Flightlab Ground School
6. Longitudinal Maneuvering Stability

Maneuvering Stability

Longitudinal maneuvering stability is really just static stability with an additional factor: pitch rate. An aircraft in accelerated (curved) flight—whether pulling up, pushing over, or turning—has a pitch rate. Figure 1 shows the simple case of an aircraft in a pull-up. The aircraft pitches about its c.g. The tail sweeps along behind, on its arm, l_T. The tail's motion creates a change in its relative wind and thus in tail angle of attack, α_T. The change in tail angle of attack due to pitch rate produces an opposing pitching moment, known as *pitch damping*.

The change in tail angle of attack, $\Delta\alpha_T$, due to pitch rate is shown in the formula below, where q is pitch rate in radians per second (one radian equals 57.3^o; and 0.1 radian/second is approximately 1 RPM). l_T is the distance between aircraft c.g. and the aerodynamic center of the tail. V_T is the velocity of the tail (taken tangentially to the aircraft's flight path).

Thus the faster you pitch, and/or the farther back your tail, the greater the change in α_T, but it's all inversely proportional to speed, V_T, as the formula shows.

Figure 1
Pitch Damping

$$\Delta\alpha_T = \frac{ql_T}{V_T}$$

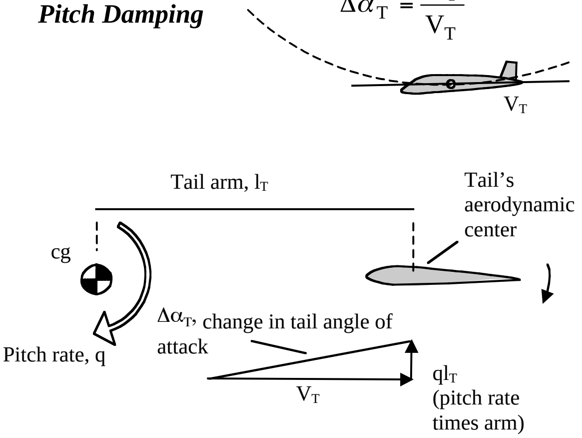
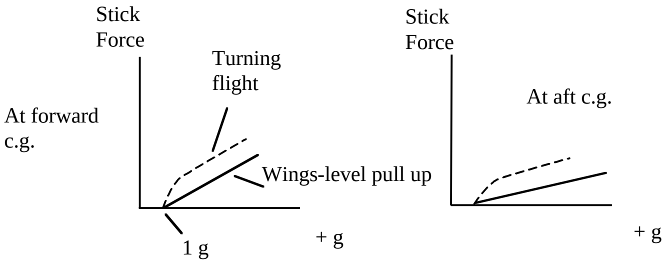


Figure 2
Stick force-per-g gradient versus c.g.



The actual tail angle of attack will also depend on the increased downwash produced by the wing as its lift coefficient rises in the pull-up, and a proper formula would take that into account.

Because of pitch damping, an aircraft is actually more stable in maneuvering flight than in flight at 1-g. Remember, we assess stability in terms of the force needed to displace the aircraft from equilibrium (trim). We assess static stability in terms of the push or pull on the stick necessary to change the coefficient of lift, C_L, and to produce airspeeds different than trim, while flying at 1-g. In maneuvering flight at more than 1-g, pitch damping increases the stick force we have to apply to displace the aircraft from equilibrium. How rapidly stick forces will increase as we increase g depends on the maneuvering characteristics for which the aircraft was designed, and its c.g. location. We can examine an aircraft's *stick-fixed* (elevator position-per-g) and the really more germane—since it's what the pilot feels—*stick-free* (stick force-per-g) maneuvering characteristics.

Figure 2 shows how the gradient, or slope, of stick *force*-per-g depends on the location of the aircraft c.g. Forward c.g. increases an aircraft's maneuvering stability, and therefore stick forces become heavier. As you move the c.g. back, stick forces required to pull g go down. (The stick *position*-per-g curve behaves similarly. As c.g. moves aft, the deflection required to pull g goes down.)

Stick force-per-g also varies directly with wing loading (aircraft weight divided by wing area). Highly wing loaded aircraft may need the help of a powered control system to keep forces in check. Raising the wing loading has the same effect as moving the c.g. forward.

Stick force-per-g is a particularly important parameter and one of the basic handling quality differences between aircraft designed for different missions. When we maneuver an aircraft, we tend to evaluate its response in terms of the *force* we apply to the stick rather than the change in stick *position*. We know the stick has returned to the equilibrium trim position, for example, when the force disappears (at least ideally—friction and other factors can get in the way). And when we move the c.g. well aft in an aircraft—or take that first aerobatic flight—it's the reduction in stick forces we probably notice first.

Fighters and aerobatic aircraft require lower forces-per-g than do normal or transport category aircraft because their g envelopes are wider and the total stick force necessary at high g would otherwise be too great for the pilot to sustain. So a fighter operating at up to 9-g or more needs a shallower force-per-g gradient than a transport expected to operate at no greater than the 1.5-g approximately required for a 45-degree-bank level turn. The fighter's shallow force-per-g gradient would be devastating in a transport because the pilot could easily overstress the aircraft. The transport's steeper gradient would have the fighter pilot pulling with both hands while pushing on the instrument panel with his feet.

The importance of stick force-per-g in fighters became apparent during World War II. It was decided that the upper limit should be about 8 lb/g to keep the pilot from tiring in a fight, with a lower limit of 3 lb/g to prevent overstressing the aircraft and losing by default.

Overstress is the big worry; so FAR Part 23.155 specifies the *minimum total* control force necessary to reach an aircraft's positive limit maneuvering load factor (g limit). It's based on aircraft weight and the type of control. For wheel controls the minimum force has to be at least 1% of the aircraft's maximum weight or 20 pounds, whichever is greater, but doesn't have to exceed 50 pounds. For stick controls, minimum force for maximum g has to be at least max weight/140, or 15 pounds, whichever is greater, but doesn't have to exceed 35 pounds.

To figure out what that would mean in terms of required average *minimum* control-force-per-g gradient, you can take the design load limit of the airplane (6-g's for our trainers), subtract 1-g to get the maximum g-load actually applied, and then divide that into the minimum total force required by regulation. For the Air Wolf (6-g's and 2900 lbs. maximum aerobatic weight):

$$\frac{2900/140}{5} = 4.1 \text{ lb/g minimum allowable stick force}$$

A Cessna 172's yoke force is greater than 20lb/g. A wings-level, 1.7-g pull-up in a Boeing 777 requires 135 pounds. The Boeing is certified under FAR Part 25, which actually doesn't contain sustained maneuvering control force requirements.

The FARs doesn't specify *maximum* stick-force-per-g, but the military does, depending on the type of aircraft.

Aircraft with shallow stick force-per-g gradients can feel dramatically sensitive if your muscle memory expects greater forces. Even experienced aerobatic pilots stepping up to higher performance aerobatic aircraft usually find themselves pulling too hard, detaching the boundary layer, and buffeting the aircraft—especially in the excitement of aerobatic competition. This is seen from the ground as an abrupt flattening in the arc of a loop, and from the cockpit as a sudden g-break. But after one becomes accustomed to those shallow gradients, the lower performance aerobatic aircraft one trained in can seem disagreeably reluctant to maneuver. The physical effort now feels out of proportion to the result.

On the other hand, pilots of early swept wing fighters had to worry about "g-limit overshoot" because of the forward shift in the center of lift as the tips began to stall. The F-86E Sabre Aircraft Operating Instructions cautioned pilots against “A basic characteristic toward longitudinal instability under conditions of high load factor, which … results in a tendency to automatically increase the rate of turn or pull-up to the point where the limit load factor may be exceeded.” Fortunately, this was preceded by lots of warning buffet.

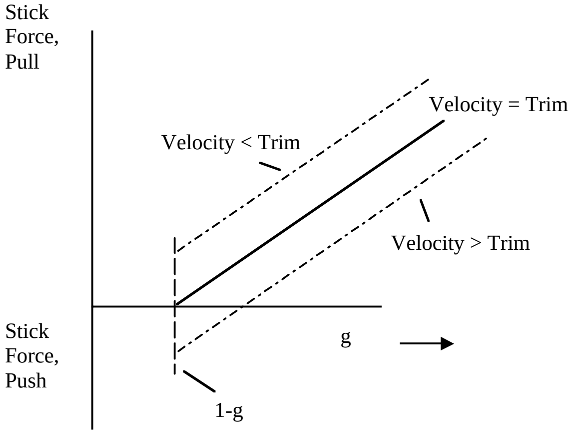
As noted, pitch damping depends on pitch rate. Pitch rate depends not just on how hard you pull, but also on the kind of maneuver you’re pulling in. *At a given load factor, n*, (where n = lift/weight) a level turn actually requires a higher pitch rate than a wings-level pull-up.

For a level (constant altitude) turn at a given velocity, pitch rate is a function of n - 1/n, but for a wings-level pull-up it’s the smaller function of n - 1. That greater pitch rate in the level turn means more pitch damping. As a result a 2-g turn, for example, requires more stick force than a 2-g pull-up. Accordingly, a high-performance turn takes more pilot muscle than a loop entry at the same load factor. See the dotted versus the solid lines in Figure 2.

Our trainers have reversible controls (wiggle an elevator by hand and the stick wiggles as well). In aircraft with reversible controls, at any given altitude and c.g., the gradient of the stick force-per-g curve is independent of airspeed. Figure 3 shows how the gradient remains constant as airspeed shifts from trim. The figure also shows how the absolute stick force needed to obtain a given g will depend on the relationship between trim speed and actual airspeed. For example, when the aircraft is flying slower than trim, static stability leads to a nose-down pitching moment, which adds to the pull force a pilot has to hold to maintain a given g. But when flying faster than trim, static stability leads to a nose-up pitching moment that decreases the pull force necessary to maintain a given g. Because of the change in absolute stick force necessary to hold a given g at speeds slower or faster than trim, test pilots try to maintain trim speed when examining stick-force-per-g in “windup turns.” Otherwise the data would plot an inaccurate stick force-per-g gradient.

The stick force needed to pull a given g remains the same at any trim speed. Say the trim speed rises. Because the elevator’s effectiveness increases with airspeed, you don’t have to deflect it as much to produce a given pitch rate and load factor as you do at lower speeds. Less deflection would mean *lower* forces, except that control surface hinge moments—which are what the pilot feels through the control system gearing—also increase with airspeed. The decrease in required deflection is canceled out by the increase in hinge moment, and the stick force required for a given g load is the same at all trim velocities (at a constant altitude and c.g.). This holds as long as compressibility effects associated with high Mach numbers don’t become a factor. Compressibility tends to produce an increase in stick force-per-g.

Figure 3
Stick force- per-g gradient is constant at constant cg and altitude.



Damping versus Altitude

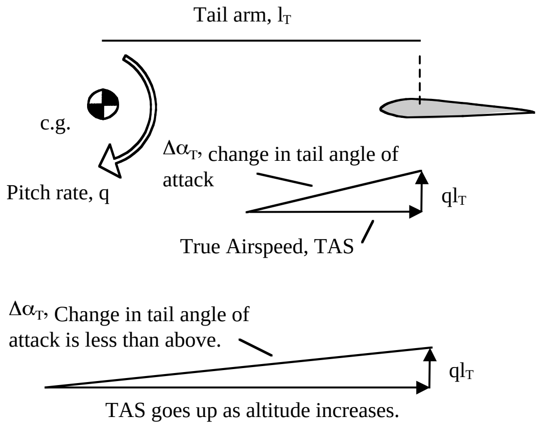
While static stability is not a function of altitude, maneuvering stability is. Stick force-per-g goes down as you go up. That’s because damping decreases along with the decrease in air density as you climb.

At least that’s the short explanation. Actually, in responding to a given control input an airplane doesn’t care about altitude, it cares about airspeed. Compressibility effects aside, for a given input it will generate the same pitching (or rolling or yawing) moment at a given EAS (equivalent airspeed, meaning calibrated airspeed corrected for compressibility) regardless of whether it’s flying down low or up high. But the damping this moment has to overcome is a function of altitude, because damping is a function of TAS (true airspeed, or equivalent airspeed corrected for density altitude), as Figure 4 explains. TAS goes up as altitude increases.

The figure shows that for a given pitch rate, *q*, the velocity component generated by the movement of the tail, ql_T, is the same regardless of altitude. But since true airspeed is higher at altitude, the vectors add up to less change in tail angle of attack, and so less damping.

This is why an airplane will feel more responsive and less stable at altitude, or perhaps even lower down on a hot, high-density-altitude day. The reduction in damping also applies to an aircraft’s directional and lateral stability. Stability augmentation systems, like yaw dampers, earn their keep up high.

Figure 4 Damping and TAS



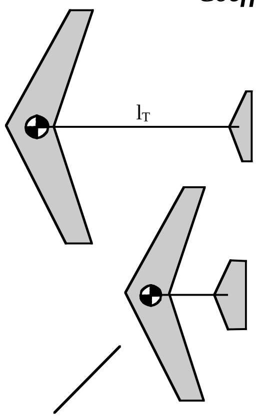
Tail Volume

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. One factor is the tail-volume coefficient, $\bar{V}$. This is the product of the distance between the aircraft c.g. and the tail’s aerodynamic center, l_T, times the tail area, S_T. The result is then divided by the mean aerodynamic cord of the wing, $\bar{c}$, times the wing area, S.

$$\bar{V} = \frac{l_T S_T}{\bar{c} S}$$

In other words, the tail volume coefficient relates the area of the tail and its distance from the c.g. to the cord and area of the wing. It suggests how effective the tail is going to be at producing pitching moments. You can achieve a given tail volume for a wing of a given size either by having a small tail on a long fuselage, or a large tail on a short fuselage (Figure 5).

Figure 5 Tail Volume Coefficient



Same tail volume coefficient as above, but shorter l_T.
Less pitch damping makes the aircraft more maneuverable.

Since *pitch damping is a function of the square of the tail's lever arm*, l_T^2, the farther back your tail is the greater the opposing aerodynamic damping generated when you start pitching it around to maneuver. The design criterion for rapid maneuvering is a big tail on a short fuselage—a hallmark of modern fighter design. Transports have proportionately smaller tails on longer fuselages.

Neutral Points Again

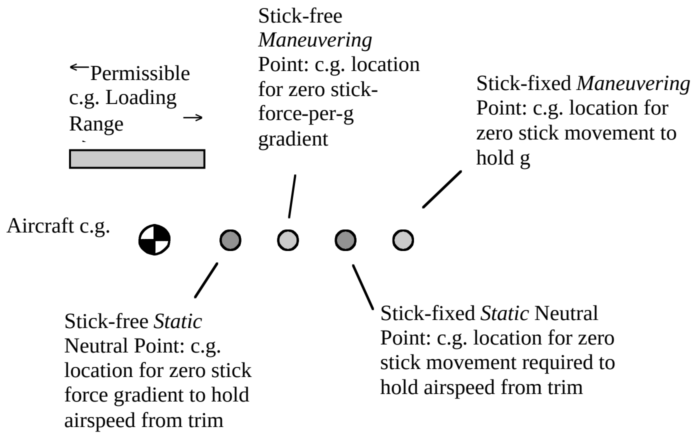
Figure 6 adds the stick-fixed *maneuver* neutral point and the stick-free *maneuver* neutral point to the stick-fixed and stick-free *static* neutral points discussed in the ground school briefing "Longitudinal Static Stability." The aft shift of the corresponding maneuver points reflects the stabilizing effect of pitch damping. Because damping goes down with altitude, the maneuver points actually sneak forward as you climb.

The stick-free maneuver point is the c.g. position at which the gradient of stick force-per-g becomes zero. The more rearward stick-fixed maneuver point is the c.g. position at which stick movement-per-g becomes zero.

If we had a weight on rails and could move the c.g. rearward during flight, the first thing we'd notice is a reduction in control force necessary to change α and thus airspeed from trim (static stability), accompanied by a reduction in stick force needed to pull g (maneuvering stability). Short of shifting the c.g., a knowledgeable instructor can simulate this for a student by manipulating the trim.

As tail volume increases, the neutral points move aft. This in turn increases the aft c.g. loading range.

Figure 6
Stick-fixed and free
Neutral Points



Typically for inherent stability and good handling qualities for an aircraft with reversible controls, maximum permissible aft c.g. must be ahead of all static and maneuvering neutral points, and forward of the point for minimum allowable stick-force-per-g. Maximum forward c.g. is determined by control authority need to raise the nose to C_{Lmax}, or by the maximum allowable stick-force-per-g.