Weighing the Aircraft and Determining the Empty Weight Center of Gravity

Chapter 3

Chapter 2 explained the theory of weight and balance and gave examples of the way the center of gravity could be found for a board loaded with several weights. In this chapter, the practical aspects of weighing an airplane and locating its center of gravity are discussed. Formulas are introduced that allow the CG location to be measured in inches from various datum locations and in percentage of the mean aerodynamic chord.

Requirements

Weight and balance is of such vital importance that each mechanic or repairman maintaining an aircraft must be fully aware of his or her responsibility to provide the pilot with current and accurate information for the actual weight of the aircraft and the location of the center of gravity. The pilot in command has the responsibility to know the weight of the load, CG, maximum allowable weight, and CG limits of the aircraft.

The weight and balance report must include an equipment list showing weights and moment arms of all required and optional items of equipment included in the certificated empty weight.

When an aircraft has undergone extensive repair or major alteration, it should be reweighed and a new weight and balance record started. The A&P mechanic or the repairman responsible for the work must provide the pilot with current and accurate aircraft weight information and where the new EWCG is located.

Equipment for Weighing

There are two basic types of scales used to weigh aircraft: scales on which the aircraft is rolled so that the weight is taken at the wheels, and electronic load cells type where a pressure sensitive cell are placed between the aircraft jack and the jack pads on the aircraft.

Some aircraft are weighed with mechanical scales of the low-profile type similar to those shown in Figure 3-1.

Large aircraft, including heavy transports, are weighed by rolling them onto weighing platforms with electronic weighing cells that accurately measure the force applied by the weight of the aircraft.

Electronic load cells are used when the aircraft is weighed by raising it on jacks. The cells are placed between the jack and the jack pad on the aircraft, and the aircraft is raised on the jacks until the wheels or skids are off the floor and the aircraft is in a level flight attitude. The weight measured by each load cell is indicated on the control panel. [Figure 3-27]

Mechanical scales should be protected when they are not in use, and they must be periodically checked for accuracy by measuring a known weight. Electronic scales normally have a built-in calibration that allows them to be accurately zeroed before any load is applied.

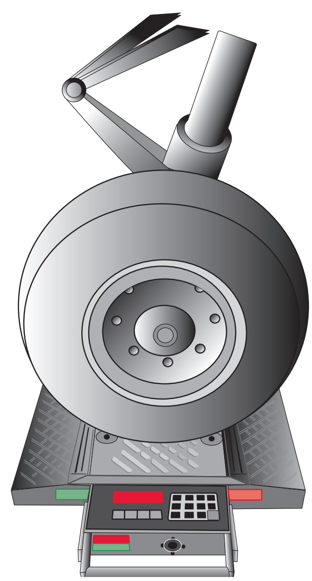

Figure 3-1. *Low profile mechanical platform scales are used to weigh some aircraft. One scale is placed under each wheel.*

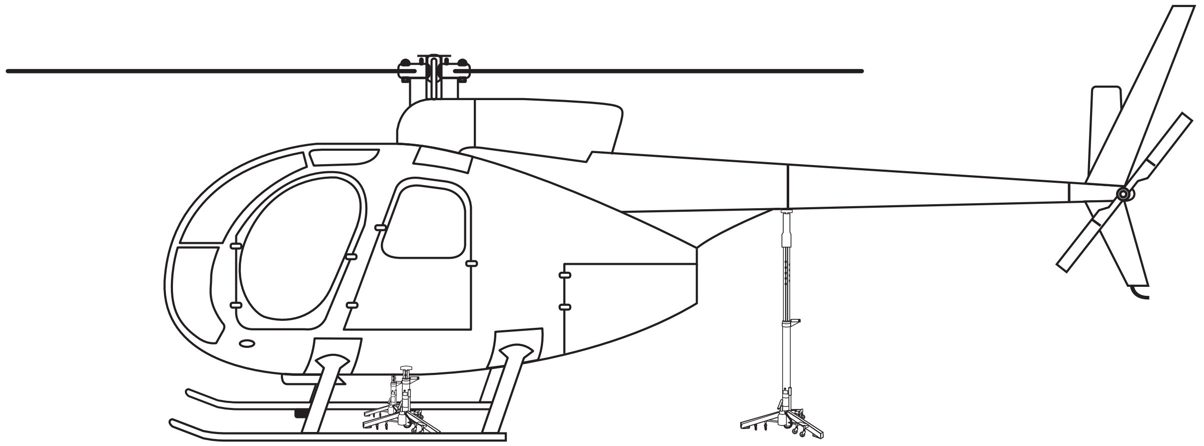

Figure 3-2. *Electronic load cell scale. A load cell is placed at each jack point.*

Preparation for Weighing

The major considerations in preparing an aircraft for weighing are discussed below.

Weigh Clean Aircraft Inside Hangar

The aircraft should be weighed inside a hangar where wind cannot blow over the surface and cause fluctuating or false scale readings.

The aircraft should be clean inside and out, with special attention paid to the bilge area to be sure no water or debris is trapped there, and the outside of the aircraft should be as free as possible of all mud and dirt.

Equipment List

All of the required equipment must be properly installed, and there should be no equipment installed that is not included in the equipment list. If such equipment is installed, the weight and balance record must be corrected to indicate it.

Ballast

All required permanent ballast must be properly secured in place and all temporary ballast must be removed.

Draining the Fuel

Drain fuel from the tanks in the manner specified by the aircraft manufacturer. If there are no specific instructions, drain the fuel until the fuel quantity gauges read empty when the aircraft is in level-flight attitude. Any fuel remaining in the system is considered residual, or unusable fuel and is part of the aircraft empty weight.

If it is not feasible to drain the fuel, the tanks can be topped off to be sure of the quantity they contain and the aircraft weighed with full fuel. After weighing is complete, the weight of the fuel and its moment are subtracted from those of the aircraft as weighed. To correct the empty weight for the residual fuel, add its weight and moment. The amount of residual fuel and its arm are normally found in NOTE 1 in the section of the TCDS, "Data pertaining to all Models." See "Fuel Capacity" on page 2-10.

When computing the weight of the fuel, for example a tank full of jet fuel, measure its specific gravity (sg) with a hydrometer and multiply it by 8.345 (the nominal weight of 1 gallon of pure water whose s.g. is 1.0). If the ambient temperature is high and the jet fuel in the tank is hot enough for its specific gravity to reach 0.81 rather than its nominal s.g. of 0.82, the fuel will actually weigh 6.76 pounds per gallon rather than its normal weight of 6.84 pounds per gallon. The standard weight of aviation gasoline (Avgas) is 6 pounds per gallon.

Oil

The empty weight for aircraft certificated under the CAR, part 3 does not include the engine lubricating oil. The oil must either be drained before the aircraft is weighed, or its weight must be subtracted from the scale readings to determine the empty weight. To weigh an aircraft that does not include the engine lubricating oil as part of the empty weight, place it in level flight attitude, then open the drain valves and allow all of the oil that is able, to drain out. Any remaining is undrainable oil, and is part of the empty weight. Aircraft certificated under 14 CFR parts 23 and 25 include full oil as part of the empty weight. If it is impractical to drain the oil, the reservoir can be filled to the specified level and the weight of the oil computed at 7.5 pounds per gallon. Then its weight and moment are subtracted from the weight and moment of the aircraft as weighed. The amount and arm of the undrainable oil are found in NOTE 1 of the TCDS, and this must be added to the empty weight.

Other Fluids

The hydraulic fluid reservoir and all other reservoirs containing fluids required for normal operation of the aircraft should be full. Fluids not considered to be part of the empty weight of the aircraft are potable (drinkable) water, lavatory precharge water, and water for injection into the engines.

Configuration of the Aircraft

Consult the aircraft service manual regarding position of the landing gear shock struts and the control surfaces for weighing; when weighing a helicopter, the main rotor must be in its correct position.

Jacking the Aircraft

Aircraft are often weighed by rolling them onto ramps in which load cells are embedded. This eliminates the problems associated with jacking the aircraft off the ground. However, many aircraft are weighed by jacking the aircraft up and then lowering them onto scales or load cells.

Extra care must be used when raising an aircraft on jacks for weighing. If the aircraft has spring steel landing gear and it is jacked at the wheel, the landing gear will slide inward as the weight is taken off of the tire, and care must be taken to prevent the jack from tipping over.

For some aircraft, stress panels or plates must be installed before they are raised with wing jacks, to distribute the weight over the jack pad. Be sure to follow the recommendations of the aircraft manufacturer in detail anytime an aircraft is jacked. When using two wing jacks, take special care to raise them simultaneously, keeping the aircraft so it will not slip off the jacks. As the jacks are raised, keep the safety collars screwed down against the jack cylinder to prevent the aircraft from tilting if one of the jacks should lose hydraulic pressure.

Leveling the Aircraft

When an aircraft is weighed, it must be in its level flight attitude so that all of the components will be at their correct distance from the datum. This attitude is determined by information in the TCDS. Some aircraft require a plumb line to be dropped from a specified location so that the point of the weight, the bob, hangs directly above an identifiable point. Others specify that a spirit level be placed across two leveling lugs, often special screws on the outside of the fuselage. Other aircraft call for a spirit level to be placed on the upper door sill.

Lateral level is not specified for all light aircraft, but provisions are normally made on helicopters for determining both longitudinal and lateral level. This may be done by built-in leveling indicators, or by a plumb bob that shows the conditions of both longitudinal and lateral level.

The actual adjustments to level the aircraft using load cells are made with the jacks. When weighing from the wheels, leveling is normally done by adjusting the air pressure in the nose wheel shock strut.

Safety Considerations

Special precautions must be taken when raising an aircraft on jacks.

1. Stress plates must be installed under the jack pads if the manufacturer specifies them.
2. If anyone is required to be in the aircraft while it is being jacked, there must be no movement.
3. The jacks must be straight under the jack pads before beginning to raise the aircraft.
4. All jacks must be raised simultaneously and the safety devices are against the jack cylinder to prevent the aircraft tipping if any jack should lose pressure. Not all jacks have screw down collars, some use drop pins or friction locks.

Determining the Center of Gravity

When the aircraft is in its level flight attitude, drop a plumb line from the datum and make a mark on the hangar floor below the tip of the bob. Draw a chalk line through this point parallel to the longitudinal axis of the aircraft. Then draw lateral lines between the actual weighting points for the main wheels, and make a mark along the longitudinal line at the weighing point for the nose wheel or the tail wheel. These lines and marks on the floor allow you to make accurate measurements between the datum and the weighting points to determine their arms.

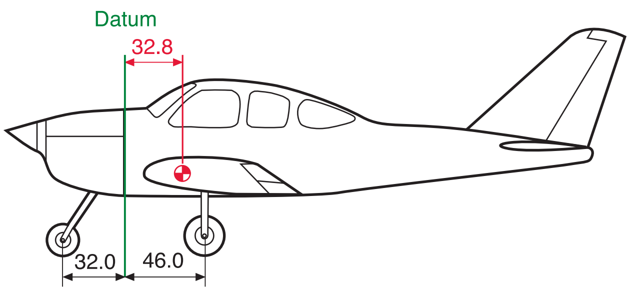

Figure 3-3. *The datum is located at the firewall.*

Determine the CG by adding the weight and moment of each weighing point to determine the total weight and total moment. Then divide the total moment by the total weight to determine the CG relative to the datum.

As an example of locating the CG with respect to the datum, which in this case is the firewall, consider the tricycle landing gear airplane in Figures 3-3 and 3-4.

When the airplane is on the scales with the parking brakes off, place chocks around the wheels to keep the airplane from rolling. Subtract the weight of the chocks, called tare weight, from the scale reading to determine the net weight at each weighing point. Multiply each net weight by its arm to determine its moment, and then determine the total weight and total moment. The CG is determined by dividing the total moment by the total weight.

$$CG = \frac{\text{Total moment}}{\text{Total weight}}$$

$$= \frac{65{,}756}{2{,}006}$$

$$= 32.8 \text{ inches behind the datum}$$

The airplane in Figures 3-3 and 3-4 has a net weight of 2,006 pounds, and its CG is 32.8 inches behind the datum.

Two Ways to Express CG Location

The location of the CG may be expressed in terms of inches from a datum specified by the aircraft manufacturer, or as a percentage of the MAC. The location of the leading edge of the MAC, the leading edge mean aerodynamic cord (LEMAC), is a specified number of inches from the datum.

Weighing Point	Scale Reading (lb)	Tare (lb)	Net Weight (lb)	Arm (in)	Moment (lb-in)	CG
Right side	846	16	830	46.0	38,180	
Left side	852	16	836	46.0	38,456	
Nose	348	8	340	–32.0	–10,880	
Total			2,006		65,756	32.8

Figure 3-4. *Locating the CG of an airplane relative to the datum, which is located at the firewall. See Figure 3-3.*

Empty-Weight Center of Gravity Formulas

A chart like the one in Figure 3-4 helps visualize the weights, arms, and moments when solving an EWCG problem, but it is quicker to determine the EWCG by using formulas and an electronic calculator. The use of a calculator for solving these problems is described in chapter 8.

There are four possible conditions and their formulas that relate the location of CG to the datum. Notice that the formula for each condition first determines the moment of the nose $\left(\frac{F \times L}{W}\right)$ wheel or tail $\left(\frac{R \times L}{W}\right)$ wheel and then divides it by the total weight of the airplane. The arm thus determined is then added to or subtracted from the distance between the main wheels and the datum, distance D.

Nose wheel airplanes with datum forward of the main wheels.

$$CG = D - \left(\frac{F \times L}{W}\right)$$

Nose wheel airplanes with the datum aft of the main wheels.

$$CG = -\left(D + \frac{F \times L}{W}\right)$$

Tail wheel airplanes with the datum forward of the main wheels.

$$CG = D + \left(\frac{R \times L}{W}\right)$$

Tail wheel airplanes with the datum aft of the main wheels.

$$CG = -D + \left(\frac{R \times L}{W}\right)$$

Datum Forward of the Airplane - Nose Wheel Landing Gear

The datum of the airplane in Figure 3-5 is 100 inches forward of the leading edge of the wing root, or 128 inches forward of the main-wheel weighing points. This is distance (D). The weight of the nose wheel (F) is 340 pounds, and the distance between main wheels and nose wheel (L) is 78 inches. The total weight of the airplane (W) is 2,006 pounds.

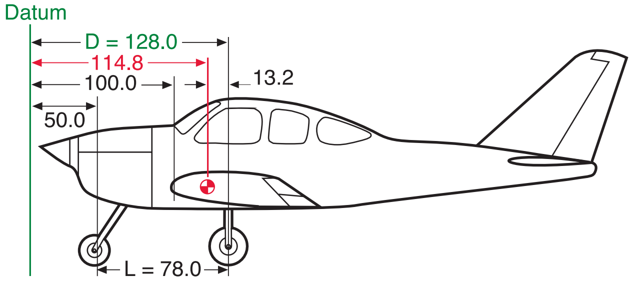

Figure 3-5. *The datum is 100 inches forward of the wing root leading edge.*

Determine the CG by using this formula:

$$CG = D - \left(\frac{F \times L}{W}\right)$$

$$= 128 - \left(\frac{340 \times 78}{2,006}\right)$$

$$= 114.8$$

The CG is 114.8 inches aft of the datum. This is 13.2 inches forward of the main-wheel weighing points which proves the location of the datum has no effect on the location of the CG so long as all measurements are made from the same location.

Datum Aft of the Main Wheels - Nose Wheel Landing Gear

The datum of some aircraft may be located aft of the main wheels. The airplane in this example is the same one just discussed, but the datum is at the intersection of the trailing edge of the wing with the fuselage.

The distance (D) between the datum of the airplane in Figure 3-6 and the main-wheel weighing points is 75 inches, the weight of the nose wheel (F) is 340 pounds, and the distance between main wheels and nose wheel (L) is 78 inches. The total net weight of the airplane (W) is 2,006 pounds.

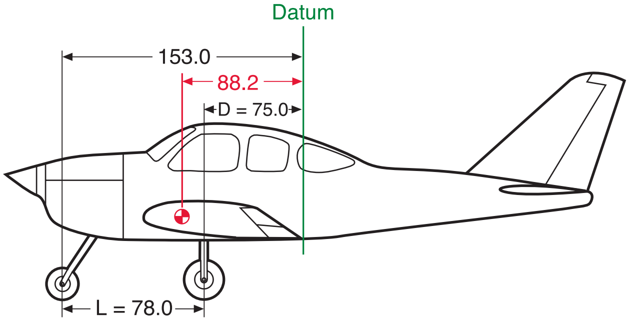

Figure 3-6. *The datum is aft of the main wheels at the wing trailing edge.*

The location of the CG may be determined by using this formula:

$$CG = -\left(D + \frac{F \times L}{W}\right)$$

$$= -\left(75 + \frac{340 \times 78}{2,006}\right)$$

$$= -88.2$$

The CG location is a negative value, which means it is 88.2 inches forward of the datum. This places it 13.2 inches forward of the main wheels, exactly the same location as it was when it was measured from other datum locations.

Location of Datum

It makes no difference where the datum is located as long as all measurements are made from the same location.

Datum Forward of the Main Wheels-Tail Wheel Landing Gear

Locating the CG of a tail wheel airplane is done in the same way as locating it for a nose wheel airplane except the formulas use $\left(\frac{R \times L}{W}\right)$ rather than $\left(\frac{F \times L}{W}\right)$.

The distance (D) between the datum of the airplane in Figure 3-7 and the main-gear weighing points is 7.5 inches, the weight of the tail wheel (R) is 67 pounds, and the distance (L) between the main-wheel and the tail wheel weighing points is 222 inches. The total weight of the airplane (W) is 1,218 pounds.

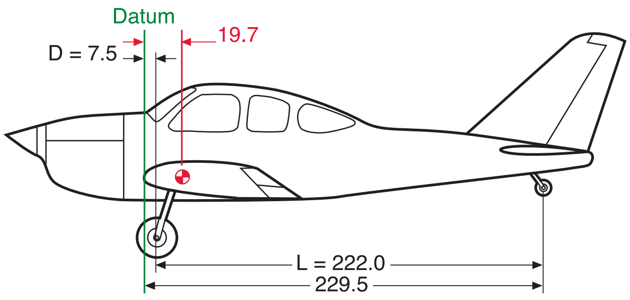

Figure 3-7. *The datum of this tail wheel airplane is the wing root leading edge.*

Determine the CG by using this formula:

$$CG = D + \left(\frac{R \times L}{W}\right)$$

$$= 7.5 + \left(\frac{67 \times 222}{1{,}218}\right)$$

$$= 19.7$$

The CG is 19.7 inches behind the datum.

Datum Aft of the Main Wheels - Tail Wheel Landing Gear

The datum of the airplane in Figure 3-8 is located at the intersection of the wing root trailing edge and the fuselage. This places the arm of the main gear (D) at -80 inches. The net weight of the tail wheel (R) is 67 pounds, the distance between the main wheels and the tail wheel (L) is 222 inches, and the total net weight (W) of the airplane is 1,218 pounds.

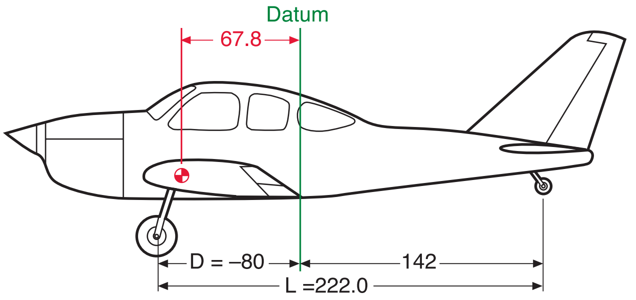

Figure 3-8. *The datum is aft of the main wheels, at the intersection of the wing trailing edge and the fuselage.*

Since the datum is aft of the main wheels, use the formula:

$$CG = -D + \left(\frac{R \times L}{W}\right)$$

$$= -80 + \left(\frac{67 \times 222}{1{,}218}\right)$$

$$= -67.8$$

The CG is 67.8 inches forward of the datum, or 12.2 inches aft of the main-gear weighing points. The CG is in exactly the same location relative to the main wheels, regardless of where the datum is located.

Location with Respect to the Mean Aerodynamic Chord

The aircraft mechanic or repairman is primarily concerned with the location of the CG relative to the datum, an identifiable physical location from which measurements can be made. But because the physical chord of a wing that does not have a strictly rectangular plan form is difficult to measure, wings such as tapered wings express the allowable CG range in percentage of mean aerodynamic chord (MAC). The allowable CG range is expressed in percentages of the MAC. The MAC, as seen in Figure 3-9, is the chord of an imaginary airfoil that has all of the aerodynamic characteristics of the actual airfoil. It can also be thought of as the chord drawn through the geographic center of the plan area of the wing.

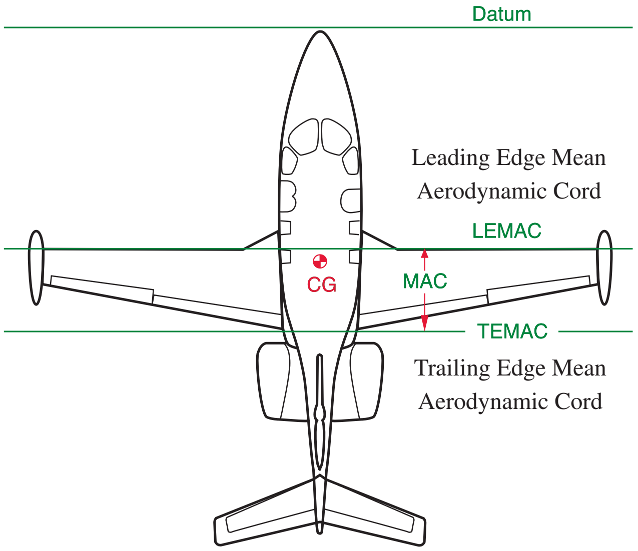

Figure 3-9. *The MAC is the chord drawn through the geographic center of the plan area of the wing.*

The relative positions of the CG and the aerodynamic center of lift of the wing have critical effects on the flight characteristics of the aircraft.

Consequently, relating the CG location to the chord of the wing is convenient from a design and operations standpoint. Normally, an aircraft will have acceptable flight characteristics if the CG is located somewhere near the 25 percent average chord point. This means the CG is located one-fourth of the total distance back from the leading edge of the wing section. Such a location will place the CG forward of the aerodynamic center for most airfoils.

In order to relate the percent MAC to the datum, all weight and balance information includes two items: the length of MAC in inches and the location of the leading edge of MAC (LEMAC) in inches from the datum.

The weight and balance data of the airplane in Figure 3-10 states that the MAC is from stations 144 to 206 and the CG is located at station 161.

MAC = 206" - 144" = 62" inches
LEMAC = station 144
CG is 17 inches behind LEMAC
(160 - 144 = 17.0 inches)

The location of the CG expressed in percentage of MAC is determined using this formula:

$$\text{CG in \% MAC} = \frac{\text{Distance aft of LEMAC} \times 100}{\text{MAC}}$$

$$= \frac{17 \times 100}{62}$$

$$= 27.4$$

The CG of the airplane is located at 27.4% MAC.

It is sometimes necessary to determine the location of the CG in inches from the datum when its location in %MAC is known.

The CG of the airplane is located at
27.4% MAC
MAC = 206 - 144 = 62
LEMAC = station 144

Determine the location of the CG in inches from the datum by using this formula:

$$\text{CG inches from datum} = \text{LEMAC} + \frac{\text{MAC} \times \text{CG \% MAC}}{100}$$

$$= 144 + \frac{62 \times 27.4}{100}$$

$$= 160.9$$

The CG of this airplane is located at station 160.9 inches aft of the datum. It is important for longitudinal stability that the CG be located ahead of the center of lift of a wing. Since the center of lift is expressed as a percentage of the MAC, the location of the CG is expressed in the same terms.

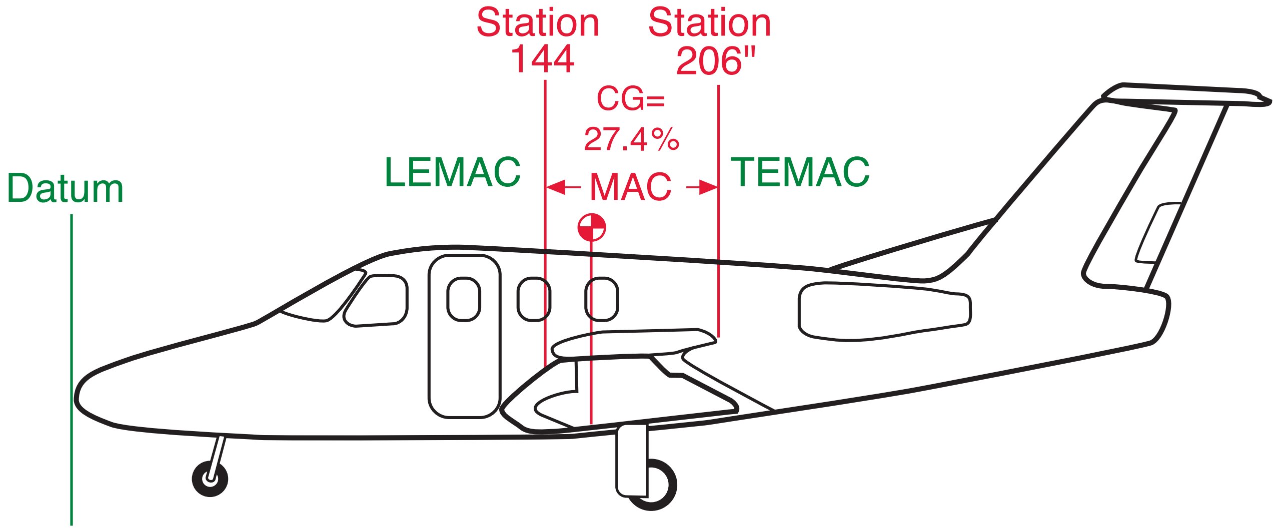

Figure 3-10. *Aircraft weight and balance calculation diagram.*