

Chapter 6

Fuselage and tail sizing

(Lectures 23 to 30)

Keywords: Features of the fuselages of general aviation aircraft and transport airplanes ; desired features of fuselage design; guidelines for sizing of fuselages of general aviation aircraft and transport airplanes; Preliminary sizing of horizontal and vertical tails – choice of aspect ratio, taper ratio; sweep and airfoil section; engine location; landing gear.

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Chapter 6

Fuselage and tail sizing - 1

Lecture 23

Topics

6.1 Introduction

6.2 Fuselage sizing

6.2.1 Features of the fuselage of a general aviation aircraft

6.2.2 Features of the fuselage of a passenger airplane

6.1 Introduction

In this chapter first the procedure to obtain the internal and external dimensions of the fuselage are discussed. Subsequently, the procedure to obtain an initial estimate of the sizes of the tail surfaces is dealt with. These two aspects and the dimensions of wing obtained in the previous chapter would later enable preparation of a revised layout of the airplane which is better than that obtained in chapter 2. With this layout an approximate location of the centre of gravity (c.g.) of airplane can be obtained (chapter 8).

6.2 Fuselage sizing:

The primary purpose of the fuselage is to house the payload. As mentioned in Appendix 2.2, the payload is the part of useful load from which the revenue is derived or for which the airplane is designed. In transport airplanes the payload includes the passengers, their luggage and cargo. In military airplanes it is the ammunition and /or special equipment.

In addition to the payload, the fuselage accommodates the following.

- (a) The flight crew and the cabin crew in the transport airplane and the specialist crew members in airplanes used for reconnaissance, patrol and remote sensing.
- (b) Fuel, engine and landing gear when they are housed inside the fuselage.

(c) Systems like airconditioning system, pressurization system,hydraulic system, electrical system, pneumatic system, electronic systems, emergency oxygen, floatation vests and auxilliary power unit.

At this juncture, three typical fuselages are briefly described with the help of Figs. 6.1, 6.2 and Fig.A2.1.3b of Appendix 2.1. The purpose here is to introduce the terminology and to describe the important items inside the fuselage.

6.2.1 Features of the fuselage of a general aviation aircraft

Figure 6.1 shows the schematic side view and plan view of the fuselage of a four seater general aviation aircraft with low wing and tractor propeller. An explanation of the term “General aviation aircraft” is given in the remark at the end of subsection 1.4.1.

It is observed from Fig.6.1 that the propeller is located ahead of the fuselage. A spinner is located just ahead of the propeller. It is a streamlined fairing over the propeller hub (Ref.1.2) and enables smooth entry of air flow in the propeller. The length of the spinner is roughly 20% of the diameter of the propeller.

The engine is located inside the engine compartment. The engine is attached to the fuselage by an engine mounting. The length of the engine compartment is approximately 1.5 times the length of the engine (Ref.1.18, chapter 10). The width of the engine compartment is approximately 1.2 times the width of the engine. The rest of airplane is separated from the engine compartment by a fire wall which is a fire-resistant sheet attached to a bulk head (Ref.1.2).When the airplane has a nose wheel type landing gear, the nose wheel strut is attached to the frame inside the engine compartment (Fig.6.5).

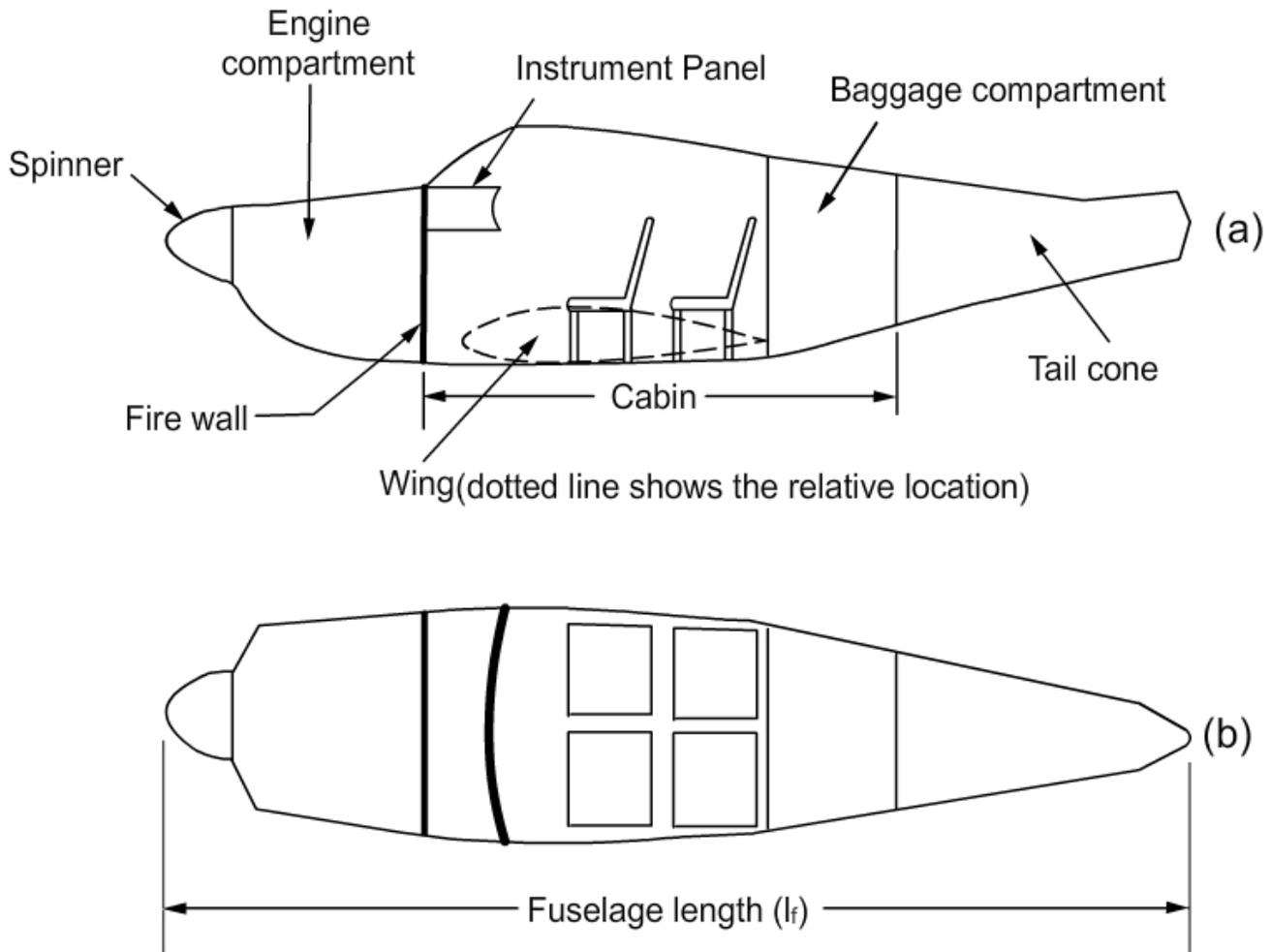


Fig.6.1 Schematic side view and planview of the fuselage of a four seater general aviation aircraft with low wing and tractor propeller
(a) Side view (b) Plan view

The cabin is the portion of fuselage that extends from the firewall to the end of the baggage compartment. This definition of cabin appears to be the practice followed by Cessna aircraft company. The cabin consists of (a) the portion of fuselage including rudder pedals and instrument panel (b) the seats of pilot and passengers and (c) the baggage compartment. Some companies consider the cabin as the portion of fuselage between the instrument panel and the end of baggage compartment. The distance between the firewall and the instrument panel is approximately 0.7 m.

The cabin accommodates the pilot and the passengers. Its internal dimensions are decided by human factors. The passengers must be comfortable and the pilot should be able to fly the airplane efficiently without undue strain. Ergonomics is the branch of science dealing with the topics like human behaviour, dimensions of the parts of human body and the range of their movements. Reference 1.12, part III, chapter 3 and Ref.1.24, chapter 7 be consulted for brief information on ergonomics and for reference to books on this topic. The former reference (Ref.1.12), shows dimensions of cabins of single seater, two seater (with side by side or tandem seating), four seater and six seater airplanes propelled by single piston engine propeller combination.

The gap between the instrument panel and the front seat is between 0.69 to 0.84 m. The seat pitch (distance between back of one seat to the back of next seat) is between 0.71 to 0.84 m. The minimum width of cabin for a two seater airplane with side by side seating arrangement is between 1.04 to 1.13 m. The maximum height of the cabin for such an airplane is between 1.13 to 1.25 m. For a single seater airplane or a two seater airplane with tandem seating, the width would be between 0.58 m to 0.7 m. The thickness of the cabin wall is between 6 cm to 10 cm.

The baggage compartment is located behind the passenger seats. The volume of the baggage compartment for such airplanes is between 0.17 to 0.23 m³ per occupant (passanger / pilot).

In this type of airplane, the tail cone is the portion of the fuselage aft of the baggage compartment. The length of the tail cone is obtained as a compromise between the aerodynamic, structural and stability considerations.

The aerodynamic consideration, for this type of airplane, requires that the drag of the fuselage should be minimum.

In this context, instead of the length of the fuselage, the fineness ratio of the fuselage (A_f) is used as the parameter. It is defined as :

$$A_f = l_f / d_e \quad (6.1)$$

where, l_f = length of fuselage

d_e = equivalent diameter of fuselage

$$\frac{\pi}{4} d_e^2 = \text{area of the maximum cross section of the fuselage}$$

The drag coefficient of fuselage (C_{Df}), for low speed airplanes, is the sum of the pressure drag coefficient and the skin friction drag coefficient. Wind tunnel test on bodies of different fineness ratios indicated that the drag coefficient is minimum for A_f between 3 and 4 (Ref.1.9, chapter 3). This led to the pod and boom configuration of the airplane (Fig. 1.2i). However, for the conventional configuration, with horizontal tail behind the wing and located on the rear fuselage, the length of the fuselage is decided based on the tail length (l_t). The quantity (l_t) is the distance between the c.g. of the airplane and the aerodynamic centre of the horizontal tail. It may be recalled that the contribution of the horizontal tail to the longitudinal static stability ($C_{m_{\alpha}}$) depends mainly on the product $l_t S_{ht}$; where, S_{ht} is the area of the horizontal tail (see section 2.4 of Ref.3.1). A large value of l_t would reduce S_{ht} but that would require a long fuselage. This would increase the structural weight of fuselage and result in higher skin friction drag. As a compromise, the value of l_t lies between $(2.5 \text{ to } 3) \bar{c}$ for the general aviation aircraft with conventional tail. The quantity \bar{c} is the mean aerodynamic chord of the wing. Appendix 2.2 be referred to for definition of \bar{c} .

It is observed in Fig.6.1a that the fuselage has a non-zero height at its rear end. The reasons for this shape are as follows.

In certain airplanes the elevator and or rudder extend beyond the rear end of the fuselage. In this configuration the horizontal and or vertical tails are shifted rearward. This shift results in increased tail arms for the horizontal tail (l_t) and the vertical tail (l_v). The arm of the vertical tail (l_v) is the distance between the c.g. of airplane and the aerodynamic centre of the vertical tail. Further, the contributions of horizontal and vertical tails depend respectively on the product $S_{ht} l_t$ and $S_{vt} l_v$, where S_{vt} is the area of the vertical tail. The textbooks on airplane stability (e.g. Ref.3.1, chapters 2 & 5) may be referred to for details. Thus, when l_t increases S_{ht} decreases and when l_v increases S_{vt} decreases. Reduction in S_{ht} and S_{vt} result in lower drag and weight of horizontal tail and vertical tail. However, the fixed parts of the horizontal tail and vertical tail have to

be attached to the fuselage structure. Their attachments require sufficient height and or width at the rear end of the fuselage. This would increase the drag and weight of fuselage. Thus, locations of h.tail and v.tail on fuselage are decided after considering these two factors. Lowest drag and or weight of tail cone of the fuselage plus empennage would be the optimization criterion.

Remark:

In the case shown in Fig.6.1 only the elevator projects beyond the rear end of the fuselage (Fig.6.6a).

6.2.2 Features of the fuselage of a passenger airplane

Figure 6.2 shows the side view, plan view and cabin layout of a medium range passenger jet airplane with low wing. A cross of fuselage with six abreast seating is shown in Fig.6.3b.

The portion of the fuselage ahead of the cockpit is referred to as nose (item ① in fig.6.2a). It generally houses the radar.

The cockpit (item ② in Fig.6.2) houses the pilots and other flight crew. It is also called the flight deck or crew station. It has the flight instruments and controls.

The considerations for the design of the cockpit are as follows.

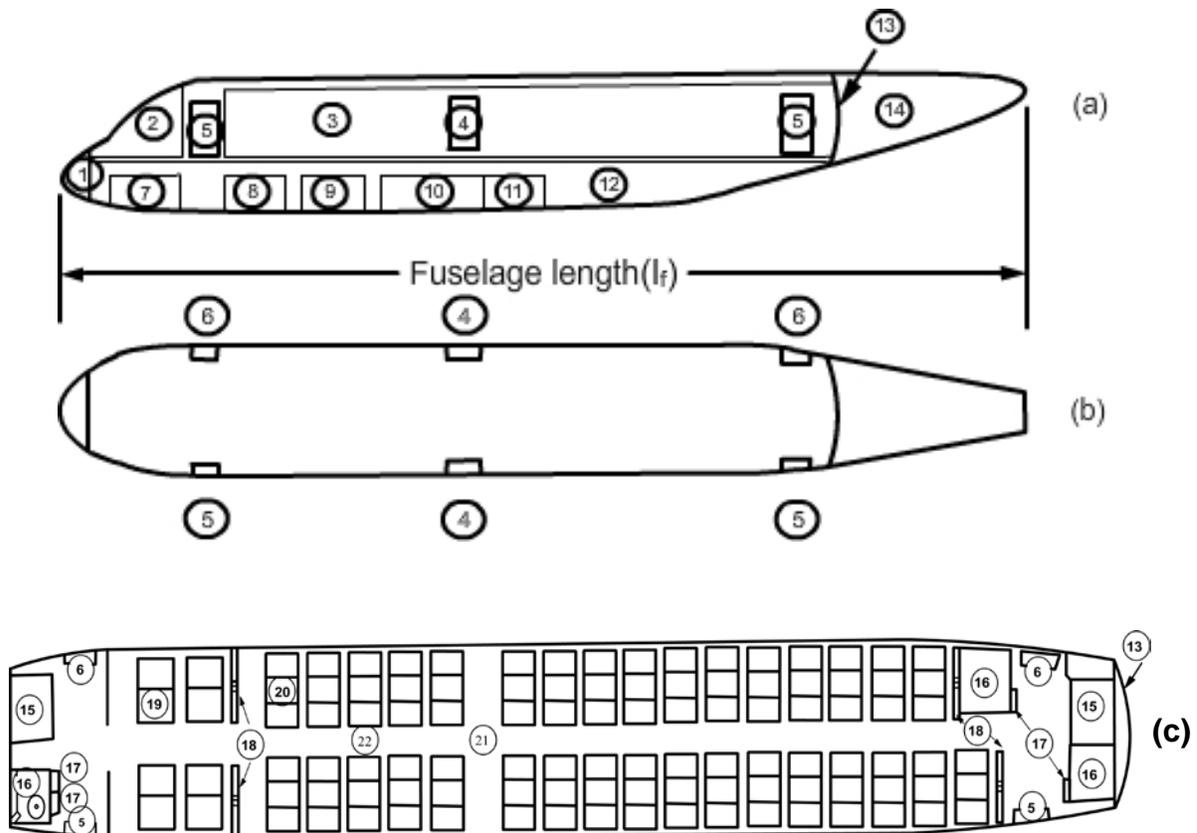
- a) The pilots and the crew members should be able to reach all controls comfortably. They must be able to see all instruments and communicate by voice or touch between them without undue efforts.
- b) Visibility from cockpit should adhere to the standards during take-off, landing, and other phases of the flight. The shape of the wind shield, besides giving a smooth aerodynamics shape, must also confirm to the specified values of vision angles like over-nose angle and over-the-side angle. Reference 1.24, Chapter 7 be referred to for the specifications of these angles for different types of airplanes.

The suggested overall cockpit lengths for transport airplanes are as follows
(Ref.1.18, chapter 9)

Two man crew : 2.54 m (100")

Three man crew : 3.30 m (130")

Four man crew : 3.84 m (150")



- ① Nose, ② Cockpit or flight deck, ③ Passanger cabin, ④ Emergency exit,
- ⑤ Passanger door, ⑥ Service door, ⑦ Nose wheel well, ⑧ Systems,
- ⑨ Front cargo compartment, ⑩ Wing box, ⑪ Main wheel well, ⑫ Aft cargo compartment, ⑬ Aft pressure bulk head, ⑭ Auxilliary power unit, ⑮ Galley,
- ⑯ Toilet, ⑰ Cabin attendant seat, ⑱ Screen, ⑲ First class seat,
- ⑳ Economy class seat, ㉑ Larger gap between seats near emergency exits,

22) Aisle

Fig.6.2 Schematic side view, plan view and cabin layout of a medium range passenger jet airplane with low wing

(a) Side view (b) Plan view (c) Layout of cabin

Note : Figures (b) and (c) are not to the same scale

The layout of the cockpit, the instruments in it, the displays, the control stick or wheel, are interesting topics. The student is referred to Ref.1.12, part III, chapter 2 ; Ref. 1.18, chapter 9 ; Ref.1.19, chapter 15 ; Ref. 1.24, chapter 7 and internet (www.google.com).

The passenger cabin (item 3) in Fig.6.2) houses (a) the passengers, (b) cabin crew, (c) furnishings (items 19 and 20), (d) passenger and service doors (items 5 and 6), (e) emergency exits (item 4), (f) galleys (item 15), (g) toilets (item 16), (h) cabin attendant seats (item 17), (i) screen (item 18) etc. The major portion of the cabin is in the midfuselage which has a constant cross section. Some portion of the cabin is also in the tail cone. Refer Fig. A 2.1.3 in Appendix 2.1 of chapter 2 for definitions of midfuselage and tail cone.

Jet airplanes cruise at altitudes of 10 to 14 km. The temperature and pressure are low at these altitudes. For the comfort of passengers and crew, the cockpit and cabin are air-conditioned and a pressure corresponding 8000 ft (2438 m) in ISA is maintained in these portions of the fuselage. The shell of the fuselage has to be designed to withstand the pressure difference between inside and outside the cabin. Secondly, to isolate the cockpit and cabin, from ambient conditions, the cabin is terminated with a pressure bulk head (item 13) in Fig.6.2).

The auxilliary power unit (APU) (item 14) in Fig.6.2) supplies power to start the main engines and to supply power to accessories when the engines are off.

As mentioned earlier, the airplane has airconditioning, pressurization, electrical, electronic, hydraulic, pneumatic and other systems. These are located under the floor of the cabin. The nose wheel well (item 7) in Fig.6.2), main wheel well (item 11) in Fig.6.2), front and aft cargo compartment (items 9) and 12) in Fig.6.2) are also shown schematically in this figure.

Remarks :

1) The size of passanger doors, emergency exits and the numbers of cabin attendants depend on the number of passengers in the airplane. The FAA(Federal Aviation Agency) has set guidelines for these. Reference 1.18, chapter 9 and Ref.1.9, chapter 3 be consulted for brief information on this topic.

2) Seating arrangement

A typical cross section of the fuselage is shown in Fig.6.3a. Some of the parameters are defined below.

Seat pitch : It is the distance between the back of one seat to the back of the next seat. It includes the seat length and the leg room.

The terms (a) seat width, (b) aisle width, (c) elbow gap, (d) gap between seat and wall of cabin (e) head room, (f) aisle height, (g) cabin width and (h) fuselage width, are shown in Fig.6.3a.

The carry-on baggage of the passangers is stored in the overhead racks. The checked-in baggage is stored in the front and the aft cargo compartments. For ease of loading and unloading and for segregation of cargo intended for different destinations, the cargo in large airplanes is stored in pallets. The shapes and sizes of pallets have been standardised. Figures 6.3a and b show two type of pallets. Reference 1.14, chapter 5; Ref.1.18, chapter 9 and internet (www.google.com) be referred to for details of pallets.

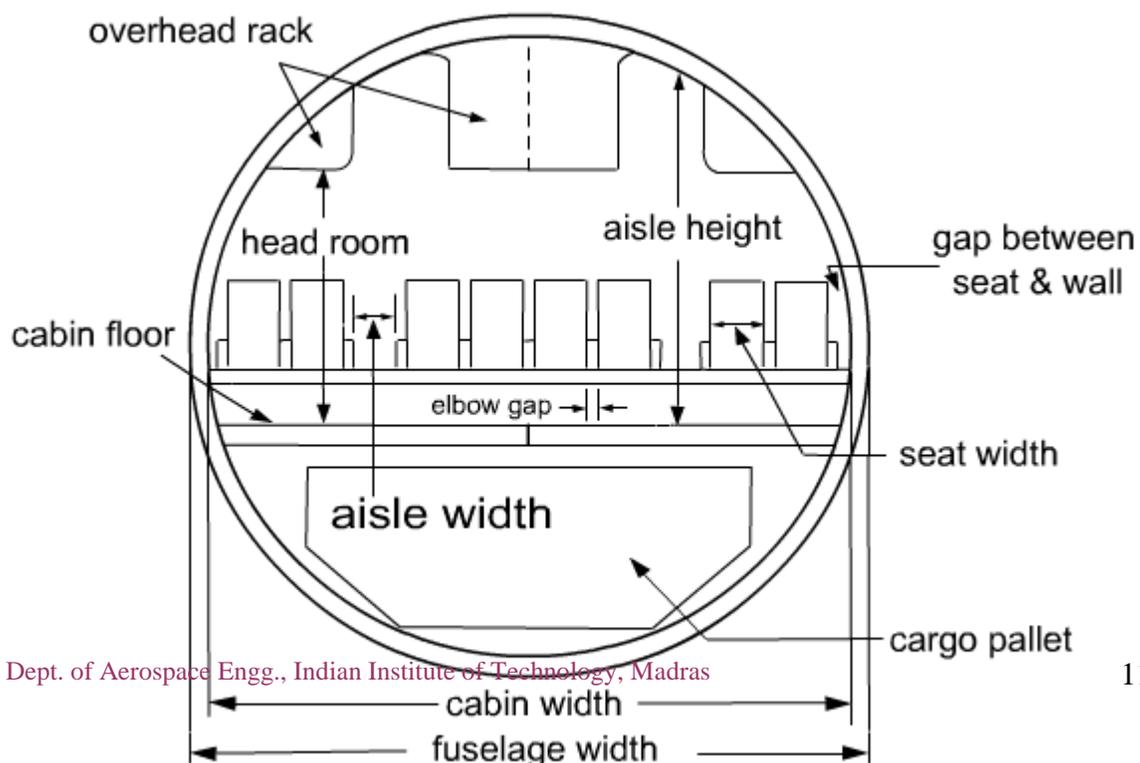


Fig.6.3a Passenger compartment with eight seat layout

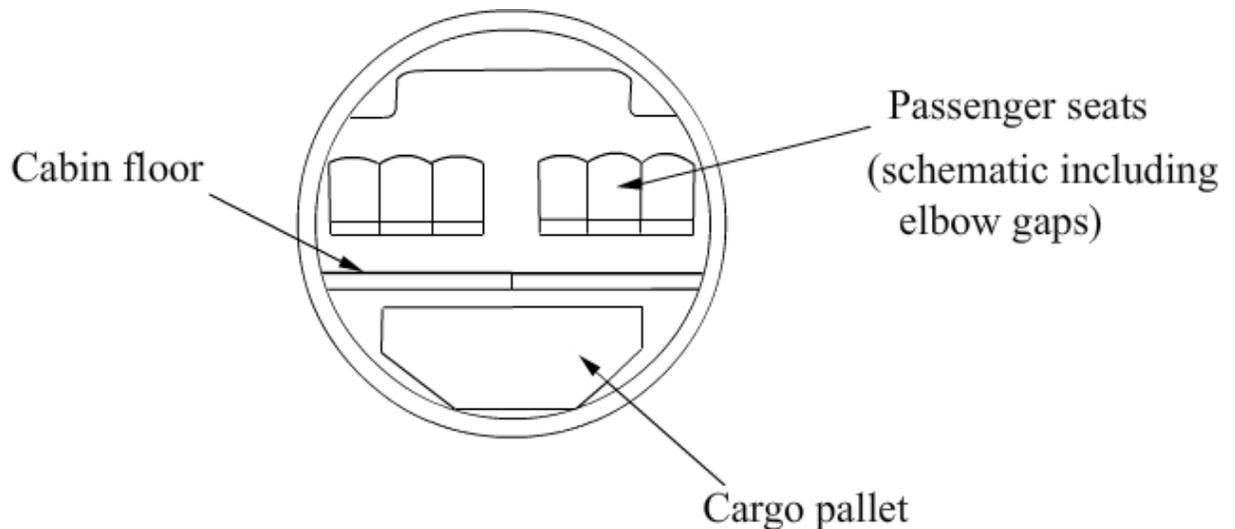


Fig.6.3b Another cabin layout with six seats and different type of cargo pallet

The type of seating arrangements are classified as first class, business class, economy class and tourist class. The dimensions of seat width, seat pitch and aisle width are the highest for the first class and are the lowest for the tourist class. Very important persons (VIP), like the President and Prime minister, generally have airplanes with special features.

As mentioned in subsection 6.2.1, a longer fuselage provides longer tail arm but has higher structural weight. The size of hanger needed to park the airplane also increases corresponding to the increase in the length of the fuselage. Thus, the length of fuselage is a compromise between various considerations. Secondly, the number of passenger in an airplane, assuming it to have single class of seats, would be equal to the number of seats in a row multiplied by the number of rows. Hence, to have an optimum length of the fuselage, the number of seats abreast, increases with the increase in the number of passengers. Reference 1.19, chapter 6, indicates the following. Smaller airplanes upto about 20 passengers, would have two abreast seating. Those upto 50 seats may have 3 or 4 abreast seating. Those around 100 seats may have 5 abreast seatings. Those

upto about 150 seats may have 6 abreast seating. All these airplanes would have a single aisle. However, the FAA requirements stipulate that no more than three seats be accessed from one aisle. Hence, the airplanes with more than six abreast seating, need to have more than one aisle (see Fig.6.3a). Such airplanes are called wide-body airplanes. Configurations with 7 to 10 seats abreast have been designed. Airbus 380 has a double-deck arrangement which is seen in the cut-away drawing in Appendix 1.1.

A mixed class seating arrangement is offered by many airlines to cater to the needs of different clients. Figure 6.2c shows a medium range airplane having 107 seats. Out of these, eight seats of first class, are in two rows of four abreast seats. Rest of the 99 seats are of economy class - sixteen rows have 6 abreast seats and the last row has three seats on the left side. It may be pointed out that the first row of seats in the economy class is generally for passengers with babies-in-arm. The pitch of rows of seats near emergency exit, is larger for faster evacuation of passengers in the event of emergency landing.

3) Dimensions of cabin :

From Fig.6.3a, the width of the cabin at the level of elbow rest (W_{cer}) can be expressed as :

$$W_{cer} = (\text{No. of seats abreast}) \times \text{seat width} + (\text{No. of aisles}) \times \text{aisle width} \\ + (\text{No. of elbow gaps}) \times \text{elbow gap} + 2 \times (\text{gap between seat and cabin wall}) \quad (6.2)$$

The seat width, aisle width, seat pitch etc. depend to some extent on the choices made by the airline. However, based on Ref.1.14, chapter 5; Ref.1.15, chapter 9 and Ref.1.19, chapter 6, the following values can be given as guidelines.

The pitch of seats also depends on the duration/range of flight - larger pitch in airplanes having longer range. The pitch of seats is between 0.76 to 0.81 m for economy/tourist class ; 0.84 to 0.91 m for business class and 0.97 to 1.02 m for first class seating arrangement.

The seat width lies between 0.41 to 0.46 m for economy/tourist class; 0.43 to 0.51 m for business class and 0.51 to 0.71 m for first class seating arrangement.

The aisle width should be greater than 0.3 m for economy class; between 0.46 to 0.51 m for business class and between 0.51 to 0.71 m for first class seating arrangement. The aisle height is between 1.5 to 1.93 m.

The elbow rest need to be provided on both sides of the seats. Its width is 0.0375 to 0.05 m (1.5 to 2.0 inches) in economy class and could be double this width in first class seating arrangement. A gap of 1 to 4 cm is provided between the elbow rest near the wall and the wall of the fuselage. Wide body airplanes have larger radius of fuselage and may require a smaller gap.

The cabin width is arrived at considering (a) W_{cer} , (b) head room (c) aisle height, (d) height of seat above cabin floor and (e) shape of cabin. Example 6.1 explains the process of obtaining the cabin size.

4) Cargo volume : Reference 1.18, chapter 9, mentions that the cargo volume per passenger is approximately 0.244 m^3 (8.6 ft^3) for short range airplanes and 0.442 m^3 (15.6 ft^3) for long range airplanes.

It may be pointed out that the airplanes with upto about 70 passengers and with four abreast seating arrangement, the diameter of the fuselage is less than 3m. In such cases, the depth of fuselage below the cabin floor is not adequate for the cargo compartment. Consequently, the cargo compartment is located ahead and / or behind the passenger compartment.

5) Thickness of cabin : The wall thickness of the fuselage includes (a) thickness of structural members (bulkhead), (b) sound proofing and (c) interior decoration. The thickness is between 6.2 to 10 cm (2.5 to 4 inches) for the fuselage with the two and three abreast seating arrangement respectively. The thickness would increase roughly by 1.25 cm (1/2 inch) as the number of seats abreast increases by one (Ref.1.19, chapter 6) i.e. for a four abreast seating arrangement, the wall thickness would be 11.4 cm (4.5 inches) and for a ten abreast seating, it would be 19.00 cm (7.5 inches).

6) Tail cone/rear fuselage:

At the end of subsection 6.2.1, some remarks have been made regarding the tail cone of a general aviation aircraft. Further, in the case of a passenger airplane the midfuselage has a cylindrical shape and is followed by the tail cone or rear

fuselage (Fig.A 2.1.3a) of a tapering shape. In passenger airplanes the tail cone is of substantial length and the cabin layout extends into the rear fuselage. Galleys, toilets and storage compartments are also located here along with the auxiliary power unit (APU). The rear fuselage also supports the horizontal and vertical tail surfaces and the engine installation for rear mounted engines. The lower side of the rear fuselage should provide adequate clearance (about 0.15 m) for airplane during take-off and landing attitude (Fig.6.4). The length of the rear fuselage and upsweep angle (Fig. A 2.1.3a) are also affected by (a) the height of the main landing gear and (b) the length of the midfuselage after the main landing gear.

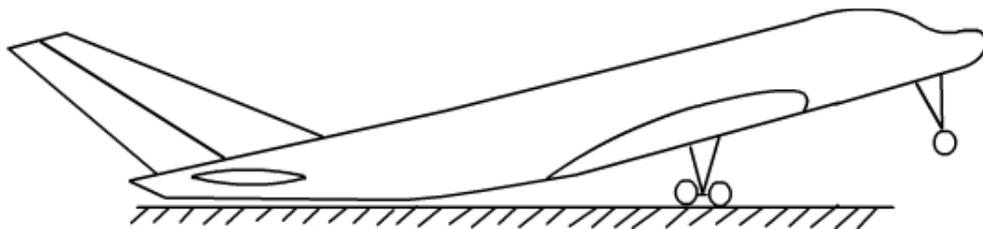


Fig.6.4 Rear fuselage shape

For passenger airplanes (a) the ratio of length of the rear fuselage to the equivalent diameter of the midfuselage is between 2.5 to 3.5 and (b) the upsweep angle is between 15 to 20°. For Boeing 777-300 this angle is 17°. (Ref.1.24, chapter 7).