Chapter 5

Wing design - selection of wing parameters – 2

Lecture 20

Topics

5.2.4 Effect of geometric parameters, Reynolds number and roughness on aerodynamic characteristics of airfoils

The important aerodynamic characteristics of airfoil from the point of view of design are angle of zero lift (α_{ol}), maximum lift coefficient (C_{lmax}), stall pattern, minimum drag coefficient (C_{dmin}), lift coefficient corresponding to C_{dmin} which is also called optimum lift coefficient (C_{lopt}), extent of drag bucket for low drag airfoils, moment coefficient about aerodynamic centre (C_{mac}) and critical Mach number. At subsonic speeds these characteristics are affected by geometrical parameters viz. camber, thickness ratio (t/c), airfoil shape, Reynolds number and roughness. Various chapters in Refs.5.1 and 5.2 contain information about characteristics of NACA airfoils. These effects can be summarized as follows.

(i) The camber decides α_{0l}, C_{lopt} and C_{mac}. For a given family of airfoils, with increase of camber, α_{0l} and C_{mac} become more negative whereas C_{lopt} increases.

(ii) The thickness ratio influences C_{dmin} and C_{lmax}. For a given family of airfoils, the minimum drag coefficient (C_{dmin}) increases with (t/c). The maximum lift coefficient (C_{lmax}) is highest for (t/c) between 12 to 16%. The stall pattern is also gradual for these thickness ratios.

(iii) The Reynolds number (Re) mainly influences C_{lmax} and C_{dmin}. The former (C_{lmax}) increases with Re and the latter generally decreases with Re. As noted in the previous subsection, the extent of drag bucket indicated by the nomenclature of the airfoil is at Re = 9 x 10^6.

(iv) The surface roughness influences C_{lmax} and C_{dmin}. With increase of roughness C_{lmax} decreases and C_{dmin} increases.

(v)The critical Mach number, in connection with the airfoil, is defined as the "Free stream Mach number at which the maximum Mach number on the airfoil is unity". This quantity can be obtained theoretically by calculating the pressure distribution on the airfoil, but cannot be determined experimentally. However, when the critical Mach number is exceeded, the drag coefficient starts to increase. Making use of this behavior, the term 'Drag divergence Mach number (M_D)' is defined as the Mach number at which the drag coefficient shows an increase of 0.002 over the subsonic drag value (Fig.5.4).

Some authors (Ref.4.3) define M_D as the Mach number at which the slope of the C_d vs. M curve has a value of 0.1 i.e. $(dC_d/dM) = 0.1$

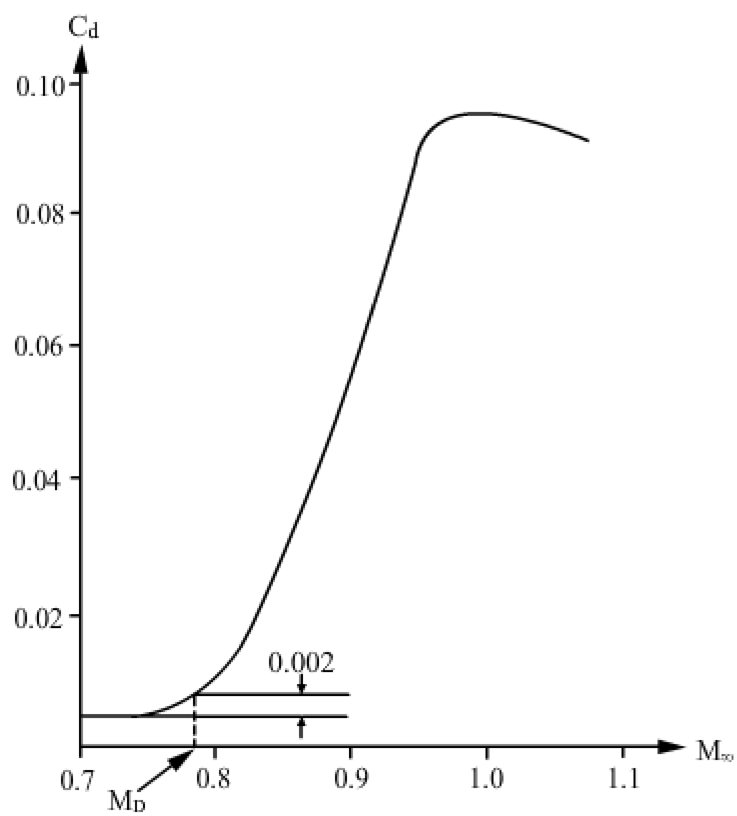

Fig.5.4 Drag divergence Mach number

The drag divergence Mach number (M_D) depends on airfoil shape, thickness ratio, and lift coefficient. For a given airfoil M_D is highest near C_{lopt}. It decreases with thickness ratio.

Supercritical airfoil

For airplanes flying at high subsonic speeds the lift coefficient under cruising condition (C_{Lcr}) is around 0.5. At this value of lift coefficient, the older NACA airfoils have drag divergence Mach number (M_D) of around 0.68 for a thickness ratio (t/c) of around 15%.

With the advancements in computational fluid dynamics (CFD) it was possible, in 1970's to compute transonic flow past airfoils. This enabled design of improved airfoils, called supercritical airfoils, which have M_D around 0.75 for t/c of 15% (Ref.1.12 part II, chapter 6). For comparison, the shapes of older airfoil (NACA 66_2 - 215) and a supercritical airfoil are shown in Fig.5.3 d and g. Note the flat upper surface of the supercritical airfoil. Refer chapter 3 of Ref.3.4 and Ref.5.4, for additional information.

Remarks :

(i) To illustrate the effects of Reynolds number, roughness, camber and thickness and ratio on C_l, C_d and C_{mac}, the experimentally obtained variations (Ref.5.5) are presented in Figs.5.5 a to e. They related to NASA MS(1)-0317, MS(1)-0313 and LS(1)-0417 airfoils. It may be mentioned that the airfoil LS(1)-0417 is 17% thick airfoil with $C_{ldesign}$ of 0.4. It is designed specifically for low speed airplanes. Later NASA MS(1)-0317 with, thickness ratio of 17% was designed for applications to medium speed airplanes ($M \approx 0.7$). The value of $C_{ldesign}$ is 0.3. The airfoil NASA MS(1)-0313 is similar to NASA MS(01)-0317, but has t/c of 13%

Figure 5.5a shows the effect of varying Reynolds number from $2x10^6$ to 12×10^6 on lift characteristics of NASA MS (01)-0317 airfoil. It is observed that C_{lmax} increases from about 1.6 to 2.0. Note that α_{ol} is -3^o.

Figure 5.5b shows the effect of varying Reynolds number on C_d vs C_l curve of the same airfoil. It is seen that C_{dmin} occurs around $C_l = 0.3$ but is almost constant between $C_l = 0.1$ to 0.5, effect of Reynolds number on C_{dmin} is not very clear, near C_l = 0.3 but at higher values of C_l (C_l > 0.75) the values of C_d decrease as Re increases.

Figure 5.5c shows the C_d vs C_l curves with Re as parameter for the same airfoil but with rough surface details of roughness see Ref.5.5 comparing Figs.5.5 b and c. It is seen that C_{dmin} is significantly higher for the rough airfoil as compared to the smooth one. The value of C_{dmin} decreases with Re.

Figure 5.5d compares the C_l vs α, C_d vs C_l and $C_{m\frac{c}{4}}$ vs C_l curves for NASA LS(1)-0417 and MS(1)-0.317 airfoils. The cambers of the two airfoils are different, being higher for LS(1)-0.417. It is seen that α_{ol} and $C_{m\frac{c}{4}}$ are more negative for the LS(1)-0417.

Figure 5.5 e compares C_l vs α, C_d vs C_l and $C_{m\frac{c}{4}}$ vs C_l curves for NASA MS(1)-0317 and MS(1)-0313 airfoils. It is observed that the thinner airfoil has slightly lower value of C_{dmin}.

(ii)Appendix F of Ref.1.20 gives the designations of airfoils used on many airplanes.

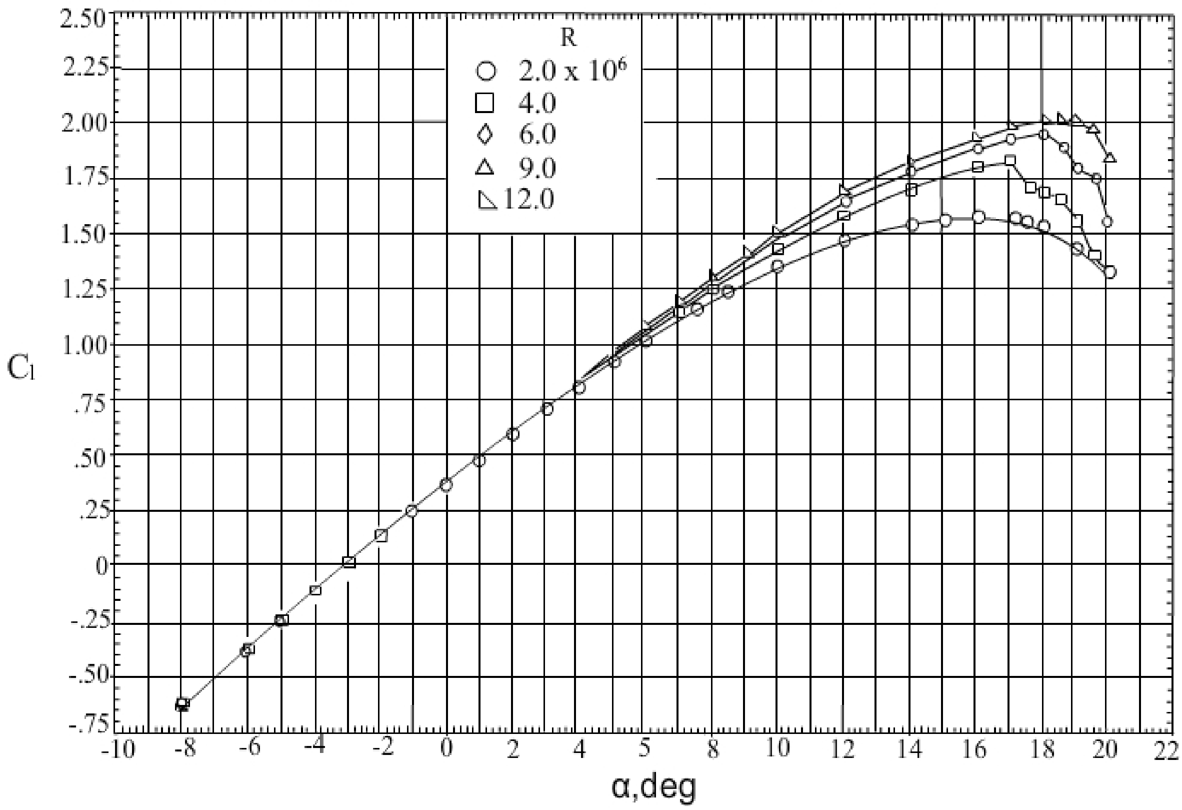

Fig.5.5a Effect of Reynolds number on C_l vs α curve

Airfoil : NASA MS(1)-0317; M = 0.15 ; smooth surface

(Adapted from Ref.5.5)

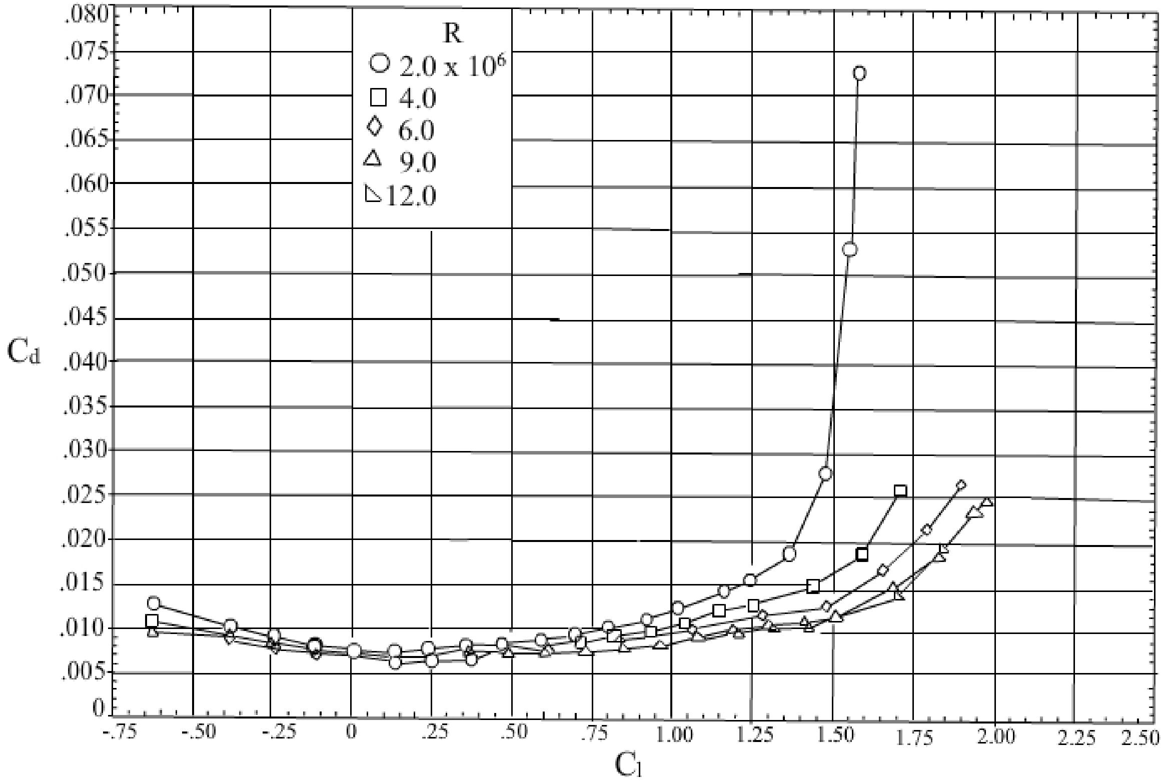

Fig.5.5b Effect of Reynolds number on C_d vs C_l curve

Airfoil : NASA MS(1)-0317; M = 0.15 ; smooth surface

(Adapted from Ref.5.5)

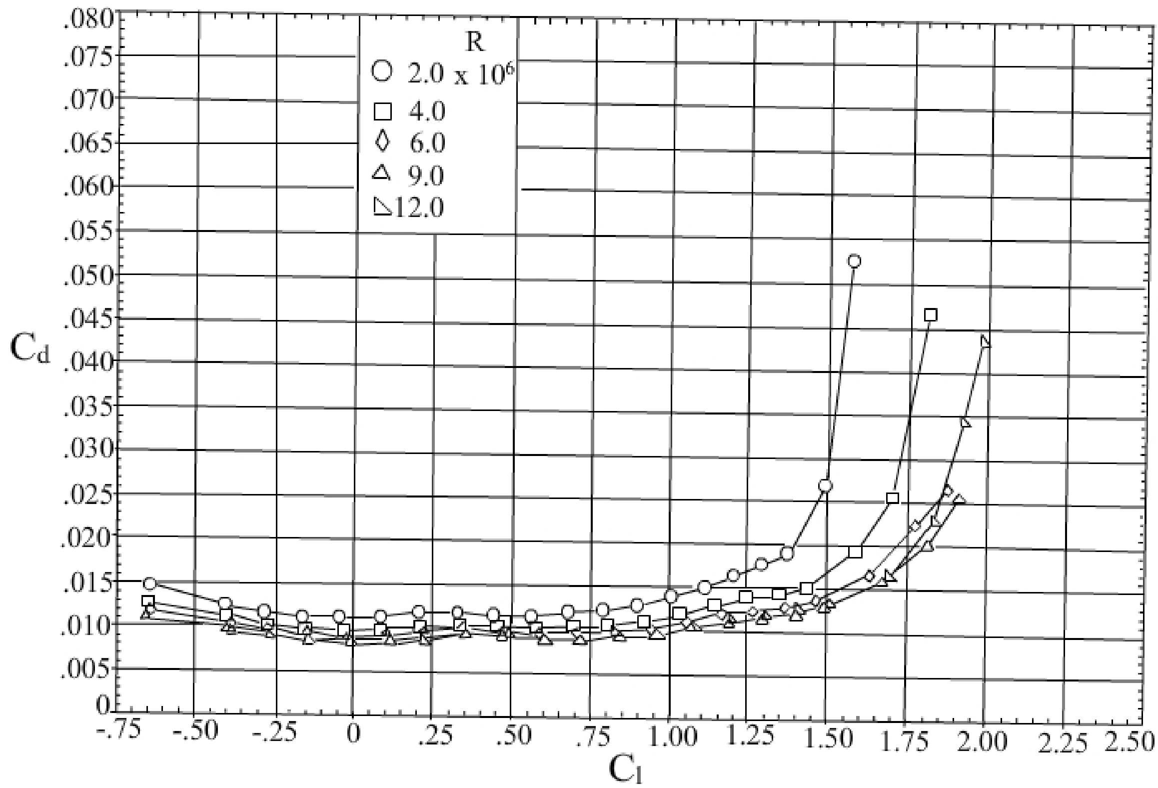

Fig.5.5c Effect of Reynolds number on C_d vs C_l curve

Airfoil : NASA MS(1)-0317; M = 0.15 ; Rough surface

(Adapted from Ref.5.5)

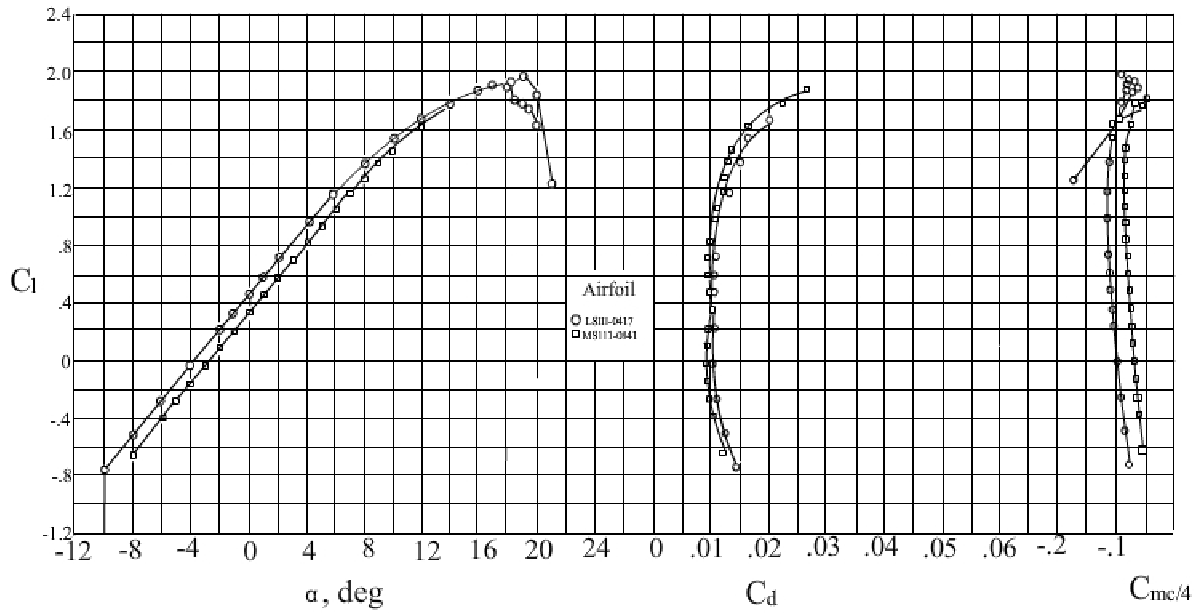

Fig.5.5d C_l vs α, C_l vs C_d, C_l vs $C_{mc/4}$ curves for NASA LS(1)-0417 and NASA MS(1)-0317 airfoils; Re = 6 x 10^6 ; M = 0.15 ; Rough surface (Adapted from Ref.5.5)

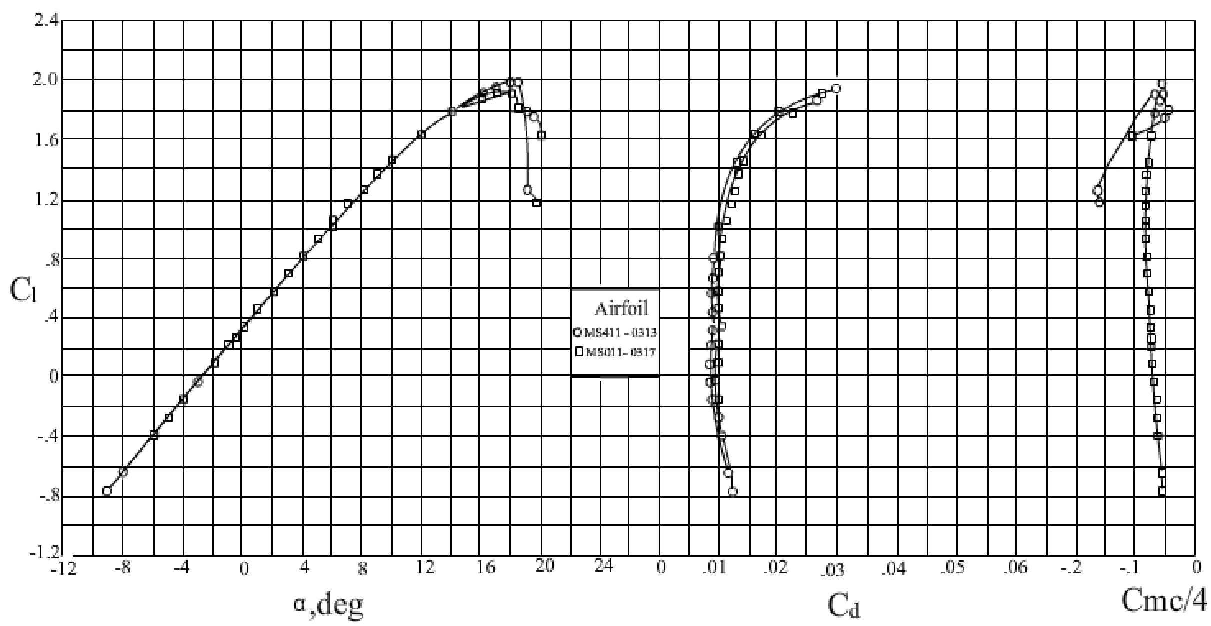

Fig.5.5e C_l vs α, C_l vs C_d, C_l vs $C_{mc/4}$ curves for NASA MS(1)-0317 and NASA MS(1)-0313 airfoils; Re = 6 x 10^6 ; M = 0.15 ; Rough surface (Adapted from Ref.5.5)

5.2.5 Choice of airfoil camber

The choice of the airfoil for the airplane wing involves the selection of camber, thickness ratio and shape of the airfoil. The camber decides the C_{lopt} of the airfoil and the thickness ratio decides the characteristics like C_{lmax}, C_{dmin}, drag divergence Mach number (M_D), weight of the wing and the stall pattern. For a good design, the camber should be chosen such that C_{lopt} of the airfoil is close to the lift coefficient of the aircraft (C_L) in the flight corresponding to the mission of the airplane. This lift coefficient is called design lift coefficient ($C_{Ldesign}$). In most of the cases, this would correspond to the cruise flight condition.

Assuming $L = W = \frac{1}{2}\rho V^2 S C_L$

$C_{Ldesign} = \dfrac{W}{\frac{1}{2}\rho V^2 S}$; ρ and V correspond to mission of the airplane e.g cruise

Remark:

The camber of the airfoil is chosen such that C_{lopt} approximately equals $C_{Ldesign}$.

5.2.6 Choice of airfoil thickness ratio (t/c)

The thickness ratio (t/c) affects C_{dmin}, C_{lmax}, stall pattern, wing structural weight and M_D. The influence of (t/c) on C_{dmin}, C_{lmax} and stall pattern has been dealt with in subsection 5.2.4.

The following may be noted to understand the effect of thickness ratio (t/c) on the structural weight of the wing.

The wing structure consists of spars (front and rear), stingers and skin (see Airbus 380 cut-away section in Appendix 1.1 and cut away drawing of airplanes in Ref.1.21).The spars are like I section beams. The flanges of the I section take the bending moment and the web takes the shear. If the wing section is thicker, then the spar flanges will be away from the centroidal axis of the section. Now, the bending moment resisted by an 'I' section beam is proportional to the product of the area of the flange and the distance of flange from centroidal axis.Thus, for a given bending moment, a thicker I beam would require lower area of flange. Consequently, it would be lighter. Thus, a thicker wing will result in lighter wing.

Reference 1.9, chapter 8; Ref.1.12, Pt.V, ch.9; Ref.1.15, chapter 6; Ref.1.18, chapter 15; Ref.1.19, chapter 8 and Ref.1.20, chapter 20 give formulae for the weight of wing (W_W) in terms of the geometrical parameters of the wing. Based on these, W_w can be expressed as :

$$W_W = C S_w^a A^b (t/c)^c (1+\lambda)^d (\cos\Lambda)^e \quad (5.5)$$

where, S_W = wing area, A = aspect ratio,

t/c = thickness ratio, λ = taper ratio and Λ = sweep and C is a constant.

The exponents a to e depend on the type of airplane. Their values lie in the following ranges.

a = 0.62 to 0.76; b = 0.5 to 0.79; C = -0.3 to -0.4 ; d = 0.05 to 0.1 and e = -1.

Remarks:

(i) The final selection of the airfoil involve trade-off studies. It is seen that an increase in (t/c) results in increase of C_{lmax}, decrease in wing weight and increase in C_{dmin}. The trade-off studies would involve selecting different (t/c) values and examining which value gives minimum weight or fuel required etc.

At the preliminary design stage the guidelines are obtained from the airfoils used on similar airplanes. Low speed airplanes have thickness ratio between 15 to 18%. NASA LS(1) – 0417 is being used on low speed airplanes.

NASA MS (01)-031 is being used on medium speed airplanes with turboprop engines. The high subsonic airplanes use supercritical airfoils of camber which would give $C_{lopt} = C_{ldesign}$ and (t/c) around 14%. At supersonic speeds, C_{dmin} is proportional to $(t/c)^2$. These airplanes have (t/c) between 3 to 5%. Concorde airplane had biconvex airfoil of t/c = 0.035.

(ii) Sometimes the (t/c) of the airfoil at the wing root is larger than the (t/c) of airfoil near wing tip. This is a compromise between the conflicting effects of increase of (t/c) on C_{dmin} and the wing weight. Values of (t/c) = 0.18 at root and 0.15 at tip have been used.

5.3 Selection of wing parameters

In this section, the selection of aspect ratio (A), sweep(Λ) and taper ratio(λ) are considered.

5.3.1 Choice of aspect ratio(A)

Aspect ratio affects the slope of the lift curve $(C_{L\alpha})$, the induced drag (C_{Di}), the structural weight of the wing and the wing span.

a)Effect of aspect ratio on slope of the lift curve

The slope of lift curve of a wing in subsonic flow for A > 4, is given by :
(Ref.5.6, section 3.2)

$$C_{L\alpha} = \frac{2\,\pi\,A}{2 + \sqrt{4 + \frac{A^2\,\beta^2}{\eta^2}\left(1 + \frac{\tan^2\Lambda_{\frac{1}{2}}}{\beta^2}\right)}} \qquad (5.6)$$

where $\beta^2 = 1 - M^2$, $\eta = C_{l\alpha} / (2\,\pi)$, $\Lambda_{\frac{1}{2}}$ = sweep of the half chord line ,

$C_{l\alpha}$ is the slope of lift curve of the airfoil used on wing.

Equation (5.6) shows that $(C_{L\alpha})$, decreases as aspect ratio decreases.

b)Effect of aspect ratio on induced drag

The induced drag coefficient (C_{Di}) of a subsonic airplane is given by :

$$C_{Di} = \frac{C_L^2}{\pi A}(1+\delta) \qquad (5.7)$$

where, δ depends on wing geometry i.e. aspect ratio, taper ratio and sweep.

c)Effect of aspect ratio on structural weight

Equation (5.5) shows that the wing weight increases as A^b where b = 0.5 to 0.79. The reason for this is as follows.

As the aspect ratio increases the wingspan(b) increases ($b=\sqrt{AS}$). An increase in the span would increase the bending moment at the wing root. This would require higher moment of inertia of the spar and hence higher weight.

d) Effect of aspect ratio on span

For a chosen wing area, the aspect ratio decides the span of the wing $\left\{b = (A \times S)^{1/2}\right\}$. In turn the span decides the hanger space needed for the airplane. Hence, for personal airplanes, a moderate aspect ratio of 6 to 7 is generally chosen. Further, the ride in turbulent weather is poor for a high aspect ratio wing. Hence, agricultural and other airplanes, which fly in proximity of ground, are subjected to air turbulence and have moderate aspect ratio of 6 to 7.

Remark :

The final choice of the aspect ratio would be arrived at after the trade-off studies which would involve selecting various values of aspect ratio and examining their effect on the criterion for the design of the particular airplane. At the preliminary design stage guidelines are obtained from the aspect ratios used on similar airplanes.

Low speed airplanes of earlier designs had aspect ratio between 6 to 7.5, but the current trend is to choose between 7.5 to 8.5.

The medium speed airplane, using turboprop engines, of earlier design had aspect ratio between 9 to 11. The current trend is the aspect ratio between 11 to 13. The high subsonic jet transport of earlier designs had aspect ratio between 7 to 8. The current trend is between 8.5 to 10.0. The trend towards higher aspect ratio appears to be due to availability of carbon epoxi material for fabrication of wing. This material is lighter than aluminium and has more stiffness.

Reference 1.18, chapter 4 be referred for guidelines to select aspect ratios of other types of airplanes.