Chapter 4

Estimation of wing loading and thrust loading

(Lectures 9 to 18)

Keywords : Choice of wing loading based on considerations of landing field length, prescribed flight speed, absolute ceiling, maximum rate of climb, range, take-off balance field length, specific excess power, sustained turn rate and turbulence. Choice of engine; characteristics of piston engine, turboprop, turbofan and turbojet engines; propeller characteristics, selection of propeller diameter. choice of engines for different ranges of flight speeds.

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Chapter 4

Estimation of wing loading and thrust loading - 1

Lecture 9

Topics

4.1 Introduction

As pointed out in the beginning of the last chapter, the wing loading (W/S) and the thrust loading (T/W) or the power loading (W/P) influence a number of performance items like take-off distance (s_{to}), maximum speed (V_{max}) , maximum rate of climb $(R/C)_{max}$, absolute ceiling (H_{max}) and maximum rate of turn ($\dot{\psi}_{max}$). Thus, the wing loading (W/S) and the thrust loading (T/W) or power loading (W/P) are the two most important parameters affecting the airplane performance. It may be recalled that for airplanes with jet engines, the parameter characterising engine output is the thrust loading (T/W) and for airplane with engine-propeller combination the parameter characterising the engine output is

the power loading (W/P). It is essential that good estimates of (W/S) & (T/W) or (W / P) are available before the initial layout is begun.

The approaches for estimation of (W/S) and (T/W) or (W/P) can be divided into two categories.

(I) In the approach given by Lebedinski (Ref.1.6), the variations, of the following quantities are obtained when the wing loading is varied.

a) (T / W) or (W / P) required for prescribed values of V_p, H_{max} $(R/C)_{max}$ and s_{to}.

b) Weight of the fuel (W_f) required for a given range (R).

c) Distance required for landing (s_{land}).

From these variations, the wing loading which is optimum for each of these items is obtained. However, the optimum values of W/S in various cases are likely to be different. The final wing loading is chosen as a compromise.

(II) In the approach followed by Raymer (Ref.1.18), (T/W) or (P/W) is chosen from statistical data correlations and then W/S is obtained from the requirements regarding V_{max}, R_{max}, $(R/C)_{max}$, H_{max}, $\dot{\psi}_{max}$, landing distance and take-off distance. Finally, W/S is chosen such that the design criteria are satisfied.

 These two approaches are described in the subsequent sections. However, during the presentation, information from Ref.1.6 and 1.18 and other sources is used as required.

4.2 Introductory remarks on approach of Ref.1.6 for choosing wing loading (W/S) and thrust loading (T/W) or power loading (W/ P)

It is felt that the approach of Ref.1.6, though presented about 50 years ago, is still relevant. It was presented by Prof. A.A. Lebedinski of Moscow Aviation Institute, in his lectures on 'Airplane design' at Indian Institute of Science Bangalore, India during 1963-64. The salient features of this approach are as follows.

(i) Derive simplified relations between the chosen performance parameter and the wing loading.

(ii) Obtain the wing loading which satisfies/optimizes the chosen parameter e.g. landing distance, thrust required for V_p, fuel required for range.

(iii) Examine the influence of allowing small variations in wing loading from the optimum value and obtain a band of wing loadings. This would give an estimate of the compromise involved when (W/S) is non-optimum.

(iv) After all important cases are examined, choose the final wing loading as the best compromise.

(v) With the chosen wing loading, obtain (T/W) or (W/P) which satisfy requirements of V_{max}, $(R/C)_{max}$, ceiling (H_{max}), take-off field length (s_{to}) and maximum turn rate ($\dot{\psi}$). If the requirements of engine output in these cases are widely different, then examine possible compromise in specification. After deciding the (T/W) or (W/P) obtain the engine output required. Choose the number of engine(s) and arrive at the rating per engine. Finally choose an engine from the engines available from different engine manufacturers.

Remark:

A novel feature of the procedure of Ref.1.6 is as follows.

During the process of optimizing the wing loading, a reasonable assumption is to ignore the changes in weight of the airplane (W_0). However, when W_0 is constant but W/S changes, the wing area and in turn, the drag polar would change. This is taken into account by an alternate representation of the drag polar (see subsection 4.4.1).

4.3 Selection of wing loading based on landing distance.

Landing distance (S_{land}) is the horizontal distance the airplane covers from being at the screen height till it comes to a stop. As seen in Fig.3.5, the approach to landing begins at the screen height of 50'(15.2 m). The flight speed at this point is called 'Approach speed' and denoted by V_A. The glide angle during approach is generally 3°. Then, the airplane performs a flare to make the flight path horizontal and touches the landing field at touch down speed (V_{TD}). Subsequently, the airplane rolls for a duration of about 3 seconds and then the brakes are applied. The horizontal distance covered from the start of the approach till the airplane comes to a halt is the landing field length.

Remarks:

(i) It may be added that in actual practice the airplane does not halt on the runway. After reaching a sufficiently low speed the pilot takes the airplane to the allotted parking place.

(ii) Landing ground run is the distance the airplane covers from the point the wheels first touch the ground to the point the airplane comes to a stop.

(iii) $V_A = 1.3(V_s)_{land}$, $V_{TD} = 1.15(V_s)_{land}$ (4.1)

$(V_s)_{land}$ is the stalling speed in landing configuration.

Exact estimation of landing distance (s_{land}) is difficult as some phases like flare depend on the piloting technique. Further regulations like FAR (Federal Aviation Regulation) prescribe as to how the landing distance is to be obtained from flight tests. FAR 23 governs the regulations for normal, aerobatic, utility and agricultural airplanes. For further details refer to FAA website and Appendix F of Ref.1.18. For larger civil airplanes FAR 25 is applicable. Military airplanes are governed by MIL standards.

At the present stage of preliminary design, a relationship between FAR landing field length and the parameters of the airplane and atmospheric properties would be adequate to select wing to landing based on consideration of landing distance.

Reference 3.2 has analyzed the FAR 23 and FAR 25 landing field lengths for several civil airplanes.

Based on this data, Ref.1.17, section 13 and Ref.1.18, chapter 5 have presented relationships, between s_{land} and the approach speed (V_A) in FPS units. When SI units are used the relationships are:

FAR 23: s_{land} (in m) = 0.35 V_A^2 ; V_A in m/s   (4.2)

FAR 25: s_{land} (in m) = 0.3455 V_A^2 ; V_A in m/s   (4.2a)

$$V_A = 1.3 (V_s)_{land}$$ (4.3)

Remarks:

(i)Section 13 of Ref.1.17 and chapter 5 of Ref.1.18 may be referred to for further discussion.

(ii)For military airplanes, the relationship, when SI units are used, appears as (section 13 of Ref.1.17) :

$$s_{land} = 0.3546 \ V_A^2 \ ; V_A = 1.2 \ V_s \tag{4.4}$$

4.3.1 Relation between s_{land} and wing loading

To illustrate the steps, Eq.(4.2a) which is applicable for airplanes governed by FAR 25, is considered.

$$s_{land} = 0.3455 \ V_A^2 \tag{4.2a}$$

Note that $V_A = 1.3 \ V_S$ and

$$V_S = \left(\frac{2W_{land}}{\rho_0 \sigma S C_{Lmax}} \right)^{\frac{1}{2}} ; \ \rho_0 = \text{atmospheric density at sea level and } \sigma = \rho/\rho_0 \ .$$

Denoting $p_{land} = W_{land}/S$ gives :

$$V_S = \left(\frac{2p_{land}}{C_{Lmax}\rho_0 \sigma} \right)^{\frac{1}{2}} \tag{4.5}$$

$$\text{Or } \ p_{land} = C_{Lmax} \frac{\rho_0 \sigma}{2} (V_s)_{land}^2 \tag{4.6}$$

$$\text{Or } \ p_{land} = C_{Lmax} \frac{\rho_0 \sigma}{2} \left(\frac{V_A}{1.3} \right)^2$$

Using Eq.(4.2a) yields:

$$p_{land} = C_{Lmax} \frac{\rho_0 \sigma}{2} \frac{1}{1.69} \frac{s_{land}}{0.3455}$$

$$\text{Or } p_{land} = 0.8563 \ \rho_0 \sigma \ C_{Lmax} \ s_{land} \tag{4.7}$$

Remarks:

(i) Equation (4.7) indicates that to obtain p_{land} for a prescribed s_{land} , the values of σ and C_{Lmax} need to be specified. Unless otherwise prescribed, the altitude of landing field is taken as sea level i.e. $\sigma = 1.0$ .The guidelines for the value of C_{Lmax} are given in the next subsection.

(ii) In certain cases, instead of s_{land} the stalling speed in landing configuration $(V_S)_{land}$ may be prescribed. In this case, Eq.(4.6) is used to obtain $p_{land.}$

4.3.2 Guidelines for values of C_{Lmax} of wings with various high lift devices

The value of C_{Lmax} depends on the following.

a) The geometry of the wing i.e. aspect ratio (A), taper ratio (λ) and sweep (Λ).

b) Airfoil shape.

c) Flap type, ratio of flap area to wing area (S_{flap} /S) and flap deflection (δ_{flap}).

d) Type of leading edge slat and its deflection.

e) Reynolds number.

f) Surface texture.

g) Interference effects due to fuselage, nacelle and pylons.

h) Influence of propeller slip stream, if present.

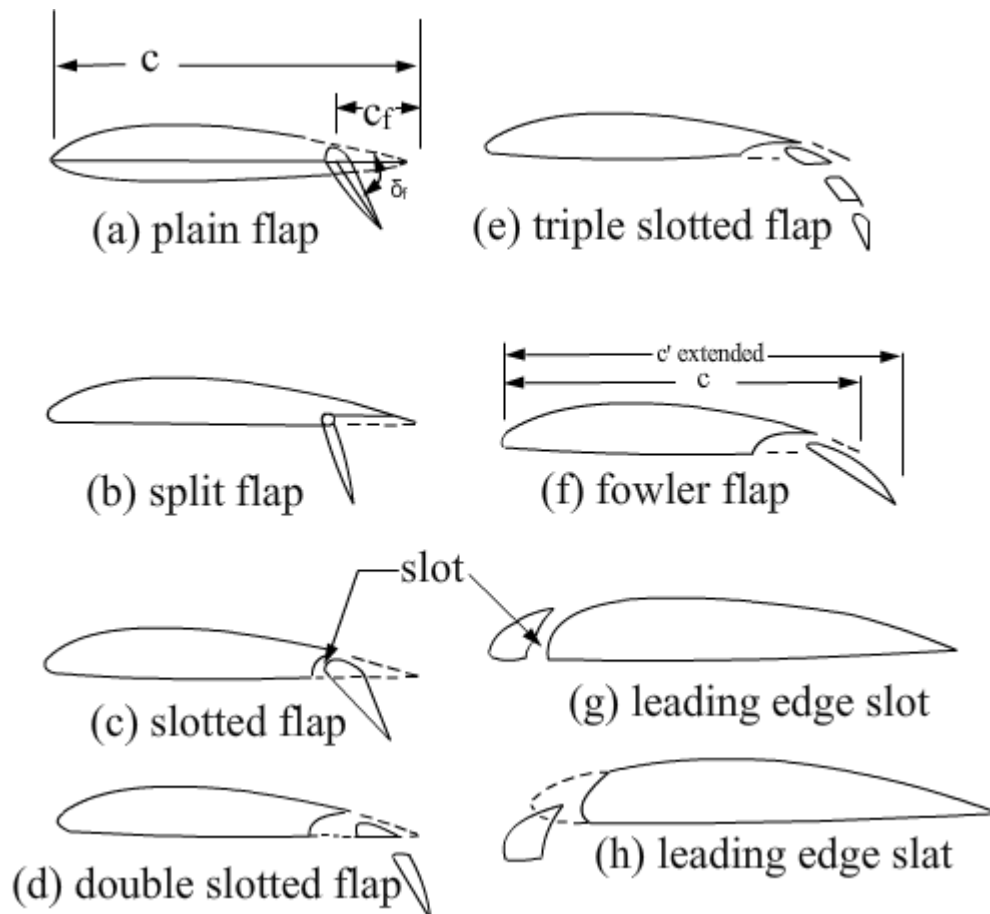Commonly used flaps, slot and slat are shown in Fig.4.1.

Fig.4.1 Flaps, slot and slat

For a brief discussion on high lift devices refer to section 3.7 of Ref.3.3.

At this stage of preliminary design, the data collection, and the three view drawing presented in chapter 2, give some information about the type of high lift devices likely be used on the wing and the amount of wing sweep. Accordingly, the ball - park values of C_{Lmax} presented in Table 4.1 can be used. These are based on data in (a) Ref.4.1, chapter 5, (b) Ref.1.18, chapter 5 and (c) Ref.1.15, chapter 5.

They can be used for initial estimate of C_{Lmax} for subsonic airplanes with unswept wings of aspect ratio greater than 5.

The quarter chord sweep ($\Lambda_{c/4}$) has predominant effect on C_{Lmax}. This effect can be roughly accounted for by using the following cosine relationship:

$$(C_{Lmax})_{\Lambda} = (C_{Lmax})_{\Lambda=0} \, \cos \Lambda_{c/4} \tag{4.8}$$

For example, when an unswept wing without flap has C_{Lmax} of 1.5, the same wing with 30^0 sweep would have roughly a C_{Lmax} of 1.5 × cos 30^0 or 1.3. Similarly, an unswept wing with Fowler flap has C_{Lmax} of 2.5. The same wing with 30^0 sweep would have C_{Lmax} of 2.5 × cos 30^0 or 2.17. With addition of leading edge slat, this can go upto 2.43. Figure 4.2 shows C_{Lmax} for some passenger airplanes. The solid lines correspond to the cosine relation given above. The following may be noted.

(a) The value of C_{Lmax} shown in Table 4.1 can be used in landing configuration. The flap setting during take-off is lower than that during landing. The maximum lift coefficient during take off can be taken approximately as 80% of that during landing.

(b) Do not use the values in Table 4.1, for supersonic airplanes with low aspect ratio wings and airfoil sections of small thickness ratio. Reference 4.2, section 4.1.3.4 may be referred to for estimating C_{Lmax} in these cases.

Type of flap	Guideline for C_{Lmax} in landing configuration
No flap	1.5
Plain flap	1.8
Single slotted flap	2.2
Double slotted flap	2.7
Double slotted flap with slat	3.0
Triple slotted flap	3.1
Triple slotted flap with slat	3.4
Fowler flap	2.5
Fowler flap with slat	2.8

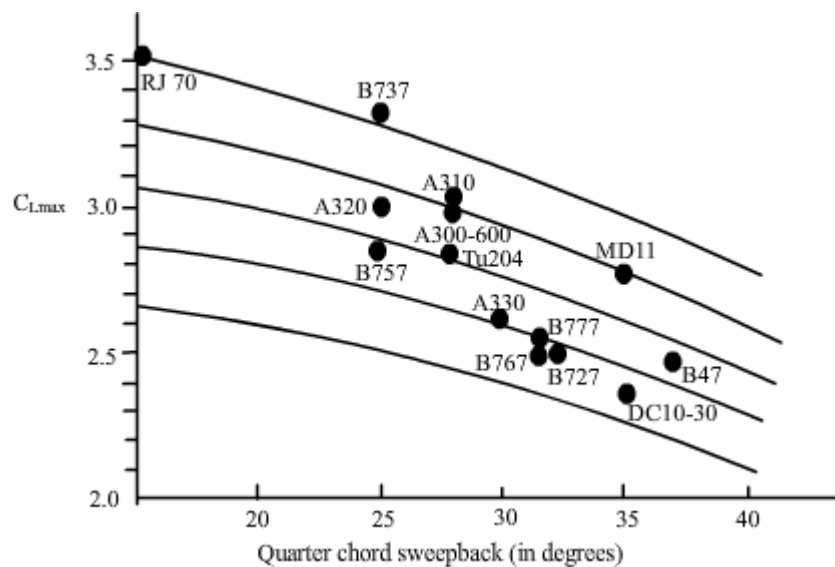Table 4.1 Guidelines for C_{Lmax} of subsonic airplanes of moderate aspect ratio

Fig.4.2 Maximum lift coefficient of passenger airplanes operating at high

subsonic Mach numbers

(Adapted from Ref.1.14, chapter 8 with permission of authors)

Example 4.1

Consider a jet airplane with a prescribed s_{land} of 1425 m. Obtain the wing loading from this consideration. Assume, C_{Lmax} = 3.0 and σ = 1.0 .

Solution :

From Eq.(4.7)

p_{land} = 0.8563 x 1.225 x 1 x 3.0 x 1425 = 4484 N/m^2

Answer : p_{land} = 4484 N/m^2

Figure 4.3 shows the variation of p_{land} with s_{land} in this case.
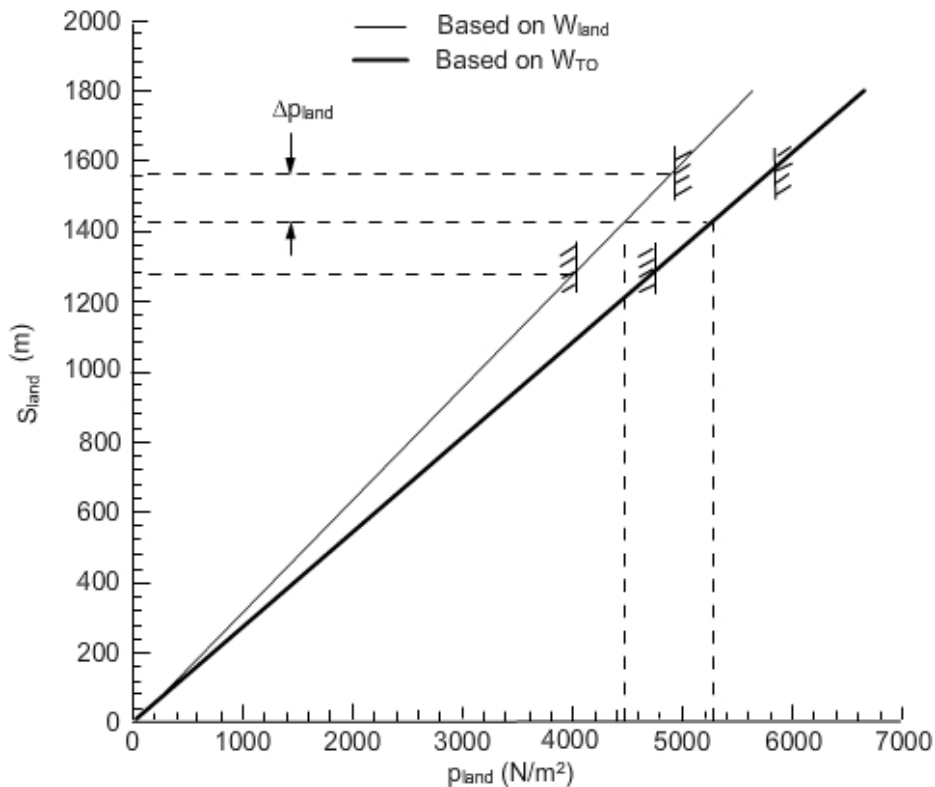

Fig.4.3 Landing distance vs wing loading

4.3.3 Permissible variation in p_{land} by allowing reasonable variation in s_{land}

The choice of wing loading will also be affected by other requirements like V_{max} and $(R/C)_{max}$. Since design is a compromise between possibly conflicting requirements, the change in p_{land} when s_{land} is varied within $\pm \Delta s_{land}$ needs to be examined. Figure 4.3 also shows the limits within which p_{land} can be varied with landing distance within $s_{land} \pm \Delta s_{land}$.

In the case of example 4.1, if s_{land} is permitted to vary between ±10% of the specified value, or s_{land} = (1425 ± 142.5) m, then using Eq.(4.7) it is deduced that p_{land} can be within a band of 4036 to 4933 N/m^2.(see Fig.4.3).

4.3.4 Wing loading from landing consideration based on take-off weight
$(W_{TO}/S)_{land}$

The wing loading (W/S) of the airplane is always specified with reference to the take-off weight (W_{TO} or W_o).

Hence, the wing loading from landing consideration, based on take-off weight, is

$$(W/S)_{land} = p_{Land} \times (W_{TO} / W_{land}) \tag{4.9}$$

The weight of the airplane at the time of landing (W_{land}) is generally lower than W_{TO}. The difference between the two weights is due to the consumption of fuel and dropping of any disposable weight. However, to calculate W_{land} only a part of the fuel weight is subtracted, from the take off weight. The relationship between W_{land} and W_{TO} is expressed as:

$$\frac{W_{land}}{W_{TO}} = (1 - k \,\overline{W}_f - \overline{W}_d) \tag{4.10}$$

where, $\overline{W}_f = W_{fuel} / W_{TO}$ and

$$\overline{W}_d = \frac{W_{disposable\ or\ released}}{W_{TO}}$$

According to Ref.1.18, chapter 5,

k = 0 for propeller airplane and trainers

= 0.5 for military airplane

For jet airplanes $W_{land} = 0.85\, W_{T0}$ $\hspace{4cm}$ (4.11)

Remarks:

(i) The value of W_{land} given by Eq.(4.11) is perhaps applicable to long range jet airplanes. Reference 1.15 chapter 7 gives, the following expression for jet airplanes.

$$\frac{W_{land}}{W_{TO}} = 0.98 \text{ for R< 1000 km}$$

$$= 0.98 - 0.00002\ (R-1000) \text{ for R > 1000 km}$$

(ii) Reference 1.15, chapter 7 and Ref.1.12, part I, chapter 3 may be referred to for further details.

(iii) For the case of jet airplane considered in example 4.1, let

$W_{T0} = W_{land} / 0.85$.

Consequently, the optimum wing loading from landing consideration, but based on take off weight would be 4484/0.85 = 5276 N/m^2. Further, the band of wing loading from landing consideration with s_{land} = (1425 ± 142.5) m, would be 4748 to 5803 N/m^2 (Fig.4.3).

4.3.5 Different types of wing areas – planform area, exposed wing area, reference area and wetted area.

At this juncture, the definitions of different types of wing areas are presented below.

Planform is the geometric shape of the wing in the plan view. The area of this shape is the planform area.

Exposed wing area is the planform area of the wing outside the fuselage.

Reference wing: For subsonic airplanes the reference wing is a trapezoidal wing as shown in Fig.A2.1.1. This shape is obtained by extending the leading and trailing edges of the exposed wing upto the fuselage centre line as shown in Fig.4.4a. The planform area of this wing is the reference area of the wing. It may be noted the fillet near the wing fuselage junction and the rounding off near the wing tip are not considered.

Equivalent trapezoidal wing: It is a trapezoidal wing whose root chord is at the fuselage centre line and has the area same as the planform area. Figure 4.4 b shows a cranked wing and the corresponding equivalent wing. In a cranked wing the trailing edge is parallel to the y-axis over a part of the span (see subsection 5.3.2).

Wetted area of wing or for that matter any part of the airplane is the area of surface that would get wet when dipped in water. This area is used to calculate the skin friction drag.
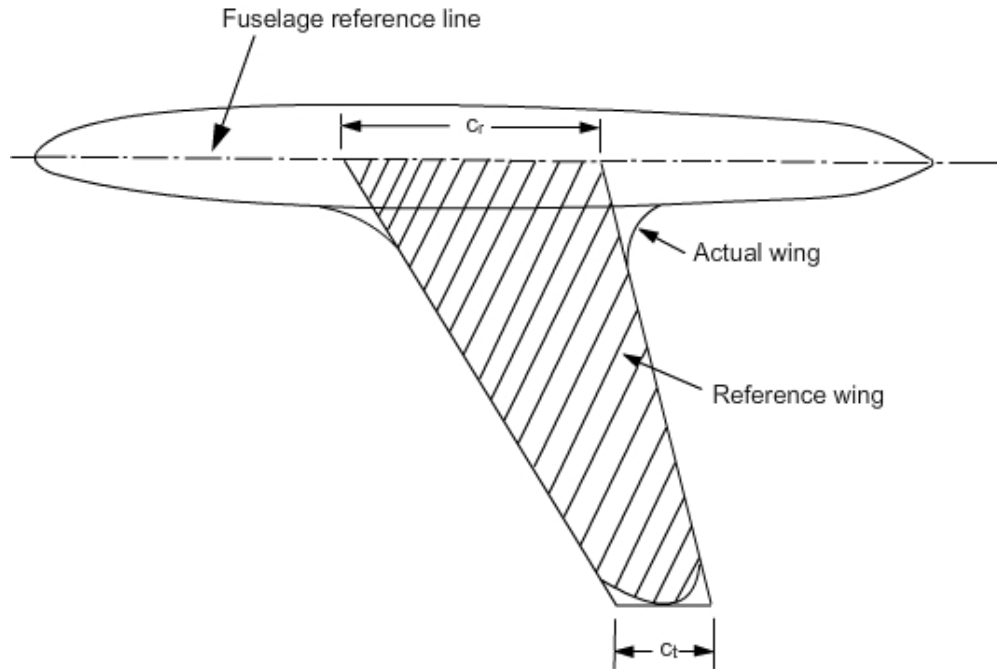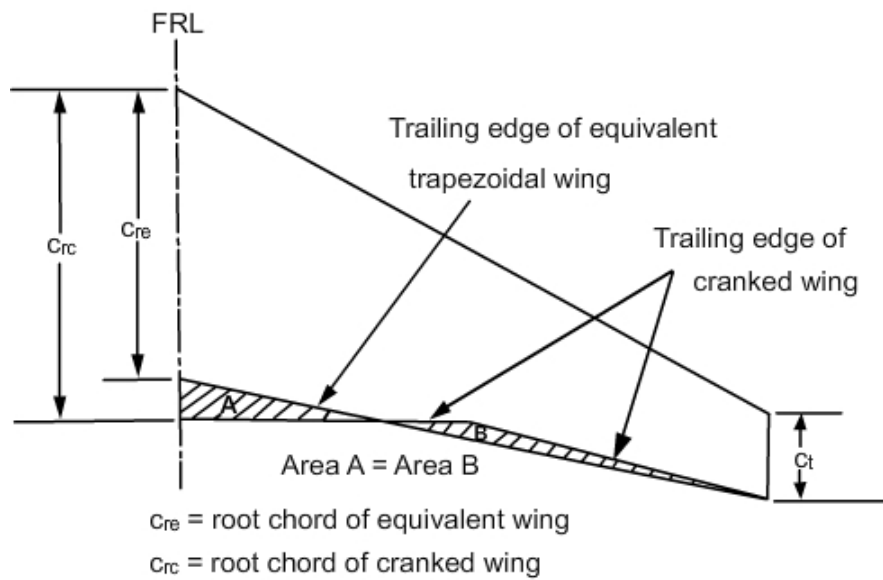
Fig.4.4a Reference wing

Fig.4.4b Equivalent trapezoidal wing of a cranked wing