Chapter 8

Weights and centre of gravity

(Lectures 32 and 33)

Keywords

Subdivisions of airplane weight – structures group, propulsion group, equipment group; estimation airplane weight – approximate group weight method, statistical group weight method; calculation of c.g. location; balance table; c.g. shift

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8.1. Introduction

The weight of an airplane changes in the flight due to consumption of fuel and 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. 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 controlability of the airplane. Hence, this chapter deals with the methods to obtain the weights of various components of the airplane and calculation of the 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:

Following Reference 1.18, Chapter 15, the weights in the above three groups can be further subdivided as follows.

1) The structures group consists of the following components.

wing

horizontal tail /canard

vertical tail

ventral fin

fuselage

landing gear – main and nose/tail wheel

arresting gear and catapult gear for ship based airplanes

nacelle, engine pod and air intake

2) The propulsion group consists of the following components :

engine as installed; reduction gear for turboprop engine

propeller for piston and turboprop engines

exhaust system

cooling provisions

engine controls

starting system

fuel system and tanks

3) The equipment group consists of the following items:

flight controls

auxilliary power unit (APU)

instruments

hydraulic, pneumatic, electrical, armament, air conditioning, anti-icing and other systems

avionics

furnishings in passenger airplanes

photographic equipment in reconnaisance/patrol airplanes; weapon deployment equipment and armament loading and handling systems in military airplanes.

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

4) The useful load consists of :

(i) crew

(ii) fuel – usable and trapped

(iii) oil

(iv) payload – passengers, cargo and baggage in transport airplane; ammunition, expendable weapons and other items in military airplanes.

Remarks:

Commonly used terms regarding the weights are as follows.

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 is the weight at which the 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 (Defence 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 that 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 airplane weight

Reference 1.18, 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.1.18, chapter 15 gives the weights of wing, fuselage, tails, landing gear, engine and other items in terms of the parameters relevant to the component(Table8.1). The approximate location of c.g of each of these items is also given in Table 8.1.

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 of the component is obtained in kgf

$15% of this weight is allocated to the nose gear and 85% to the main gear.

£ Perhaps the weight of the fuselage includes weight of the fuselage structure plus those of furnishings and consumables.

Table 8.1 Approximate empty weight build-up

(Adapted from Ref.1.18, Chapter 15)

Remarks:

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 arrive at the approximate location of the centre of gravity of the wing, first 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 1.18, chapter 15 also gives the weights of items like missiles, guns, seats and instruments.

8.2.2. Statistical group weights method

Reference 1.12, part V and Ref.1.18, chapter 15 deal with the estimation of weights of individual components. An expression for the weight of a specific airplane component is obtained, based on statistical data on similar airplanes. The expression involves the geometrical parameters and other features of the component. As an example, Eq.(5.5) expresses weight of wing in terms of aspect ratio, taper ratio, sweep and thickness ratio of the airfoil. The formulae for the weights of various components depend on the type of airplane.

8.2.3 Additional considerations in weights estimation

(i)The statistical equations described in Ref.1.12, part V and Ref.1.18, chapter 15 are based on database of existing airplanes. For novel configurations, the weights given by these expressions need to be adjusted using "correction factors". For example, a wing made of advanced composites would weigh only 85 to 90% of a wing made of aluminium.

(ii) The empty weight of the airplane changes over the years due to modifications carried out on the airplane. Ref.1.18, chapter 15 presents typical variations of such changes. For example the weight of a passanger airplane would go up by 3 to 5% over the years.

General remarks:

(i)The aim of estimating the weights of individual components and their c.g. is to obtain the location of the c.g. of the airplane. Then, the shift in the airplane c.g. is examined under various conditions like (a) with full fuel and full payload (b) with full fuel and reserve fuel (c) with partial payload and full or reserve fuel etc. (section 8.3). At this stage of preliminary design, especially in student design projects, the weights of individual components are estimated using simpler method like using Table 8.1. The sum of the weights of the components may work out to be different from the empty weight obtained in chapter 3 (example 3.1 may be referred to again).

This is resolved as follows :

(a) Noting that the c.g.'s of the fuselage and the systems are nearly at the same location ; the two items are taken as a unit. (b)The weight of this unit is taken as :

$$\frac{W_{fuselage}+W_{system}}{W_g}=\frac{W_{empty}}{W_g}-\left(\frac{W_{wing}}{W_g}+\frac{W_{h.tail}}{W_g}+\frac{W_{v.tail}}{W_g}+\frac{W_{engine}}{W_g}+\frac{W_{landinggear}}{W_g}\right)$$

(ii) After the c.g. shift is estimated, a lay out of the airplane which is more refined than that in chapter 2, is arrived at.Subsequently, the design of h.tail and v.tail is revised as indicated in chapter 9.

Subsequently, the drag polar of the airplane is estimated and performance of the airplane worked out. If the performance is satisfactory, the next stage of design begins. In this stage, the individual parameters can be optimised using wind tunnel tests and CFD. The weights of the components are revised using statistical group methods in airplane design literature or the formulae obtained by the design bureau based on its previous experience. If the revised weight of the airplane is significantly different from the earlier weight, then the preliminary design process is carried out again.

The final weight of the actual airplane is obtained after weighing individual sub-assemblies.

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

At this stage of the preliminary design, the lay-outs of fuselage with tail surfaces, payload and equipment are approximately known. The weights of these items can be calculated using Table 8.1. Subsequently, the c.g locations of these items are also 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 these items can also be assigned. This group may be called wing group.

Based on these data a balance table as shown Table 8.2 can be prepared.

Item	Weight (W)	c.g. location (x)	W.x
Fuselage structure			
Equipment			
Landing gear			
Fuel in fuselage			
Payload			
Special equipment			
Horizontal tail			
Vertical tail			
Wing group			

Table.8.2 Balance table

Note:

(i)In the above table ‘x’ is the location of the c.g. of a particular component measured from the fuselage nose along the fuselage reference line. (ii) As regards the c.g. of the wing group it is with respect to the leading edge of the root chord of wing. (iii)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 requirement 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 on the m.a.c. of wing in the range of values indicated in Table 8.3. The steps to arrive at the location of wing are illustrated through example 8.1.

Type of airplane	Recommended c.g. location as fraction of m.a.c; with W= $W_{takeoff}$ or W_g or W_0
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 8.3 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.This condition would occur as the airplane approaches its destination.

(ii) Full payload with no fuel.This would be a rare eventuality.

(iii) No payload but full fuel.

(iv) No payload and no fuel.

The cases (iii) and (iv) may occur when an airplane carries out a rescue mission.

(v) Half payload in front.

(vi) Half payload in rear.

The cases (v) and (vi) are hypothetical cases and can be avoided by suitable allocation of seats.

(vii) Any other critical case.

The permissible c.g. shift is generally 8% of m.a.c. for low speed airplanes. It could be between 15 to 30 % of m.a.c. 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 explored.