



# **Subsonic pressure drag of boat-tails with negligible annular base area in the presence of a central propulsive jet**

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The technical work involved in the assessment of the available information and the development and subsequent construction of the Data Item method was carried out under contract to ESDU by Mr A.J. Clarke.

SUBSONIC PRESSURE DRAG OF BOAT-TAILS WITH NEGLIGIBLE ANNULAR  
BASE AREA IN THE PRESENCE OF A CENTRAL PROPULSIVE JET

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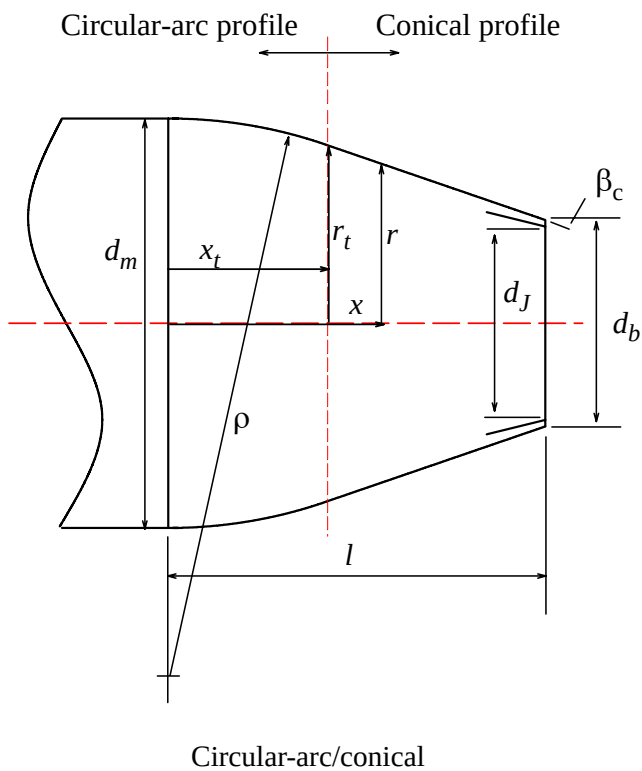
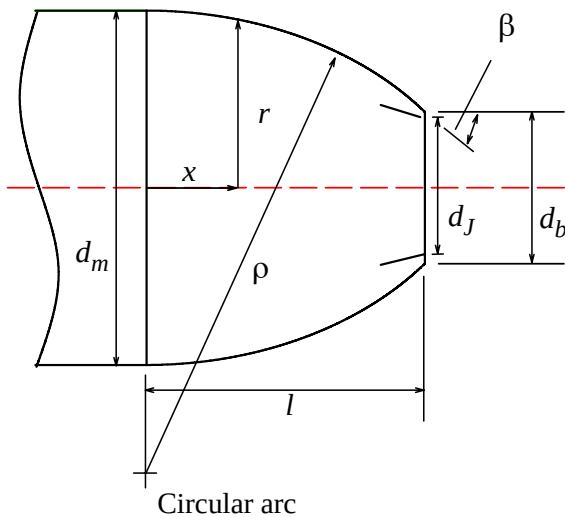
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## SUBSONIC PRESSURE DRAG OF BOAT-TAILS WITH NEGLIGIBLE ANNULAR BASE AREA IN THE PRESENCE OF A CENTRAL PROPULSIVE JET

### 1. NOTATION AND UNITS

|              |                                                                                                                                            | <i>SI</i>      | <i>British</i>    |
|--------------|--------------------------------------------------------------------------------------------------------------------------------------------|----------------|-------------------|
| $A$          | body cross-sectional area at station $x$                                                                                                   | $\text{m}^2$   | $\text{ft}^2$     |
| $A_b$        | body cross-sectional area at base                                                                                                          | $\text{m}^2$   | $\text{ft}^2$     |
| $A_m$        | maximum cross-sectional area of body                                                                                                       | $\text{m}^2$   | $\text{ft}^2$     |
| $A_t$        | body cross-sectional area at point of tangency ( $x = x_t$ )<br>for circular-arc/conical boat-tail                                         | $\text{m}^2$   | $\text{ft}^2$     |
| $C_{D\beta}$ | boat-tail pressure drag coefficient, based on $A_m$                                                                                        |                |                   |
| $d_b$        | base diameter                                                                                                                              | $\text{m}$     | $\text{ft}$       |
| $d_J$        | jet exit diameter                                                                                                                          | $\text{m}$     | $\text{ft}$       |
| $d_m$        | maximum body diameter                                                                                                                      | $\text{m}$     | $\text{ft}$       |
| $l$          | boat-tail length                                                                                                                           | $\text{m}$     | $\text{ft}$       |
| $M_\infty$   | freestream Mach number                                                                                                                     |                |                   |
| $p_\infty$   | freestream static pressure                                                                                                                 | $\text{N/m}^2$ | $\text{lbf/ft}^2$ |
| $p_{TJ}$     | jet total pressure                                                                                                                         | $\text{N/m}^2$ | $\text{lbf/ft}^2$ |
| $R_L$        | Reynolds number based on body length                                                                                                       |                |                   |
| $r$          | local radius at station $x$ , see Sketch 1.1                                                                                               | $\text{m}$     | $\text{ft}$       |
| $r_t$        | radial distance from boat-tail axis to point where<br>circular-arc and conical portions of boat-tails meet<br>tangentially, see Sketch 1.1 | $\text{m}$     | $\text{ft}$       |
| $x$          | axial distance along boat-tail aft of point of maximum<br>cross-sectional area, see Sketch 1.1                                             | $\text{m}$     | $\text{ft}$       |
| $x_t$        | axial distance along boat-tail to point where<br>circular-arc and conical portions of boat-tail meet<br>tangentially, see Sketch 1.1       | $\text{m}$     | $\text{ft}$       |
| $\beta$      | circular-arc boat-tail angle, see Sketch 1.1                                                                                               | $\text{deg}$   | $\text{deg}$      |

|                |                                                                                      |     |     |
|----------------|--------------------------------------------------------------------------------------|-----|-----|
| $\beta_c$      | boat-tail angle of conical section of circular-arc/cone<br>boat-tail, see Sketch 1.1 | deg | deg |
| $\rho$         | radius of curvature of circular arc, see Sketch 1.1                                  | m   | ft  |
| $\bar{\nabla}$ | integral mean slope for boat-tail, see Equation (3.1)                                |     |     |



Sketch 1.1 Boat-tail geometry

## 2. INTRODUCTION

This Item presents a prediction method for pressure drag of axisymmetric boat-tails with a central propulsive jet with near-zero annular base area at subsonic speeds. The method is based on a correlation of wind-tunnel-test data taken from parametric studies covering a range of closure and fineness ratios over the freestream Mach number range 0.6 to 0.94 and jet pressure ratio range 1.5 to 4 at zero angle of attack. Although derived primarily for boat-tails of circular-arc profile, the method may also be applied to boat-tails of similar shape, such as parabolic and combination profiles where, at some point aft of the boat-tail shoulder, the circular-arc (or parabolic) profile runs tangentially into a conical section. The method only applies to boat-tails fitted with convergent nozzles and the data used in the correlations are from tests where cold air was used to simulate the jet exhaust.

The method is presented in Section 3 and the accuracy and applicability are discussed in Section 4. Worked examples are given in Section 6.

Data for jet-off subsonic and transonic base and boat-tail pressure drag of circular-arc boat-tails are available in Data Item No. 96012 (Reference 7).

## 3. METHOD

Based on an extensive analysis of data from parametric wind-tunnel studies, Derivation 2 presents correlations of drag data for a wide range of afterbody configurations by means of a simple geometrical parameter at given jet pressure ratios and Mach numbers. The parameter is an integral mean slope, defined as the dimensionless slope of the cross-sectional area distribution, weighted by projected area, and is derived from area rule considerations. In general form it is given by the equation

$$\bar{\nabla} = \frac{-1}{1-(A_b/A_m)} \int_{A_b/A_m}^1 \frac{d(A/A_m)}{d(x/d_m)} d(A/A_m). \quad (3.1)$$

The method of this Item presents correlations for  $C_{D\beta}$  based on the parameter  $\bar{\nabla}$  using parametric test data for the nine circular-arc boat-tails considered in Derivations 3 and 4. It differs from the original correlations in Derivation 2 because there the drag coefficient was based on projected, annular boat-tail area. However, the data of Derivations 3 and 4 demonstrated that a better correlation is obtained using a drag coefficient based on maximum body cross-sectional area.

The method for circular-arc boat-tails is given in Section 3.1 and its application to boat-tails of other profiles is discussed in Section 3.2.

### 3.1 Circular-arc Boat-tails

Figures 1 to 5 present  $C_{D\beta}$  as a function of integral mean slope,  $\bar{\nabla}$ , and jet pressure ratio,  $p_{TJ}/p_\infty$ , at freestream Mach numbers of 0.6, 0.8, 0.9, 0.92 and 0.94, respectively. Graphical interpolation between Figures is required for intermediate Mach numbers.

To a sufficiently good accuracy,  $\bar{\nabla}$ , for a circular-arc boat-tail, may be estimated from the formula

$$\bar{\nabla} = \left( \frac{1.23}{l/d_m} \right) \left( 1 - \frac{A_b}{A_m} \right). \quad (3.2)$$

Equation (3.2) is a simple fit to exact values of  $\bar{V}$  calculated for boat-tails whose closure and fineness ratios fall in the ranges  $0.8 \leq l/d_m \leq 2.5$  and  $0.4 \leq d_b/d_m \leq 1$ .

Equations for the circular-arc boat-tail geometry are given in Appendix A.

## 3.2 Boat-tails of Other Profiles

Because all geometric effects are catered for in Figures 1 to 5 by means of the integral mean slope parameter, those Figures should, in principle, allow reasonable estimates to be obtained for boat-tails of other, similar profiles, including parabolic and circular-arc with a conical aft portion. The parabolic boat-tail is sufficiently similar in profile to the circular-arc that Equation (3.2) may be used to evaluate  $\bar{V}$ . For circular-arc/cone boat-tails  $\bar{V}$  may be estimated using

$$\bar{V} = \frac{1}{1 - A_b/A_m} \left\{ \left( \frac{1.23}{x_t/d_m} \right) \left( 1 - \frac{A_t}{A_m} \right)^2 + \frac{8}{3} \left[ \left( \frac{A_t}{A_m} \right)^{3/2} - \left( \frac{A_b}{A_m} \right)^{3/2} \right] \tan \beta_c \right\}. \quad (3.3)$$

Equations for the geometry of circular arc/conical boat-tails are given in Appendix A.

For other boat-tail shapes the integral in Equation (3.1) may be evaluated graphically if an analytical expression is unavailable.

The method is not applicable to conical boat-tails or any other profiles with discontinuity in slope.

## 4. ACCURACY AND APPLICABILITY

The ranges of parameters covered by the data of Derivations 3 and 4 and used in the development of Figures 1 to 5 are given in Table 4.1.

TABLE 4.1

| $d_b/d_m$        | $l/d_m$    | $\beta$ (deg) | $\bar{V}$      | $M_\infty$  | $R_L$                                    |
|------------------|------------|---------------|----------------|-------------|------------------------------------------|
| 0.51, 0.61, 0.71 | 0.8 to 2.0 | 8.3° to 34°   | 0.315 to 1.142 | 0.6 to 0.94 | $1.08 \times 10^7$ to $2.18 \times 10^7$ |

A comparison of  $C_{D\beta}$ , as predicted by the method of Section 3, with experimental data is given in Sketch 4.1. The parametric test data of Derivations 3 and 4 and the independent data from Derivation 1 are within about  $\pm 0.01$  of the predicted values.