



ESDU 78019

Issued July 1978
With Amendments A to D
March 2017
Supersedes ESDU
Aero B.02.04.01 to 03

Profile drag of axisymmetric bodies at zero incidence for subcritical Mach numbers

Associated software: ESDUpac A7819



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THE PREPARATION OF THIS DATA ITEM

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PROFILE DRAG OF AXISYMMETRIC BODIES AT ZERO INCIDENCE FOR SUBCRITICAL MACH NUMBERS

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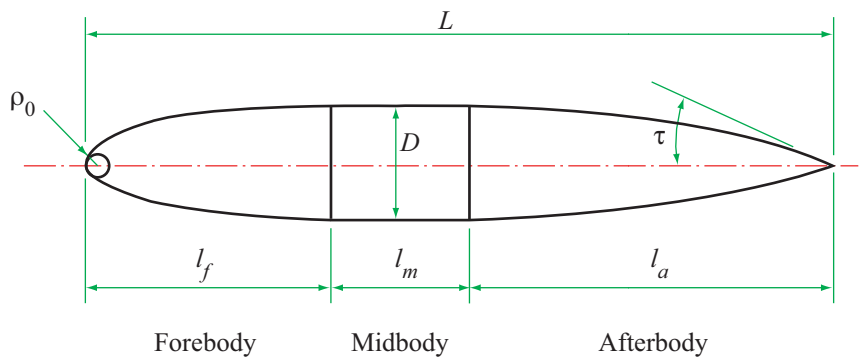
PROFILE DRAG OF AXISYMMETRIC BODIES AT ZERO INCIDENCE FOR SUBCRITICAL MACH NUMBERS

1. NOTATION AND UNITS (see Sketch 1.1)

		<i>SI</i>	<i>British</i>
A	afterbody parameter, $(l_a/D) \tan \tau$		
B	index in expression for flat plate mean skin friction coefficient with fully-turbulent boundary layer, see Equation (4.3)		
C_D	body profile drag coefficient based on surface area, $D_P/(q_\infty \times \pi D L C_S)$		
C_F	flat plate mean skin friction coefficient (based on skin friction and area of one side of plate)		
C_{F0}	flat plate mean skin friction coefficient (fully-turbulent boundary layer, $x_{tr}/L = 0$), see Equation (4.2)		
C_S	area coefficient, ratio of body surface area to surface area of enclosing cylinder, $S/(\pi D L)$		
C_V	volume (or prismatic) coefficient of body, ratio of body volume to volume of enclosing cylinder, $4V/(\pi D^2 L)$		
C_{Va}	volume coefficient of afterbody, $4V_a/(\pi D^2 l_a)$		
C_{Vf}	volume coefficient of forebody, $4V_f/(\pi D^2 l_f)$		
D	maximum diameter of body	m	ft
D_P	profile drag of body	N	lbf
F_f	correction to correlating parameter C_S/C_V^n to allow for forebody shape and length, see Section 4.2		
F_{M1}, F_{M2}	functions of Mach number, see Equations (4.4) and (4.5)		
K_M	correction factor for M , see Equation (4.1)		
K_{tr}	correction factor for x_{tr}/L , see Equation (4.1)		
k_1	family parameter for Body 7 in ESDU 77028		
L	body length	m	ft
l_a	afterbody length	m	ft

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l_f	forebody length	m	ft
l_m	midbody length	m	ft
M	free-stream Mach number		
n	function of C_V and D/L , see Section 4.2		
$\left. \begin{matrix} p \\ q \end{matrix} \right\}$	functions of $l_f(l - C_V p)/L$, see Section 4.3		
q_∞	free-stream kinetic pressure	N/m ²	lbf/ft ²
R_L	Reynolds number based on body length		
S	body surface area	m ²	ft ²
V	body volume	m ³	ft ³
V_a	afterbody volume	m ³	ft ³
V_f	forebody volume	m ³	ft ³
x_{tr}	axial distance of boundary-layer transition from nose	m	ft
λ	normalised drag parameter, C_D/C_F		
λ_G	value of λ relating to required body at datum boundary-layer and flow conditions, see Section 4.2		
ρ_0	nose radius of curvature	m	ft
$\bar{\rho}_0$	non-dimensional nose radius, $\rho_0 l_f/D^2$		
τ	tail half-angle	degree	degree



Sketch 1.1 Body geometry

2. INTRODUCTION

This Item presents a simple method for estimating the profile drag of any closed axisymmetric body (with or without a cylindrical midbody) at zero incidence and at Mach numbers for which the flow over the body is wholly subsonic.

The method chosen to provide the source data for profile drag was a slightly modified form (see Section 3) of that outlined in Derivation 4. Its choice (Derivation 6) was based largely on its ability to provide predictions of body profile drag that compared well with reliable experimental data.

The presentation of the profile drag data is, for reasons of convenience, given in terms of a factor, λ , in which the profile drag coefficient is normalised with respect to the mean skin friction coefficient of a flat plate (see Section 4.4) with the same boundary-layer transition position, Reynolds number and free-stream Mach number as for the body under consideration, *i.e.* $\lambda = C_D/C_F$.

The drag prediction method of this Item (see Section 4) was developed from data for a family of bodies with variable fineness ratio, L/D , the shapes of individual members being defined in terms of four geometrical parameters. The values of λ for this family have been correlated in terms of body geometry and are presented for datum values of transition position, Reynolds number and Mach number (see Section 4.2). To account for transition position and flow variables different from the datum values, correction factors are given in graphical form (see Section 4.3). Finally, charts for the mean skin friction coefficient of a flat plate, C_F , are given (see Section 4.4).

The applicability and accuracy are discussed in Section 5. Advice on body geometrical data is given in Section 6. The Derivation and References are listed in Section 7. The worked examples in Section 8 include one to show the effect on body profile drag of variation in shape and length of the forebody and afterbody.

Although the method of Section 4 is relatively simple to apply, it is still fairly time consuming to evaluate by hand. Addendum A gives a simplified method, using analytic equations developed using the original database described in Section 3. The equations are easily programmed and give a correlation only marginally worse than the method of Section 4. Moreover, they extend the method to cover a greater range of boundary-layer transition positions. Tentative provision is also made for bodies of non-circular cross section. A program of the method of Addendum A is provided as ESDUpac A7819 and is described in Addendum B.

3. THE DRAG CALCULATION METHOD

The method due to Myring (Derivation 4), which accounts iteratively for the displacement effects of the boundary layer and wake, was used to provide the source data for body profile drag from which the prediction method of this Item was developed.

In the computer program used to generate the data, the potential flow method is that due to Smith and Hess (Reference 14) which is extended to compressible flow by the Göthert (Reference 10) transformation. The laminar boundary layer is calculated by the method of Luxton and Young (Reference 13); the boundary-layer transition position (assumed to be axisymmetric and to occur at a line) is specified and the turbulent boundary-layer is calculated by Head's method (Reference 12) extended to axisymmetric compressible flow by Myring (Reference 15).

Instead of the Ludwig-Tillmann law (Reference 11) for skin friction in the presence of a pressure gradient used in Derivation 4, the program contains a modification to give good agreement with the Spalding and Chi law (Derivation 3) in the limiting case of a flat plate.

Downstream of the tail the wake is calculated using turbulent boundary-layer momentum integral and entrainment equations as a basis up to a specified truncation point ($1.8 \times$ body length in the calculations for the Item). Downstream of truncation the wake method due to Squire and Young (Reference 9) is used.

4. BASIS OF THE DRAG PREDICTION METHOD

4.1 General

In order to account for the effects of body shape on profile drag coefficient, a series of calculations was carried out on a family of bodies at datum values of transition position, Reynolds number and free-stream Mach number.

The bodies used for the calculations (Derivation 7) consisted of three sections, *i.e.* forebody, cylindrical midbody and afterbody. To avoid any possible computing problems involving discontinuities in body curvature at the junction of the forebody and afterbody with the midbody, the forebodies and afterbodies denoted as ESDU I and II respectively in ESDU 77028 were used. For a given fineness ratio, particular members of the family were defined in terms of the overall body volume coefficient, C_V , the volume coefficients of the forebody, C_{Vf} , and afterbody, C_{Va} , and the forebody length ratio, l_f/L . Implicit in a knowledge of these parameters are the midbody and afterbody lengths.

4.2 Effect of Body Shape on Profile Drag Coefficient

Calculations (Derivation 7) were carried out for the family of bodies defined in Section 4.1 for datum values of boundary-layer transition position, Reynolds number and free-stream Mach number taken as

$$\frac{x_{tr}}{L} = 0, R_L = 10^7, \text{ and } M = 0.$$

The fineness ratio, L/D , was varied from 4 to 20 and each of the four geometrical parameters used to define the body shape was varied in turn about a datum value to cover a reasonably practical range.

Analysis of the profile drag coefficient data in terms of a factor, λ_G (*i.e.* C_D/C_F for datum boundary-layer and flow conditions), showed that, for a given fineness ratio, the effect of body shape could be correlated in terms of a parameter combination $F_f C_S / C_V^n$, see Figure 1. The basis of this analysis lies in the fact that, for bodies with moderate volume coefficients and forebodies not too bluff, the drag coefficient based on $(\text{volume})^{2/3}$ provides a good correlation (Derivation 7). The index n (see Figure 2) was found to be a function of C_V and D/L . The factor F_f (see Figure 3) is a function of forebody bluntness, characterised by the parameter $l_f(1 - C_{Vf})/L$. Thus afterbody volume coefficient, C_{Va} , does not occur explicitly in the correlation.

4.3 Corrections for Transition Position and Flow Conditions

In order to correct the λ_G values obtained from Figure 1 (in conjunction with Figures 2 and 3) for transition position and flow conditions different from the datum values (Section 4.2) use is made of the expression

$$\lambda = \frac{C_D}{C_F} = K_{tr} K_M \lambda_G \quad (4.1)$$

in which K_{tr} is a correction factor for x_{tr}/L , given in Figure 4, and K_M is a correction factor for M , given in Figure 5.

Derivation 7 shows that, within about ± 0.5 per cent, λ is substantially independent of Reynolds number over the range of R_L from 10^6 to 10^9 .

It was found in Derivation 7 that K_{tr} correlates well in terms of the forebody bluntness parameter $l_f(1 - C_{vp})/L$ and is largely independent of body fineness ratio for boundary-layer transition positions forward of the position of minimum pressure on the forebody. The curves in Figure 4 have been cut off just forward of this position, which can be taken as representing the aftermost position of transition likely in practice.

Derivation 7 has shown that K_M is a function of $l_f(1 - C_{vp})/L$, but, unlike K_{tr} , is in addition a function of D/L . The effects of Mach number, via K_M , are correlated reasonably well in terms of a parameter combination $(M/p)(D/L)^q$, see Figure 5, in which p and q are functions of $l_f(1 - C_{vp})/L$, see Figure 6.

4.4 Flat Plate Mean Skin Friction Coefficient

In order to calculate C_D from Equation (4.1) it is necessary to evaluate C_F , the mean skin friction coefficient of a flat plate with the same boundary-layer transition position, Reynolds number and free-stream Mach number as for the body under consideration. In deriving the λ data in this Item the following method of evaluating C_F was used.

In incompressible flow the laminar flow was represented by the Blasius theory (see Derivation 2 for example) and the turbulent flow by the method of Spalding and Chi (Derivation 3). For reasons of simplicity, and especially in view of the small changes involved for Mach numbers less than unity, it can be assumed that the Mach number effect on the part-laminar, part-turbulent boundary-layer is the same as that for the fully-turbulent boundary-layer.

To simplify the analysis a fit (to within ± 0.1 per cent over the range $10^6 \leq R_L \leq 10^9$) to the Spalding and Chi law for fully-turbulent boundary-layers given by

$$F_{M1} C_{F0} = \frac{0.455}{(\log_{10} F_{M2} R_L)^B}, \quad (4.2)$$

see Figures 7a and 7b, was used, where

$$B = 2.62105 - 0.0042167 \log_{10}(F_{M2} R_L), \quad (4.3)$$

$$F_{M1} = \frac{0.178 M^2}{[\tan^{-1}(0.4219 M)]^2}, \quad (4.4)$$

with the inverse tangent evaluated in radians,

$$\text{and} \quad F_{M2} = \frac{[1 + 0.178 M^2]^{-0.702}}{F_{M1}}, \quad (4.5)$$

see Figure 8.

To account for the effect of transition position a combination of the Spalding and Chi law for the turbulent part of the boundary layer together with the Blasius law for the laminar part gives C_F/C_{F0} as presented in Figure 9.

Thus, from Figures 7 to 9

$$C_F = \frac{C_F}{C_{F0}} C_{F0}. \quad (4.6)$$

5. APPLICABILITY AND ACCURACY

5.1 Applicability

Although the source data used to derive the prediction method of this Item related to bodies with continuous curvature, incorporating the ESDU I and II families of forebody and afterbody, the Item is considered to apply to any closed axisymmetric body whose forebody and afterbody blend, without discontinuity in surface slope, into a cylindrical midbody or into each other. In this context the method has been evaluated against calculations for other families (from Derivation 5 in particular) and has been shown to be generally applicable within the constraints in geometry delineated here.

The data apply only to bodies at zero incidence with fully-attached flow and at Mach numbers for which the flow over the body is wholly subsonic. In practice, provided that transition occurs at the nose, the profile drag coefficient is unlikely to be very sensitive to small changes (less than 3 degrees, say) of incidence about zero.

The range of body shapes for which the method of this Item has been found to provide good agreement (see Section 5.2.1) with C_D calculated by Myring's method can be briefly summarized in terms of body geometry as follows.

l_f/L	$\bar{p}_0$	C_{Vf}	l_m/L	l_a/L	A	C_{Va}	C_V	C_S
0.10 to 0.5	0 to ∞	0.56 to 0.86	0 to 0.6	0.25 to 0.6	0 to 2	0.37 to 0.71	0.50 to 0.85	0.63 to 0.93

The Item should be used with caution for bodies outside these ranges. The majority of the systematic data related to bodies with $D/L = 0.1$ and 0.2 , although such data as were obtained for other D/L values in the range $0.05 \leq D/L \leq 0.25$ correlated well. Few data, other than for $D/L = 0.1$, were obtained for bodies with pointed noses (*i.e.* $\bar{p}_0 = 0$).

The Item provides data that are applicable to any specified boundary-layer transition position between the nose and, roughly, the position of minimum pressure on the forebody, which can be taken as representing the aftermost transition position in practice, a guide for which is given by the hatched line in Figure 4. Estimation of the actual transition position is made difficult by the fact that it is influenced by so many factors, such as, Reynolds number, free-stream turbulence, pressure gradient and surface irregularities. For example, if a circumferential skin gap or a line of rivets is situated forward of the position represented by the hatched line in Figure 4 then it can be fairly safely assumed that transition will not be aft of the skin gap or line of rivets. Also, the effect of even small changes in incidence on the position of the suction peak and the magnitude of the pressure gradients over the forebody will greatly affect the transition position and its symmetry. In most practical situations with uncertain transition position it is prudent to assume that it occurs at the nose.

The range of Reynolds number covered is from 10^6 to 10^9 and the data concerning Mach number effect are applicable up to the critical Mach number for the body under consideration (see ESDU 74013 in the Transonic Aerodynamics Series).

It is important to note that varying the body geometry can have a much greater influence on the **profile drag** than on the **profile drag coefficient** because of the involvement of surface area in the definition of C_D ; in fact, the trend of the drag with geometry changes can even be the reverse of the trend of the coefficient (see example in Section 8.2).

5.2 Accuracy

The ranges of body geometry for bodies against which the method has been evaluated are tabulated in Section 5.1. Caution should be exercised if the required body falls outside these ranges.

5.2.1 Comparison with computed data

The method of this Item has been compared with computed data for 80 bodies comprising, largely, the ESDU bodies considered in Derivation 7 at the datum values of transition position, Reynolds number and Mach number (see Section 4.2). The remainder was largely made up of various members of the family of bodies considered by Myring in Derivation 5 at $x_{tr}/L = 0.03$, $R_L = 10^7$ and $M = 0$, together with a selection of bodies from the DTMB 58 series (Derivation 1) at $x_{tr}/L = 0.05$, $R_L \approx 10^7$ and $M = 0$. The computed profile drag coefficients for all these bodies are correlated by the method of this Item to within about ± 1 per cent. In general, for other than datum boundary-layer and flow conditions, the computed data for the bodies considered in Derivation 7 are correlated to within about ± 2 per cent.

It is important to note that the drag reduction factor $(1 - K_{tr}C_F/C_{F0})$ due to non-zero boundary-layer transition position can be significantly greater than the drag increment factor $(\lambda_G - 1)$ due to body geometry, particularly for slender bodies ($D/L \leq 0.1$, say) so that the accuracy of the prediction given by this Item can be no better than the confidence with which transition position can be defined (see Section 5.1).

5.2.2 Comparison with experimental data

The method of this Item is consistent (to within about ± 5 per cent) with the few reliable low-speed experimental data (Derivation 8) available, for bodies with $D/L = 0.105$ and 0.143 over the range $3 \times 10^6 < R_L < 10^7$. These data were singled out as being probably the most reliable since they were obtained from a careful series of tests which included comparisons of drag measurements using a balance and a wake traverse technique. The results from the two drag determinations correlated well.

The lack of reliable data arises from the difficulty in accurately measuring the drag of a closed body. Since the body cannot be conventionally sting-mounted, resort has to be made to strut or wire mounting with their attendant problems of tare drag and flow interference. In addition, it is necessary to fix the boundary-layer transition position artificially, usually by means of a “minimum” roughness band* with an accurately definable drag increment.

No suitable data for compressible flow were found and so to this extent the Mach number effect in Figure 5, although plausible, is untried; in particular, application of the data to bodies with high D/L should be treated with some caution, especially for Mach numbers approaching the critical.

6. BODY GEOMETRICAL DATA

In order to use the method of this Item to predict the drag of a given axisymmetric body it is necessary to know the surface area and component volume coefficients of the body. Such data may be obtained for a range of typical forebody and afterbody shapes from ESDU 77028.

* *i.e.* a band of roughness particles of minimum height and density of distribution required to fix transition fully.

7. DERIVATION AND REFERENCES

Derivation

The Derivation lists selected sources that have assisted in the preparation of this Item.

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8. EXAMPLES

- 8.1 Find the profile drag coefficient at zero incidence of a three-section axisymmetric body of overall length 2 m and diameter 0.2 m. The forebody, of length 0.4 m, utilises Body 7 of ESDU 77028 with $k_1 = 1$ and the afterbody, of length 0.6 m, utilises Body 9 with $A = 0.75$. The parallel midbody is therefore of length 1 m. The flight Mach number is 0.7 and the Reynolds number based on body length is 10^7 . It may be assumed that boundary-layer transition occurs 5 per cent of the body length aft of the nose.

The required body is that of Example 7.1 in ESDU 77028. From Section 7.1 of that Item it is found that

$$D/L = 0.1, C_{Vf} = 0.688, l_f/L = 0.2, C_S = 0.853 \text{ and } C_V = 0.783.$$

Effect of body geometry

From Figure 2, with $D/L = 0.1$ and $C_V = 0.783$,

$$n = 0.637.$$

From Figure 3, with $l_f(1 - C_{Vf})/L = 0.2(1 - 0.688) = 0.062$,

$$F_f = 1.00.$$

Therefore, $F_f C_S / C_V^n = 1.00 \times 0.853 / (0.783)^{0.637} = 0.997$.

From Figure 1, with $D/L = 0.1$ and $F_f C_S / C_V^n = 0.997$,

$$\lambda_G = 1.078.$$

Effect of transition position and Mach number

From Figure 4, with $l_f(1 - C_{Vf})/L = 0.062$ and $x_{tr}/L = 0.05$,

$$K_{tr} = 1.017.$$

From Figure 6, with $l_f(1 - C_{Vf})/L = 0.062$,

$$p = 0.753 \text{ and } q = 0.656.$$

Therefore, for $M = 0.7$ and $D/L = 0.1$,

$$\frac{M}{p} \left(\frac{D}{L} \right)^q = 0.205.$$

From Figure 5, with $(M/p)(D/L)^q = 0.205$,

$$K_M = 1.018.$$

Therefore, from Equation (4.1), the value of λ after correction for transition position and Mach number different from datum is

$$\lambda = C_D/C_F = K_{tr}K_M\lambda_G = 1.035\lambda_G = 1.116.$$

Flat plate mean skin friction coefficient, C_F

From Figure 8, with $M = 0.7$,

$$F_{M1} = 1.058 \text{ and } F_{M2} = 0.892.$$

From Figure 7a, with $F_{M2}R_L = 8.92 \times 10^6$,

$$F_{M1}C_{F0} = 0.00299,$$

giving $C_{F0} = 0.00299/1.058 = 0.00283$.

From Figure 9, with $R_L = 10^7$ and $x_{tr}/L = 0.05$,

$$\frac{C_F}{C_{F0}} = 0.9695.$$

Therefore $C_F = \frac{C_F}{C_{F0}}C_{F0} = 0.9695 \times 0.00283 = 0.00274$.

Body profile drag coefficient

The body profile drag coefficient is therefore

$$C_D = \lambda C_F = 1.116 \times 0.00274 = 0.00306.$$

8.2 For the body of Section 8.1 find the effect on the low-speed profile drag of varying in turn the shape and length of the forebody and afterbody using other family members of Bodies 7 and 9 in ESDU 77028. It may be assumed that $M = 0$, $x_{tr}/L = 0$ and $R_L = 10^7$.

- (i) The variation of forebody shape will be covered by considering Body 7 with $k_1 = -0.25, 1$ and ∞ .
- (ii) The variation of forebody length will be covered by considering $l_f/L = 0.2, 0.35$ and 0.5 .
- (iii) The variation of afterbody shape will be covered by considering Body 9 with $A = 0.4, 0.75$ and 1.5 .
- (iv) The variation of afterbody length will be covered by considering $l_a/L = 0.3, 0.45$ and 0.6 .

The calculations for the nine resulting bodies are very similar to those detailed in Section 8.1 and so only a tabulation of the main parameters is given in Tables 8.1 and 8.2.

Note that although the effect of body geometry variation on C_D (via λ_G) is comparatively small in this example the effect on the profile drag itself (which for given body diameter, length, boundary-layer transition position and flow conditions is proportional to $\lambda_G C_S$) is very considerable.

Sketches 8.1 to 8.4 illustrate the effect on profile drag (via $\lambda_G C_S$) of varying each of the four geometry parameters.