Aircraft Weight and Balance Handbook

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the aircraft must be reconfigured or placarded to prevent the pilot from loading the aircraft improperly. It is sometimes possible to install a fixed ballast in order for the aircraft to operate again within the normal CG range.

The FAA-certificated mechanic or repairman conducting an annual or condition inspection must ensure the weight and balance data in the aircraft records is current and accurate. It is the responsibility of the PIC to use the most current weight and balance data when operating the aircraft.

Stability and Balance Control

Balance control refers to the location of the CG of an aircraft. This is of primary importance to aircraft stability, which is a factor in flight safety. The CG is the point at which the total weight of the aircraft is assumed to be concentrated, and the CG must be located within specific limits for safe flight. Both lateral and longitudinal balance are important, but the prime concern is longitudinal balance; that is, the location of the CG along the longitudinal or lengthwise axis.

An airplane is designed to have stability that allows it to be trimmed to maintain straight-and-level flight with hands off the controls. Longitudinal stability is maintained by ensuring the CG is slightly ahead of the center of lift. This produces a fixed nose-down force independent of the airspeed. This is balanced by a variable nose-up force, which is produced by a downward aerodynamic force on the horizontal tail surfaces

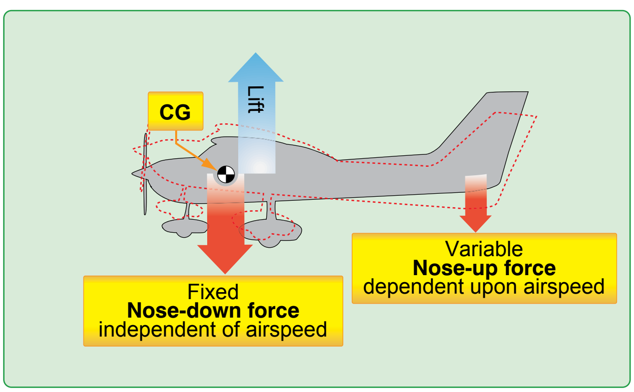

Figure 1-1. *Longitudinal forces acting on an airplane in flight.*

that varies directly with the airspeed. *[Figure 1-1]* If a rising air current should cause the nose to pitch up, the airplane slows and the downward force on the tail decreases. The weight concentrated at the CG pulls the nose back down. If the nose should drop in flight, the airspeed increases and the increased downward tail load brings the nose back up to level flight

As long as the CG is maintained within the allowable limits for its weight, the airplane has adequate longitudinal stability

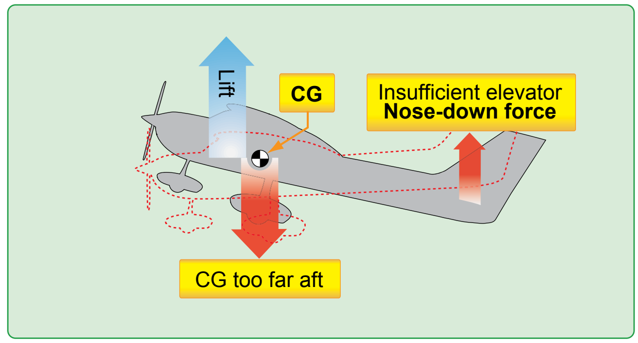

Figure 1-2. *If the CG is too far aft at the low stall airspeed, there might not be enough elevator nose-down authority to get the nose down for recovery.*

and control. If the CG is too far aft, it is too near the center of lift; the airplane is unstable and difficult to recover from a stall. *[Figure 1-2]* If the unstable airplane should enter a spin, the spin could become flat making recovery difficult or impossible. If the CG is too far forward, the downward tail load needs to be increased to maintain level flight. This increased tail load has the same effect as carrying additional weight; the aircraft must fly at a higher angle of attack and drag increases.

A more serious problem caused by the CG being too far forward is the lack of sufficient elevator authority. At low takeoff speeds, the elevator might not produce enough nose-up force to rotate; on landing there may not be enough elevator force to flare the airplane. *[Figure 1-3]* Both takeoff and landing runs are lengthened if the CG is too far forward. The basic aircraft design is such that lateral symmetry is assumed to exist. For each item of weight added to the left of the center line of the aircraft (also known as buttock line zero or BL-0), there is generally an equal weight at a corresponding location on the right.

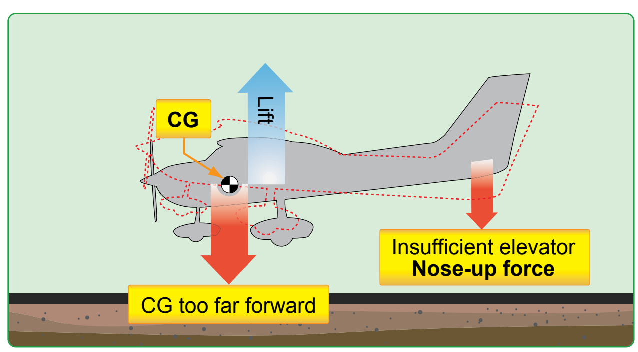

Figure 1-3. *If the CG is too far forward, there is not enough elevator nose-up force to flare the airplane for landing.*

The lateral balance can be upset by uneven fuel loading or burnoff. The position of the lateral CG is not normally computed for an airplane, but the pilot must be aware of the adverse effects that result from a laterally unbalanced condition. *[Figure 1-4]* This is corrected by using the aileron trim tab until enough fuel has been used from the tank on the heavy side to balance the airplane. The deflected trim tab deflects the aileron to produce additional lift on the heavy side, but it also produces additional drag, and the airplane flies inefficientl

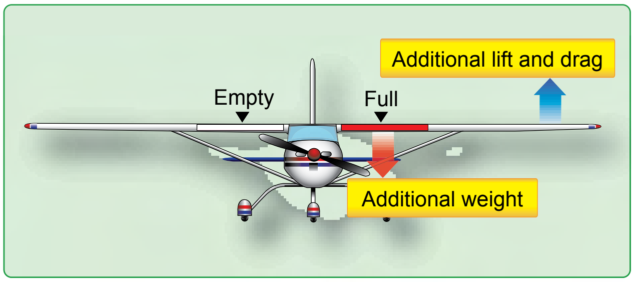

Figure 1-4. *Lateral imbalance causes wing heaviness, which may be corrected by deflecting the aileron. The additional lift causes additional drag, and the airplane flies inefficiently.*

Helicopters are more often affected by lateral imbalance than airplanes. If a helicopter is loaded with heavy occupants and fuel on the same side, it could be out of balance enough to make it unsafe to fly. It is also possible that if external loads are carried in such a position that requires large lateral displacement of the cyclic control to maintain level fl ght, the fore-and-aft cyclic control effectiveness is limited.

Swept-wing airplanes are more critical due to fuel imbalance because as the fuel is used from the outboard tanks, the CG shifts forward. As fuel is used from the inboard tanks, the CG shifts aft. *[Figure 1-5]* For this reason, fuel-use scheduling in swept-wing airplanes operation is critical.

Weight Control for Aircraft Other Than Fixed and Rotor-wing

Some light aircraft utilize different methods of determining weight and balance from the traditional fixed and rotor-wing aircraft. These aircraft achieve flight control by methods different from the fixed-wing airplane or helicopter. Most notable of these are weight-shift control (WSC) aircraft (also known as trikes), powered parachutes, and balloons. These aircraft typically do not specify either an EWCG or a CG range. They require only a certified or approved maximum weight. To understand why this is so, a look at how flight control is achieved is helpful.

Airplanes and WSC aircraft control flight under the influenc of the same four forces (lift, gravity, thrust, and drag), and around the same three axes (pitch, yaw, and roll). However, each aircraft accomplishes this control in a very different manner. This difference helps explain why the fixed-wing

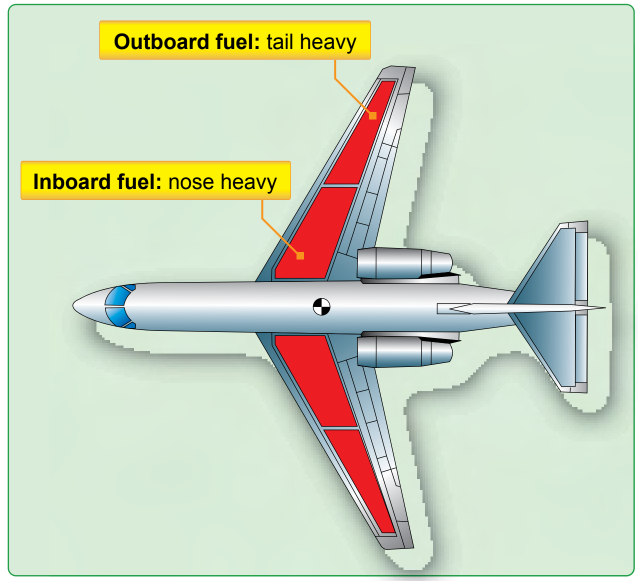

Figure 1-5. *Fuel in the tanks of a swept-wing airplane affects both lateral and longitudinal balance. As fuel is used from an outboard tank, the CG shifts forward.*

airplane requires an established weight and a known CG, whereas the WSC aircraft only requires the known weight.

The fixed-wing airplane has movable controls that alter lift on various airfoil surfaces to vary pitch, roll, and yaw. In turn, these changes in lift affect the characteristics of the flight parameters. Weight normally decreases in flight due to fuel consumption, and the airplane CG changes with this weight reduction. An airplane utilizes its variable fligh controls to compensate and maintain controllability through the various flight modes and as the CG changes. An airplane has a CG range or envelope within which it must remain if the flight controls are to remain effective and the airplane safely operated.

Weight-Shift Control Aircraft

The WSC aircraft has a relatively set platform wing without a tail. The pilot achieves control by shifting weight. In the design of this aircraft, the weight of the airframe and its payload is attached to the wing at a single point in a pendulous arrangement. The pilot, through the flight controls, controls the arm of this pendulum and thereby controls the aircraft. When a change in flight parameter is desired, the pilot displaces the aircraft's weight by the appropriate distance and direction. This change momentarily disrupts the equilibrium between the four forces acting on the aircraft. The wing, due to its inherent stability, then moves appropriately to reestablish the desired relationship between these forces; the wing flexes and alter its shape. As the shape is changed, lift is varied at different points on the wing to achieve the desired flight parameters

Weight and Balance Theory

Two elements are vital in the weight and balance considerations of an aircraft.

- The total weight of the aircraft must be no greater than the maximum weight allowed by the FAA for the make and model of the aircraft.
- The center of gravity (CG), or the point at which all of the weight of the aircraft is considered to be concentrated, must be maintained within the allowable range for the operational weight of the aircraft.

Arm

The arm is usually measured and expressed in inches and refers to the horizontal distance between the CG of an item or object and the datum, a point from where all measurements are taken. Arms to the left of the datum are negative (–) and those to the right of the datum are positive (+). The datum is an imaginary vertical plane from which all horizontal distances are measured for balance purposes. The position of the reference datum varies by aircraft design and manufacturer. When the datum is located off of the lever and to the left, all of the arms are positive and computational errors are minimized. Note: When the datum is established ahead of the aircraft, for example at the aircraft nose, all of the arms are positive and computational errors are minimized.

Moment

A moment is a force that tries to cause rotation and is the product of the arm, in inches, and the weight, in pounds. Moments are generally expressed in pound-inches (lb-in) and may be either positive or negative.

The Law of the Lever

Weight and balance problems are based on the physical law of the lever. This law states that a lever is balanced when the weight on one side of the fulcrum (a pivot point for the lever) multiplied by its arm is equal to the weight on the opposite side multiplied by its arm. In other words, the lever is balanced when the sum of the moments about the fulcrum is zero. This is the condition in which the positive moments (those that try to rotate the lever clockwise) are equal to the negative moments (those that try to rotate it counterclockwise). In an aircraft, the balance point is referred to as the CG.

One of the easiest ways to understand weight and balance is to consider a lever with weights placed at various locations. The balance point or CG of the lever can be changed by either moving the weights closer or farther from the fulcrum or by increasing or decreasing the weights. The balance point or CG of a lever may be determined by using these four steps:

1. Measure the arm of each weight in inches from the datum.
2. Multiply each arm by its weight in pounds to determine the moment in pound-inches of each weight.
3. Determine the total of all weights and of all the moments. (Disregard the weight of the lever).
4. Divide the total moment by the total weight to determine the balance point.

Consider these facts about the lever in *Figure 2-1*. The 100-pound weight A is located 50 inches to the left of the fulcrum (the datum, in this instance), and it has a moment of $100 \times -50 = -5{,}000$ lb-in. The 200-pound weight B is located 25 inches to the right of the fulcrum, and its moment is $200 \times +25 = +5{,}000$ lb-in. In *Figure 2-2,* the sum of the moments is $-5{,}000 + 5{,}000 = 0$, and the lever is balanced. The forces that try to rotate it clockwise have the same magnitude as those that try to rotate it counterclockwise. If either weight is moved or changed, the balance point or CG changes and the lever becomes unbalanced.

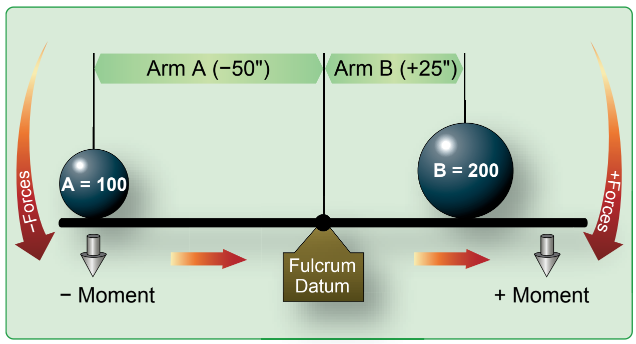

Figure 2-1. *Balance lever.*

Item	Weight (lb)	Arm (in)	Moment (lb-in)
Weight A	100	−50	−5,000
Weight B	200	+25	+5,000
	300		0

Figure 2-2. *Balance point locations.*

In *Figure 2-3,* the datum is located off the lever to the left of weight A. Using the information provided in *Figure 2-3,*

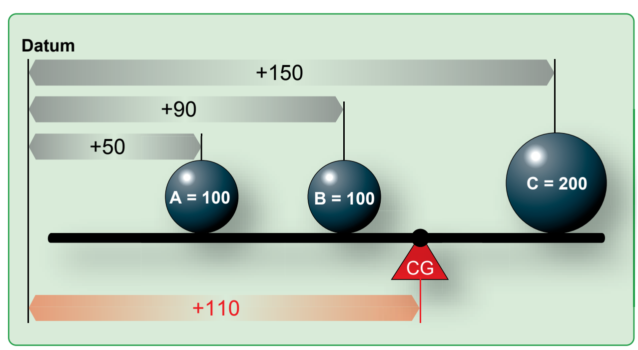

Figure 2-3. *Balance lever datum located off the lever.*

determine the balance point by making a chart like the one in *Figure 2-4*.

Item	Weight (lb)	Arm (in)	Moment	CG
Weight A	100	50	5,000	
Weight B	100	90	9,000	
Weight C	200	150	30,000	
	400		44,000	110

Figure 2-4. *Finding balance point with datum located off the lever.*

As noted in *Figure 2-4*, A weighs 100 pounds and is 50 inches from the datum; B weighs 100 pounds and is 90 inches from the datum; C weighs 200 pounds and is 150 inches from the datum. The total of the weights is 400 pounds, and the total moment is 44,000 lb-in.

Determine the balance point by dividing the total moment by the total weight. A balance point is equal to the CG and can be mathematically written as:

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

To prove this is the correct balance, move the datum to a location 110 inches to the right of the original datum and determine the arm of each weight from this new datum. *[Figure 2-5]* Then, make a new chart similar to the one in *Figure 2-6*. If the balance point is correct, the sum of the moments is zero.

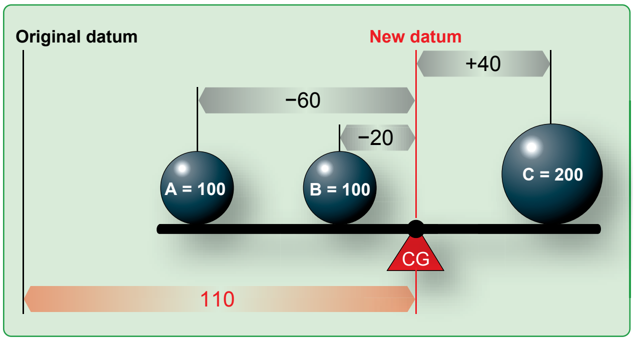

Figure 2-5. *Locating balance point.*

Item	Weight (lb)	Arm (in)	Moment (lb-in)
Weight A	100	−60	−6,000
Weight B	100	−20	−2,000
Weight C	200	+40	+8,000
			0

Figure 2-6. *Proving balance point with three weights is correct.*

The new arm of weight A is 60 inches (the difference between 110 and 50), and since this weight is to the left of the datum, its arm is negative or –60 inches. The new arm of weight B is 20 inches (110 – 90), and it is also to the left of the datum, so it is –20; the new arm of weight C is 40 inches (150 – 110). It is to the right of the datum and is therefore positive.

The lever is balanced when the sum of the moments is zero. The location of the datum used for determining the arms of the weights is not important; it may be in various locations, but all of the measurements must be made from the same datum location.

The procedure for finding the balance point is the same anywhere the datum is located. In *Figure 2-7,* the datum is located at C. Weight A has an arm of –100 inches (negative because it is to the left) of the datum and weight B has an arm of –60 inches from the datum. The table in *Figure 2-8* is used to determine the new balance point.

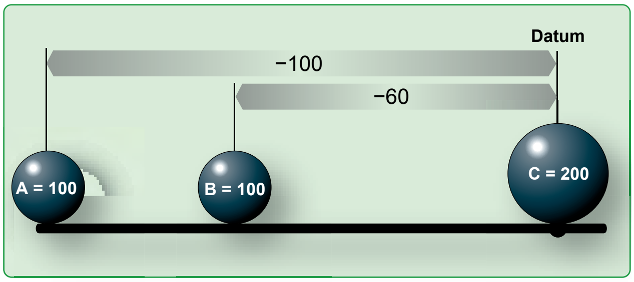

Figure 2-7. *Locating balance point with datum at C.*

Item	Weight (lb)	Arm (in)	Moment	CG
Weight A	100	−100	−10,000	
Weight B	100	−60	−6,000	
Weight C	200		0	
	400		−16,000	−40

Figure 2-8. *Determining new balance point.*

To verify that this is the correct balance point, move the datum 40 inches to the left of the original datum and determine the arm of each weight from this new datum as in *Figure 2-9*.

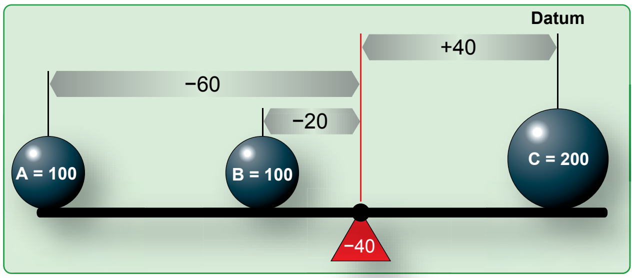

Figure 2-9. *Locating balance point with datum left of original.*

The new arm for weight A would be –100 + 40 = –60; for weight B, –60 + 40 = –20; and point C, is +40. The lever is balanced and the balance point is correct when the sum of the moments is zero. *[Figure 2-10]*

Item	Weight (lb)	Arm (in)	Moment (lb-in)
Weight A	100	−60	−6,000
Weight B	100	−20	−2,000
Weight C	200	40	+8,000
			0

Figure 2-10. *Proving the new balance point is correct.*

Shifting the Balance Point or CG

One common weight and balance problem involves moving or shifting weight from one point to another in order to move the balance point or CG to a desired location. This can be demonstrated by using a lever with three weights to work out the problem.

Solution by Chart

As the lever is loaded in *Figure 2-11,* it balances at a point 72 inches from the CG of weight A.

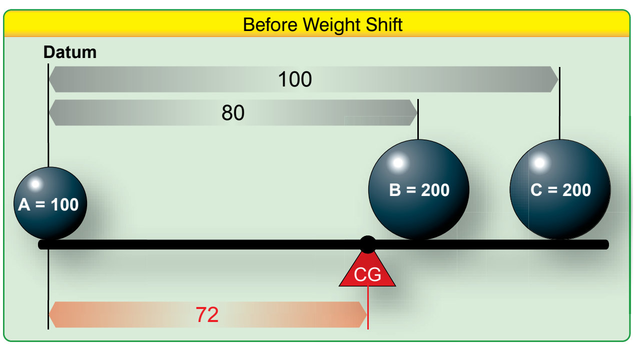

Figure 2-11. *Locating balance point with three weights.*

To shift weight B so the lever balances about its center, 50 inches from the CG of weight A, first determine the arm of weight B that produces a moment that causes the total moment of all three weights around this desired balance point to be zero. The combined moment of weights A and C around this new balance point is 5,000 lb-in, so the moment of weight B must be –5,000 lb-in for the lever to balance. *[Figure 2-12]*

Item	Weight (lb)	Arm (in)	Moment (lb-in)
Weight A	100	−50	−5,000
Weight B			
Weight C	200	+50	+10,000
			+5,000

Figure 2-12. *Proving the new balance point is correct.*

Determine the arm of weight B by dividing its moment, –5,000 lb-in, by its weight of 200 pounds. The arm is –25 inches. To balance the lever at its center, weight B must be placed so its CG is 25 inches to the left of the center of the lever. *[Figure 2-13]*

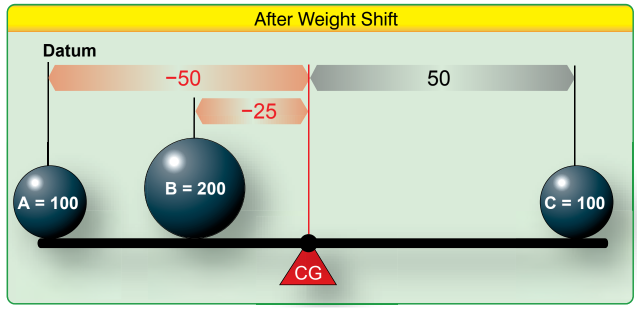

Figure 2-13. *Weight distribution to balance lever.*

Figure 2-14 indicates that the shift in weight depicted in *Figure 2-13* allows the lever to balance as the sum of the moments is zero.

Item	Weight (lb)	Arm (in)	Moment (lb-in)
Weight A	100	−50	−5,000
Weight B	200	−25	−5,000
Weight C	200	+50	+10,000
			0

Figure 2-14. *Weight shift provides correct CG.*

Basic Weight and Balance Equation

The following formulas can be used to determine the distance weight must be shifted to obtain a desired change in the CG location. The equation can also be rearranged to fi d the amount of weight required to be shifted to move the CG to a desired location, to find the distance the CG is moved when a specified amount of weight is shifted, or to find the total weight that would allow shifting a specified amount of weight to move the CG a given distance.

$$\frac{\text{Weight to be shifted}}{\text{Total weight}} = \frac{\Delta\ \text{CG}}{\text{Distance weight is shifted}}$$

$$\text{Total weight} = \frac{\text{Weight shifted} \times \text{Distance weight is shifted}}{\Delta\ \text{CG}}$$

$$\text{Weight shifted} = \frac{\text{Total weight shifted} \times \Delta\ \text{CG}}{\text{Distance weight is shifted}}$$

$$\Delta\ \text{CG} = \frac{\text{Weight shifted} \times \text{Distance weight is shifted}}{\text{Total weight}}$$

$$\text{Distance weight is shifted} = \frac{\text{Total weight} \times \Delta\ \text{CG}}{\text{Weight shifted}}$$

Solution by Formula

The problem in *Figure 2-11* can be solved by using variations of this basic equation. First, rearrange the formula to determine the distance weight B must be shifted:

$$\text{Distance weight B is shifted} = \frac{\text{Total weight} \times \Delta\ \text{CG}}{\text{Weight shifted}}$$

$$= \frac{500 \times -22}{200}$$

$$= -55 \text{ inches}$$

The CG of the lever in *Figure 2-11* was 72 inches from the datum. This CG can be shifted to the center of the lever as in *Figure 2-13* by moving weight B. If the 200-pound weight B is moved 55 inches to the left, the CG shifts from +72 inches to +50 inches, a distance of 22 inches.

When the distance the weight is to be shifted is known, the amount of weight to be shifted to move the CG to any location can be determined by another arrangement of the basic equation. Use the following arrangement of the formula to determine the amount of weight that has to be shifted from station 8 to station +25, to move the CG from station +72 to station +50.

$$\text{Weight shifted} = \frac{\text{Total weight} \times \Delta\ \text{CG}}{\text{Distance weight is shifted}}$$

$$= \frac{500 \times 22}{55}$$

$$= 200 \text{ inches}$$

If the 200-pound weight B is shifted from station +80 to station +25, the CG moves from station +72 to station +50.

A third arrangement of this basic equation is used to determine the amount the CG is shifted when a given amount of weight is moved for a specified distance (as it was done in *Figure 2-11*). The following formula is used to determine the amount the CG is shifted when 200-pound weight B is moved from +80 to +25.

$$\Delta\ \text{CG} = \frac{\text{Weight shifted} \times \text{Distance it is shifted}}{\text{Total weight}}$$

$$= \frac{200 \times 55}{500}$$

$$= 22 \text{ inches}$$

Moving weight B from +80 to +25 moves the CG 22 inches from its original location at +72 to its new location at +50 as seen in *Figure 2-13*.

To complete the calculations, return to the original formula and enter the appropriate numbers.

$$\frac{\text{Weight to be shifted}}{\text{Total weight}} = \frac{\Delta\ \text{CG}}{\text{Distance weight is shifted}}$$

$$\frac{200}{500} = \frac{22}{55}$$

$$.4 = .4$$

The equation is balanced.

Mean Aerodynamic Chord

The CG point affects the stability of the aircraft. To ensure the aircraft is safe to fly, the CG must fall within specified limits established by the manufacturer.

On some aircraft, the CG is expressed as a percentage of the length of the mean aerodynamic chord (MAC) or "percent MAC." *[Figure 2-14]* In order to make such a calculation, the position of the leading edge of the MAC must be known ahead of time.

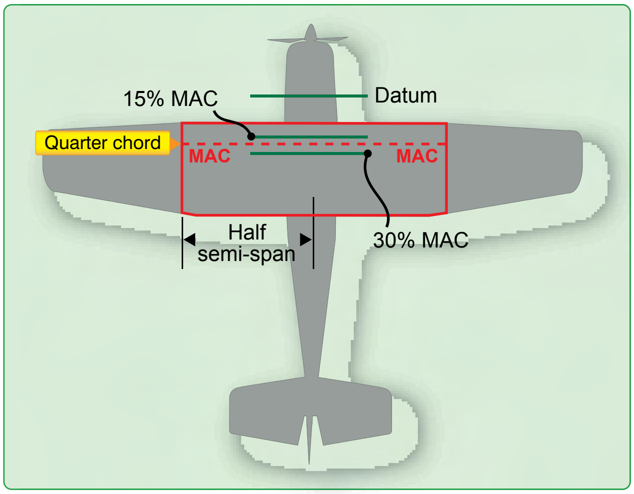

Figure 2-14. *Center of gravity expressed as percent mean aerodynamic chord.*

CG limits are specified forward and aft and/or lateral (left and right) limits within which the aircraft's CG must be located during flight. The area between the limits is called the CG range of the aircraft.