L_c + L_a$.

3.3 Estimation of the Cowl Profile Drag Coefficient

In order to estimate the cowl profile drag coefficient for use in Equations (2.1) to (2.4) the form factors obtained from Section 3.2 are used as follows

$$C_{Dp} = \lambda C_{DF} \quad (3.6)$$

$$\text{with } C_{DF} = C_F (A_S / A_m) \quad (3.7)$$

where λ is the complete cowl form factor obtained from Section 3.2 as λ_2 or λ_3 for a cowl with or without, respectively, a cylindrical midbody,

C_F is the mean skin friction coefficient evaluated at the free-stream Mach number and Reynolds number based on cowl total length and may be estimated by the charts of Reference 20

and A_S/A_m is the ratio of cowl wetted area to the maximum cross-sectional area.

For the particular cowl geometry of a NACA 1-series forebody and a circular-arc afterbody the ratio A_S/A_m may be evaluated using Figures 4a and 4b which present surface area coefficients for NACA 1-series forebodies and circular-arc afterbodies respectively. The surface area coefficients (C_{Sf} and C_{Sa}) give the ratio of the wetted area of the body to the wetted area of the enclosing cylinder.

The ratio A_S/A_m is therefore given by

$$\frac{A_S}{A_m} = 4 \left(C_{Sf} \frac{L_f}{D_m} + C_{Sa} \frac{L_a}{D_m} + \frac{L_c}{D_m} \right). \quad (3.8)$$

For forebodies with increased leading-edge radius, relative to the equivalent NACA 1-series shape, the surface area coefficient is given approximately by

$$C_{SfR} = C_{Sf} [1 + 0.0085(\rho - 1)] \quad (3.9)$$

where ρ is the ratio of the forebody leading-edge radius to that of the equivalent NACA 1-series forebody (*i.e.* that with the same $D_i/(D_m$ and $L_f)/D_m$)
and C_{Sf} is the surface area coefficient, obtained from Figure 4a, for the equivalent forebody.

Equation (3.9) has been based on the forebody designs of Derivation 18. For these forebodies the ratio (A_S/A_m) is then evaluated using Equation (3.8) with C_{Sf} replaced by C_{SfR} . Surface area coefficients for other forebodies and afterbodies may be evaluated with the aid of the charts of Reference 21.

4. SPILLAGE DRAG COEFFICIENTS

4.1 Spillage Drag Coefficients for Cylindrical Forebodies with Sharp Leading-edges

For the special case of a cylindrical forebody with a sharp leading-edge the flow is separated for all flow area ratios less than unity (*i.e.* for $A_0/A_i < 1.0$) such that the forebody force (ϕ_f) is zero. In this case the spillage drag coefficient is given by

$$\Delta C_{Ds} = C_{\phi pre} \quad (4.1)$$

where $C_{\phi pre}$ is the pre-entry force coefficient. $C_{\phi pre}$ may be estimated by the equations given in Reference 24 or obtained from Figure 5 as a function of free-stream Mach number (M_0) and flow area ratio (A_0/A_i). The values of $C_{\phi pre}$ in Figure 5 are approximate since they have been calculated assuming one-dimensional flow theory. The presence of a stagnation line contravenes the strict application of this approach. However, the use of one-dimensional methods is common for inlet flows and comparisons with exact theory indicate that the errors involved are not large.

4.2 Spillage Drag Coefficients for Forebodies with Rounded Leading-edges

For forebodies with rounded leading-edges two characteristics reduce the spillage drag coefficients with respect to those obtained with sharp leading-edges.

- (i) Flow separations for rounded leading-edges are delayed to flow area ratios lower than unity.
- (ii) Because a forebody suction force (ϕ_f) is generated with a rounded leading-edge, even when the flow is separated the spillage drag coefficients are less than those for a forebody with a sharp leading-edge operating at the same flow area ratio.

These characteristics are reflected in the method for evaluating the spillage drag for practical forebody shapes which have rounded leading-edges.

The NACA 1-series (Derivation 1) is the only family of forebodies which has been extensively tested. Charts for these forebodies, introduced in Section 4.2.1, form the basis of the spillage drag estimation method and have been obtained from use of measured data given in Derivations 2, 4, 6, 12, and 14. These forebody shapes are used for many cowl designs although more recent investigations reveal that increased leading-edge radius, relative to that for NACA 1-series forebodies, can improve the spillage drag characteristics at low speeds.

Based on the measured data from Derivations 9 and 18, which are limited to a few forebody configurations, an indication of the incremental spillage drag improvements possible are given in Section 4.2.2.

4.2.1 Spillage drag coefficients for NACA 1-series cowls

The onset of spillage drag is delayed to flow area ratios (A_0/A_i) less than unity, by an amount which is a function of the forebody leading-edge radius.

The critical value of A_0/A_i for the onset of flow separation is obtained from Figure 6 as a function of a leading-edge radius parameter $S [1 - (D_i/D_m)]^2/(L_f/D_m)$, where S for NACA 1-series forebodies is unity.

Thus, for $(A_0/A_i) \geq (A_0/A_i)_{crit}$

$$\Delta C_{Ds} = 0.$$

For $(A_0/A_i) < (A_0/A_i)_{crit}$ the spillage drag coefficient is given by

$$\Delta C_{Ds} = K_6 K_7 K_8 C_{\phi pre} \left(\frac{D_i}{D_m} \right)^2 \quad (4.2)$$

where K_6 is given in Figure 7a as a function of $\Delta(A_0/A_i)$, where $\Delta(A_0/A_i) = (A_0/A_i)_{crit} - (A_0/A_i)$,

K_7 is given in Figure 7b as a function of D_i/D_m ,

K_8 is given in Figure 7c as a function of M_0 and $(D_m - D_i)/L_f$,

and $C_{\phi pre}$ is obtained from Figure 5 as a function of M_0 and A_0/A_i .

4.2.2 Spillage drag coefficients for forebodies with increased leading-edge radius

The use of increased leading-edge radius can, for some forebody geometries, reduce the critical flow area ratio. In addition, the shape of the spillage drag curve is modified, particularly at low speed where the drag increase, although delayed, is more rapid. An illustration of this is shown in Example 8.3.

The factors presented in this Section are based on measured data for a limited range of geometries (see Table 9.2b) and should be used with caution for forebodies outside the range tested.

For these forebodies the critical flow area ratio for the onset of spillage drag is again obtained from Figure 6 with S now being obtained from Figure 8a as a function of free-stream Mach number (M_0) and the ratio (ρ) of the forebody leading-edge radius to that for the equivalent NACA 1-series forebody.

As before, for $(A_0/A_i) \geq (A_0/A_i)_{crit}$

$$\Delta C_{Ds} = 0.$$

For $(A_0/A_i) < (A_0/A_i)_{crit}$ the spillage drag coefficient is given by

$$\Delta C_{Ds} = K_9 [K_6 K_7 K_8 C_{\phi pre} (D_i/D_m)^2] \quad (4.3)$$

where K_9 is given in Figure 8b as a function of M_0 and ρ .

The coefficients enclosed in brackets in Equation (4.3) are obtained as described for Equation (4.2).

In the analysis of the test data given in Derivations 9 and 18 the radius ratio ρ has been estimated by taking the initial radius of curvature of the NACA 1-series profile as

$$\frac{R_f}{D_m} = 0.1365 \frac{[1 - (D_i/D_m)]^2}{L_f/D_m}. \quad (4.4)$$

5. WAVE DRAG COEFFICIENTS

5.1 Drag-rise Mach Number

Because most cowl tests have been carried out with the forebody followed by a long cylindrical section, *i.e.* the “isolated” forebody, it is convenient to consider the drag-rise Mach number for this configuration first and then to consider afterbody/forebody interference effects.

5.1.1 Drag-rise Mach number for an isolated forebody

For the case of high intake mass flow the drag-rise Mach number for the isolated forebody (M'_{Df}) is a function of forebody geometry. For the case of low intake mass flow there is a gradual reduction in drag-rise Mach number as the mass flow ratio is decreased below the critical value (*i.e.* for $(A_0/A_i) < (A_0/A_i)_{crit}$). An approximate allowance for this effect has been made based on measured data given in Derivations 2, 6 and 18 such that the forebody drag-rise Mach number is given as follows:

- (i) For $(A_0/A_i) \geq (A_0/A_i)_{crit}$

$$M_{Df} = M'_{Df} \quad (5.1)$$

- (ii) For $(A_0/A_i) < (A_0/A_i)_{crit}$

$$M_{Df} = M'_{Df} - 0.15[(A_0/A_i)_{crit} - (A_0/A_i)] \quad (5.2)$$

In Equations (5.1) and (5.2) M'_{Df} is obtained from Figure 9a and $(A_0/A_i)_{crit}$ evaluated from Section 4. Equation (5.2) thus indicates an interaction between spillage drag onset and the drag-rise Mach number; although the combination of high Mach number and low mass flow is unlikely to be encountered in practice.

5.1.2 The effect of afterbody/forebody interference on the drag-rise Mach number

The data on which to base a method for the estimation of the effect of afterbody/forebody interference on the drag-rise Mach number are limited to a few experimental results (Derivation 5) and a brief theoretical investigation (Derivation 19). The method should therefore be regarded as approximate. The interference effect has been obtained as a function of the initial radius of curvature of the afterbody (R_a , see Sketch 2.2) and the length of the midbody (L_c) separating the forebody and afterbody. Thus, the complete cowl drag-rise Mach number, including interference effects, is given by

$$M_{DR} = M_{Df} - K_{10}\Delta M_{Df} \quad (5.3)$$

where M_{Df} is the drag-rise Mach number of the isolated forebody obtained from Section 5.1.1

and ΔM_{Df} and K_{10} are given in Figures 9b and 9c, respectively, as functions of R_a/D_m and L_c/D_m .

Equation (5.3) is valid for afterbodies whose profiles blend tangentially with the cowl midbody or forebody.

For the particular case of a circular-arc afterbody R_a/D_m is given by

$$\frac{R_a}{D_m} = \frac{(L_c/D_m)^2}{[1 - (D_e/D_m)]} + \frac{[1 - (D_e/D_m)]}{4} \quad (5.4)$$

5.2 Wave Drag Coefficients

The method for estimating the wave drag coefficient has been obtained from Derivation 19 and validated using measured data given in Derivations 2, 6 and 9.

The method is based on the observation that as the free-stream Mach number increases above the drag-rise value the drag coefficient rises rapidly but the surface Mach number distribution on the forebody becomes, approximately, "frozen" with the shock downstream of the location where the maximum diameter is first reached. Assuming a frozen local Mach number distribution a theoretical estimate of the change in drag with free-stream Mach number can be made based on the pressure ratio (p/P) distribution associated with this condition. In practice the "sonic freeze" is not complete and the surface Mach numbers do increase

slowly, as the free-stream Mach number increases, resulting in a slight reduction in the rate of drag increase relative to that obtained assuming a sonic-freeze condition. An empirically determined correction term to allow for this is included in the wave drag equation, which is

$$\begin{aligned}\Delta C_{Dw} = & \left[(C_{\phi pre})_0 \frac{A_i}{A_m} - \frac{(A_m - A_i)}{0.7 M_0^2 A_m} \right] \\ & - \left[(C_{\phi pre})_{DR} \frac{P_0}{P_{DR}} \frac{A_i}{A_m} \frac{M_{DR}^2}{M_0^2} - \frac{P_0}{P_{DR}} \frac{(A_m - A_i)}{0.7 M_0^2 A_m} \right] \\ & - K_{11} (1 - M_{DR}) \left[1 - \left(\frac{1 - M_0}{1 - M_{DR}} \right)^3 \right] \frac{(A_m - A_i)}{0.7 M_0^2 A_m} \frac{P_0}{P_0},\end{aligned}\quad (5.5)$$

where the first two terms are the theoretical expression and the third term is the empirically derived correction.

Rearranging Equation (5.5) gives,

$$\begin{aligned}\Delta C_{Dw} = & \frac{A_i}{A_m} \left[(C_{\phi pre})_0 - (C_{\phi pre})_{DR} \frac{P_0}{P_{DR}} \frac{M_{DR}^2}{M_0^2} \right] \\ & + \frac{[1 - (A_i/A_m)]}{0.7 M_0^2} \left\{ \left(\frac{P_0}{P_{DR}} - 1 \right) - K_{11} (1 - M_{DR}) \left[1 - \left(\frac{1 - M_0}{1 - M_{DR}} \right)^3 \right] \frac{P_0}{P_0} \right\}\end{aligned}\quad (5.6)$$

where,

$$\left. \begin{aligned} & \text{for } (M_0 - M_{DR}) \leq 0.1 \\ & K_{11} = 0.2 + M_0 - M_{DR} \\ & \text{and for } (M_0 - M_{DR}) > 0.1 \\ & K_{11} = 0.3. \end{aligned} \right\} \quad (5.7)$$

The pressure ratios are

$$\frac{P_0}{P_{DR}} = \left[\frac{1 + 0.2 M_0^2}{1 + 0.2 M_{DR}^2} \right]^{3.5}, \quad (5.8)$$

$$\text{and} \quad \frac{P_0}{P_0} = (1 + 0.2 M_0^2)^{3.5}. \quad (5.9)$$

$$\text{Also,} \quad \frac{A_i}{A_m} = \left(\frac{D_i}{D_m} \right)^2.$$

In Equation (5.6), $(C_{\phi pre})_0$ is the pre-entry force coefficient evaluated at M_0 and $(C_{\phi pre})_{DR}$ is the pre-entry force coefficient evaluated at M_{DR} , both obtained from Figure 5.

Equation (5.5) has been based on measured data obtained at moderate values of flow area ratio (typically $(A_0/A_i) < 0.85$). The method should therefore be used with caution for high flow area ratios. However, in practice the combination of high flow area ratio and high subsonic free-stream Mach numbers is unlikely to be encountered because the internal choking conditions will limit the flow area ratio. The theoretical values of the flow area ratio at the choking condition can be evaluated from Reference 24 if the cowl internal geometry is known.

6. ACCURACY

It is not possible to give a single accuracy figure for the cowl drag coefficient estimated by use of this Item because of the differing characteristics of the various drag components. Thus the accuracy associated with the estimation procedure for each component is considered in turn.

(i) Profile drag coefficient

The profile drag coefficients are presented as form factors, calculated using measured pressure distributions obtained for the forebody and afterbody geometries listed in Table 9.1. The measured pressures have been obtained for Reynolds numbers of about 2×10^6 (based on cowl maximum diameter) and it has been assumed that the form factors obtained are independent of Reynolds number. The validity of this assumption cannot be checked although the data for axisymmetric bodies presented in Item No. 78019 (Reference 22) obtained in a similar fashion (but using calculated pressure distributions) show that the form factors are substantially independent of Reynolds number, to within ± 0.5 per cent, for Reynolds numbers (based on total body length) from 10^6 to 10^9 .

There are relatively few complete cowl tests for which measured drags are available from which to assess the accuracy of the profile drag coefficient estimation method. Also, most of the cowls for which test data are available incorporate long cylindrical sections so that the cowl form factors are close to unity and most of the measured drag is attributable to skin friction.

It is not possible, therefore, to give an accuracy figure based on many comparisons of estimates and experimental data. However, it is expected that profile drag coefficients estimated by use of this Item will be accurate to within about 8 per cent.

(ii) Spillage drag characteristics

The spillage drag characteristics are described by the critical flow area ratio for the onset of flow separations and by the procedure for estimation of the associated spillage drag coefficients. The spillage drag characteristics presented are based on measured data obtained for the forebodies listed in Table 9.2.

The critical flow area ratios, $(A_0/A_i)_{crit}$, are estimated within an accuracy of, in general, ± 0.075 .

The accuracy of the spillage drag coefficient estimation procedure in this Item has been assessed by comparing estimated and measured drag coefficients. For moderate free-stream Mach numbers ($M_0 \leq 0.7$) the spillage drag coefficient estimates should be accurate to within ± 25 per cent. For the combination of low flow area ratio and high subsonic Mach number, the forebody flows can be complex (as outlined in Section 2.2.1) and larger errors may occur. Because the critical values of flow area ratio, $(A_0/A_i)_{crit}$, mark the onset of a rapid drag increase (*i.e.* the spillage drag) a relatively small error in the estimation of $(A_0/A_i)_{crit}$