That Shifting Center of Gravity

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When Lindbergh guided the *Spirit of St. Louis* across the Atlantic in 1927, he endured many hours of monotony. Some of these were spent contemplating trivial aspects of the flight. At one point, for example, he calculated that his nine-cylinder Wright Whirlwind engine would have to produce 15 million power strokes during the 33½-hour flight from Roosevelt Field to LeBourget Airport. This staggering figure, he admitted later, gave him some cause for concern. After all, how could any engine endure so many punishing "explosions" without failing?

On a lighter note, Lindbergh observed a stowaway housefly aboard his Ryan monoplane. He knew that when the fly was at rest, it added infinitesimally to the payload. But what about when the fly was winging about the cabin? When the housefly supports its own weight, does this relieve the aircraft of having to support the load?

"If this is so," Lindbergh mused, "then perhaps I should not allow the fly to rest and needlessly burden the *Spirit of St. Louis.*" Lindbergh knew, however, that it made no difference whether the fly was airborne or at rest on the instrument panel. When flying, the insect's wings deflected air downward. Eventually, this minute quantity of air pressed against the cockpit floor with a force equal to the weight of the fly. The only way to eliminate such a "load" is to eject the stowaway bug through an open window.

A few years ago, the Lufthansa airline magazine, *Jet Tales,* posed a similar problem:

"If a Lufthansa 747 freighter is loaded with 50 tons of live doves and if all of these birds were to fly around in their containers at the same time, would the jumbo jet lose 50 tons of weight?"

Obviously not. There would be, however, a record number of midair collisions and busted beaks.

This problem, however, leads to another. If all of the birds were to suddenly fly from the floor to the ceiling, would this have any effect on the jumbo's center of gravity? Absolutely.

Assume that the dove-loaded aircraft is cruising at 41,000 feet and all the birds are at rest. When the birds fly toward the ceiling, the CG is displaced *vertically* to a higher location in the aircraft. The new CG could, for example, be 10 feet above the original CG. Now, would this have any effect on the 747's flight path?

It may not be immediately obvious, but the reaction of 50 tons of cargo rising to the ceiling causes the aircraft to lose as much altitude as is gained by the center of gravity (10 feet, in this case). Everything else being equal, it is the center of gravity that maintains a constant altitude, not the aircraft. If this were not so, then a drowning swimmer could lift himself out of the water by pulling up on his own hair.

When the birds tire of such folly and return to the cabin floor, the CG returns to its original location and the aircraft gains the altitude previously lost.

It is also interesting to note that the three motions of an airplane—pitch, roll and yaw—all take place about the center of gravity. In other words, when the CG changes location, so does the airplane's aerodynamic pivot point.

Most pilots aren't particularly concerned about the center-of-gravity's vertical movement, but they do (or should) regard seriously its longitudinal (fore and aft) travel. When CG limits are violated, both plane and pilot may be in jeopardy. But even when specified limits are observed, the location of the CG can significantly alter performance.

For example, does an airplane fly faster with an aft CG, a forward CG, or does this have no effect on airspeed? Initially, the answer seems illogical, but once understood provides some insight as to the effects of CG movement.

If the average pilot were to guess, he might suggest that CG location has no effect on airspeed. He'd be wrong. Next, he might speculate that a forward CG improves performance because this helps to keep the nose down. An aft CG, he might reason, causes the tail to sag resulting in a nose-high attitude and mushing flight. Wrong again. Generally speaking, an aft CG results in the fastest airspeed; a forward CG reduces airspeed.

Figure 1 shows a 4,000-pound airplane in cruise flight at a constant airspeed. Notice that the center of gravity is forward of the center of pressure, a theoretical point at which all wing lift appears to be concentrated. For most light airplanes, this is the normal relationship between lift and weight.

If wing lift and gross weight were the only vertical forces present, the airplane would have an overwhelming urge to pitch earthward.

Figure 2 introduces another factor: the horizontal stabilizer. This surface is called upon to produce "negative lift," a downward force on the tail that prevents the nose from pitching down. The wing, therefore, must not only overcome aircraft weight, it also must generate enough additional lift to offset the downward force on the tail. To maintain equilibrium in this case, wing lift must equal the sum of aircraft weight (4,000 pounds) plus the negative tail load (200 pounds, for example) or a total of 4,200 pounds.

Figure 3 shows the same airplane after the center of gravity has been moved aft to a point vertically aligned with the center of lift. Since lift and weight are in balance, a download on the tail is unnecessary. As a result, the wing needs to produce only 4,000

Figure 1

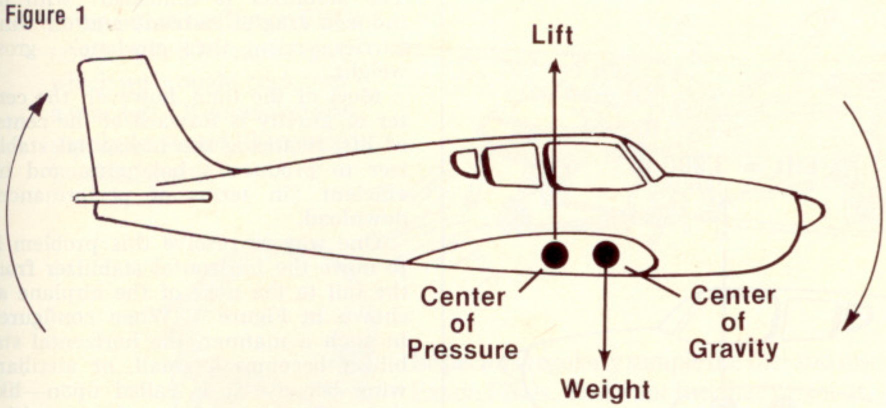
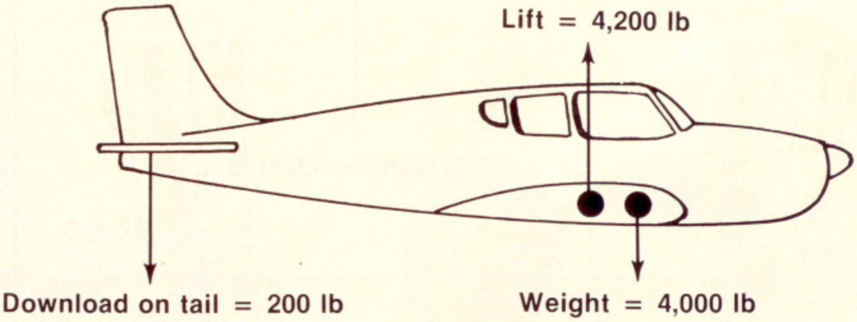


Figure 2



pounds of lift compared to 4,200 pounds when the center of gravity was forward.

Since the wing does not need to produce as much lift when the center of gravity is aft, it is flown at a smaller angle of attack. As a result, drag is reduced and airspeed increases. Or, the same airspeed can be maintained at a reduced power setting.

When speed is important, a few knots can often be gained with aft loading. By placing heavier baggage and passengers as far rearward as is *legally allowable,* tail loading is reduced, which allows the wing to be flown at a smaller angle of attack. Several air carriers use this technique on cargo flights. Aft loading saves considerable fuel (and increases range) because cruise speed is achieved with slightly reduced thrust.

When operating some aircraft, a similar result can be achieved by burning fuel from forward tanks. As the

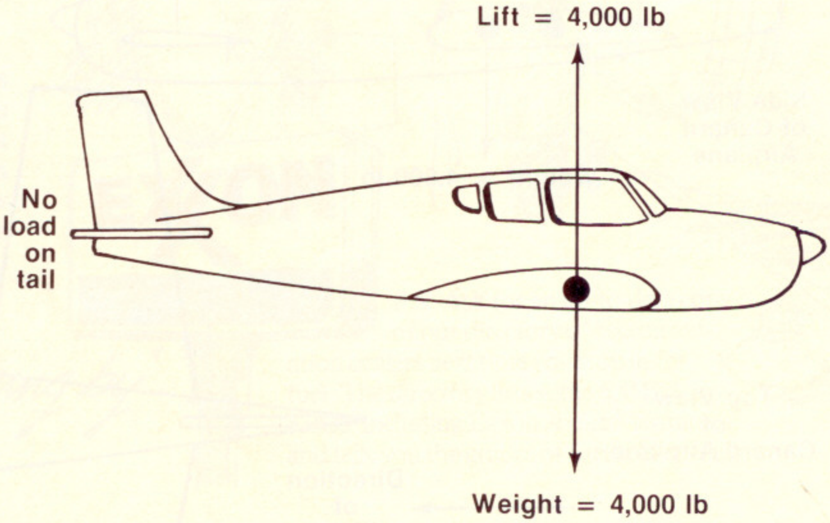


Figure 3

flight progresses, the center of gravity moves gradually aft and a slight increase in airspeed can be detected.

Since the wing carries "less weight" when the center of gravity is aft, it might be concluded that stall speeds are reduced at such a time. That's true. And, as the center of gravity moves forward, stall speeds increase. At least one major airframe manufacturer has been known to take advantage of this little-known fact. Stall speeds shown in operating handbooks often are valid only for when the center of gravity is at the extreme aft limit. At other times, when the CG is more normal, stall speeds are greater. This, however, cannot be found anywhere in the pilot's handbook. Very sneaky!

It is beneficial, therefore, to fly with an aft center of gravity. But it is possible to get too much of a good thing.

Figure 4 shows an airplane with its center of gravity *behind* the center of lift. To keep such an airplane in balance, it is necessary for the horizontal stabilizer to develop *positive* lift. This takes even more load off the wing, which further decreases the necessary angle of attack and reduces wing drag. But there's a catch. Since the stabilizer is generating lift, it also must create additional drag. As a result, very little may be gained.

In terms of performance, therefore, the best place for the center of gravity is at or very close to the center of lift. The stabilizer is unloaded (with no induced drag of its own) and the wing carries only the airplane's gross weight.

Most of the time, however, the center of gravity is forward of the center of lift, requiring the horizontal stabilizer to produce a balancing and inefficient (in terms of performance) download.

One way to resolve this problem is to move the horizontal stabilizer from the tail to the nose of the airplane as shown in Figure 5. When configured in such a manner, the horizontal stabilizer becomes a small, or auxiliary wing because it is called upon—like the main wing—to produce positive lift, a necessity if the airplane is to be kept in balance. This configuration is referred to as a canard airplane and the forward-located horizontal stabilizer is called a canard surface.

There is nothing new about a canard; it has been applied to various airplane designs for close to 75 years (beginning with the Wright *Flyer*).

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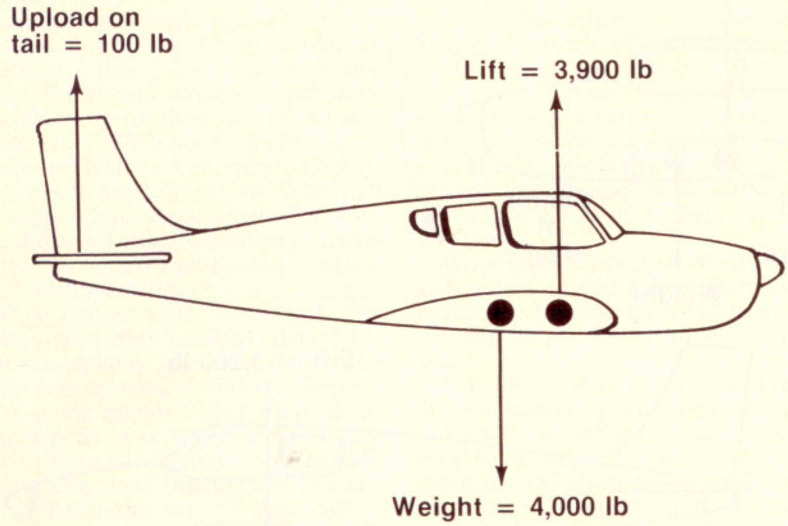


Figure 4

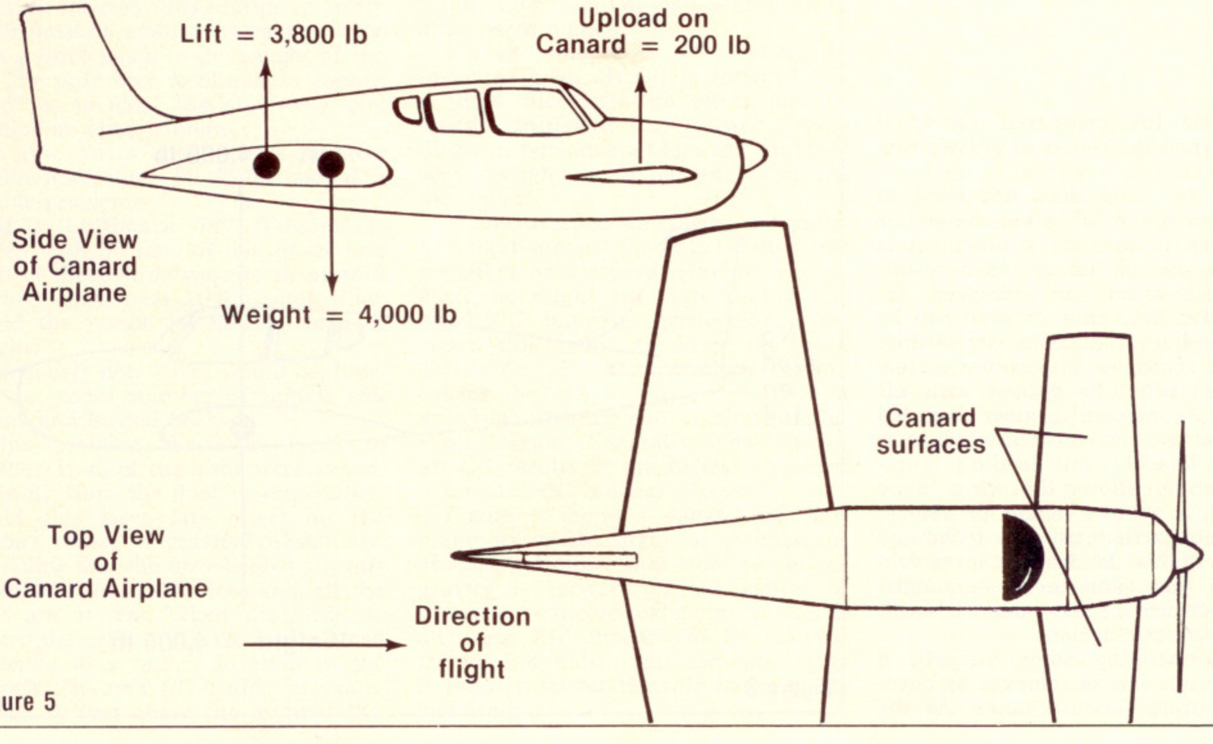


Figure 5

Although the canard surface is generally more efficient than a conventional horizontal stabilizer, inherent difficulties with longitudinal stability have prevented popularization of the concept. Interest in the canard, however, has been recently revitalized. Burt Rutan, who designed the VariEze, VariViggan and Defiant, seems to have overcome some of the canard's critical design aspects.

But for those of us who must be content to fly with conventional tail surfaces, we'll simply have to compensate as much as possible by maintaining an aft center of gravity.

There is nothing wrong with an aft center of gravity as long as it is kept within limits designated by the airframe manufacturer. Violating an aft CG limit, however, can result in an unacceptable decrease in longitudinal (pitch) stability, something far more dangerous than most pilots understand.

Simply stated, longitudinal stability is the ability of an airplane to return to its trimmed angle of attack (or airspeed) if disturbed from that angle of attack (or airspeed).

There are many forces created by an airplane, which contribute to longitudinal stability, but the horizontal stabilizer generally is the most influential. In a crude manner of speaking, an airplane's tailfeathers really are like feathers, the feathers of an arrow. Without them, a conventional airplane would wallow and wobble uncontrollably.

The stabilizing role of the horizontal tailfeathers can be appreciated by visualizing an airplane flying steadily at a given angle of attack. Suddenly the plane is assaulted by an updraft, which momentarily increases that angle of attack. The stabilizer also would be flying at a larger and possibly positive angle of attack as shown in Figure 6. As a result, the tail would temporarily create more lift (or less download). Since the horizontal stabilizer is situated way behind the center of gravity, this forces the nose to pitch down, tending to return the aircraft to its original angle of attack. This is longitudinal stability.

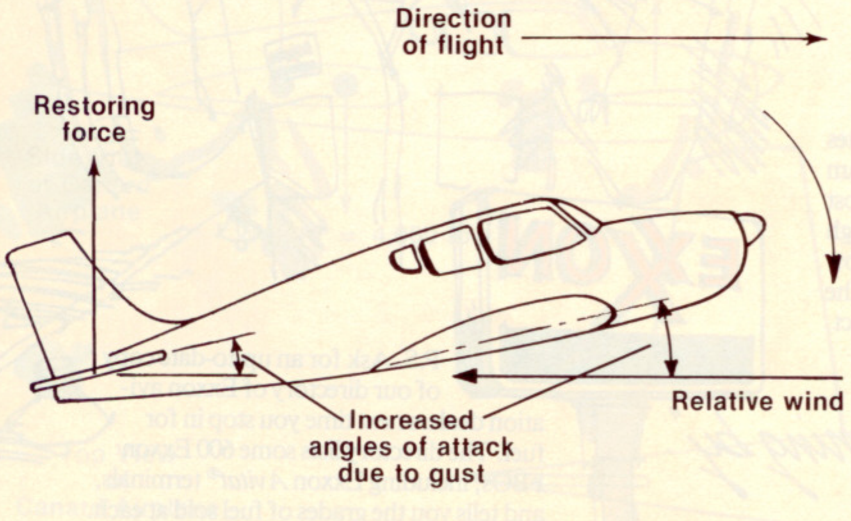
Like a wing, the horizontal stabilizer performs only when supplied with a healthy diet of airspeed. Reduce that life-supporting flow of air across the tail and the forces produced by the stabilizer can change dramatically.

Consider the balanced aircraft as shown in Figure 2. The forces are aligned normally and the engine is developing cruise power. Propwash flowing across the tail, therefore, is helping the stabilizer to do its job: create negative lift.

Assume now that the pilot suddenly retards the throttle. The amount of propwash flowing across the horizontal stabilizer decreases, which causes a decrease in the negative lift produced by this tail surface. In other words, the download produced by the tail is reduced. As a result, the nose drops.

Conversely, when power is added, the negative lift produced by the stabilizer increases and the aircraft nose rises. (Other factors also are responsible for these pitching reactions to power changes, but the action of the stabilizer is usually most influential.)

Now let's consider the potentially critical situation as shown in Figure 4, where the center of gravity has been shifted beyond its aft limit to a point behind the center of lift. To maintain balance, obviously, the horizontal stabilizer must produce upward lift.



Restoring force produced by horizontal stabilizer raises tail and lowers nose.

Figure 6

If power is reduced at such a time, the horizontal stabilizer receives less propwash and is unable to produce as much lift and the tail descends. Imagine such a situation! Retard the throttle and the nose goes up.

Perhaps the converse would be even more disastrous. By applying power (such as during a missed approach), the nose would plunge earthward . . .

(The lofty horizontal stabilizers of some T-tailed aircraft are above the propwash and do not react as abruptly to power changes.)

The trend is clear: as the center of gravity moves aft, longitudinal stability decreases. Eventually, *instability* sets in. Flying such a machine would be a fatiguing, full-time, dangerous operation. And this is why airplanes have center of gravity limits that must be strictly observed.

Additional problems created by an *excessively* aft CG include potentially violent stall characteristics, a tendency for normal spins to develop into flat spins (from which recovery may not be possible) and a reduction of control wheel forces that make it easier for a pilot to overcontrol and overstress the airplane.

On the other hand, an excessively *forward* center of gravity introduces another set of adverse flight characteristics. These include faster stalling speeds, decreased performance and excessive longitudinal stability that increases the control-wheel forces required to control pitch. So much up-elevator may be required to maintain equilibrium that there may not be enough left over to safely flare during landing. This can result in an overly stressed nosewheel or prevent a taildragger from making a 3-point landing (which is why you should not solo a Piper J-3 Cub from the front seat).

Since the vertical and longitudinal shifting of the CG has been considered, it would be unfair not to at least mention lateral movement of the center of gravity.

If fuel is improperly managed and is consumed unevenly from wing or tip tanks, it is possible to notice a lateral shift of the CG by the tendency of one wing to fly lower than the other.

Can this affect performance? Yes, because having to continuously deflect the ailerons (with or without trim) creates unnecessary drag. In extreme cases, so much aileron might be required to hold up a heavy wing that insufficient roll control may be left to counter a strong crosswind during landing.

While it might be nit-picking to consider the weight of a housefly or the effect of doves hovering in the cockpit, an improperly located center of gravity could have serious consequences. □