CHAPTER 8

Weights and centre of gravity

8.1. Introduction

The weight of an airplane changes in the flight due to consumption of fuel, dropping off/ release of armament or supplies. Further, the payload and the amount of fuel carried by the airplane may vary from flight to flight.

All these factors lead to change in the location of the centre of gravity (c.g) of the airplane. The shift in the c.g location affects the stability and controllability of the airplane. Hence in this chapter we discuss methods to obtain weights of various components of the airplane and calculation of c.g location under various operating conditions.

The weight of entire airplane can be sub divided into empty weight and useful load. The empty weight can be further subdivided into weights of

(i) structures group

(ii) propulsion group and

(iii) equipment group.

Remark :

Reference 1.11, chapter 15 sub-divides the weights in the above three groups as follows.

1) The components of the structures group are :

wing

horizontal tail /canard

vertical tail

ventral fin

body

alighting or landing gear-main and auxiliary

arresting gear

catapult gear

nacelle/engine pod

air intake

2) The components of the propulsion group are :

engine-as installed

accessory gearbox and drive for turbo prop engine

propeller for piston and turbo prop engines

exhaust system

cooling provisions

engine controls

starting system

fuel system/tanks

3) The components of the equipment group are :

- flight controls
- APU
- instruments
- hydraulic, pneumatic, electrical, armament, air conditioning, anti-icing and other systems
- avionics
- furnishings in passenger airplanes
- photographic/weapon deployment equipment and cargo/armament loading and handling systems in military airplanes.

Sum of the weights of structures, propulsion and equipment groups constitutes the total empty weight.

4) The useful load consists of :

crew

fuel-usable and trapped

oil

payload-passengers, cargo and baggage in transport airplane; ammunition, expendable weapons etc., in military airplanes.

Remark:

Commonly used terms to prescribe weights are

i) Take off Gross weight : It is the sum of the empty weight and the useful load. It denotes the weight at take off for normal design mission.

ii) Flight design Gross weight : It indicates the weight at which structure will withstand the design load factors. This may be same as the take off gross weight. In some cases this is the weight after the airplane has taken off and climbed to the chosen altitude.

iii) DCPR weight : DCPR (Defense Contractor Planning Report) weight equals empty weight minus the weights of wheels, brakes, tires, engines, starters, batteries, equipments, avionics etc. It can be viewed as the weight of the parts of the airplane that the manufacturer makes as opposed to those of items bought out and installed.

iv) Operational Empty Weight : It is the weight of the aircraft that is operational but ,without payload and fuel.

v) Zero Fuel weight : It is the operational empty weight plus payload.

vi) Ramp Weight : It is the take-off weight plus fuel used for engine run up and taxiing out prior to take-off.

vii) Landing weight: It is the permissible weight of the airplane at the time of landing considering the structural limit.

8.2. Estimation of weight

Reference 1.11,chapter 15 presents the following two methods to estimate the weights.

(i) Approximate empty weight buildup.

(ii) Statistical group weights method.

8.2.1. Approximate group weights method

Based on trends in the data of weights of major components Ref.1.11 (Table 15.2) gives weights of wing, fuselage, tails, landing gear, engine and other items. The approximate location of c.g of each of these items is also given. Table 8.1 reproduces this information.

Item	Fighters	Transports and bombers	General aviation	Multiplier	Approximate c.g. location
Wing	44*	49*	12*	$S_{exposed}$ m^2	40 % MAC
Horizontal tail	20*	27*	10*	$S_{exposed}$ m^2	40 % MAC
Vertical tail	26*	27*	10*	$S_{exposed}$ m^2	40 % MAC
Fuselage	23*	24*	7*	S_{wetted} m^2	40-50% length
Landing gear $	0.033 0.045 Navy	0.043	0.057	TOGW	-
Installed engine	1.3	1.3	1.4	Engine weight	-
All-else empty	0.17	0.17	0.10	TOGW	40-50% length

***The value is in kgf/ m^2, when multiplied by the appropriate area in m^2, the weight will be in kgf. $15% to nose gear; 85% to main gear.**

Table 8.1 Approximate empty weight buildup (Adapted from Ref. 1.11, chapter 15)

Remark :

i) To illustrate the use of Table 8.1 consider a transport airplane. To obtain the weight of the wing calculate the area of the exposed wing and express it in m^2. This quantity is called "multiplier". Multiply it by the factor 49 kgf /m^2 for the wing of a transport airplane. This gives the weight of the wing in kgf. To obtain location of the centre of gravity of the wing, obtain the location of the mean aerodynamic chord (m.a.c) . Then the c.g of the wing is approximately at 40% of m.a.c.

ii) Reference 1.11, chapter 15 also gives the weights of items like missiles, guns, seats and instruments. These are reproduced in table 8.2.

Item	Weight in kgf.
Missiles	
Harpoon (AGM-84 A)	544
Phoenix(AIM-54 A)	454
Sparrow (AIM-7)	227
Sidewinder (AIM-9)	91
Pylon and launcher	$0.12\ W_{missile}$
M61 Gun	
Gun	113
940 rds ammunition	250
Seats	
Flight deck	27
Passenger	15
Troop	5

Table 8.2 Weights of missiles, guns , seats etc. (contd.)
(Adapted from Ref.1.11, chapter 15)

Instruments	
Altimeter,airspeed, accelerometer, rate of climb, clock, compass, turn & bank, Mach, tachometer, manifold pressure, etc.	0.5-1each
Gyro horizon, directional gyro	2-3 each
Heads-up display	18
Lavatories	
Long range aircraft	0.5 $(N_{pass})^{1.33}$
Short range aircraft	0.41 $(N_{pass})^{1.33}$
Business/Executive aircraft	1.76 $(N_{pass})^{1.33}$
Arresting gear	
Air Force-type	0.002 W_{dg}
Navy-type	0.008 W_{dg}
Catapult gear	
Navy carrier-based	0.003 W_{dg}
Folding Wing	
Navy carrier based	0.06 W_{wing}

Table 8.2 Weights of missiles, guns, seats etc.

(Adapted from Ref. 1.11, Chapter 15)

8.2.2. Statistical group weights method

Reference 1.10 part V deals with the estimation of weights of various components. Four methods namely Cessna method, USAF method, General Dynamics Method and Torenbeek Method are outlined. Among these the last method appears to be more convenient for use in student design projects. The formulae for weights of various components depend on the type of the airplane and its geometry. The procedure for estimation of weights of various components in three typical cases namely twin engine propeller airplane, jet transport and a fighter airplane is given in appendix 8.1.

8.3. Additional considerations in weights estimation

The statistical equations described in sec.8.2 are based on database of existing airplanes. For novel configurations these weights need to be adjusted using “correction factors” as given in Table.8.3

Category	Weight group	correction factor (multiplier)
Airplane with advanced composites	Wing	0.85-0.9
	Tails	0.83-0.88
	Fuselage/nacelle	0.90-0.95
	Landing gear	0.95-1.0
	Air induction system	0.85-0.09
Braced wing	Wing	0.82
Wooden fuselage	Fuselage	1.60
Steel tube fuselage	Fuselage	1.80
Flying boat hull	Fuselage	1.25

Table 8.3. Correction factors for weights of special airplanes

(Adapted from Ref.1.11, chapter 15)

Remarks :

i) As an illustration of use of Table.8.3 consider that an airplane has a wing of made of advanced composites. In this case the weight of the wing will be 85-90% of the metal wing.

ii) The weight of the airplane changes over the years due to modifications carried out. Typical increase in empty weight is shown in Fig.8.3.

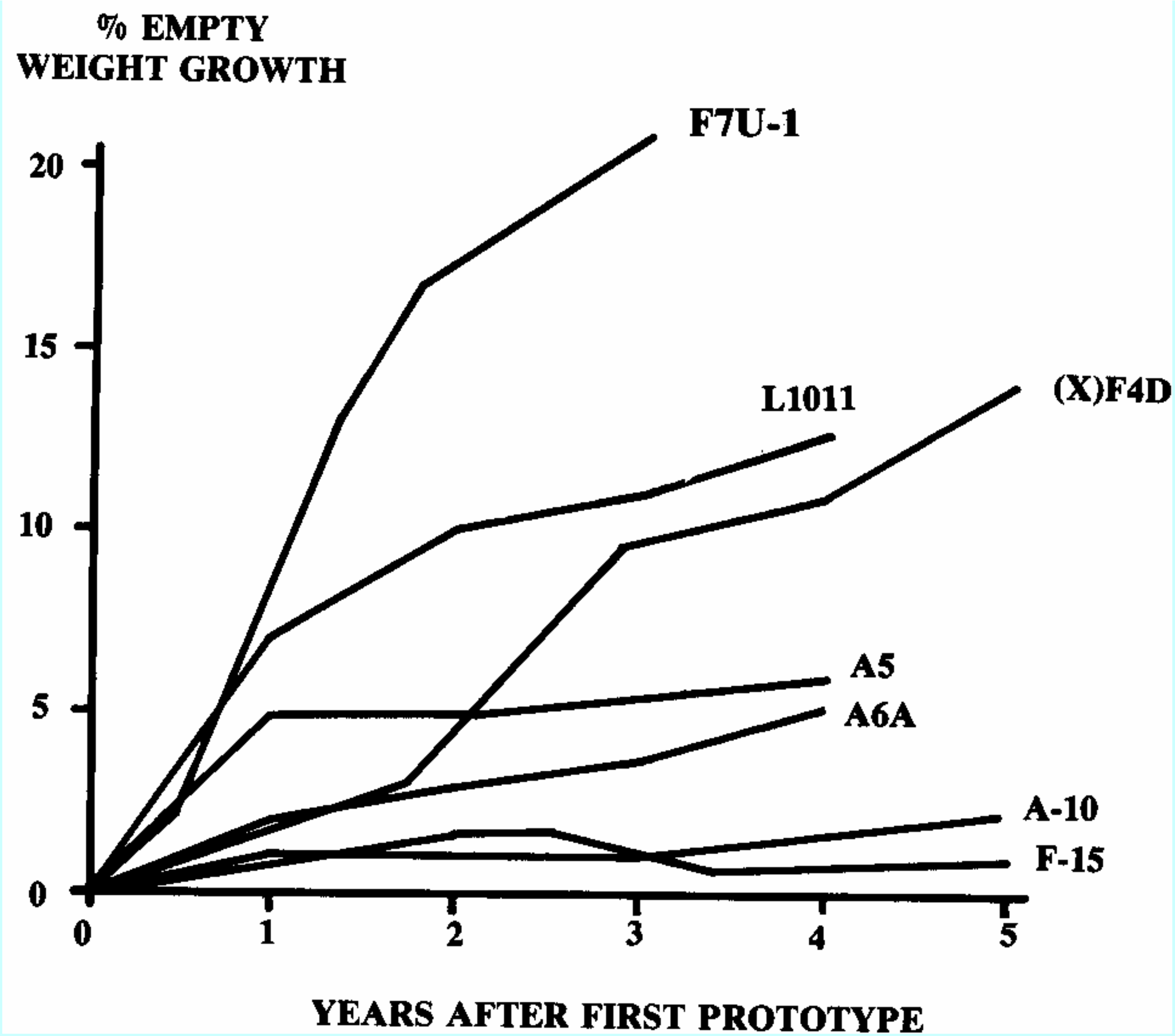

Figure 8.3. Typical increase in empty weight over the years due to changes in the prototype

(Adapted from Ref. 1.11, chapter 15)

8.4. Calculation of c.g. location and c.g. shift

At this stage of the preliminary design stage we prepare the lay-out of fuselage with tail surfaces, payload and equipment. The weights of these items are already known. Subsequently the c.g locations of these items are assigned. This group may be called fuselage group.

Similarly the weights of items mounted on the wing (e.g. engines, fuel and landing gear) are already known . The c.g locations of the these of items can also be assigned. This group may be called wing group.

Based on these data a balance table as shown Table 8.4 can be prepared.

Item	Wt (W)	x	y	W.x	W.y
Fuselage structure					
Equipment					
Landing gear					
Fuel in fuselage					
Payload					
Special equipment					
Horizontal tail					
Vertical tail					
Wing group					

Table.8.4 Balance table

Note:

'x' is the location of the c.g of a particular component along fuselage reference line from the nose. 'y' is the distance of c.g above the ground.

As regards the c.g of wing group it is with respect to the leading edge of the root chord.

As regards the c.g location of the entire airplane, the requirement is that the shift in the c.g is minimal under various distributions of weight. Based on experience (Lebedinski, unpublished notes), this is satisfied when the wing is located on the fuselage such that the c.g.of the entire airplane , with maximum take-off weight condition, lies around the following location on the mean aerodynamic chord (m.a.c) of wing (Table 8.5).

Type of airplane	Recommended c.g. location as fraction of m.a.c; with $W = W_{takeoff}$
Airplane with straight wing	0.24 – 0.28
Airplane with swept wing $\Lambda \cong 40$ degree	0.26 – 0.30
Airplane with swept wing $\Lambda \cong 55$ degree	0.30 – 0.34
Airplane with delta wing $A<2.5$	0.32 – 0.36
Tailless airplane	~ 0.3
Airplane with canard-subsonic	~ 0.2
Airplane with canard- supersonic	~ 0.3

Table 8.5 Recommended location of c.g. with $W=W_{takeoff}$

After fixing the location of wing, the c.g. of the airplane is calculated for the following cases.

(i) With full payload but reserve fuel.

(ii) Full payload with no fuel.

(iii) No payload and no fuel.

(iv) No payload but full fuel.

(v) Half payload in front.

(vi) Half payload in rear.

(vii) Any other critical case.

The permissible c.g. shift is generally 8% of m.a.c. for low speed airplanes. It could be up to 15% for commercial airplanes. If the c.g. shift is more than these limits a change in wing location or shifting of certain items may be needed.

8.5. Example

Consider a single seat acrobatic airplane (Ref.1.11, chapter 23). The break down of various weights is given below .

Component	Weight (N)	Distance from Datum x (m)	W . x (N m)
Fuselage	579.2	2.921	1692
H. Tail	178.2	5.334	950.5
V. Tail	66.8	5.715	381.8
Engine	1693	0.406	688
Gear	267.3	1.143	305.5
Fuel system	98	1.27	124.5
Flight control	22.3	2.032	45.3
Electrical	178.2	1.016	181.1
Avionics	44.6	1.524	68
Furnishing	89.2	2.54	226.6
Pilot & Chute	980.1	2.159	2116
Fuel	436.6	1.27	554.5
Total	4633		7334

The parameters of the wing are

weight = 712.8 N, wing area (S) = 10.97 m^2 ,

span(b) = 8.11 m, root chord(C_r) = 1.92 m,

Tip chord(C_t) = 0.772 m, mean aerodynamic chord

(m.a.c) = 1.422 m

The wing is unswept, Λ = 0.Hence the quarter chord line is perpendicular to x-axis. Consequently the quarter chord of the m.a.c lies on the quarter chord of the root chord

i.e. at C_r /4 = (1.92/4) = 0.48 m from leading

edge of the root chord.

Let leading edge of wing root chord be at x_{le} from the fuselage nose. Then the location of quarter chord of m.a.c from reference point would be at:

x_{le} + 0.48.

Wing group:

In this airplane the fuel and landing gear are in the fuselage and the wing group consists only of the wing.

From Table.8.1 the c.g. of the wing lies at 40% of m.a.c . Hence the location of the wing c.g. from the leading edge of the root chord is given by :

location of quarter chord of m.a.c+ (0.4–0.25) x m.a.c= 0.48 + 0.15 x 1.422=0.6933 m

To locate the wing on the fuselage let us prescribe that the c.g of the entire airplane lies at quarter chord of m.a.c. From this consideration the value of x_{le} can be found out from the following equation.

$$7334.3 + 712.8 \times (x_{le} + 0.6933) = (4633.4 + 712.8)(x_{le} + 0.48)$$

Or $7334.3 + 494.18 - 2566.18 = 4633.4\, x_{le}$

$x_{le} = 1.136$ m

Location of c.g. = 1.136 + 0.48 = 1.618 m from the nose.

Remark:

i) Show that the c.g. of the airplane, without fuel, is at 1.647 m.

ii) This means a shift of 1.647 – 1.618 = 0.029 m or 2.04% of m.a.c. This shift is low for this aircraft.

iii) See section 6 of Appendix 10.2 for estimation of weights and c.g. shift for a jet airplane. It is pointed out there that to limit the c.g. shift to 15% certain restrictions are needed on location of payload. Which would imply restrictions on certain configurations like only half the payload and that too in front off.

Exercise

8.1 A part of the payload weighing 3% of airplane's weight is shifted aft by 40% of MAC. What will be the shift in c.g. location as percentage of MAC?

[Ans: Shift=1.2%].