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Drag of stub wings and fairings on a flat plate with a turbulent boundary layer at subsonic and supersonic speeds

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THE PREPARATION OF THIS DATA ITEM

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DRAG OF STUB WINGS AND FAIRINGS ON A FLAT PLATE WITH A TURBULENT BOUNDARY LAYER FOR SUBSONIC AND SUPERSONIC SPEEDS

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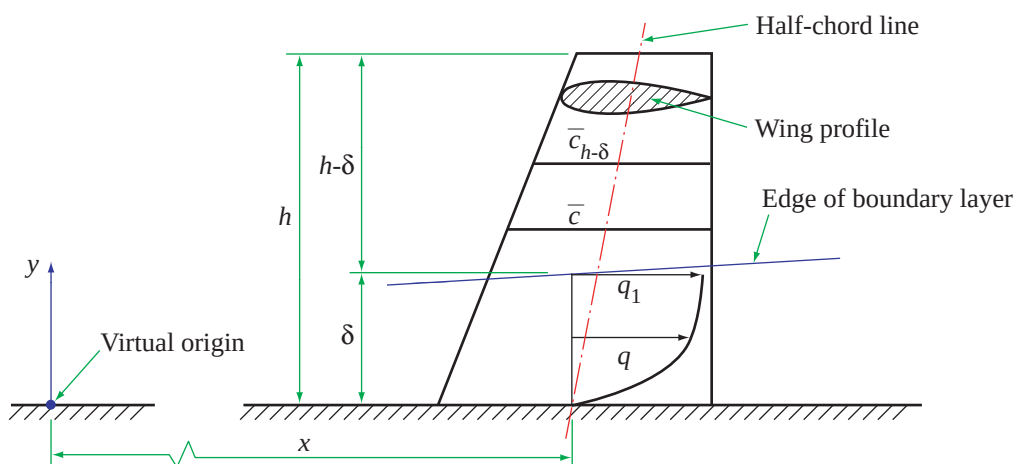
DRAG OF STUB WINGS AND FAIRINGS ON A FLAT PLATE WITH A TURBULENT BOUNDARY LAYER FOR SUBSONIC AND SUPERSONIC SPEEDS

1. NOTATION AND UNITS (see Sketches 1.1 and 1.2)

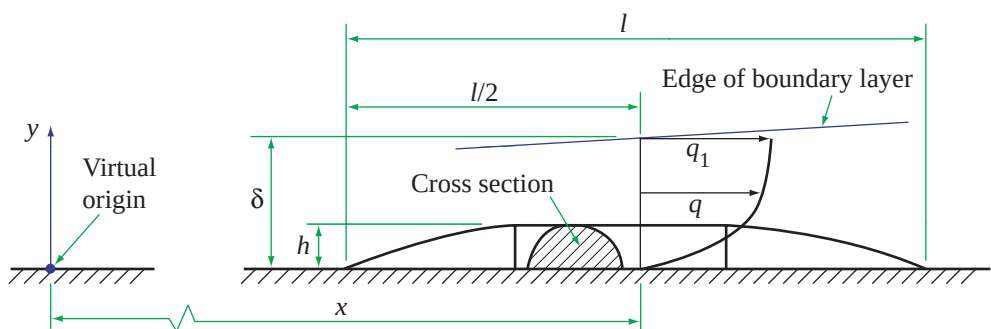
		SI	British
C_D	drag coefficient of stub wing or fairing in presence of boundary layer on flat plate, based on q_1 and frontal area		
$(C_D)_{\delta=0}$	drag coefficient of stub wing or fairing in absence of boundary layer on flat plate, based on q_1 and frontal area		
c	local chord of stub wing	m	ft
$\bar{c}$	geometric mean chord of stub wing	m	ft
$\bar{c}_{h-\delta}$	mean chord of part of stub wing external to boundary layer	m	ft
F	coefficient in Equation (3.6)		
h	height of stub wing or fairing	m	ft
l	fairing length	m	ft
M_1	Mach number at edge of undisturbed boundary layer		
m	power law index for kinetic pressure variation through boundary layer, see Equation (3.3)		
q	local kinetic pressure in boundary layer	N/m ²	lbf/ft ²
q_1	kinetic pressure at edge of undisturbed boundary layer	N/m ²	lbf/ft ²
q_{eff}	effective kinetic pressure for fairing immersed in turbulent boundary layer, see Equation (4.1)	N/m ²	lbf/ft ²
$R_{\bar{c}}$	Reynolds number based on conditions at edge of undisturbed boundary layer and $\bar{c}$		
R_l	Reynolds number based on conditions at edge of undisturbed boundary layer and l		
R_x	Reynolds number based on conditions at edge of undisturbed boundary layer and x		
R_{δ}	Reynolds number based on conditions at edge of undisturbed boundary layer and δ		
t	maximum thickness of stub wing section	m	ft

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x	streamwise distance from virtual origin of turbulent boundary layer on flat plate, see Sketches 1.1 and 1.2	m	ft
y	ordinate normal to flat plate	m	ft
δ	local thickness of boundary layer on flat plate (where local velocity reaches $0.99 \times$ velocity at edge of undisturbed boundary layer)	m	ft
$\Lambda_{1/4}$	quarter-chord line sweep of stub wing	degree	degree
λ	tip chord to root chord ratio of stub wing		



Sketch 1.1 Stub wing geometry



Sketch 1.2 Fairing geometry

2. INTRODUCTION

Drag data are given in Reference 12 for a number of proprietary aerals, pitot heads, temperature sensors etc. The data originated from flight and wind-tunnel measurements. As there are no details of the boundary layer conditions on the mounting surfaces the data cannot be used other than as a guide to drag penalties for specific configurations. However, the present Item provides a means of estimating the effect of the turbulent boundary layer on a flat plate on the drag of stub* wings and fairings mounted on the plate, which is at zero incidence. The stub wings and fairings may be either wholly or partially immersed in the boundary layer. The methods, which are empirically based, were developed using test data for stub wings that could represent blade aerals and mounting struts for sensor heads, for example, and for various fairings that could represent the many types used to cover protrusions such as warning beacons and radar antennae.

The available data are quite limited in number and scope. Nevertheless, it has been possible to develop methods, albeit tentative, with potentially wide application in terms of allowable geometry and flow conditions for Mach numbers up to about 3, excluding a transonic region from 0.8 to 1.2. The wide applicability is largely due to the fact that the methods present the drag in the presence of the boundary layer on the flat plate in terms of the drag in the absence of that boundary layer.

The drag of stub wings is dealt with in Section 3 while Section 4 deals with fairings. The methods apply to air flow with zero heat transfer and zero pressure gradient on the plate which is assumed to be aerodynamically smooth. A general discussion of applicability and an assessment of the accuracy of the methods is given in Section 5 and worked examples are given in Section 7.

Rectangular planform fairings at supersonic speeds are dealt with in Item No. 71018 (Reference 13), which provides approximate estimates of the drag when the fairing height is large compared with the boundary layer thickness on the flat plate. The wave drag data in that Item were derived using inviscid, linearised supersonic flow theory.

3. STUB WINGS

In Derivation 4 some test data for stub wings of rectangular planform at subsonic speeds were analysed allowing for the variation of kinetic pressure through the boundary layer on the flat plate. Hence a prediction method was produced for the ratio of the drag of the wing in the presence of the boundary layer to that in its absence. In Derivation 3 the method was extended to tapered stub wings on the basis that the kinetic pressure variation through the boundary layer can be represented by a power law. Such an analysis led to the following general expression for the drag coefficient ratio (see Sketch 1.1).

$$\frac{C_D}{(C_D)_{\delta=0}} = \frac{\int_0^h c q dy}{h \bar{c} q_1} = \frac{\delta}{h} \int_0^{h/\delta} \frac{c}{\bar{c}} \frac{q}{q_1} d\left(\frac{y}{\delta}\right) \quad (3.1)$$

where
$$\frac{c}{\bar{c}} = \frac{2}{1+\lambda} - 2\left(\frac{1-\lambda}{1+\lambda}\right) \frac{\delta y}{h \delta} \quad (3.2)$$

For $\delta/h \geq 1$

$$\frac{q}{q_1} = \left(\frac{y}{\delta}\right)^m, \quad 0 \leq \frac{y}{\delta} \leq \frac{h}{\delta} \quad (3.3)$$

* Note that the use of the word "stub" here relates to wings whose heights are comparable with the boundary layer thickness on the mounting surface. In this context stub wings are not necessarily low aspect ratio wings.

and hence Equation (3.1) gives

$$\frac{C_D}{(C_D)_{\delta=0}} = \frac{\delta}{h} \int_0^{h/\delta} \frac{c}{\bar{c}} \left(\frac{y}{\delta}\right)^m d\left(\frac{y}{\delta}\right) = \frac{2[1 + \lambda(1 + m)]}{(1 + \lambda)(1 + m)(2 + m)} \left(\frac{h}{\delta}\right)^m. \quad (3.4)$$

For $\delta/h < 1$

$$\left. \begin{aligned} \frac{q}{q_1} &= \left(\frac{y}{\delta}\right)^m, & 0 \leq \frac{y}{\delta} \leq 1 \\ \frac{q}{q_1} &= 1, & 1 \leq \frac{y}{\delta} \leq \frac{h}{\delta} \end{aligned} \right\} \quad (3.5)$$

and hence Equation (3.1) gives

$$\begin{aligned} \frac{C_D}{(C_D)_{\delta=0}} &= \frac{\delta}{h} \int_0^1 \frac{c}{\bar{c}} \left(\frac{y}{\delta}\right)^m d\left(\frac{y}{\delta}\right) + \frac{\delta}{h} \int_1^{h/\delta} \frac{c}{\bar{c}} d\left(\frac{y}{\delta}\right) \\ &= \frac{\delta}{h} F + \left(1 - \frac{\delta}{h}\right) \frac{\bar{c}_{h-\delta}}{\bar{c}} \end{aligned} \quad (3.6)$$

where
$$F = \frac{2}{1 + \lambda} \left[\frac{1}{1 + m} - \left(\frac{1 - \lambda}{2 + m}\right) \frac{\delta}{h} \right] \quad (3.7)$$

and
$$\frac{\bar{c}_{h-\delta}}{\bar{c}} = 1 - \left(\frac{1 - \lambda}{1 + \lambda}\right) \frac{\delta}{h}. \quad (3.8)$$

Both C_D and $(C_D)_{\delta=0}$ are defined in this Item as being based on the frontal area of the stub wing although, of course, in the normalised form of Equations (3.4) and (3.6) any reference area could be used.

In order to evaluate C_D , apart from a knowledge of the geometrical parameters h and λ , a knowledge is required of the Reynolds number per unit length, the distance, x , from the virtual origin, the thickness of the flat plate turbulent boundary layer, δ , at the stub wing location, the power law index, m , and the value of $(C_D)_{\delta=0}$.

Values of δ may be deduced from the graph of R_δ as a function of R_x in Figure 1, which was obtained from Item No. 68020 (Reference 11).

It was found in Derivation 3 that the use of values of the power law index m derived from test data for the boundary layer in the absence of the stub wing gave a reasonable fit to the rectangular planform stub wing data at subsonic speeds using Equation (3.6) for wings that extended outside the boundary layer. However, comparisons using similar data for supersonic speeds (Derivations 1 and 2) were not satisfactory, particularly for wings that were small compared with the boundary layer. It was therefore decided in Derivation 3 to use the parameter m simply as a correlating parameter.

This procedure has been adopted for the work of this Item in which values of m have been derived to give the best fit to the rectangular stub wing data of Derivations 1, 2 and 4, via Equations (3.4) and (3.6). The wings in those tests all had the RAE 103 section ($t/c = 0.15$). In using Equations (3.4) and (3.6) to deduce values of m , data for $(C_D)_{\delta=0}$ were required. In the absence of the boundary layer on the flat plate the

“half-wing and reflection plane” configuration may be assumed to be aerodynamically identical to a “complete” configuration in free air. Values of $(C_D)_{\delta=0}$ are best obtained from test data. In analysing the subsonic data of Derivation 4 it was possible to deduce values of $(C_D)_{\delta=0}$ from the test data with boundary layer transition fixed at $0.05c$. The resulting values agreed reasonably well with predictions using Item Nos Aero W.02.04.01 to 03 (References 5 to 7). In analysing the supersonic data of Derivations 1 and 2 values of $(C_D)_{\delta=0}$ were estimated by using test data from Derivation 1 for the two-dimensional drag coefficient of the RAE 103 section ($t/c = 0.15$) and correcting for finite aspect ratio from Figure 2* of Item No. 71018 (Reference 13). For rectangular and other planforms with sharp-edged sections, values of $(C_D)_{\delta=0}$ may be obtained using wave drag data from Item No. 75004 (Reference 14), together with an approximate allowance for skin friction drag using Item No. 68020 (Reference 11) with boundary layer transition assumed at the leading edge.

The values of m obtained from the analysis are presented in Figures 2a to 2c, which show that m is a function of h/δ , M_1 and R_τ . It should be noted that when $h/\delta \geq 1$ values of m are constant. The data shown as broken lines are extrapolations (see Section 5.1).

Even in the absence of more data for tapered and swept wings (see Section 5.1) it is considered reasonable to assume that Figures 2a to 2c apply to stub wings of any straight-tapered planform.

4. FAIRINGS

There are comparatively few data concerning the drag of fairings. The only systematic data are in Derivations 1 and 2; other, *ad hoc*, data are in Derivations 1, 2 and 4 and Reference 10, the last of which gives insufficient details of model geometry and test conditions. Therefore, data from Derivations 1, 2 and 4 only were used.

The general lack of systematic data and the probable occurrence of flow separation on some of the test models (see Section 5.2) have hampered the development of a prediction method. Nevertheless, an attempt has been made to produce a useful method of acceptable accuracy, bearing in mind its likely use.

Reference 10 suggests an analysis in which C_D values are based on an effective kinetic pressure in the boundary layer given by

$$\frac{q_{eff}}{q_1} = \int_0^1 \frac{q}{q_1} d\left(\frac{y}{h}\right). \quad (4.1)$$

When the power law representation of kinetic pressure in Equation (3.3) is assumed, it follows that for a body submerged in the boundary layer ($\delta/h \geq 1$ as in Sketch 1.2),

$$\frac{C_D}{(C_D)_{\delta=0}} = \frac{q_{eff}}{q_1} = \frac{1}{1+m} \left(\frac{h}{\delta}\right)^m. \quad (4.2)$$

For the case when $\delta/h \leq 1$, and the kinetic pressure is given by Equations (3.5),

$$\frac{C_D}{(C_D)_{\delta=0}} = \left(1 - \frac{\delta}{h}\right) + \frac{1}{1+m} \frac{\delta}{h}. \quad (4.3)$$

* The curve for parabolic arc profiles was considered to be the most appropriate of those given in Figure 2 of Item No. 71018 but the effect of the actual profile on the correction for aspect ratio is negligible in the present context.