## The Effect of High Altitude and Center of Gravity on The Handling Characteristics of Swept-wing Commercial Airplanes

Center of gravity (CG) and altitude significantly affect the longitudinal stability of an airplane. An understanding of handling characteristics at various CG positions and altitudes permits flight crews to use proper control inputs when manually flying throughout the flight envelope.

In addition to being fast, quiet, and comfortable, modern commercial airplanes are also aerodynamically efficient. For example, all Boeing transport models use wing sweep to minimize high-speed cruise drag. This allows airplanes to cruise at higher Mach numbers before reaching the critical Mach number at which shock waves begin to form on the wing and drag rises significantly.

With the introduction of computers into airplane flight control design, other aerodynamic improvements are possible. However, because these improvements may affect airplane stability, flight crews should be aware of how CG and altitude affect the performance and handling characteristics of the airplanes they fly. This requires an understanding of the following key concepts:

1. Positive and relaxed longitudinal static stability.
2. Flight control computers and stability augmentation.
3. Maneuvering stability.

**1 Positive and Relaxed Longitudinal Static Stability**

In flight, the wings of a conventional airplane generate a nose down pitching moment. To balance this, a download is required on the tail. Airplanes loaded with an aft forward CG require less download on the tail.

Since download on the tail is negative lift, effectively increasing the weight of the airplane, the location of the CG affects the cruise performance of any airplane. Flying at an aft CG will reduce the download on the tail and improve cruise performance.

When airplanes are operated near the aft CG limit, download on the tail is minimized and angles of attack and drag are reduced. However, moving the CG aft reduces the longitudinal static stability of the airplane, something that all flight crews should be aware of (see figure 1 and "Static Longitudinal Stability and Speed Stability" below).

As airspeed varies from a trimmed condition, the column force required to maintain a new speed (without re-trimming) is a measure of static longitudinal stability. For any conventional airplane, the location of the CG has the strongest influence on static longitudinal stability. For a statically stable airplane the required column force, as speed varies from the trimmed condition, is less at an aft CG than it is at a forward CG. The minimum average gradient allowed by U.S. Federal Aviation Administration FAR Part 25 is one pound for each six knots. As the CG moves aft, it reaches a point where the stick force per knot drops to zero, then reverses. This location is called the neutral point. The difference between the actual CG location and the neutral point is called the static margin. With a CG forward of the neutral point, an airplane has a positive static margin and positive static longitudinal stability. At a CG aft of the neutral point, an airplane has a negative static margin, is statically unstable, and requires some form of augmentation to be flown with an acceptable workload.

**2 Flight Control Computers and Stability Augmentation**

The trend in the design of modern airplanes is to have less static longitudinal stability--frequently referred to as relaxed static stability (RSS)--to capture the benefit of improved fuel efficiency. Simply stated, some airplanes are now designed to be aerodynamically efficient, and stability is augmented electronically so that stick force gradients will meet certification requirements. Many methods exist for augmenting stability. For example, the Boeing 777 and MD-11 use flight control computers that adjust the elevator actuator positions to give the appearance of more longitudinal stability than the airplane actually has. In other words, computers absorb the extra workload caused by flying with RSS.

Augmented stability provides better cruise performance with no increase in workload and no adverse effects from flying at an aft CG. This technology also allows for a smaller tail size, which further reduces drag and weight. However, FAR Part 25 requires that handling qualities remain adequate for continued safe flight and landing following an augmentation system failure. Therefore, a practical limit exists for how far aft the CG can go.

The Boeing 777 uses redundant digital flight control computers to provide positive (static longitudinal) stability and enhances that stability with airspeed feedback. The MD-11 uses computers to provide neutral speed stability. In other words, the CG of the MD-11 appears to be at the neutral point. The MD-11 uses elevator deflection to hold attitude at any speed within the normal flight envelope, then trims the stabilizer. This is known as an "attitude hold" system.

**3 Maneuvering Stability**

Maneuvering stability, like static stability, is influenced by CG location. However, when the CG is aft and near the neutral point, then altitude also has a significant effect. Since air density has a notable impact on the damping moment of the horizontal tail, higher pitch rates will result for the same elevator deflections as altitude increases. From the flight crew's perspective, as altitude increases, a pull force will result in a larger change in pitch angle, which translates into an increasing angle of attack and *g*. While a well-designed flight control system, either mechanical or electronic, will reduce the variation of stick force with CG and altitude, it is very difficult to completely eliminate the variation due to design limitations.

For example, for the same control surface movement at constant airspeed, an airplane at 35,000 ft (10,670 m) experiences a higher pitch rate than an airplane at 5,000 ft (1,524 m) because there is less aerodynamic damping. The pitch rate is higher, but the resulting change in flight path is not. Therefore, the change in angle of attack is greater, creating more lift and more *g*. If the control system is designed to provide a fixed ratio of control column force to elevator deflection, it will take less column force to generate the same *g* as altitude increases.

This principle is the essence of high-altitude handling characteristics for RSS airplanes. Unless an RSS airplane has an augmentation system to compensate its maneuvering stability, lighter column forces are required for maneuvering at altitude. Longitudinal maneuvering requires a pitch rate, and the atmosphere provides pitch rate damping. As air density decreases, the pitch rate damping decreases, resulting in decreased maneuvering stability (see figure 2 and "Maneuvering Stability" below).

An additional effect is that for a given attitude change, the change in rate of climb is proportional to the true airspeed. Thus, for an attitude change for 500 ft per minute (fpm) at 290 knots indicated air speed (kias) at sea level, the same change in attitude at 290 kias (490 knots true air speed) at 35,000 ft would be almost 900 fpm. This characteristic is essentially true for small attitude changes, such as the kind used to hold altitude. It is also why smooth and small control inputs are required at high altitude, particularly when disconnecting the autopilot.

**Summary**

The use of wing sweep and stability augmentation on modern commercial airplanes makes them more fuel efficient. However, flight crews must understand the effects of CG and altitude on performance and handling qualities. For example, operating at an aft CG improves cruise performance, but moving the CG aft reduces static longitudinal and maneuvering stability. Many modern commercial airplanes employ some form of stability augmentation to compensate for relaxed stability. However, as long as the CG is in the allowable range, the handling qualities will be adequate with or without augmentation. An understanding of static and maneuvering longitudinal stability is an essential element of flight crew training.

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**Figure 1:**
**Static Longitudinal Stability and Speed Stability**

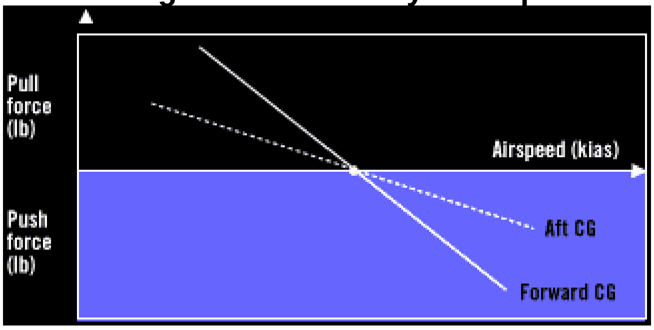


Figure 1 is a plot of speed stability, which is the manner in which static longitudinal stability is demonstrated in flight. It measures the relationship between airspeed and longitudinal control force. Simply stated, speed stability is a measure of the control force required to hold the airplane at an airspeed other than the trimmed airspeed, with the throttles fixed at the trimmed thrust setting. Airplanes with positive static longitudinal stability require a pull force to maintain a speed below the trimmed speed, and a push force to maintain a speed above the trimmed speed. For conventional airplanes (those without stability augmentation), this is a design requirement of the U.S. Federal Aviation Administration Regulations (FAR) Part 25. However, in an unstable airplane--one with negative static longitudinal stability--if the airplane is in trim and the flight crew applies a pull force, the airplane will initially pitch up and slow down, but the pitch rate will quickly become large enough to require a relaxing of the pull, and eventually a push force, to maintain a constant speed below the initial trim speed. The converse is true when the flight crew attempts to accelerate the airplane from the trimmed state. This difficult task can be accomplished without increasing the crew's workload by using electronic flight control computers for stability augmentation.

**Static Longitudinal Stability and Speed Stability**

STATIC LONGITUDINAL STABILITY

Static longitudinal stability is a measure of the tendency of an airplane to maintain its trimmed angle of attack in 1*g* flight. More strictly speaking, it is a measure of the initial pitch response of an airplane to a disturbance in angle of attack. Following a disturbance, a statically stable airplane tends to return to the angle of attack for which it is trimmed. Conversely, a statically unstable airplane tends to move away from the trimmed angle of attack following a disturbance. The term "static longitudinal stability" is the name of the stability coefficient (Cm-alpha) for the pitching moment due to a change in angle of attack. In a stable, conventional airplane, the CG is forward of the neutral point of the airplane (wing plus tail). An increase in angle of attack from trim increases the amount of lift generated by the wing and results in an increasing pitch-down moment. This drives the airplane back toward its original angle of attack. If the CG is aft of the neutral point, increasing the angle of attack causes the airplane to pitch up, away from its original trimmed condition.

SPEED STABILITY

In practice, flight test for certification of static longitudinal stability by the U.S. Federal Aviation Administration measures speed stability, a parameter equivalent to Cm-alpha. Simply stated, speed stability is a measure of the control force required to hold the airplane at an airspeed other than the trimmed airspeed. The throttles are fixed at the trimmed thrust setting to eliminate pitching moment changes due to thrust. Speed stability is measured by trimming the airplane in level flight, with throttles fixed at the trimmed condition, then slowly varying airspeed with control column input.

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**Figure 2:**
**Control Column Force**

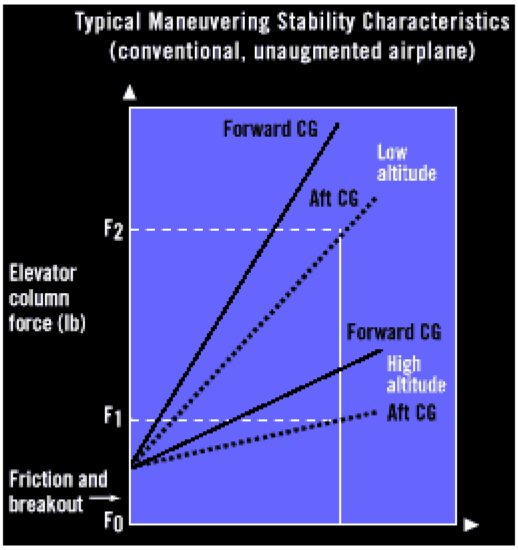


Figure 2 depicts a plot of control column force as it relates to normal acceleration for a stable airplane. It does not represent the data for any specific airplane, but instead reflects the typical maneuvering stability characteristics of a conventional, unaugmented airplane. The left axis displays elevator column force values that increase in the up direction, while the bottom axis displays normal acceleration (*g*) values that increase in the right direction. The lower the slope, the less the maneuvering stability. The lower-left corner of the graph shows that a certain amount of force must be applied before the airplane starts to move from 1*g* flight. Called friction and breakout, this situation results from the need to overcome control column static friction and the feel system centering spring.The plot makes it obvious that CG location and its effect on positive longitudinal static stability influence maneuvering stability. The maneuvering stability, or stick force per g, is higher at a forward CG, regardless of altitude. In other words, at any altitude, the stick force per*g* is higher when the CG is forward than when the CG is further aft. This has significant consequences for steep turning maneuvers. For example, to perform a level turn at 60 degrees of bank requires 2*g* in any airplane. While the plot shows that the airplane is still more stable at a forward CG than an aft CG, it also shows that altitude greatly affects the force required to pull the same

2*g* at any CG location. This plot graphically demonstrates that maneuvering at high-altitude requires less column force than it does at low altitude.

## MANEUVERING STABILITY

Maneuvering stability is related to static longitudinal stability. It is a measure of the longitudinal stability tendencies of the airplane in other than 1*g* flight, and it accounts for the effects of pitch rate aerodynamic damping during maneuvering, as in the recovery from a pitch upset.

A column force is required to maneuver longitudinally. For most airplanes, static stability attempts to maintain the airplane in 1*g* flight at the trimmed angle of attack. The column force generates a pitching moment through the elevators, or stabilizer in some airplanes, that is eventually balanced by the damping moment created by the horizontal tail and the moment due to the change in angle of attack. At this point, if the force is maintained, and there is enough thrust to maintain airspeed, the airplane stabilizes at a new angle of attack, with corresponding changes in lift and *g*. Since the pitching moments are now balanced, the pilot must hold the column force. If the column force is released, the pitching moment due to the elevator or stabilizer goes to zero, and the moments due to pitch rate and angle of attack drive the pitch rate to zero, and the airplane returns to 1*g* flight. This description of maneuvering flight points out that maneuvering stability for a given configuration manifests itself to the flight crew as the column force required to maintain a certain level of *g*. This is commonly called "stick force per *g*."