Chapter 5

Wing design - selection of wing parameters - 3

Lecture 21

Topics

5.3.2 Choice of sweep (Λ)

5.3.3 Choice of taper ratio (λ)

5.3.4 Choice of twist (ε)

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5.3.6 Choice of dihedral (Γ)

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5.3.8 Flaps

5.3.2 Choice of sweep (Λ)

The wing sweep affects the slope of the lift curve ($C_{L\alpha}$), the maximum lift coefficient C_{Lmax}, the induced drag coefficient (C_{Di}), the drag divergence Mach number (M_D), the wing weight and the tip stalling.

a) Effect of sweep on slope of lift curve

From Eq.(5.6) it is seen that $C_{L\alpha}$ decreases as sweep increases. It can be shown that $C_{L\alpha}$ of a wing of aspect ratio 9, operating at Mach number 0.8, would decrease by about 20% when sweep increases from 0^o to 30^o.

b) Effect of sweep on maximum lift coefficient(C_{Lmax})

It is pointed out in subsection 4.3.2, that the C_{Lmax} of a swept wing decreases in proportion to $\cos\Lambda$ Eq.(4.8).

c) Effect of sweep on induced drag

From Eq.(3.57) the induced drag coefficient of typical jet airplane would be:

$$C_{Di} = KC_L^2 = \frac{1}{\pi A}\left(1.0447 + \frac{0.2078}{\cos^2\Lambda_{\frac{1}{4}}}\right)$$

$$\text{Or } K = \frac{1}{\pi A}\left(1.0447 + \frac{0.2078}{\cos^2 \Lambda_{\frac{1}{4}}}\right)$$

From the above equation, the values of K shown in Table 5.1 are obtained for different values of $\Lambda_{\frac{1}{4}}$; the aspect ratio (A) is taken equal to 9.

$\Lambda_{\frac{1}{4}}$	K
0	0.0443
25^o	0.0459
30^o	0.0467
35^o	0.0479
40^o	0.0495

Table 5.1 Typical change in K due to sweep

It is observed that K and in turn the induced drag coefficient increases as angle of sweep increases.

d) Effect of sweep on divergence Mach number (M_D)

For a swept wing the change in drag divergence Mach number due to sweep angle Λ, is given approximately by the following equation (Ref.5.7, chapter 15):

$$\frac{1-(M_D)_\Lambda}{1-(M_D)_{\Lambda=0}} = 1-\frac{\Lambda}{90} \tag{5.8}$$

where, $(M_D)_{\Lambda=0}$ and $(M_D)_\Lambda$ are the drag divergence Mach numbers of the unswept and the swept wing respectively; Λ is quarter-chord sweep in degrees. As an illustration consider a wing employing a supercritical airfoil with M_D of 0.78. Ignoring the effects of aspect ratio on M_D the value of M_D would be 0.78 for a wing with $\Lambda = 0$. If the wing has a sweep of 30^o, then its M_D from Eq.(5.8) would be 0.853. The increase in M_D due to sweep is very significant. Further, when $M < M_D$, the lift to drag ratio (L/D) is high. Thus, when M_D increases the high value of (L/D) can continue upto higher values of Mach numbers or flight speeds. Equation (3.30) shows that for jet airplanes the range increases as flight speed increases. In other words, when M_D increases, the range would increase.

e) Effect of sweep on wing weight

Equation (5.5) shows that the weight of the wing is proportional to ($1 / \cos\Lambda$).

Thus, the weight of the wing increases as sweep increases.

Remarks :

i) Wing with cranked trailing edge:

Instead of having a trapezoidal wing planform, the wings of high subsonic airplanes have an unswept trailing edge up to about 30% of semi-span in the inboard region (Fig.4.4b). These wings have the following favourable effects.

(a)Higher thickness at the root.

(b)Span-wise center of pressure is brought slightly inboard which reduces the bending moment at the root as compared to the trapezoidal wing.

These two effects tend to reduce the weight of wing structure. The thicker inboard section also provides room for accommodating the back-up structure for the landing gear.

ii) From the above discussion it is noted that the sweep has the beneficial effect of increasing M_D. However, it has the adverse effects of (a) increasing C_{Di} and weight and (b) decreasing C_{Lmax}. Hence, airplanes flying upto M = 0.5 have unswept wings. The airplanes like business jets and short large jet airplanes flying at M $\approx$ 0.7, have moderate sweep of about 20^o. For the jet transport airplanes cruising at Mach number between 0.8 to 0.85, the value of sweep is chosen taking into account (a) $C_{Ldesign}$ (b) airfoil used and (c) aspect ratio of the wing. The value of $C_{Ldesign}$ for these airplanes is generally between 0.5 to 0.7. The supercritical airfoil of NASA SC series with (t/c) of 14% to 15% and camber corresponding to $C_{Ldesign}$ is generally chosen. The value of M_D for this airfoil at C_L=$C_{Ldesign}$ can be obtained from sources like Ref.5.4. Then the value of Λ that will give the desired value of M_D for the wing can be obtained from Eq.(5.7). The final value of Λ is obtained after trade-off studies which involve considering different values of Λ and assessing their influence on the criteria for design.

To avoid the adverse effects of sweep, the wings of high subsonic speed airplanes have, features like (a) complicated high lift devices to take care of effect of sweep on C_{Lmax}, (b) low taper ratio and cranked wing to alleviate the increase in structural weight due to sweep.

The wings of supersonic airplanes need values of Λ between 45^o to 60^o. Variable sweep wings have been designed for such airplanes. These wings have

(a) low sweep at flight speeds near take-off and landing (b) moderate sweep $(\Lambda \approx 35^o)$ for cruise at high subsonic Mach numbers and (c) highest sweep for cruise at supersonic Mach numbers.

Information on airplanes with variable sweep e.g. Panavia Tornado, General Dynamics F-111, Tupolev Tu-22 M-3 can be obtained from internet (www.google.com).

The wings with variable sweep are naturally heavier than those with fixed value of sweep.

5.3.3 Choice of taper ratio (λ)

The taper ratio influences the following quantities.

a) Induced drag

b) Structural weight

c) Ease of fabrication

It is known that an elliptic wing has the lowest induced drag ($\delta = 0$ in Eq.5.7). However, this planform shape is difficult to fabricate. A rectangular wing is easy to fabricate but has about 7% higher C_{Di} as compared to the elliptic wing ($\delta = 0.07$). It is also heavier structurally (Eq.5.5). An unswept wing, with (λ) between 0.3 to 0.5, has a slightly positive value of δ. Further, in a tapered wing, the span loading is concentrated in the inboard portions of the wing and the airfoil at the root is thicker than that near the tip. These factors help in reducing the wing weight Eq.(5.5). Tip stalling (discussed in section 5.3.4) is also not a problem when the taper ratio is between 0.3 and 0.5. From these considerations, a taper ratio between 0.3 and 0.5 is common for low speed airplanes.

Some airplane wings have straight central portion (Figure 2.1 shows such a Wing Planform). This appears as a compromise between (a) ease of fabrication with untapered wing and (b) lower structural weight of a tapered wing.

5.3.4 Twist

A wing is said to have a twist when the chord lines of airfoils at different spanwise stations are not parallel to each other. The difference between the angles of attack of the airfoil sections at the root and near the tip is called geometric twist (Fig. A2.1.1). Whereas, the aerodynamic twist is the difference between zero lift lines of airfoils at root and near the tip. Twist is given to prevent tip stalling which is explained below.

Tip stalling

It is a phenomenon in which the stalling on the wing begins in the region near the wing tip. This is because the distribution of local lift coefficient (C_l) is not uniform along the span and as the angle of attack of the wing increases, the stalling will begin at a location where the local lift coefficient exceeds the maximum lift coefficient (C_{lmax}) there. To understand this phenomenon better, an unswept tapered wing is considered. The lift distribution on such a wing has a maximum at the root and goes to zero at the tip. This distribution is also known as Γ distribution. Further, the local lift (ΔL) can be equated to $(1/2)\rho V_\infty^2 c C_l \Delta y$, where c is the local chord and C_l is the local lift coefficient over an element (Δy) of span. Thus, Γ distribution is proportional to the product c C_l. The local lift coefficient (C_l) is proportional to Γ/c and is not uniform along the span. The Γ distribution along the span can be approximately obtained by Schrenk's method. According to this method, c C_l distribution is roughly midway between the chord distribution of the actual wing and that of an elliptic wing of the same area. Figure 5.6 shows distributions of cC_l and c. From these distributions, the variation of C_l along the span can be calculated (Fig.5.7). It can be proved, that for a wing with taper ratio λ, and C_{lmax} constant along span, the local maximum of C_l will occur at a span-wise location (y) where:

$$y/(b/2) \approx 1-\lambda \qquad (5.9)$$

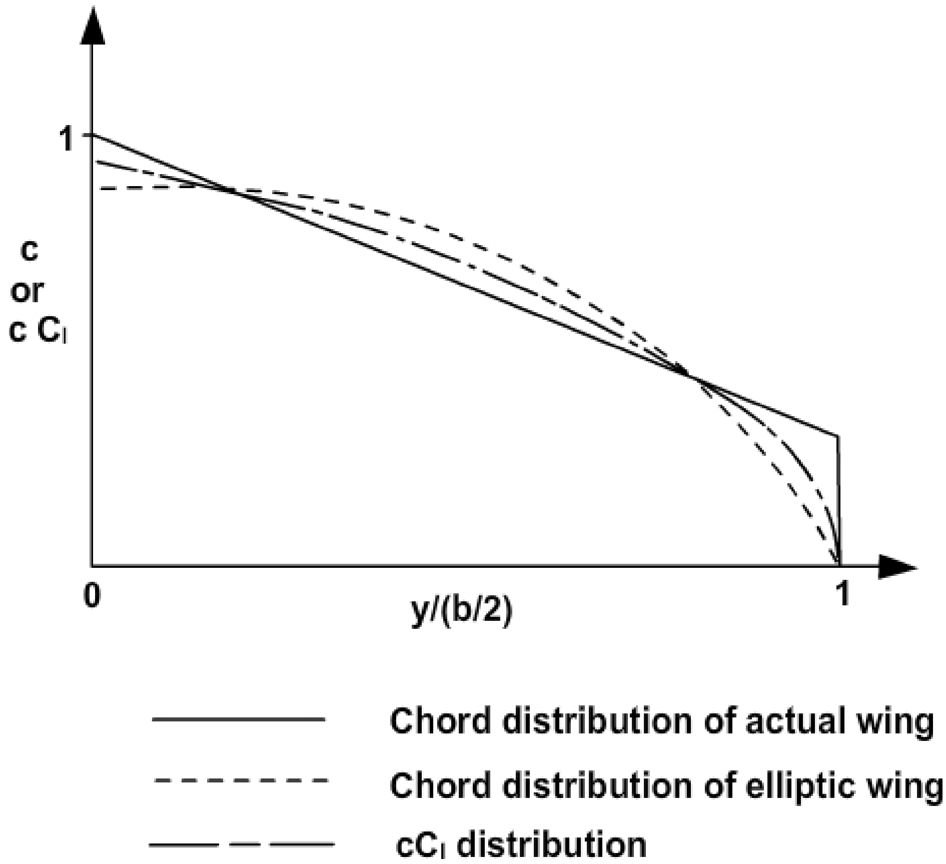

Fig.5.6 Schrenk's Method

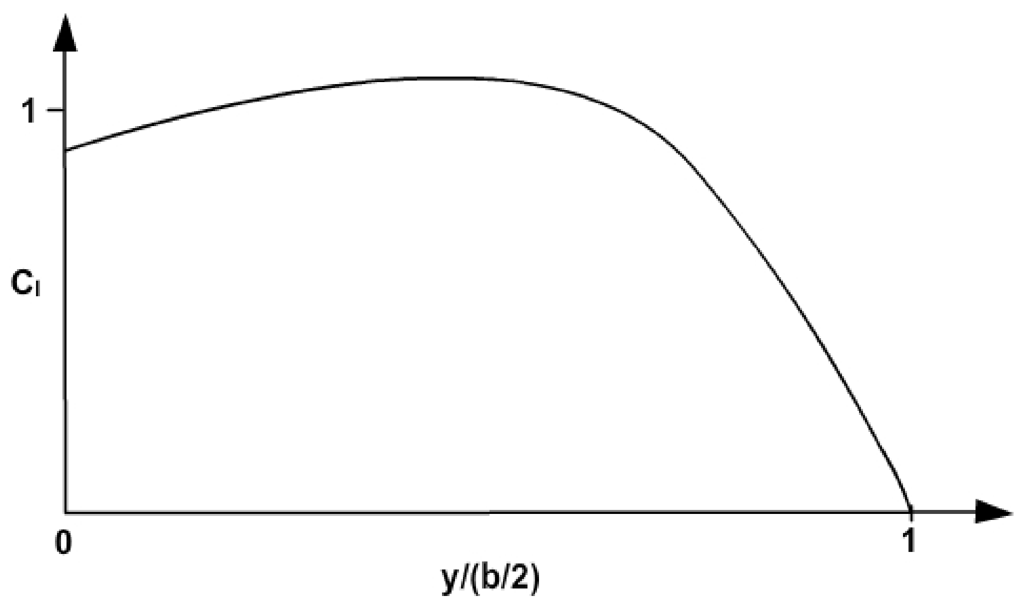

Fig.5.7 Typical distribution of C_l

It is known that the maximum lift coefficient (C_{lmax}) of an airfoil depends on the airfoil shape, surface roughness and Reynolds number. For simplicity, it is assumed that C_{lmax} is approximately constant along the span. Then from the distribution of C_l in Fig.5.7, it is observed that as the angle of attack of the wing increases, the stalling will begin at the span-wise location where local C_l equals local C_{lmax} . Subsequently, stalling will progress along the wing span and finally the wing will stall (i.e. C_L of wing will reach a maximum and then decrease). The beginning of stall near the tip is undersirable as airlerons are located in the tip region. Stalling there would reduce aileron effectiveness. For a wing of a taper ratio 0.3, the stall is likely to begin around y / (b/2) of 0.7.

Remarks :

(i) In the case of swept wings, there is a cross flow along the span and the tendency for the tip stall is enhanced.

(ii) Tip stalling can be prevented if the airfoil section in the tip region has an angle of attack lower than that at the root. In this case, the wing acquires a twist. As mentioned earlier, the difference between the angle of attack of the airfoil at the root and that near the tip is called geometric twist and denoted by ε (Fig.A 2.1.1) Twist is negative when airfoil near the tip is at an angle of attack lower than that at the root. This is also called wash-out. Sometimes airfoils with higher C_{lmax} are used near the tip. Thus airfoils at the root and near the tip may have different values of angle of zero lift (α_{0l}). This leads to aerodynamic twist which is the angle between the zero lift lines at the root and that near the tip.

To completely eliminate the occurrence of tip stalling, may require a complex variation of the angle of twist. However, for ease of fabrication, linear twist is given in which the angle of twist varies linearly along the span.

(iii) Actual value of twist can be obtained by calculating the C_l distribution on untwisted wing and then varying the twist such that tip-stalling is avoided. A value of 3^o can be used as an initial estimate.

(iv) Early swept wing airplanes had the following features to avoid tip stalling. (a)Vortex generators, (b) Fences on top surface.

Refer to Internet (www.google.com) for details of these two methods to avoid tip stalling.

5.3.5 Wing incidence

The mean aerodynamic chord is the reference line of the wing. Fuselage reference line (FRL) is the reference line for the entire airplane. The angle between fuselage reference line and the wing reference line is called wing incidence and denoted by i_w. The reason for providing the wing incidence is given below.

For the economy in fuel consumption, the drag should be minimum during cruise. The fuselage has a minimum drag when its angle of attack is zero. However, during cruise, the wing should produce sufficient lift to support the weight of the airplane. Keeping these factors in view, the wing is mounted on the fuselage in such a manner that it produces the required amount of lift in cruise while the fuselage is at zero angle of attack.

During the preliminary design phase, i_w can be obtained as follows.

a)Obtain $C_{Ldesign}$ corresponding to cruise or any other design condition i.e.

$$C_{L\,design} = \frac{W}{\frac{1}{2}\rho V^2 S}$$

where, ρ and V correspond to the design flight conditions.

b) Obtain $C_{L\alpha}$ for the wing (Eq.5.6 for subsonic airplanes)

c) Obtain zero lift angle (α_{0L}) for wing. This depends on α_{0l} of the airfoil used on the wing and the wing twist.

For an untwisted wing,

$$\alpha_{0L} = \alpha_{olr}$$

where, α_{olr} is the zero lift angle of the airfoil at the root.

Reference 4.7, chapter 2 gives the following procedure for a wing with aerodynamic twist of ε.

$$\alpha_{0L} = \alpha_{0lr} + J\varepsilon \qquad (5.10)$$

where, ε is positive when the airfoil at the tip is at an angle of attack higher than at root.

The quantity J has a weak dependence on aspect ratio and taper ratio of the wing.

However, a value of -0.4 can be taken for the first estimate of α_{0L}. For more accurate estimate of α_{0L}, refer to section 4.1.3.1 of Ref.4.2.

d) Calculate i_w from the following equation :

$$C_{Ldesign} = C_{L\alpha}\left(i_w - \alpha_{0L}\right)$$

Remark :

The final choice of i_w is arrived at from wind tunnel tests on the airplane model.

5.3.6 Dihedral (Γ)

Figure A2.1.1 shows the dihedral angle Γ. Its value is decided after the lateral dynamic stability calculations have been done for the airplane. For preliminary design purposes a value based on data collection can be used.

5.3.7 Wing vertical location

There are three choices for the location of the wing on the fuselage namely,high-, mid- and low- wing. Figure 5.8 shows three military airplanes with these locations for the wing. The advantages and disadvantages of the three configurations are as follows.

High Wing configuration

Advantages :

i) Allows placing fuselage closer to ground, thus allowing loading and unloading without special ground handling equipment.

ii) Jet engines & propeller have sufficient ground clearance without excessive landing gear length leading to lower landing gear weight.

iii) For low speed airplanes, weight saving can be effected by strut braced wing (Fig.1.2a)

iv) For short take off and landing (STOL) airplanes, the high wing configuration has the following specific advantages. (a) Large wing flaps can be used.
(b) Engines are away from the ground and hence ingestion of debris rising from unprepared runways is avoided. (c) Prevents floating of wing due to ground effect which may occur for low wing configuration.

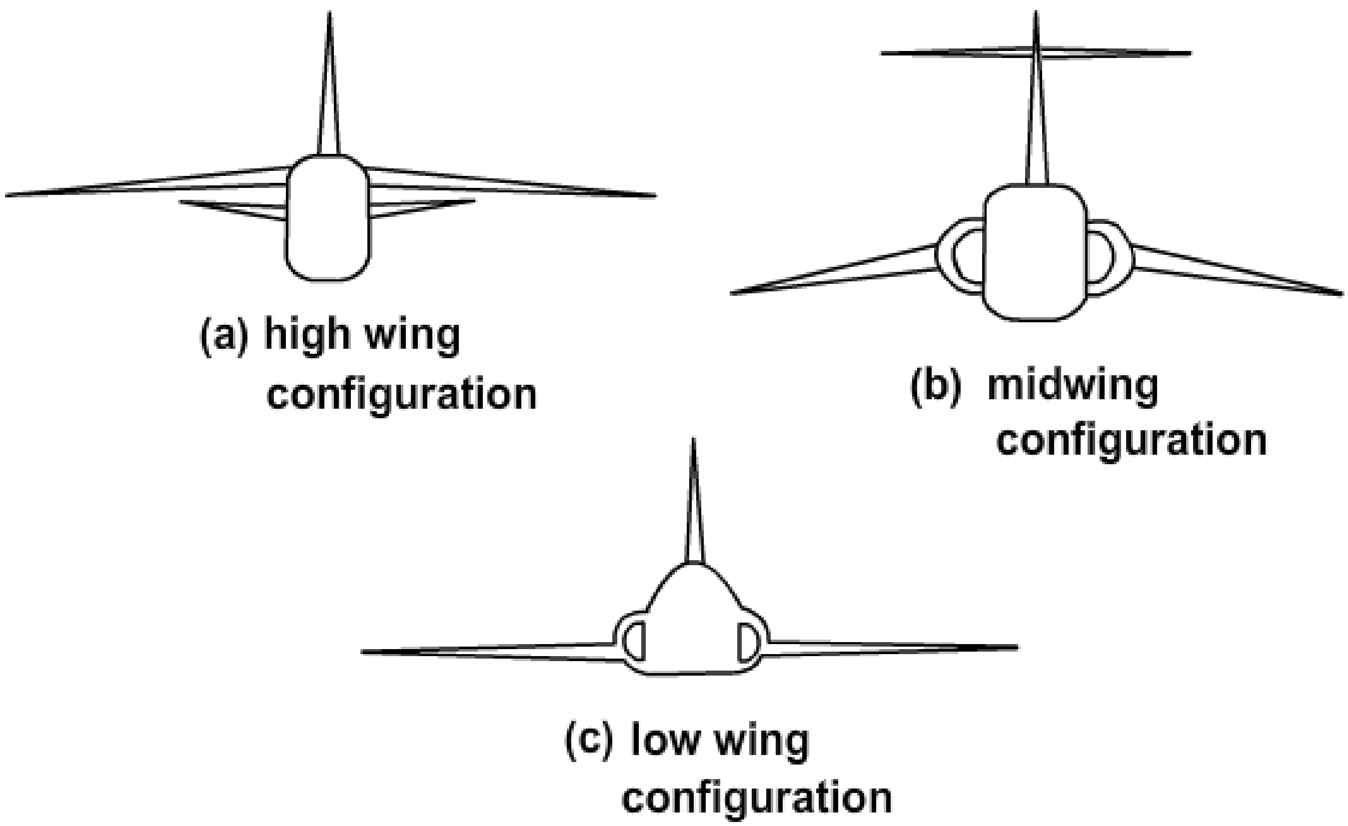

Fig.5.8 High wing, mid wing and low wing configurations

Disadvantages

i) Fuselage generally houses the landing gear in special pods leading to higher weight and drag.

ii) Pilot's visibility may be blocked during a turning flight.

Mid wing configuration

Advantages :

i) Lower drag.

ii) Advantages of ground clearance as in the case of high wing configuration.

iii) No blockage of visibility. Hence, used on some military airplanes.

Disadvantages:

Wing root structure passing through the fuselage is not possible, which leads to higher weight. However, in HFB Hansa airplane, a swept forward mid-wing is located behind the passenger cabin. This permits wing root structure passing through the fuselage.

Low-wing configuration

Advantages:

i) Landing gear can be located in the wing thereby avoiding pods on the fuselage and hence lower drag. However, to provide adequate ground clearance, the fuselage has to be at a higher level as compared to the high wing configuration.

ii) Wing structure can be through the fuselage.

Disadvantages:

(i) Low ground clearance.

(ii) A low-wing configuration has unstable contribution to the longitudinal and lateral static stability. In addition Ref.1.18, chapter 4, mentions that for low-wing airplanes the dihedral angle may be decided by need to avoid wing tip hitting the ground during a bad landing. A wing with high value of dihedral may require higher vertical tail area to prevent tendency to Dutch roll.

5.3.8 Flaps

The flaps are high lift devices. These devices are deployed to increase the maximum lift coefficient (C_{Lmax}) during take-off and landing.

Section 3.7 of Ref.3.3 be referred to for discussion on high lift devices. The flaps are generally located near the trailing edge.

The flaps in common use are : plain flap, split flap, zap flap, single slotted flap, double slotted flap, triple slotted flap and fowler flap. Along with flaps, the medium speed airplanes and the jet airplanes have slats near the leading edge. Typical values of C_{Lmax} for different types of high lift devices are given in subsection 4.3.2. The plain flap and split flap are simple to fabricate. The complexity of fabrication and the weight of the wing increase progressively for zap flap, single slotted flap, double slotted flap, triple slotted flap and fowler flap. The airplanes flying at high subsonics speed need high wing loading from the consideration of cruise (sections 4.7 and 4.9). Hence, complicated high lift devices are employed to reduce take-off and landing distances.

Considering these factors, the flaps used on different types of airplane are as follows.

(i) The homebuilt and general aviation aircraft use plain flap.

(ii) Single slotted flaps are used on general aviation aircraft and some transport airplanes with turboprop engines e.g. SAAB 2000.

(iii) Double slotted flaps are used on some turbo-prop airplanes (e.g. ATR – 72 - 200) and on some jet airplanes.(e.g. Boeing 767).

(iv) Triple slotted flaps are employed on large jet airplanes. Some airplane companies have perfected the design of such flaps and use them.

(v) Fowler flaps are used on some turboprop airplanes (e.g. IPTN M – 250 – 100 and Dash 8 – Q 300) and on many Boeing airplanes. The jet airplanes generally have leading edge slats in combination with Fowler flap to increase C_{Lmax} further.

Remarks:

(i) The C_{Lmax} with a high lift device mainly depends on (a) angle of deflection of flap, (b) the ratio of flap chord to wing chord (c_f/c_w) in the region where flap is located and (c) the spanwise extent of the flap (b_f/b). The exact values of (c_f/c_w) and (b_f/b) are obtained after CFD calculations and wind tunnel tests. As guidelines for subsonic airplanes (c_f/c_w) = 0.3 to 0.4 and b_f equals 70% of the exposed span (wing span – width of fuselage) can be used. The values of (c_f/ c_w) and (b_f/b) on similar airplanes can be used, at this stage of preliminary design.

(ii) The flap deflection during take-off $\left(\delta_{f\,to}\right)$ is lower than that during landing $\left(\delta_{fland}\right)$. Section 10.6 of Ref.3.3 describes the reasons for this difference. Chapter 5 of Ref.1.24 presents typical values of $\left(\delta_{f\,to}\right)$ and $\left(\delta_{fland}\right)$.