



COMPUTER PROGRAM FOR ESTIMATION OF AEROFOIL CHARACTERISTICS AT SUBCRITICAL SPEEDS: lift-curve slope, zero-lift incidence and pitching moment, aerodynamic centre and drag polar minimum

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1. NOTATION AND UNITS

		SI	British
a_1	lift-curve slope in initial linear range of C_L variation with α	rad^{-1}	rad^{-1}
$(a_1)_T$	inviscid lift-curve slope	rad^{-1}	rad^{-1}
C_D	drag coefficient, based on qc		
C_{Df0}	aerofoil skin friction drag at $C_L = 0$		
C_{Dmin}	drag polar minimum; strictly value of C_D at C_{Lmin} in plot of C_D against C_L for fixed boundary-layer transition positions, R and M		
C_L	lift coefficient, based on qc		
C_{Lmin}	lift coefficient for minimum drag with $x_{tru} = x_{trl} = 0.01$, at fixed R and M		
C_{m0}	pitching moment coefficient at zero lift, based on qc^2		
C_{m0i}	inviscid value of C_{m0}		
c	chord	m	ft
h_+	largest camber-line ordinate for aerofoil with simple camber line, see Sketch 3.5a; largest aft camber-line ordinate for aerofoil with rear-loading or reflex camber line, see Sketches 3.5b and 3.5c	m	ft
h_-	maximum forward camber line ordinate for aerofoil with reflex camber line, see Sketch 3.5c	m	ft
M	freestream Mach number		
R	Reynolds number based on c and freestream conditions		
t	thickness	m	ft
t_m	maximum thickness, see Sketch 3.2	m	ft

$t_{0.005}, t_{0.05},$ $t_{0.75}, t_{0.90},$ $t_{0.99}, t_1$	thickness at $x = 0.005c, 0.05c, 0.75c, 0.90c, 0.99c, c$	m	ft
x	chordwise distance measured aft from leading edge	m	ft
x_a	position of aerodynamic centre aft of leading edge	m	ft
x_{ai}	value of x_a for inviscid compressible flow	m	ft
x_{ai0}	value of x_a for inviscid incompressible flow	m	ft
x_{av0}	value of x_a for viscous incompressible flow	m	ft
x_{tm}	chordwise position of maximum thickness aft of leading edge, see Sketch 3.2	m	ft
x_{tr}	mean of x_{tru} and x_{trl}	m	ft
x_{trl}	chordwise position aft of leading edge of boundary-layer transition on lower surface	m	ft
x_{tru}	chordwise position aft of leading edge of boundary-layer transition on upper surface	m	ft
z	ordinate normal to chord line	m	ft
z_c	camber-line ordinate at x , see Sketch 3.5	m	ft
$z_{c0}, z_{c0.025},$ $z_{c0.05}, z_{c0.1},$ $\dots,$ $z_{c0.9}, z_{c0.92},$ $z_{c0.95}, z_{c1}$	values of z_c at $x = 0, 0.025c, 0.05c, 0.1c, \dots, 0.9c, 0.92c, 0.95c, c$. Values at $x = 0$ and c are required to be zero by the program	m	ft
z_u	upper-surface ordinate at x , see Sketch 3.1	m	ft
z_{um}	largest upper-surface ordinate (or largest lower-surface ordinate if greater), used as check on applicability, see Sketch 3.1	m	ft
$z_{u0.90}, z_{u0.99}$	upper-surface ordinate at $x = 0.90c, 0.99c$	m	ft
α_0	zero-lift incidence	deg	deg
τ	trailing-edge angle, see Sketch 3.4	deg	deg

τ_a	trailing-edge parameter, $\tan(\tau_a/2) = (t_{0.9} - t_{0.99})/0.18c$	rad	rad
τ_{au}	trailing-edge parameter, $\tan \tau_{au} = (z_{u0.90} - z_{u0.99})/0.09c$	rad	rad
ρ	leading-edge radius, see Sketch 3.3, (used to make good approximation of $t_{0.005}$ through relationship given in Item No. 72024; in Item No. 72024, $t_{0.005}$ is used to correlate x_{ai} , but approximation via correlation with ρ is suggested because data for ρ are generally more readily available)	m	ft

2. INTRODUCTION

This Data Item makes use of several Data Items available within the Aerodynamics Series for the prediction of aerofoil characteristics in subcritical attached flow in order to provide a single computer program that uses their methods to calculate answers.

The program provides the aerofoil lift-curve slope, zero-lift incidence and pitching moment, and aerodynamic centre. Viscous and inviscid flow values are provided where appropriate. The profile drag coefficient at the drag polar minimum, together with the skin friction drag coefficient for an aerofoil at zero (low) C_L are also given. The individual Items within the Series should be consulted for a full description of the methods, their derivation, accuracy and applicability. The program is constrained to run only within the appropriate ranges of applicability, and outputs warnings and comments in cases of violation, when values will not be calculated.

Table 2.1 lists the Items incorporated in the program. The input required for the program and the output parameters are described in Sections 3 and 4, respectively. A list of the References is given in Section 5. Examples of input and output files are presented in the worked examples in Section 6.

In Table 3.1 in Section 3, which describes the required input for the program, ranges of values are given for key parameters. Some aerofoil properties will not be calculated outside those ranges. Stricter checks on combinations of parameters are made within the program and may also result in a restricted output. Note that section trailing-edge thickness, t_1 , is not an input parameter because it is not required for calculation purposes. The methods in the source Data Items for predicting lift and drag characteristics were validated for some aerofoils with t_1 up to $0.01c$, and that value should be regarded as an upper bound for the acceptability of values calculated by the program. The methods available for the prediction of aerodynamic centre do not include a dependence on trailing-edge thickness but a similar limit should be assumed.

2.1 Running the Program

All files associated with the ESDUpac are downloaded from the ESDU website as a zip file to a directory location specified in a user's zip utility.

The program runs from a command line prompt so the user needs to

- (i) open a Command Prompt window (in Windows XP go to Start, Programs, Accessories, Command Prompt, in Vista enter 'cmd' in the 'Start Search' box under the Start Menu)
- (ii) change directory (by typing 'cd [PATH]') so that the prompt is at the folder in which the program files are located.

The command line prompt to run the program is

```
A0620V10 < I01A0620.in > R01A0620.out
```

TABLE 2.1

<i>Item No.</i>	<i>Title</i>	<i>Comments</i>
Aero W.01.01.05	Slope of lift curve for two-dimensional flow	Empirical method. Superseded by Item Nos 72024 and 97020, but provides viscous to inviscid lift-curve slope ratio for correlation purposes in method of Item No. Aero A.08.01.05.
Aero A.08.01.05	Aerodynamic centre in two-dimensional flow	Provides empirically correlated incompressible values in viscous flow via a correction to theoretical inviscid values from Reference 2. Item No. 72024 provides more accurate inviscid values but because they are different from the theoretical values used in the development of the viscous correction factor in Aero A.08.01.05 they cannot be corrected to viscous values by the method of that Item.
72024	Aerodynamic characteristics of aerofoils in compressible inviscid airflow at subcritical Mach numbers	Based on correlation of results using the methods of Lighthill (Reference 2) for incompressible flow and Sells (Reference 4) for compressible flows. An appendix provides the methods of Pankhurst (Reference 1) for zero-lift angle and pitching moment coefficient in incompressible flows, which are applicable to a wider range of camber lines than the original correlation, with a marginal loss of accuracy, and these are employed in the program associated with this Item.
87001	Wing pitching moment at zero lift at subcritical Mach numbers.	Provides an empirical compressible correction for aerofoil zero-lift pitching moment coefficient, which is applied to the incompressible value obtained from Item No. 72024.
97020	Slope of aerofoil lift-curve for subsonic two-dimensional flow	Based on a correlation of data from application of VGK method (References 7 and 8) to a range of aerofoils.
98011	Aerofoil incidence for zero lift in subsonic two-dimensional flow	Based on a correlation of data from application of VGK method (References 7 and 8) to a range of aerofoils.
00027	Aerofoil profile drag for Mach numbers below the drag-rise condition	Based on a correlation of data from application of VGK method (References 7 and 8) to a range of aerofoils.
06001	Aerofoil skin friction drag for Mach numbers below the drag-rise condition	Based on a correlation of data from application of VGK method (References 7 and 8) to a range of aerofoils.

3. INPUT

The input parameters required by the program and their descriptions are listed in Table 3.1 (see also final paragraph of Section 2). The data must be entered on sequential lines and may be in free numerical format. The geometric parameters are illustrated in Sketches 3.1 to 3.5.

TABLE 3.1

<i>Parameter</i>	<i>Description</i>
TEXT	The first three lines of the input file are read as text and are written to the output file to enable the user to describe the run. Each line may contain up to 72 characters and must end with a carriage return. A carriage return is still required for any blank line.
TEXT	
TEXT	
M	freestream Mach number ($0 \leq M < 1$)
R	Reynolds number based on c and freestream conditions ($10^6 \leq R \leq 10^8$)
x_{tru}/c	(boundary-layer transition position on upper surface)/ c ($0 \leq x_{tru}/c \leq 0.5$)
x_{trl}/c	(boundary-layer transition position on lower surface)/ c ($0 \leq x_{trl}/c \leq 0.5$)
z_{um}/c	(maximum upper-surface ordinate)/ c (see Notation)
$z_{u0.90}/c$	(upper-surface ordinate at $x/c = 0.9$)/ c
$z_{u0.99}/c$	(upper-surface ordinate at $x/c = 0.99$)/ c
t_m/c	(maximum thickness)/ c ($0 \leq t_m/c \leq 0.30$)
x_{tm}/c	(chordwise distance to t_m)/ c ($0 \leq x_{tm}/c \leq 0.45$)
$t_{0.05}/c$	(thickness at $x/c = 0.05$)/ c
$t_{0.75}/c$	(thickness at $x/c = 0.75$)/ c
$t_{0.90}/c$	(thickness at $x/c = 0.90$)/ c
$t_{0.99}/c$	(thickness at $x/c = 0.99$)/ c
ρ/c	(leading-edge radius)/ c ($0 \leq \rho/c \leq 4(t_m/c)^2$)
τ	trailing-edge angle (deg) ($0 \leq \tau \leq 30^\circ$)
h_+/c	(maximum positive camber-line ordinate)/ c ($0 \leq h_+/c \leq 0.05$)
z_{c0}/c	(camber-line ordinate at leading edge)/ $c \equiv 0$ (must be zero)
$z_{c0.025}/c$	(camber-line ordinate at $x/c = 0.025$)/ c
$z_{c0.05}/c$	(camber-line ordinate at $x/c = 0.05$)/ c
$z_{c0.1}/c$	(camber-line ordinate at $x/c = 0.1$)/ c
$z_{c0.2}/c$	(camber-line ordinate at $x/c = 0.2$)/ c
$z_{c0.3}/c$	(camber-line ordinate at $x/c = 0.3$)/ c
$z_{c0.4}/c$	(camber-line ordinate at $x/c = 0.4$)/ c
$z_{c0.5}/c$	(camber-line ordinate at $x/c = 0.5$)/ c
$z_{c0.6}/c$	(camber-line ordinate at $x/c = 0.6$)/ c
$z_{c0.7}/c$	(camber-line ordinate at $x/c = 0.7$)/ c
$z_{c0.8}/c$	(camber-line ordinate at $x/c = 0.8$)/ c
$z_{c0.9}/c$	(camber-line ordinate at $x/c = 0.9$)/ c
$z_{c0.92}/c$	(camber-line ordinate at $x/c = 0.92$)/ c
$z_{c0.95}/c$	(camber-line ordinate at $x/c = 0.95$)/ c
z_{c1}/c	(camber-line ordinate at trailing edge)/ $c \equiv 0$ (must be zero)