Chapter 5

Wing design - selection of wing parameters

(Lectures 19-22)

Keywords : **Considerations for choice of wing parameters – airfoil section, aspect ratio, sweep, taper ratio, twist, incidence, dihedral and vertical location**

Topics

Chapter 5

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Lecture 19

Topics

5.1 Introduction

In the context of wing design the following aspects need consideration.

I) Wing area (S) : This is calculated from the wing loading and gross weight which have been already decided i.e. S= W / (W / S)

II)Location of the wing on fuselage : High-, low- or mid-wing

III) Aerofoil : Thickness ratio, camber and shape

IV) Sweep (Λ) : Whether swept forward, swept backward, angle of sweep, cranked wing, variable sweep.

V) Aspect ratio (A) : High or low, winglets

VI) Taper ratio (λ) : Straight taper or variable taper.

VII)Twist (ε) : Amount and distribution

VIII) Wing incidence or setting (i_w)

IX) High lift devices : Type of flaps and slats; values of C_{Lmax}, S_{flap}/S

X) Ailerons and spoilers : Values of $S_{aileron}/S$; $S_{spoiler}/S$

XI) Leading edge strakes if any.

XII) Dihedral angle (Γ).

XIII) Other aspects : Variable camber, planform tailoring, area ruling, braced wing, aerodynamic coupling (intentionally adding a coupling lifting surface like canard).

The above parameters are dealt with in the following order.

i) Airfoil selection

ii) Aspect ratio

iii) Sweep

iv) Taper ratio

v) Twist

vi) Incidence

vii) Dihedral

viii) Vertical location

ix) Wing tips

x) Other aspects

At this stage, Fig.A2.1.1 of Appendix 2.1 which gives the geometric details of the wing may be seen again. Section 4.2.1 (Figs.4.4a and b) give the definitions of some additional terms regarding the wing.

5.2 Airfoil selection

Large airplane companies like Boeing and Airbus may design their own airfoils. However, during the preliminary design stage, the usual practical is to choose the airfoil from the large number of airfoils whose geometric and aerodynamic characteristics are available in the aeronautical literature. To enable such a selection it is helpful to know the aerodynamic and geometrical characteristics of airfoils and their nomenclature. These topics are covered in the next three subsections.

5.2.1 Presentation of aerodynamic characteristics of airfoils

Figure 5.1 shows typical experimental characteristics of an aerofoil. The features of the three plots in this figure can be briefly described as follows.

(I) Lift coefficient (C_l) vs angle of attack (α). This curve, shown in Fig.5.1a, has four important features viz. (a) angle of zero lift (α_{0l}), (b) slope of the lift curve denoted by $dC_l / d\alpha$ or a_0 or $C_{l\alpha}$, (c) maximum lift coefficient (C_{lmax}) and (d) angle of attack (α_{stall}) corresponding to C_{lmax}.

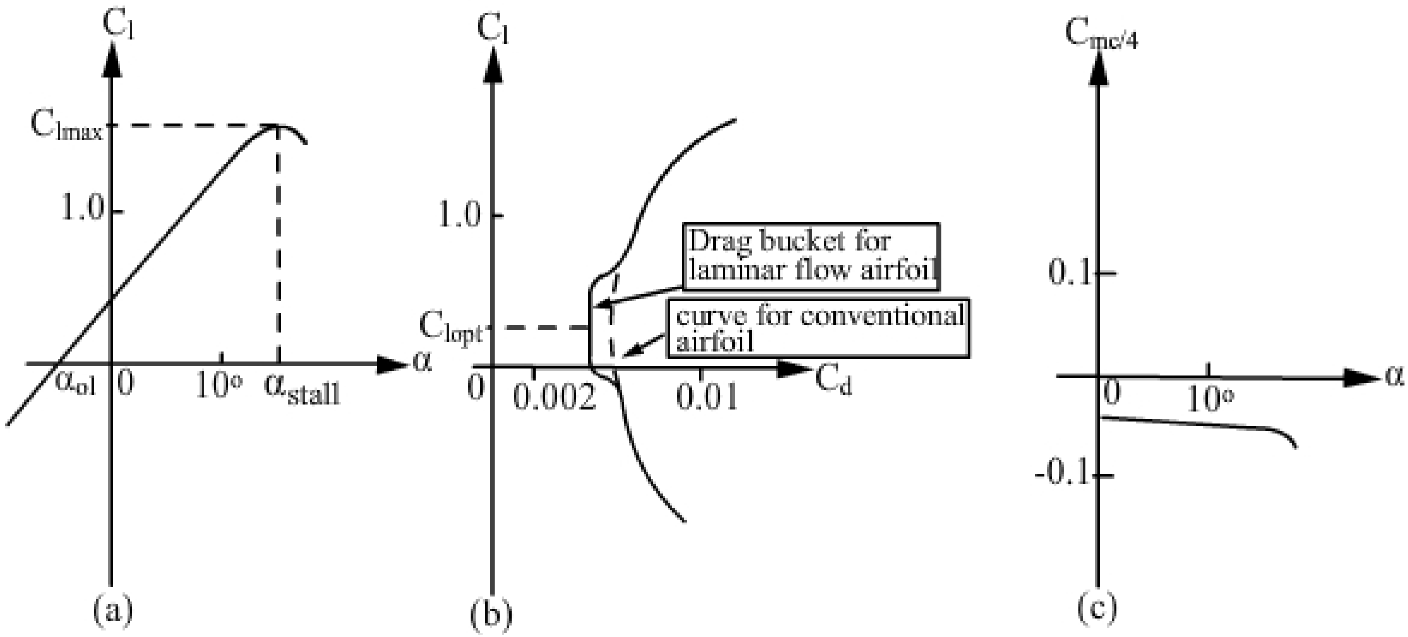


Fig.5.1 Aerodynamic characteristics of an airfoil

(a) C_l vs α (b) C_l vs C_d (c) $C_{mc/4}$ vs α

(II) Drag coefficient (C_d) vs C_l. This curve, shown in Fig.5.1b, has two important features viz. (a) minimum drag coefficient (C_{dmin}) and (b) lift coefficient (C_{lopt}) corresponding to C_{dmin}. In some airfoils, called laminar flow airfoils or low-drag airfoils, the minimum drag coefficient extends over a range of lift coefficients (Fig.5.1b). This feature is called 'Drag bucket'. The extent of the drag bucket and the lift coefficient at the middle of this region are also characteristic features of the airfoil. It may be added that the camber decides C_{lopt} and thickness ratio decides the extent of the drag bucket.

(III) Pitching moment coefficient about quarter-chord $C_{mc/4}$ vs α . This curve is shown in Fig.5.1c. Sometimes this curve is also plotted as $C_{mc/4}$ vs C_l. From this curve, the location of the aerodynamic center (a.c.) and the moment about it (C_{mac}) can be worked out. It may be recalled that a.c. is the point on the chord about which the moment coefficient is independent of C_l.

(IV) Stall pattern : Variation of the lift coefficient with angle of attack near the stall is an indication of the stall pattern. A gradual pattern as shown in Fig.5.1a is a desirable feature. Some airfoils display abrupt decrease in C_l after stall. This behaviour is undesirable as pilot does not get adequate warning regarding impending loss of lift. Airfoils with thickness ratio (t/c) between 6 – 10% generally display abrupt stall while those with t/c more than 14% display a gradual stall. It may be added that the stall patterns on the wing and on the airfoil are directly related only for high aspect ratio (A > 6) unswept wings. For low aspect ratio highly swept wings three-dimensional effects may dominate.

5.2.2 Geometrical characteristics of airfoils

To describe the geometrical characteristics of airfoils, the procedure given in chapter 6 of Ref.5.1 is followed. In this procedure, the camber line or the mean line is the basic line for definition of the aerofoil shape (Fig.5.2a). The line joining the extremities of the camber line is the chord. The leading and trailing edges are defined as the forward and rearward extremities, respectively, of the mean line. Various camber line shapes have been suggested and they characterize various families of airfoils. The maximum camber as a fraction of the chord length (y_{cmax}/c) and its location as a fraction of chord (x_{ycmax}/c) are the important parameters of the camber line.

Various thickness distributions have been suggested and they characterize different families of airfoils Fig.5.2b. The maximum ordinate of the thickness distribution as fraction of chord (y_{tmax}/c) and its location as fraction of chord (x_{ytmax}/c) are the important parameters of the thickness distribution.

Airfoil shape and ordinates

The aerofoil shape (Fig.5.2c) is obtained by combining the camber line and the thickness distribution in the following manner.

a) Draw the camber line shape and draw lines perpendicular to it at various locations along the chord (Fig.5.2c).

b) Lay off the thickness distribution along the lines drawn perpendicular to the mean line (Fig.5.2c).

c) The coordinates of the upper surface (x_u, y_u) and lower surface (x_l, y_l) of the airfoil are given by the four equations presented in Eq.(5.1) :

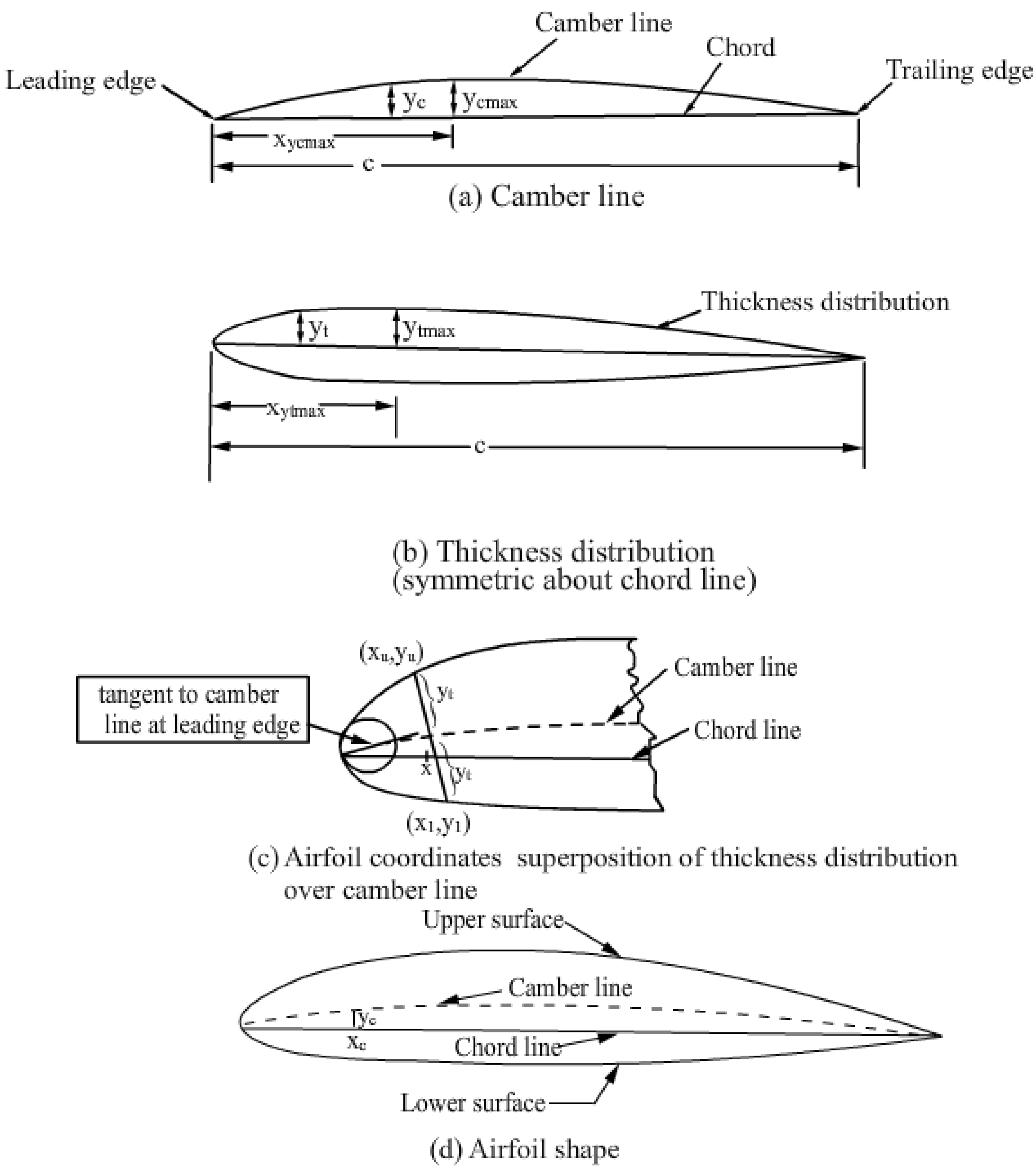


Fig.5.2 Airfoil geometry

$$\left.\begin{aligned} x_u &= x - y_t \sin\theta \\ y_u &= y_c + y_t \cos\theta \\ x_l &= x + y_t \sin\theta \\ y_l &= y_c - y_t \cos\theta \end{aligned}\right\} \qquad (5.1)$$

where y_c and y_t are the ordinates, at location x, of the camber line and the thickness distribution respectively; tan θ is the slope of the camber line at location x (see also Fig.5.2c and d).

d)The leading edge radius is also prescribed for the aerofoil. The center of the leading edge radius is located along the tangent to the mean line at the leading edge (Fig.5.2c).

e)Depending on the thickness distribution, the trailing edge angle may be zero or have a finite value. In some cases, thickness may be non-zero at the trailing edge.

5.2.3 Airfoil nomenclature/designation

Early airfoils were designed by trial and error. Royal Aircraft Establishment (RAE), UK and Gottingen laboratory of the german establishment which is now called DLR(Deutsches Zentrum für Luft-und Raumfahrt – German Centre for Aviation and Space Flight) were the pioneers in airfoil design. Clark Y airfoil shown in Fig.5.3a is an example of a 12% thick airfoil with almost flat bottom surface which has been used on propeller blades.

Taking advantage of the developments in airfoil theory and boundary layer theory, NACA (National Advisory Committee for Aeronautics) of USA systematically designed and tested a large number of airfoils in 1930’s. These are designated as NACA airfoils. In 1958 NACA was superseded by NASA (National Aeronautic and Space Administration). This organization has developed airfoils for special purposes. These are designated as NASA airfoils.

A brief description of their nomenclature is presented below. The description of NACA airfoils is based on chapter 6 of Ref.5.1.

NACA four-digit series airfoils

Earliest NACA airfoils were designated as four-digit series. The thickness distribution was based on successful RAE & Gottigen airfoils. It is given as :

$$\pm y_t = \frac{t}{20}\left[0.2969\sqrt{x} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4\right] \qquad (5.2)$$

where, t = maximum thickness as fraction of chord.

The leading radius is : $r_t = 1.1019\ t^2$

Appendix I of Ref.5.1 contains ordinates for thickness ratios of 6%, 9%, 10%, 12%, 15%, 18%, 21% and 24%. The thickness distributions are denoted as NACA 0006, NACA 0009,……..,NACA 0024. Figure 5.3 b shows the shape of NACA 0009 airfoil. It is a symmetrical airfoil by design. The maximum thickness of all four-digit airfoils occurs at 30% of chord. In the designation of these airfoils, the first two digits indicate that the camber is zero and the last two digits indicate the thickness ratio as percentage of chord.

The camber line for the four-digit series airfoils consists of two parabolic arcs tangent at the point of maximum ordinate. The expressions for camber(y_c) are :

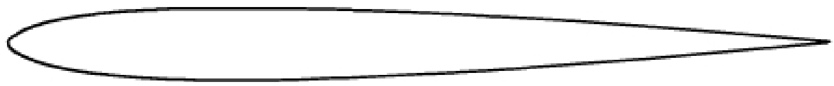
$$\left.\begin{aligned} y_c &= \frac{m}{p^2}\left(2px - x^2\right);\ x \le x_{ycmax} \\ &= \frac{m}{(1-p)^2}\left[(1-2p) + 2px - x^2\right];\ x > x_{ycmax} \end{aligned}\right\} \text{------------------------} (5.3)$$

m = maximum ordinate of camber line as fraction of chord

p = chordwise position of maximum camber as fraction of chord

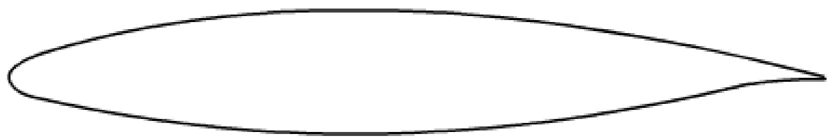
The camber lines obtained by using different values of m & p are denoted by two digits, e.g. NACA 64 indicates a mean line of 6% camber with maximum camber occuring at 40% of the chord. Appendix II of Ref.5.1 gives ordinates for NACA 61 to NACA 67 mean lines. The ordinates of other meanlines are obtained by suitable scaling. For example, NACA 24 mean lines is obtained by multiplying the ordinates of NACA 64 mean line by (2/6).

a) Clark Y - Airfoil with flat bottom surface,used on propeller blades

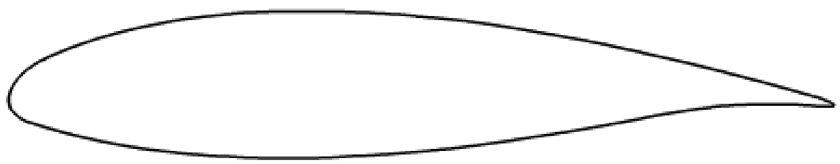


b) NACA 0009 - Symmetrical airfoil used on control surfaces

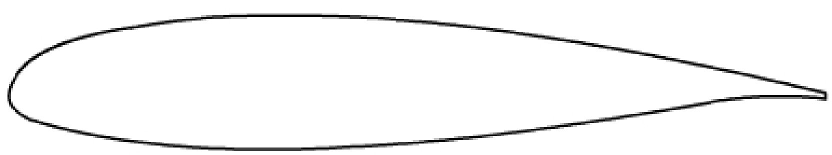
c) NACA 23012 - Airfoil with high C_{lmax}, low speed airplanes



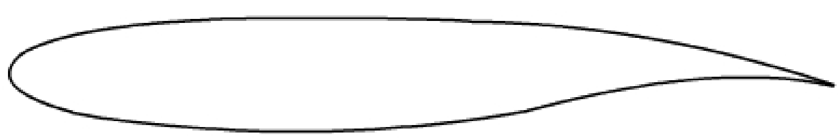
d) NACA 66_2-215 - Laminar flow or low drag airfoil



e) NASA GA(W) - 1 or LS(1)-0417 - Airfoil specially designed for general aviation aircraft



f) NASA MS(1)-0317 - Airfoil specially designed for medium speed subsonic airplanes



g) NASA SC(2)-0714 - Supercritical with high critical Mach number, specially designed for high subsonic airplanes

Fig.5.3 Typical airfoils

A cambered airfoil of four-digit series is obtained by combining meanline and the thickness distribution as described in the previous subsection. For example, NACA 2412 airfoil is obtained by combining NACA 24 meanline and NACA 0012 thickness distribution. This airfoil has (a) maximum camber of 2% occurring at 40% chord and (b) maximum thickness ratio of 12%.

Appendix III of Ref.5.1, be referred for ordinates of the upper and lower surfaces of several four-digit series airfoils. Appendix IV of the same reference presents the low speed aerodynamic characteristics at M = 0.17 and various Reynolds numbers. Chapter 7 of the same reference gives details of experimental conditions and comments on the effects of parameters like camber, thickness ratio, Reynolds number and roughness on aerodynamic characteristics of airfoils.

NACA five-digit series airfoils

During certain tests it was observed that C_{lmax} of the airfoil could be increased by shifting forward the location of the maximum camber. This finding led to development of five-digit series airfoils. The new camber lines for the five-digit series airfoils are designated by three digits. The same thickness distribution was retained as that for NACA four-digit series airfoils. The camber line shape is given as :

$$\left.\begin{aligned} y_c &= \frac{1}{6}k_1\left[x^3 - 3mx^2 + m^2(3-m)x\right],\ 0 < x \le m \\ &= \frac{1}{6}k_1 m^3\left[1-x\right];\ m<x<1 \end{aligned}\right\} \text{-------------------(5.4)}$$

The value of ‘m’ decides the location of the maximum camber and that of k_1 the design lift coefficient(C_{li} or C_{lopt}). A combination of m = 0.2025 and k_1 = 15.957 gives C_{li} = 0.3 and maximum camber at 15% of chord. This meanline is designated as NACA 230. The first digit ‘2’ indicates that C_{li} = 0.3 and the subsequent two digits (30) indicate that the maximum camber occurs at 15% of chord.

A typical five-digit cambered airfoil is NACA 23012. Its shape is shown in Fig.5.3c. The digits signify :

First digit(2) indicates that C_{li} = 0.3.

Second & third digits (30) indicate that maximum camber occurs at 15% of chord.

Last two digits (12) indicate that the maximum thickness ratio is 12%.

Remarks:

(i) Appendices II, III and IV of Ref.5.1 be referred for camber line shape, ordinates and aerodynamic characteristics of five-digit series airfoils.

(ii)Modified four and five digit series airfoils were obtained when leading edge radius and position of maximum thickness were altered. For details Ref.5.1, chapter 6 may be consulted.

Six series airfoils

As a background to the development of these airfoils the following points may be mentioned.

(i)In 1931 T.Theodorsen presented 'Theory of wing sections of arbitrary shape' NACA TR 411, which enabled calculation flow past airfoils of general shape .

(ii)Around the same time the studies of Tollmien and Schlichting on boundary layer transition, indicated that the transition process, which causes laminar boundary layer to become turbulent, depends predominantly on the pressure gradient in the flow around the airfoil.

(iii)A turbulent boundary layer results in a higher skin friction drag coefficient as compared to when the boundary layer is laminar. Hence, maintaining a laminar boundary layer over a longer portion of the airfoil would result in a lower drag coefficient.

(iv)Inverse methods, which could permit design of meanline shapes and thickness distributions, for prescribed pressure distributions were also available at that point of time.Section 4.4 of Ref.5.1 may be consulted for details.

Taking advantage of these developments, new series of airfoils called low drag airfoils or laminar flow airfoils were designed. These airfoils are designated as

1-series, 2-series,…….,7-series. Among these the six series airfoils are commonly used airfoils. Refer Ref.5.1, chapter 6 for more details.

When the airfoil surface is smooth, these airfoils have a C_{dmin} which is lower than that for four-and five-digit series airfoils of the same thickness ratio. Further, the minimum drag coefficient extends over a range of lift coefficient. This extent is called drag bucket (see Fig.5.1b).

The thickness distributions for these airfoils are obtained by calculations which give a desired pressure distribution. Analytical expressions for these thickness distributions are not available. However, Appendix I of Ref.5.1 gives symmetrical thickness distributions for t/c between 6 to 21%.

The camber lines are designated as : a = 0, 0.1, 0.2 …., 0.9 and 1.0. For example, the camber line shape with a = 0.4 gives a uniform pressure distribution from x/c = 0 to 0.4 and then linearly decreasing to zero at x/c = 1.0. If the camber line designation is not mentioned, ‘a’ equal to unity is implied.

An airfoil with a designation as NACA 66_2-215 is shown in Fig.5.3d. It is obtained by combining NACA 66_2 – 015 thickness distribution and a = 1.0 mean line. The digits signify :

1st digit ‘6’ indicates that it is a 6 series airfoil

2nd digit ‘6’ denotes the chordwise position of the minimum pressure in tenths of chord for the symmetrical airfoil at $C_l = 0$. i.e. the symmetrical section (NACA 66_2 - 015) would have the minimum pressure at x/c = 0.6 when producing zero lift.

The suffix ‘2’ indicates that the drag bucket extends ± 0.2 around C_{lopt}.

The digit ‘2’ after the dash indicates that C_{lopt} is 0.2. Thus in this case, drag bucket extends for $C_l = 0.0$ to 0.4.

The last two digits ”15” indicate that the thickness ratio is 15%.

Since, the value of ‘a’ is not explicitly mentioned, the camber line shape corresponds to a = 1.0.

Remarks:

(i)Refer appendices I, II, III and IV of Ref.5.1 for details of thickness distribution, camber distribution, ordinates and aerodynamic characteristics of various six series airfoils.

(ii)The lift coefficient at the centre of the drag bucket (C_{lopt}) depends on the camber. The extent of drag bucket depends on the thickness ratio and the Reynolds number. The value given in the designation of the airfoil is at R_e = 9 x 10^6. The extent is about ± 0.1 for t/c of 12%, ± 0.2 for t/c of 15% and ± 0.3 for t/c of 18%. When the extent of the drag bucket is less than ± 0.1, the subscript in the designation of the airfoil is omitted, e.g. NACA 66-210

NASA airfoils

NASA has developed airfoil shapes for special applications. For example GA(W) series airfoils were designed for general aviation aircraft. The 'LS' series of airfoils among these are for low speed airplanes. A typical airfoil of this category is designated as LS(1) - 0417. In this designation, the digit '1' refers to first series, the digits '04' indicate C_{lopt} of 0.4 and the digits '17' indicate the thickness ratio of 17%. Figure 5.3e shows the shape of this airfoil. For the airfoils in this series, specifically designed for medium speed airplanes, the letters 'LS' are replaced by 'MS'(see Fig.5.3f).

NASA NLF series airfoils are 'Natural Laminar Flow' airfoils.

NASA SC series airfoils are called 'Supercritical airfoils'. These airfoils have a higher critical Mach number. Figure 5.3g shows an airfoil of this category. Refer chapter 3 of Ref.3.4 for further details.

Remarks:

(i)Besides NACA & NASA airfoils, some researchers have designed airfoils for specialized applications like (a) low Reynolds number airfoils for micro air vehicles, (b) wind mills, (c) hydrofoils etc.These include those by Lissaman, Liebeck, Eppler and Drela. Reference 1.18, chapter 4, and internet (www.google.com) may be consulted for details.

(ii)The coordinates of NACA, NASA and many other airfoils are available on the website entitled 'UIUC airfoil data base'.