Flightlab Ground School
5. Longitudinal Static Stability

Longitudinal Static Stability

Stability is a subject that gets complicated fast. Many factors contribute, yet the aerodynamics literature lacks an accessible, lucid account. The emphasis here—and in the Flightlab ground school texts on maneuvering and dynamic stability—is to give information that allows a pilot to observe an aircraft's stability characteristics in a thoughtful way, and to understand how those characteristics may vary under different conditions and from type to type.

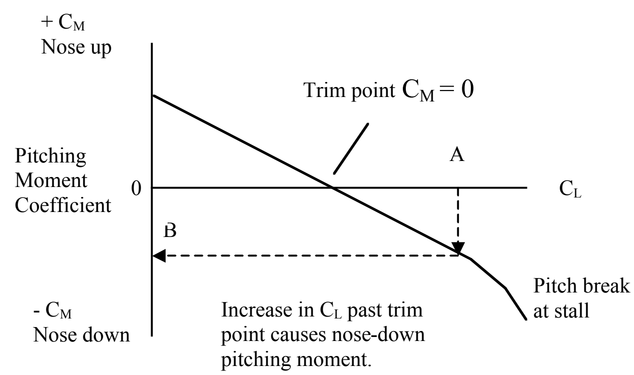
An aircraft has positive longitudinal *static* stability if its initial response in pitch, in 1-g flight, is to return to equilibrium around its trim point after displacement by a gust or by the temporary movement of the elevator control. (The term longitudinal *maneuvering* stability describes behavior in more than 1-g flight. *Dynamic* stability refers to response over time.)

When you trim an aircraft to fly at a given coefficient of lift, C_L, but then push or pull on the stick and hold it there in order to fly at a different C_L (or the equivalent angle of attack or airspeed) you're working against the aircraft's inherent stability. The aircraft generates a restoring moment that's proportional, if you don't retrim, to the force you feel against your hand. The faster that force rises with stick deflection, the more stable your aircraft.

Classical stability depends on the distance between the aircraft's center of gravity and a set of *neutral points* farther aft along the longitudinal axis—the larger the distance between c.g. and neutral point the higher the stability. We'll get back to neutral points later on.

An aircraft in trim is in an equilibrium state around its pitch, or y, axis. All the competing up or down moments (see Figure 4) generated by the various parts of the aircraft, and acting around its c.g., are in balance. In aerodynamics notation, a pitch-down moment carries a negative sign; pitch up is positive. In equilibrium, all moments sum to zero.

Figure 1
Pitching Moment versus C_L



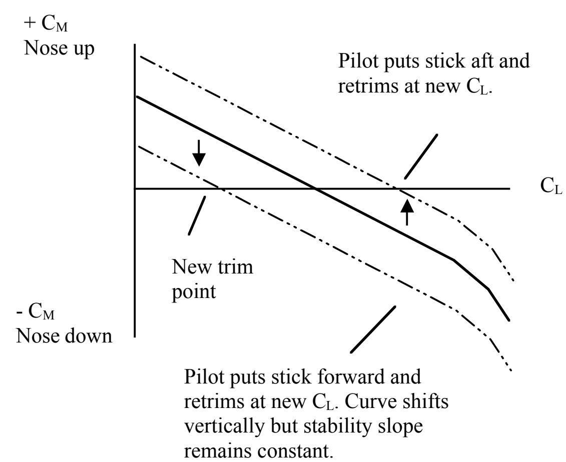


Figure 1, top, shows the change in coefficient of moment in pitch, C_M, which results from a change in coefficient of lift for a statically stable aircraft. The longitudinal static stability curve crosses the C_L axis at the trim point, where C_M = 0. If the relative wind is displaced by a temporary gust or a pull on the stick, so that the

C_L of the wing goes up to point *A*, a negative pitching moment results, *B*, which restores the aircraft to its trimmed angle of attack, α, and thus C_L.

The bottom of Figure 1 shows how the stability curve moves vertically when you change elevator angle to fly at a different C_L. Note that the aircraft's stability remains the same (same slope), but the trim point shifts.

The stability (or $\Delta C_M/\Delta C_L$) curve typically takes a downward turn to a more negative slope as the aircraft passes the stalling angle of attack (Δ, pronounced "delta," means change). This is because the downwash at the tail decreases as the wing gives up lift (assuming a root-first stall and a receptive tail location), and because the pitching moment of the wing itself becomes more negative as its center of pressure suddenly moves rearward at the stall. The increase in downward pitching moment, $-C_M$, is helpful since it aids stall recovery. If such a *pitch break (or g-break)* occurs at the stall, it must be in the stable direction throughout the aircraft's c.g. envelope under the requirements of FAR Parts 23.201and 25.201.

On the early swept-wing aircraft with a tendency to stall at the wingtips first—causing the center of lift to shift forward and the aircraft to pitch up—an initially negative, stable curve might actually reverse its slope at high C_L and produce an unstable pitch break.

A negative slope ($\Delta C_M/\Delta C_L < 0$) is necessary for positive static stability. The more negative the slope the more stable the aircraft. In addition, there must be a positive pitching moment, C_M, associated with $C_L = 0$.

The curve for a neutrally stable aircraft has a zero slope; so no change in pitching moment results from a change in angle of attack (Figure 2).

The $\Delta C_M/\Delta C_L$ curve for a statically unstable aircraft has a positive slope ($\Delta C_M/\Delta C_L > 0$). For normal certification, it must be necessary to pull in order to obtain *and hold* a speed below the aircraft's trim speed, and push to obtain *and hold* a speed above trim speed. A statically unstable aircraft doesn't obey this (Figure 3). Instead, a change in angle of attack from trim leads to a pitching moment that takes the aircraft farther from equilibrium, and actually produces a reversal in the direction of stick forces.

Figure 2
Curve Slope

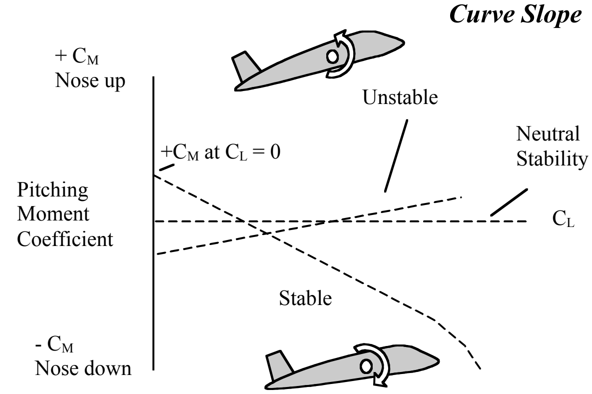
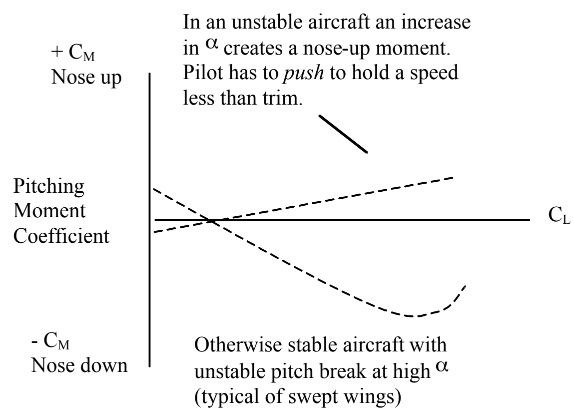


Figure 3
Examples of
Instability



The result of moderate instability might still be a flyable aircraft, but the workload goes up. Look at the positive, unstable slope in Figure 3. If you pulled back on the stick the aircraft would pitch up and slow. But if you then let go of the stick the nose would continue to pitch up, since a positive pitching moment would remain. It would require a *push* force to maintain your climb angle, not the mandated pull. If you pitched down and let go, the nose would tend to tuck under. You'd have to apply a *pull* force to hold your dive angle, not the mandated push. That's how the Spirit of St. Louis behaved. (The EAA's flying replica provides a fascinating example of the original's unstable flying qualities. It's laterally and directionally unstable, as well. But it's not hard to fly—you just have to fly it all the time.)

Pilots experience longitudinal static stability most directly through the control force (and to a lesser extent the deflection) needed to change the aircraft's equilibrium from one airspeed trim point to another. The steeper the slope of the $\Delta C_M/\Delta C_L$ curve, the more force needed.

High performance, competition aerobatic aircraft tend to be somewhere on the stable side of neutral. Compared to other types, aerobatic aircraft can feel twitchy at first, partly because the light control forces associated with their shallow $\Delta C_M/\Delta C_L$ curves cause pilots to over control. But compared to aerobatic types, more stable aircraft can feel stiff and reluctant. It depends on where your most recent muscle memory comes from. FAR Part 25.173(c) requires that transport category aircraft have a minimum average stick force gradient not less than one pound for each six knots from trim speed. FAR Part 23.173(c) takes things more broadly, requiring only "that any substantial speed change results in a stick force clearly perceptible to the pilot."

Figure 4 shows how the different parts of an aircraft contribute to longitudinal stability characteristics. The fuselage and the wing are destabilizing. Static stability depends on the restoring moment supplied by the horizontal tail being greater than the destabilizing moments caused by the other parts of the aircraft. If you require an aircraft with a wide center of gravity loading range, make sure to give it a powerful enough tail (large area, large distance from c.g., both) to supply the necessary restoring moments.

On conventional aircraft, once the design is set, static longitudinal stability and the control force necessary to overcome that stability are both functions of aircraft center of gravity location. Both decrease as the c.g. moves aft. Figure 5 shows how the $\Delta C_M/\Delta C_L$ curve changes with c.g. position.

Figure 4 Stability Components

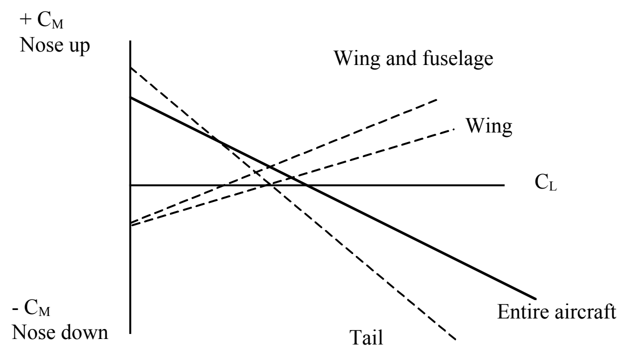


Figure 5 Stability versus c.g.

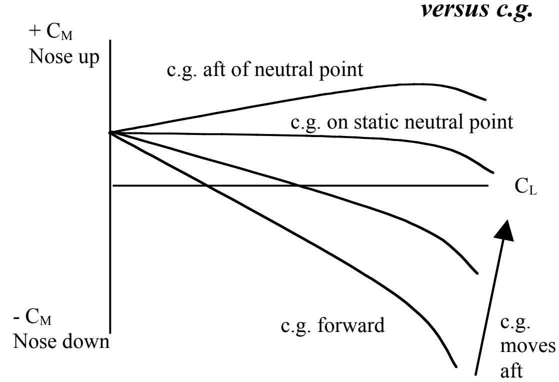


Figure 6 shows how the curve for control force necessary to fly at airspeed other than trim varies with c.g. position. The forces necessary are greatest at forward c.g. Note that we're switching from a $\Delta C_M/\Delta C_L$ curve, which a pilot can infer but can't experience directly, to forces and speeds that he can.

The tendency of an aircraft to return to trim speed when the controls are released is friction and c.g. dependent. As the c.g. goes aft and the force returning the stick to the trim position becomes less powerful, friction effects become more apparent. The aircraft can appear to have nearly neutral stability within a given airspeed band when there's appreciable friction. If you displace the stick, let the aircraft establish a new speed, and then let go, friction may prevent the elevator from returning to its original position and the aircraft from settling back to its original speed.

The speed it does settle on is called the *free return speed*, which for Part 23 certification must be less than or equal to ten percent of the original trim speed. To determine free return speeds, trim your aircraft for cruise and then raise the nose, allowing speed to stabilize about 15 knots slower. Then *slowly*, so as not to provoke the phugoid, release aft pressure to lower the nose back down to trim attitude and *hold* it there, gradually releasing aft pressure as necessary. (Don't push, since this immediately wipes out the friction—the effect of which you're trying to measure.) When you've released all aft pressure, note the speed. Repeat the exercise with a push. First let the aircraft accelerate 15 knots, and then release forward pressure to bring the nose slowly back up to trim attitude. (Don't pull—friction, again) Hold that attitude and note the speed at which the necessary push force disappears. The numbers show your free return trim speed band, and may explain why you're always fussing with the trim wheel! A wide band makes an aircraft difficult to trim.

The trim speed band may become wider as the c.g. moves aft. Aft movement reduces stability, which in turn causes the slope of the control force curve to become less negative (Figure 6). Less return force is then generated to oppose the friction within the system.

Figure 6
Control force versus c.g.

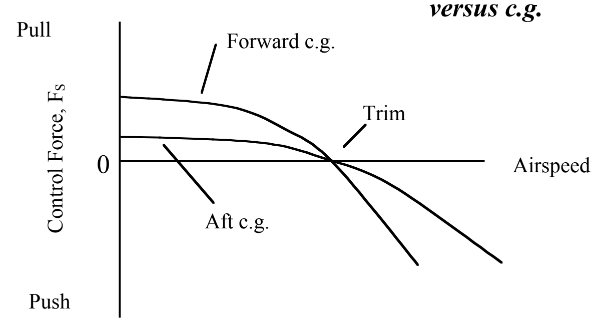


Figure 7
Free Return Speed

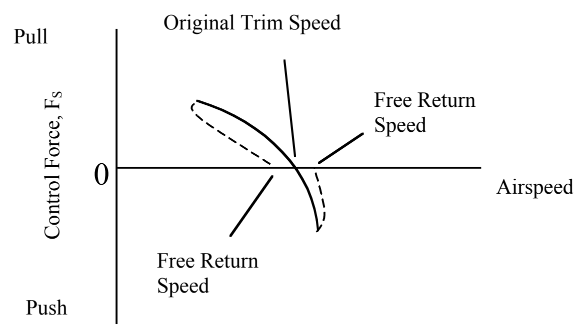
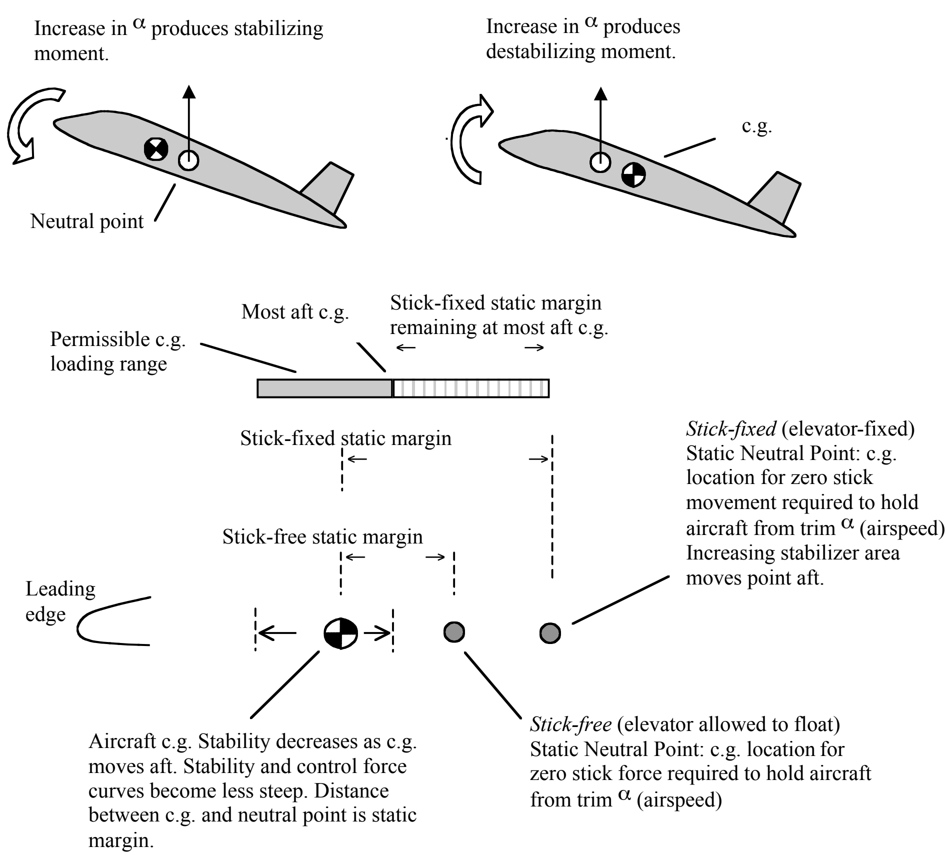


Figure 8
Static Neutral Points



Neutral Points

When the angle of attack of an aircraft changes, the net change in lift generated by the wings, stabilizer, and fuselage acts at the neutral point. The neutral point is sometimes referred to as the *aerodynamic center of the aircraft as a whole*, similar to the more familiar aerodynamic center of a wing. There's no moment change about the neutral point (or about wing aerodynamic center) as angle of attack changes—only a change in lift force.

In order for an aircraft to be longitudinally stable, the center of gravity must be ahead of the neutral point. Given that condition, the top left of Figure 8 shows what happens when a gust or a pilot input increases angle of attack, α, above trim. The increased lift, acting at the neutral point some distance from the c.g., generates a stabilizing, nose-down pitching moment around the c.g. A stabilizing, nose-up pitching moment occurs if α goes down.

The aircraft on the right shows the unstable response when the c.g. lies behind the neutral point.

Static stability decreases as the c.g. moves aft, toward the neutral point. The $\Delta C_M/\Delta C_L$ curve becomes increasingly flat. If you shift the c.g. all the way back to the neutral point, there'll be a change in lift whenever α changes, but no moment change. With the c.g. at the neutral point, pitching moment, C_m, becomes independent of α. The aircraft will have neutral static stability. Since the aircraft no longer generates a stabilizing moment, the pilot feels no opposing force in the stick when he moves it to fly at a new C_L.

The aircraft becomes statically unstable when the elephant finally gets loose and moves the c.g. aft of the neutral point. Once again there's a change in moment around the c.g. when α changes, but now it's destabilizing.

On a statically stable aircraft, the distance between the most permissible aft c.g. and the neutral point (both of which are expressed as percentages of the mean aerodynamic chord of the wing) is known as the *static margin*. The greater the static margin, the greater the stability becomes (and thus the more negative the slope of the stability curve).

Actually, as Figure 8 indicates, there're two static stability neutral points: *stick-fixed* (elevator and trim tab held in the prevailing trim position), and *stick-free* (hands off, elevator allowed to float in streamline as the angle of attack at the tail changes). In flight-testing, stick-fixed stability determines the amount of control and elevator *movement* needed to change airspeed (or C_L, or α) from trim. Stick-free stability determines the required *force*. We'll amplify this below.

Stick-fixed Neutral Point

With a powered, irreversible control system the elevator usually doesn't float unless something broke, and so only the stick-fixed stability normally matters. (However, sometimes a programmed, artificial float is introduced to cure stability problems. Also, a control system can revert in case of hydraulic failure. The Boeing 737 reverts to a reversible system following hydraulic failure. Its predecessor, the 707, was reversible to begin with.)

At a given center of gravity position, an aircraft's *static stick-fixed stability is proportional to the rate of change of elevator angle with respect to aircraft lift coefficient* (aircraft lift coefficient includes the combined wing and fuselage lift effects). In other words, the more stable the aircraft is (the larger the static margin) the farther you have to haul back or push on the stick. As you bring the c.g. back, less stick movement is needed to produce an equivalent change in C_L and airspeed—and less spinning of the trim wheel is necessary to trim out the resulting forces. If the c.g. is brought back to the *stick-fixed* static neutral point, the change in stick position needed to sustain a change of airspeed is zero. Once you've moved the stick to attain a new angle of attack, you can put it back to where it was before.

Reportedly, the Spitfire has just about neutral stick-fixed static stability in all flight modes. The DC-3 is stable in power-off glides or at cruise power but unstable at full power or in a power approach at an aft c.g.

Stick-free Neutral Point

The *stick-free* static neutral point is the c.g. position at which the aircraft exhibits neutral static stability (slope of the $\Delta C_M/\Delta C_L$ stability curve = 0) with the elevator allowed to float. In other words, it's the position where pitching moment, C_M, is independent of C_L with the stick left free.

Your intuition may tell you that *stick-fixed* static stability is likely to be greater than the elevator-floppy situation of stick-free, because of the fixed elevator's greater efficiency in producing restoring pitching moments. The actual difference between fixed and free in an aircraft with reversible controls (with reversible controls, wiggling the control surface wiggles the stick) depends on elevator control system design, in particular the control surface hinge moments. Aerodynamic balance used to reduce hinge moments, and thus reduce the force a pilot has to apply to deflect the elevator, also reduces floating tendency—and therefore increases the stick-free static stability margin. The stick-free neutral point usually lies ahead of the stick-fixed point. Just how far ahead depends directly on how much the elevator tends to float.

Figure 6 showed how the longitudinal stick force, F_S, necessary to move an aircraft off its trim point decreases as the center of gravity moves aft. This is the logical result of the accompanying decrease in static stability. When the aircraft's c.g. lies on the stick-free neutral point, no change in *force* is needed to change airspeeds.

Conventional handling qualities require that the aircraft c.g. lie ahead of the stick-free static neutral point. If c.g. moves *behind* the neutral point, control forces reverse. A pull force becomes necessary to hold the aircraft in a dive; a push force becomes necessary in a climb.