



Aerofoil skin friction drag for Mach numbers below the drag-rise condition

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AEROFOIL SKIN FRICTION DRAG FOR MACH NUMBERS BELOW THE DRAG-RISE CONDITION

CONTENTS

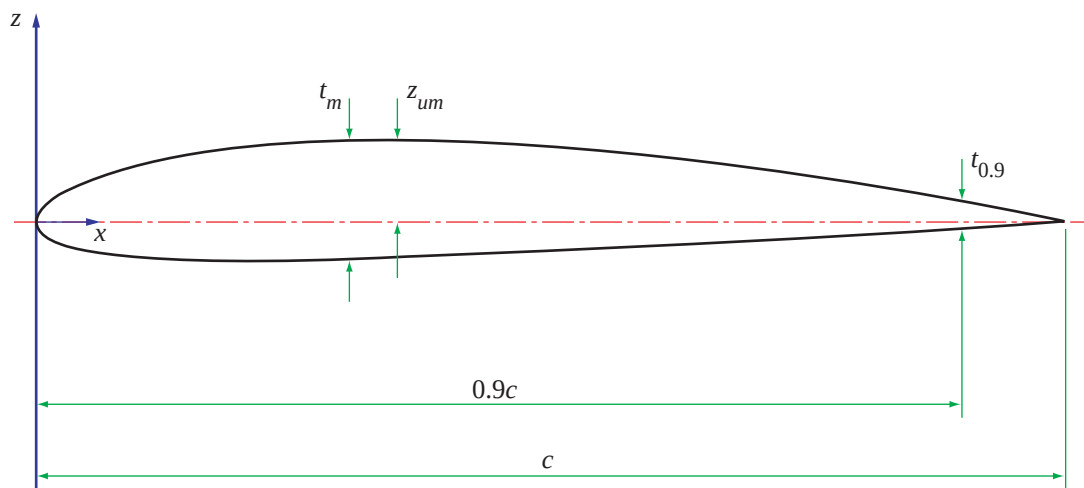
	Page
1. NOTATION AND UNITS	1
2. INTRODUCTION	3
3. METHOD	4
4. PARAMETRIC EFFECTS	5
4.1 Effect of Reynolds Number	6
4.2 Effect of Boundary-layer Transition Position	7
4.3 Effect of Aerofoil Geometry	8
4.4 Effect of Compressibility	9
5. ACCURACY AND APPLICABILITY	10
6. DERIVATION AND REFERENCES	13
6.1 Derivation	13
6.2 References	13
7. WORKED EXAMPLE	14
7.1 Graphical Method	15
7.2 Equation Method	16
FIGURES 1 to 3	18 to 20

AEROFOIL SKIN FRICTION DRAG FOR MACH NUMBERS BELOW THE DRAG-RISE CONDITION

1. NOTATION AND UNITS

		SI	British
C_{Df}	aerofoil skin friction drag coefficient, based on c		
C_{Df0}	value of C_{Df} at $C_L = 0$, see Sketch 4.1		
$(C_{Df0})_{M=0}$	value of C_{Df0} in incompressible flow, see Section 3		
C_L	aerofoil lift coefficient, based on c		
c	aerofoil chord length, see Sketch 1.1	m	ft
k_M	compressibility factor applied to $(C_{Df0})_{M=0}$, see Section 3		
M	freestream Mach number		
R_c	Reynolds number based on c and freestream flow conditions		
t_e	aerofoil effective thickness, see Equation (3.2)	m	ft
t_m	aerofoil maximum thickness, see Sketch 1.1	m	ft
$t_{0.9}$	aerofoil thickness at $x = 0.9c$, measured perpendicular to chord line, see Sketch 1.1	m	ft
x	chordwise distance aft of leading edge, see Sketch 1.1	m	ft
x_{tr}	mean of chordwise distances to upper and lower surface boundary-layer transition positions, measured aft of leading edge	m	ft
z	aerofoil surface ordinate, see Sketch 1.1	m	ft
z_l	aerofoil lower-surface ordinate	m	ft
z_u	aerofoil upper-surface ordinate	m	ft
z_{um}	maximum value of z_u , see Sketch 1.1	m	ft

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Sketch 1.1 Aerofoil geometric parameters

2. INTRODUCTION

This Data Item provides a means of predicting the skin friction drag coefficient of symmetrical and cambered aerofoil sections with smooth surfaces and attached flow, in the presence of a pressure field. The predicted skin friction drag coefficient is the value occurring at zero lift ($C_L = 0$). This is also representative of values of skin friction drag coefficient at other low values of lift coefficient when boundary-layer transition position is fixed, because the variation of skin friction drag coefficient with lift coefficient is small in this case (Section 4).

The method was created from an analysis of a database built by using the VGK program* (Derivations 1 and 2). A systematic study was conducted to investigate the effects of Reynolds number, boundary-layer transition position, Mach number and aerofoil geometry on skin friction drag coefficient.

The method for predicting aerofoil skin friction drag coefficient, described in Section 3, uses a factor allowing for compressibility that is applied to the value of skin friction drag coefficient associated with incompressible flow. Knowledge of Mach number, Reynolds number and the mean chordwise position of upper and lower surface boundary-layer transition is required. The aerofoil geometry is defined using an empirically derived effective thickness parameter which accounts for maximum section thickness and trailing-edge geometry.

The effects of Reynolds number, boundary-layer transition position, section geometry and Mach number on skin friction drag coefficient are discussed in Section 4.

The accuracy and applicability are discussed in Section 5, and the Derivation and References are listed in Section 6. A worked example showing the application of the method is given in Section 7.

* The VGK (Viscous Garabedian and Korn) method is a computational method for determining two-dimensional attached flow past an aerofoil immersed in a subsonic freestream, with allowance for viscous effects. The method couples finite difference solutions of inviscid flow about the aerofoil with solutions for the displacement effects of the boundary-layers. External to the boundary layer the inviscid flow element is governed by the full potential equation. The boundary-layer development is predicted by forward integration of three simultaneous ordinary differential equations (momentum integral equation, entrainment equation and an equation derived from the turbulent energy equation). An iterative approach allows boundary-layer displacement and momentum thickness distributions to be calculated, with allowance for the effects of the pressure field obtained from the inviscid flow element. The turbulent boundary layer is assumed to start at a selected transition point and the laminar calculations at this point form the initial conditions. The method of coupling the viscous and inviscid flow elements permits converged solutions to be obtained for flows with attached boundary layers.

3. METHOD

Analysis of data from VGK computations for a systematic selection of aerofoils, listed in Table 5.2, has shown that for Mach numbers below the drag-rise condition, the value of skin friction drag coefficient, C_{Df0} , can be represented by the relationship

$$C_{Df0} = k_M (C_{Df0})_{M=0}, \quad (3.1)$$

where $(C_{Df0})_{M=0}$ is the value for incompressible flow and the factor k_M accounts for the effect of compressibility.

Figures 1 and 2 give $(C_{Df0})_{M=0}$ as a function of the Reynolds number (as $\log_{10} R_c$) and the mean of the upper and lower surface boundary-layer transition positions, x_{tr}/c , for values of the empirical effective thickness parameter, t_e/c , of 0.05 and 0.45, respectively. Linear interpolation is required for other values of t_e/c .

The effective thickness parameter is given by

$$\frac{t_e}{c} = \frac{t_m + 5t_{0.9}}{c}, \quad (3.2)$$

where t_m is the maximum aerofoil thickness and $t_{0.9}$ is the aerofoil thickness at $x = 0.9c$, see Sketch 1.1.

The parametric equation used to analyse the VGK aerofoil database and plot Figures 1 and 2 is

$$(C_{Df0})_{M=0} = k_1 + k_2 \left(\frac{t_e}{c} \right) + k_3 \left(\frac{x_{tr}}{c} \right) + k_4 \left(\frac{t_e}{c} \right) \left(\frac{x_{tr}}{c} \right). \quad (3.3)$$

The factors k_1 , k_2 , k_3 and k_4 model the variation of $(C_{Df0})_{M=0}$ with t_e/c and x_{tr}/c , for any particular Reynolds number R_c :

$$k_1 \times 10^3 = 4.08 + 0.823(8.5 - \log_{10} R_c)^2, \quad (3.4)$$

$$k_2 \times 10^3 = 2.00 + 0.220(8.5 - \log_{10} R_c)^2, \quad (3.5)$$

$$k_3 \times 10^3 = -3.67 - 0.343(8.5 - \log_{10} R_c)^2 \quad (3.6)$$

$$\text{and} \quad k_4 \times 10^3 = -3.06 - 0.031(8.5 - \log_{10} R_c)^2. \quad (3.7)$$

The effect of compressibility requires the use of the factor k_M , which is presented as a function of Mach number M , and t_m/c in Figure 3. The equation used to plot Figure 3 is

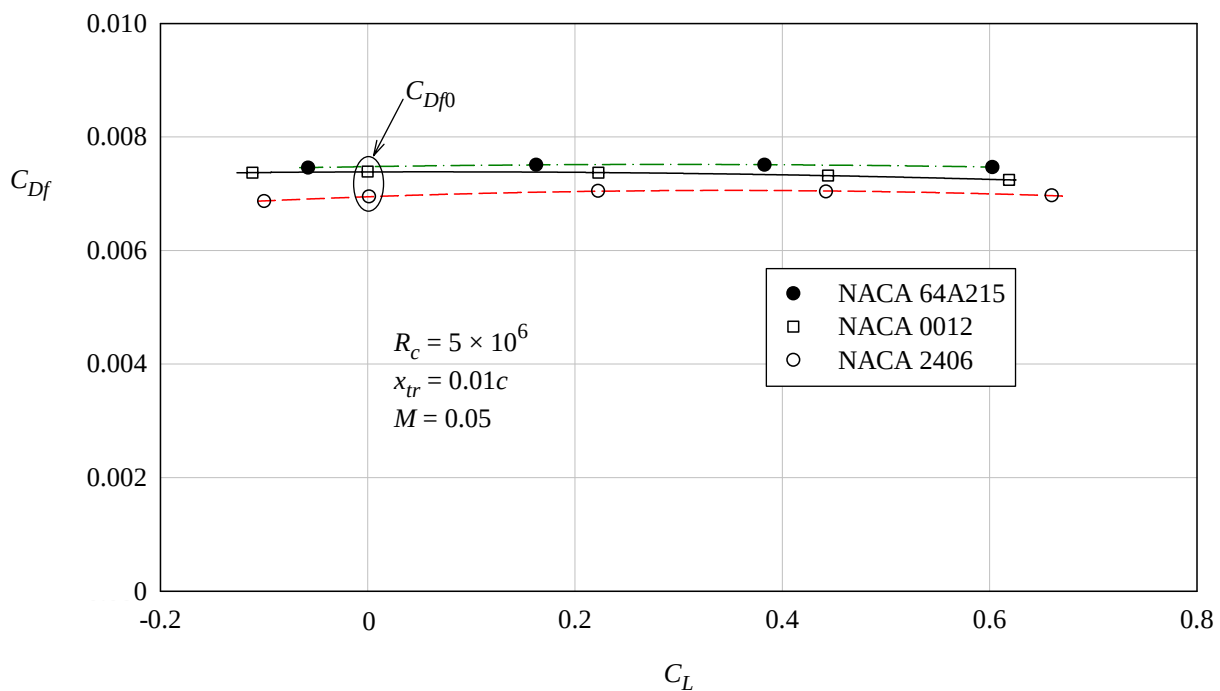
$$k_M = 1 - \left(0.067 + 0.840 \frac{t_m}{c} \right) M^2. \quad (3.8)$$

An approximate limit to the applicability for symmetrical sections (to remain below the drag-rise condition) is shown dashed on the Figure (see Section 5).

4. PARAMETRIC EFFECTS

Skin friction drag is the resultant force in the streamwise direction due to shear stresses at the surface of the aerofoil. The VGK program may be used to obtain the skin friction drag coefficient, C_{Df} , of an aerofoil within a pressure field. The program calculates the value of C_{Df} by integrating local values of skin friction drag coefficient around the aerofoil surface. The local skin friction drag coefficient in the laminar part of the boundary layer is obtained from Thwaites's method (Reference 4), which gives an approximate integration of Von Karman's momentum equation (Reference 4). The local skin friction drag coefficient in the turbulent part of the boundary layer is related to the skin friction drag coefficient on a flat plate by an empirical expression employing the known surface pressure distribution (Reference 6). The flat plate skin friction drag coefficient is obtained from the correlation of Winter and Gaudet (Reference 5), approximated by the formula given by Green (Reference 6).

The variation of C_{Df} with C_L for three selected aerofoil sections at $M = 0.05$ and $R_c = 5 \times 10^6$, obtained using the VGK method with fixed boundary-layer transition position, is shown in Sketch 4.1. For fixed boundary-layer transition the effect of lift coefficient on C_{Df} is small. The present method predicts the value of C_{Df} at $C_L = 0$, denoted as C_{Df0} , see Sketch 4.1.



Sketch 4.1 Variation of C_{Df} with C_L for three selected aerofoils