



ESDU 99003

Issued March 1999

Generation of GUNACA 23-series of low-drag aerofoils

**Associated software: ESDUpacs A9903
B9903**

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GENERATION OF GUNACA 23-SERIES OF LOW-DRAG AEROFOILS

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GENERATION OF GUNACA 23-SERIES OF LOW-DRAG AEROFOILS

1. NOTATION AND UNITS

		<i>SI</i>	<i>British</i>
a, b	parameters used in defining GU and GUNACA series (Sections 3.2 to 3.4)		
C_D	aerofoil drag coefficient, based on c and free-stream kinetic pressure		
C_L	aerofoil lift coefficient, based on c and free-stream kinetic pressure		
$(C_L)_1$	aerofoil C_L at lower limit of design low-drag range, see Sketch 3.1		
$(C_L)_2$	aerofoil C_L at upper limit of design low-drag range, see Sketch 3.1		
C_{m0}	aerofoil zero-lift pitching moment coefficient, based on c^2 and free-stream kinetic pressure		
C_p	aerofoil surface pressure coefficient		
c	aerofoil chord	m	ft
c, d, e	parameters used in defining GU series (Section 3.2)		
R_c	Reynolds number based on c and free-stream flow properties		
r, s, tt	parameters used in defining NACA 6 and 6A series and GUNACA series (Sections 3.1 and 3.4)		
t	maximum thickness of aerofoil section	m	ft
U_∞	velocity of free-stream	m/s	ft/s
u_α	speed of flow tangential to aerofoil surface at incidence ($\alpha - \alpha_0$) as fraction of U_∞		
$(u_\alpha)_1$	value of u_α corresponding to $(C_L)_1$		
$(u_\alpha)_2$	value of u_α corresponding to $(C_L)_2$		
x	chordwise distance aft of aerofoil leading edge, see Sketch 4.1	m	ft
z	ordinate of aerofoil surface measured perpendicular to chord line, see Sketch 4.1	m	ft
z_c	aerofoil camber-line ordinate at station x	m	ft

α	aerofoil incidence measured relative to chord line	degree	degree
α_0	aerofoil zero-lift incidence	degree	degree
α_1	value of α corresponding to $(C_L)_1$	degree	degree
α_2	value of α corresponding to $(C_L)_2$	degree	degree
θ	angular co-ordinate of point on unit circle onto which aerofoil is mapped by conformal transformation, see Sketch 4.1	degree	degree
κ	$\frac{u_\alpha}{\left \cos((\theta/2) - (\alpha - \alpha_0)) \right }$, see Section 5		

2. INTRODUCTION

The purpose of the computer programs, ESDUpacs A9903 and B9903, associated with this Item is the evaluation of the shape, surface velocity distribution and other aerodynamic characteristics in inviscid low-speed flow, of any specified GUNACA 23-SERIES aerofoil. The philosophy of the design of such aerofoils, developed at Glasgow University by Professor T.R.F. Nonweiler, is described in detail in Section 3. Briefly, they are a set of low-drag aerofoils, produced by using the theoretical method of Lighthill (Derivations 1 and 2). This provides a more precise design technique than the methods that were practicable at the time when the low-drag NACA 6-series was conceived and exact methods required approximations to make solutions possible in an acceptable timescale.

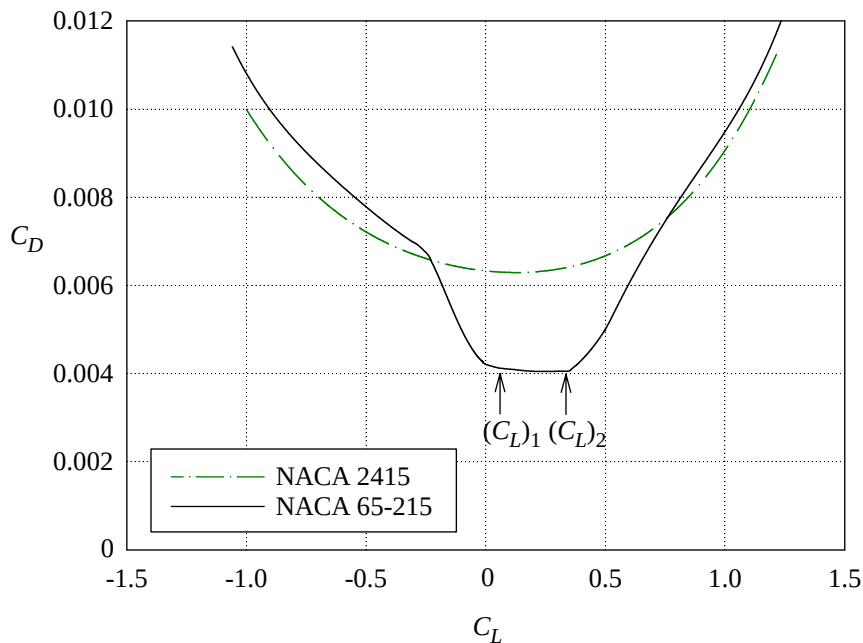
Section 3 introduces the NACA 6-series and goes on to describe the GU-series of aerofoils in general terms. Following this there are descriptions of the specific GU 23-series and the related GUNACA 23-series of aerofoils.

Section 4 describes the input for the directed input version of the program, ESDUpac A9903, and Section 5 describes the output. Section 6 describes the screen prompt version of the program, ESDUpac B9903. Section 7 gives the Derivation and References. Section 8 provides examples of particular cases using the directed input version (Section 8.1) and the screen prompt version (Section 8.2). Appendix A compares the geometric and aerodynamic characteristics of NACA 6-series and GUNACA 23-series aerofoils. Further theoretical comparisons are given in Reference 6.

3. LOW-DRAG AEROFOIL SECTIONS

A low-drag aerofoil is one that has been designed to provide particularly low drag over a limited range of lift coefficient. This is achieved by ensuring that the airflow accelerates over the forward portion of the aerofoil for the low-drag range of lift coefficient. Provided the aerofoil surface is smooth, the extensive favourable pressure gradient inhibits turbulent or separated flow over the forward portion of the aerofoil and assists the attainment of low values of C_D , see Sketch 3.3.

Sketch 3.1 illustrates the experimental drag characteristics of the NACA 65-215 and the NACA 2415 aerofoil sections, both of which have the same t/c . The NACA 65-215 section (a member of the NACA 6-series of low-drag aerofoils) displays a low-drag “bucket”, indicating a range of C_L for which low drag may be attained. The conventional NACA 2415 aerofoil does not exhibit a low-drag bucket. It is possible, however, for the drag of a conventional aerofoil to be less than the drag of a NACA 6-series aerofoil outside its low-drag range, as illustrated by Sketch 3.1.



Sketch 3.1 Experimental drag characteristics at $R_c = 9 \times 10^6$

The low-drag bucket exhibited by aerofoils of the NACA 6-series is formed by abrupt changes in C_D at two values of C_L which mark the extremities of the low-drag region. These large increases in C_D are due to the development of an adverse pressure gradient over the forward portion of either the upper or lower aerofoil surface, and are characterised by a large forward movement of boundary-layer transition position. The upper-surface boundary layer becomes extensively turbulent when C_L exceeds the upper limit of the design low-drag range, $(C_L)_2$. Conversely, the lower-surface boundary layer becomes extensively turbulent below $C_L = (C_L)_1$, the lower limit of the design low-drag range.

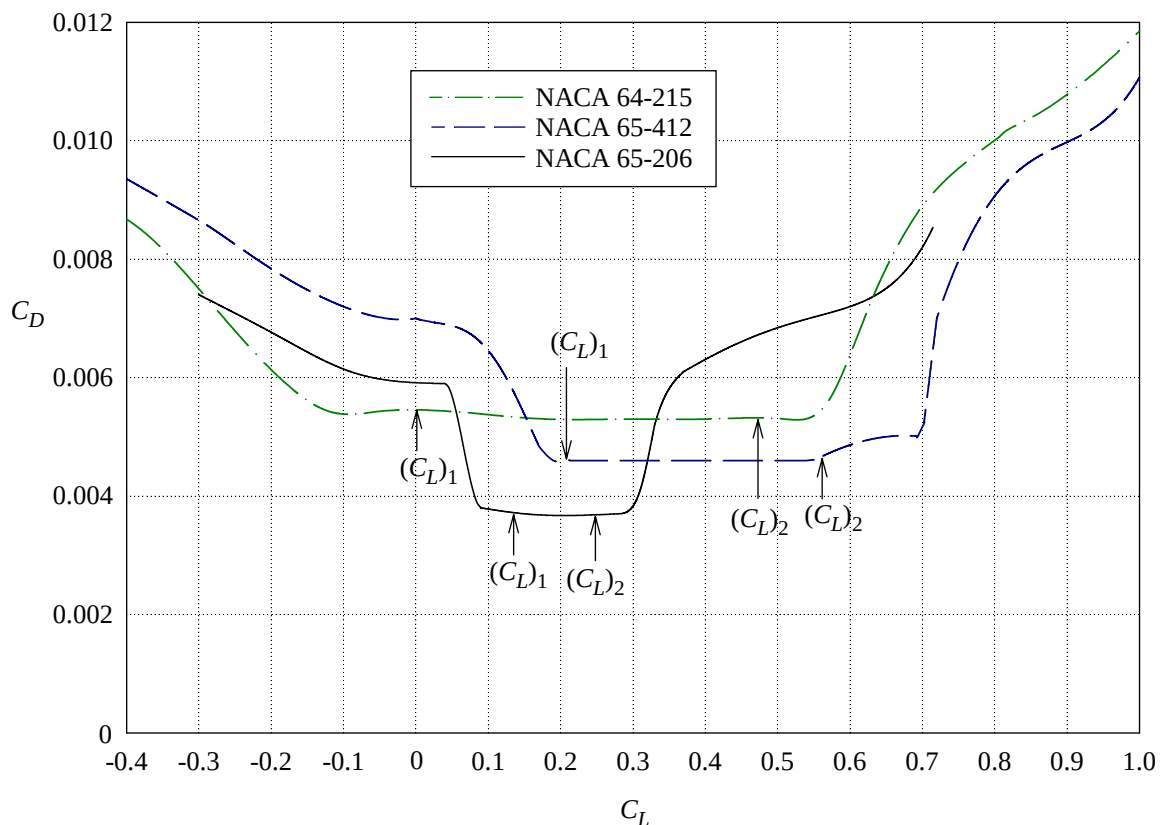
3.1 NACA 6-Series of Aerofoil Sections

The NACA 6-series was developed in 1949 using an approximate design method, with the objective of obtaining desirable characteristics for the drag, critical Mach number, and maximum lift (Reference 4).

The designation number of each section (apart from the initial “6”) describes its geometric and aerodynamic characteristics. If the designation is given the general form NACA 6r-stt then;

- r The first integer “r” following the 6 indicates the extent in tenths of the chord of the region of accelerating flow (which is therefore the front half-chord for the NACA 65-215). Increasing the extent of the accelerating region makes the low-drag bucket deeper but narrower (and conversely, decreasing it makes it shallower but wider).
- s The integer “s” following the hyphen denotes the lift coefficient in tenths in the middle of the low-drag range. This is referred to as the *aerofoil design lift coefficient* (Reference 4) (and is 0.2 for the NACA 65-215, see Sketch 3.1). An increase in design lift coefficient requires an increase in aerofoil camber.
- tt Finally, the last integer “tt” denotes the thickness of the section as a percentage of the chord (and so the NACA 65-215 has a 15% thickness/chord ratio). Increasing the thickness widens the low-drag range.

To illustrate these points the drag characteristics of three NACA 6-series aerofoils are shown by the curves in Sketch 3.2. Comparison of the drag characteristics of the NACA 64-215 and NACA 65-412 aerofoils illustrates that an increase in the extent of the favourable pressure gradient combined with a reduction of aerofoil t/c makes the low-drag bucket deeper and narrower. Likewise, a further reduction in aerofoil t/c deepens and reduces the low-drag range of C_L , as illustrated by the NACA 65-206 low-drag bucket. The NACA 65-412 aerofoil has the largest design lift coefficient (due to its larger camber) and this is shown in Sketch 3.2 as a translation of the low-drag bucket so that the middle of the low-drag range occurs at $C_L = 0.4$, rather than 0.2 as for the other two aerofoils.

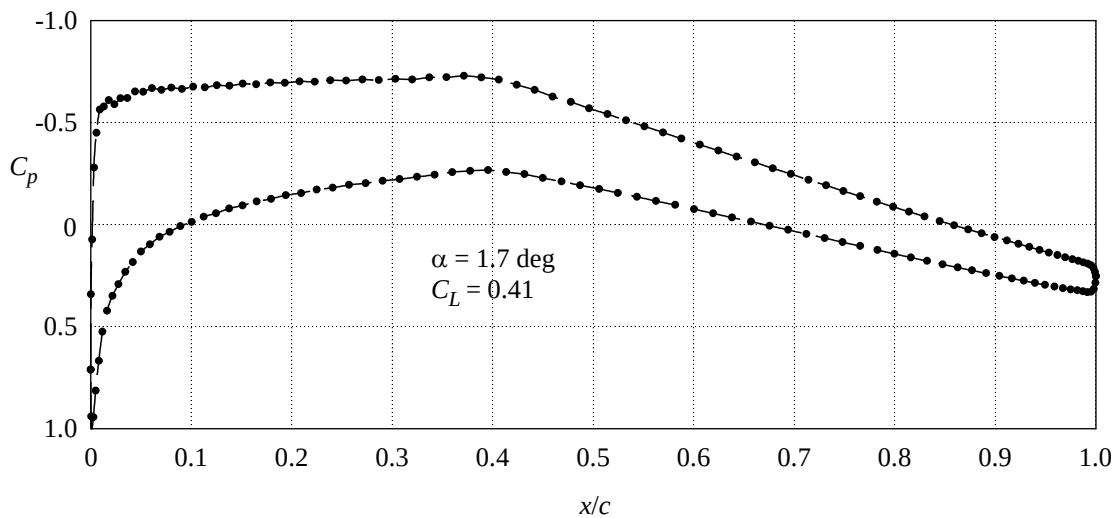


Sketch 3.2 Low-drag aerofoil comparison at $R_c = 3 \times 10^6$

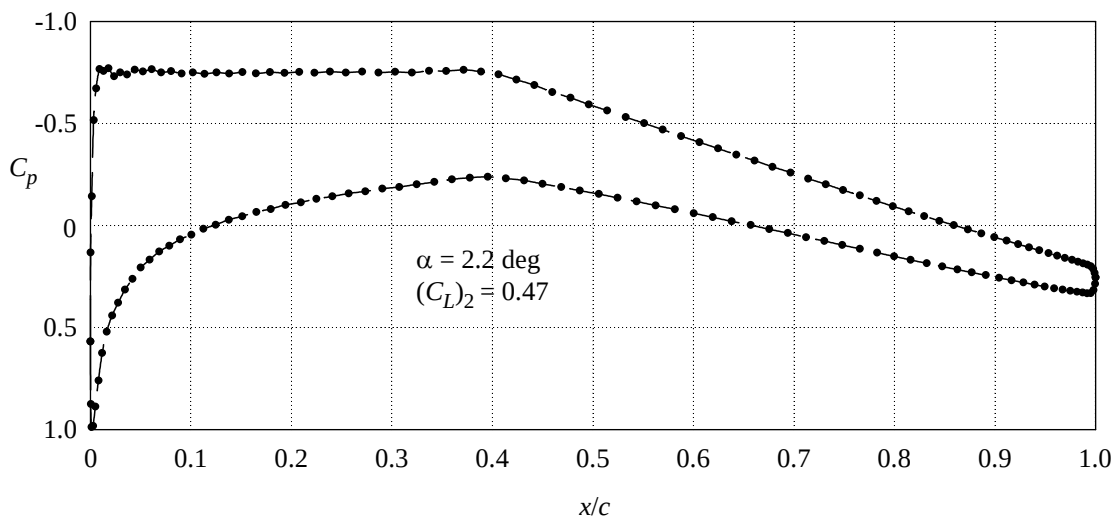
The values of $(C_L)_1$ and $(C_L)_2$ are defined such that for the range $(C_L)_1 < C_L < (C_L)_2$ the inviscid pressure distributions over the forward aerofoil surfaces are wholly favourable. Low drag may therefore be predicted with reasonable confidence over the range $(C_L)_1 < C_L < (C_L)_2$ provided that the aerofoil surfaces are aerodynamically smooth.

Sketches 3.3 to 3.5 indicate how the NACA 64-215 aerofoil pressure distribution varies in inviscid flow with C_L around the upper extent of its low-drag region.

Sketch 3.3 shows that $C_L = 0.41$ lies within the low-drag range since favourable pressure gradients exist over the forward portions of both surfaces of the aerofoil. The pressure distribution at $(C_L)_2$ is defined by an extensive roof-top region of near constant pressure on the upper aerofoil surface (Sketch 3.4). As C_L increases above $(C_L)_2$, a leading-edge suction peak develops on the upper surface, the magnitude of which increases with C_L .

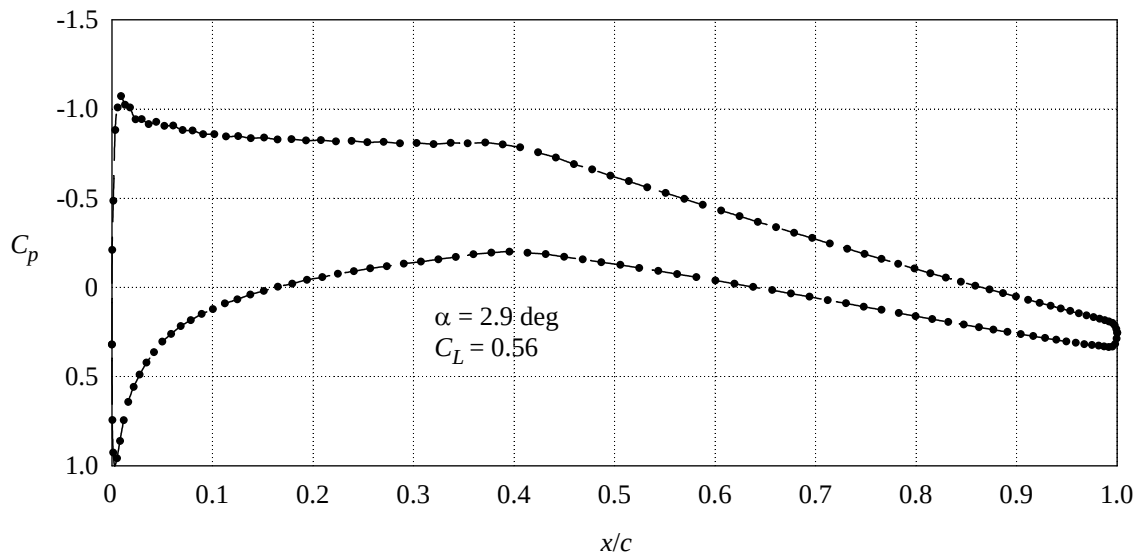


Sketch 3.3 Inviscid pressure distribution of NACA 64-215 aerofoil at $C_L = 0.41$



Sketch 3.4 Inviscid pressure distribution of NACA 64-215 aerofoil at $(C_L)_2$

Sketch 3.5 illustrates the magnitude of the leading-edge suction peak at $C_L = 0.56$. This suction peak is sufficient to move the boundary-layer transition position to the leading edge, causing an associated drag increase. The magnitude of the suction peak necessary to cause the forward movement of boundary-layer transition is, however, hard to predict. Hence the upper extent of the experimental low-drag range is also hard to predict.



Sketch 3.5 Inviscid pressure distribution of NACA 64-215 aerofoil at $C_L = 0.56$

At the lower extent of the design low-drag range, $(C_L)_1$, a roof-top region of constant pressure exists on the lower surface of the NACA 64-215 aerofoil. At values of C_L less than $(C_L)_1$ a leading-edge suction peak develops on the aerofoil lower surface, the magnitude of which increases as C_L is reduced. The lower extent of the experimental low-drag range, like the upper extent, has a dependence on the magnitude of the suction peak and is likewise hard to predict. Sketch 3.2 demonstrates that, although the experimental low-drag range is hard to predict, it exceeds the range $(C_L)_1 < C_L < (C_L)_2$. This sketch also shows that as aerofoil low-drag buckets become shallower and wider, the experimental low-drag ranges become less well defined.

A typical NACA 6-series aerofoil has reflex curvature and a cusped trailing edge. Structural design may be simplified by modifying the trailing-edge region of the NACA 6-series aerofoil so that its surfaces are substantially straight from about $0.8c$ to the trailing edge. Aerofoils designed with the trailing edge constrained in this way also have small changes to the section ordinates on the remainder of the aerofoil, and are designated as the NACA 6A-series (Reference 4).

3.2 The GU-series of low-drag aerofoils

The approximate method used to derive the NACA 6-series (Reference 4) is applicable to aerofoils of moderate thickness and camber, but should not be extended to high thickness or camber. The exact method of Lighthill (Derivation 1) is, however, applicable to aerofoils of any thickness or camber, but it entails extensive calculations. With the advent of the digital computer it became possible to program the Lighthill method to design aerofoils for conditions that combine higher lift and lower drag. This work was undertaken at Glasgow University and led to a family of aerofoils known as the **GU-series** (Derivation 3).

The programmed Lighthill method, developed from Derivation 2, provides design flexibility which can eliminate regions of reflex curvature and the cusped trailing edges typical of the NACA 6-series, and so simplify structural design. Lighthill's use of intrinsic coordinates* leads to finite trailing-edge angles and enhances the inherent freedom within the method to specify the trailing-edge velocity distribution. The method allows some freedom in the choice of leading-edge radius of curvature, to facilitate modification of the leading-edge velocity peak, which is important in relation to usable maximum lift.

The method of Lighthill enables an aerofoil section to be designed at a given incidence with a fairly flat velocity distribution over the forward portion of the chord, which may either fall off evenly towards the rear of the aerofoil or jump down to another flat portion. Various flow requirements, for example deferring transition or separation of the boundary layer, can be met by imposing certain conditions on the velocity distribution along the surface, as calculated by the classical potential theory.

The GU-series of aerofoils has been derived to give a constant velocity distribution (a roof-top distribution) over the forward upper surface at the highest C_L of the design low-drag range, $(C_L)_2$, and over the forward lower surface at the lowest C_L of the design low-drag range, $(C_L)_1$. The aerofoil incidences α_1 and α_2 are those corresponding to $(C_L)_1$ and $(C_L)_2$, respectively. Between those limits there is an accelerating airflow on the forward portions of both aerofoil surfaces. Like the NACA 6-series, the GU-series has the ability to achieve a low-drag bucket. The GU-series has, however, been designed to give a wider low-drag range of C_L than the NACA 6-series, for the same t/c . As with the NACA 6-series, the GU-series aerofoil profiles have no trailing-edge thickness.

For conciseness, the particular aerofoils of the series are specified by the letters GU, followed by a five figure identifier, as follows:

GU ab-cde.

The integers a, b, c, d, and e specify 5 parameters, and if any parameter cannot be represented by an integer, it may be replaced by a bracketed number, see Section 3.4 for an example. The significance of each parameter is described below. The parameters 'a' and 'b' modify the section shape and surface velocity distribution obtained by the Lighthill design process. The leading-edge parameter 'a' affects the whole aerofoil geometry apart from the surface slopes at the trailing edge. The trailing-edge parameter 'b' mainly affects the aft portion of the geometry.

- a is a measure of the extent of modification of the velocity peak in the leading-edge region (which exists outside the design low-drag range of C_L), adopted in order to achieve a larger nose radius of curvature. A zero value denotes no modification, and is valid only for symmetrical sections: a value of 2 is a "normal" figure; values much higher than 4 tend to produce a shape having a flat nose with two "sharp" shoulders, and are not to be recommended.

* In intrinsic coordinates the perturbation velocity potential and stream function at a point are expressed in terms of its distance along a streamline and its inclination to a reference line from an origin, at the trailing edge in this instance.

- b is a measure of the extent of modification of the velocity distribution at the trailing edge, adopted in order to achieve a finite trailing-edge angle and reduce regions of reflex curvature. In Derivation 3 it is noted that the addition of a finite trailing-edge angle to the GU-series does not substantially alter their design low-drag range. The section will have the same difference in surface slopes (between top and bottom surfaces) at approximately $b\%$ of the chord forward of the trailing edge as at the trailing edge. This produces a more or less wedge-shaped trailing edge extending in practice over a considerably greater extent. The effect of variation of 'b' is local to the trailing-edge region, so that to all intents and purposes the trailing-edge angle can be adjusted at will, by suitable choice of 'b', without significant effect upon any of the other features.
- c is a measure of the extent of the favourable pressure gradient, within the design range of incidence, approximately equal to the fraction of the chord from the leading edge in tenths.
- d is the "design" incidence in degrees, which is at the middle of the design low-drag range and is measured relative to the zero-lift incidence^{*}.
- e is the design range of incidence, which extends from $(d-e/2)$ to $(d+e/2)$ degrees relative to the zero-lift incidence.

For thin aerofoils, because the lift-curve slope is about 0.1 per degree, the values of "d" and "e" could be interpreted approximately as the design C_L (denoted by "s" in the NACA 6-series), and the low-drag range of C_L in tenths.

The NACA 6-series has been exhaustively tested in wind tunnels and flight, and these aerofoils have an excellent record. The GU-series aerofoils have been developed on a purely theoretical basis, but in Derivation 3 the view was expressed that the sophistication of the Lighthill design method should reveal advantages in experiment as well as theory. The realisation of such advantages would naturally require that the aerofoils be manufactured accurately and free of any surface roughness and waviness, because the extent of the low-drag range depends on boundary-layer transition being delayed.

3.3 GU 23-series

The GU 23-series aerofoils are a subset of the GU-series that embody specific forms of leading-edge and trailing-edge shape, designated by $a = 2$ and $b = 3$, respectively. A GU 23-series aerofoil is therefore specified by the designation GU 23-cde. The choice of $a = 2$ is well founded in that it provides what can be identified in theory as the smoothest flow division at the forward stagnation point. The choice of $b = 3$, is more arbitrary and was made because a limited region of reflex curvature can exist if $b < 3$.

3.4 GUNACA 23-series

Instead of using the GU23-cde code it is convenient to use the same descriptors (r, s, tt) that were chosen to define an individual NACA 6-series section to generate a particular member of the GU 23-series. The shape obtained is designated GUNACA 23r-stt, where the last three parameters have exactly the same significance for each GUNACA section as they have for the NACA 6-series sections (Section 3.1). But it should be noted that there are significant differences in geometry between the GUNACA and NACA sections with the same r-stt descriptors, see Appendix A.

An iterative process is necessary to identify the GU 23-cde designation, described in Section 3.2, that corresponds to a given GUNACA 23r-stt designation and this is accomplished by the GUNACA program.

* The design incidence used in the aerofoil designation has been calculated from the method of Lighthill, where incidence is measured relative to the zero-lift incidence.

For example, the GUNACA 235-215 section is found to correspond most closely to the section designated by the GU ab-cde scheme as GU 23-(5.2235)(1.6448)(5.0605). Thus the design extent of the favourable pressure gradient aft of the leading edge is $0.52c$; the design incidence measured relative to zero lift is 1.64° ; and the design range of incidence extends over 5.06° . Given that the zero-lift incidence, $\alpha_0 = -0.96^\circ$ for this aerofoil the design incidence measured relative to the chord is 0.68° . The design range of incidence is therefore $\alpha_1 = -1.85^\circ < \alpha < 3.21^\circ = \alpha_2$, where α_1 and α_2 are measured relative to the chord line.

The NACA 6-series aerofoils have been extensively tested for the following ranges of defining parameters: $3 \leq r \leq 7$, $0 \leq s \leq 6$ and $06 \leq tt \leq 21$. In Derivation 3 it is anticipated that GUNACA aerofoils with defining parameters within the same ranges will prove experimentally viable, since they have been designed to improve upon the NACA 6-series. In the original NACA development, some aerofoil sections would have been ignored as their calculation would infringe the limitations of linearised theory; such sections can be computed accurately by the full theory used for generating the GUNACA sections. For this reason limiting values have not been applied to r , s and tt . However, outside of the ranges $3 \leq r \leq 7$, $0 \leq s \leq 6$ and $06 \leq tt \leq 21$ caution should be applied due to the lack of corroborative wind-tunnel testing.

3.5 Comparison of GUNACA 23-Series and NACA 6-Series Aerofoils

The use of the VGK CFD program* enabled comparisons of GUNACA 23-series, NACA 6-series and NACA 6A-series aerofoils to be made, the results of which are discussed in greater detail in Appendix A and Reference 6.

Consistent differences exist between aerofoils of each series bearing the same r - stt designations. Although the GUNACA 23-series has a slightly reduced leading-edge radius, the significant differences in section geometries are mainly confined to the trailing-edge region. The GUNACA 23-series has greatly reduced rear camber so that α_0 is much reduced in magnitude. This requires the design C_L of a GUNACA 23-series aerofoil to be achieved at a higher aerofoil incidence than the incidence for the design C_L for the NACA 6-series and NACA 6A-series with the same r - stt designation. The reduced rear camber also gives the GUNACA 23-series aerofoil the advantage of a much reduced magnitude of zero-lift pitching moment coefficient, C_{m0} . However, the combination of the smaller leading-edge radius and smaller trailing-edge camber of the GUNACA 23-series may cause some loss in maximum lift (Reference 5). The reduced rear loading of the GUNACA 23-series when compared to the NACA 6-series also indicates a possible reduction in performance for aerofoils of this GUNACA series at high subsonic free-stream Mach numbers.

A significant advantage of the GUNACA 23-series is a large increase in design low-drag C_L range when compared to the NACA 6-series and NACA 6A-series; an improvement that can exceed 100%.

* The VGK method is a computational method for determining two-dimensional attached flow past an aerofoil immersed in a subsonic free-stream, 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 viscous flow element representing the boundary layers is governed by integral equations. 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 method of coupling the viscous and inviscid flow elements permits converged solutions to be obtained for flows with attached boundary layers.