Flightlab Ground School
7. Longitudinal Dynamic Stability

Introduction to Stability

Stability is the general term for the tendency of an object to return to equilibrium if displaced.

Static stability is an object's *initial* tendency upon displacement. An object with an initial tendency to return to equilibrium is said to have *positive* static stability. For those blessed with a conventional pilot's education, the concept of stability normally evokes the textbook image of a marble rolling around in something like a teacup, as shown in Figure 1.

An airplane can't be trimmed unless it has longitudinal (around the y axis) static stability—in other words, unless pitching forces tending to equilibrium are present. But the greater an aircraft's static stability (thus the greater the forces tending to equilibrium) the more resistant the aircraft is to the displacement required in maneuvering. For a given aircraft, the most important factor in determining longitudinal static stability is c.g. position. Moving the c.g. aft reduces static stability.

Dynamic stability, our real subject here, refers to the time history that transpires following displacement from equilibrium, as shown in Figures 1and 2.

Aircraft can either have *inherent* aerodynamic stability (the typical case), or *de-facto* stability, in which stability requirements are met with the aid of a control system augmented with sensors and feedback. For example, in order to achieve maximum maneuverability, the F-18 lacks inherent stability, and can't be flown without some operational brainpower on board in addition to the pilot. The Boeing 777 has *relaxed* inherent longitudinal static stability, which produces efficiencies in cruise from a more rearward c.g. and a physically lighter tail structure than otherwise possible. Boeing transport aircraft have conventional downward-lifting tails that, like all such tails, in effect add weight to the aircraft by virtue of the "down-lift" they generate (and also drag, the by-product of that lift). The main wing has to produce additional lift in compensation, and consequently produces more drag itself, which costs money at the gas truck. Moving the c.g. aft reduces the necessary down-force. The 777's digital flight computers make up for the resulting longitudinal stability deficit—but the aircraft still has to have sufficient inherent stability to be flown safely and landed should the digital augmentation go bust. The monster Airbus A380 employs an aft center of gravity for the same reason. It can pump fuel aft to shift the c.g.

Figure 1
Static Stability

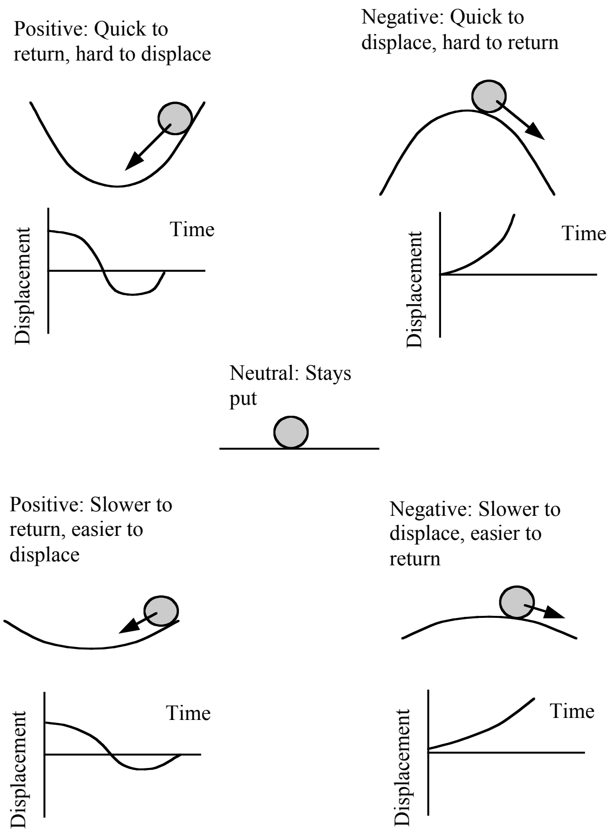


Figure 2
Dynamic Stability

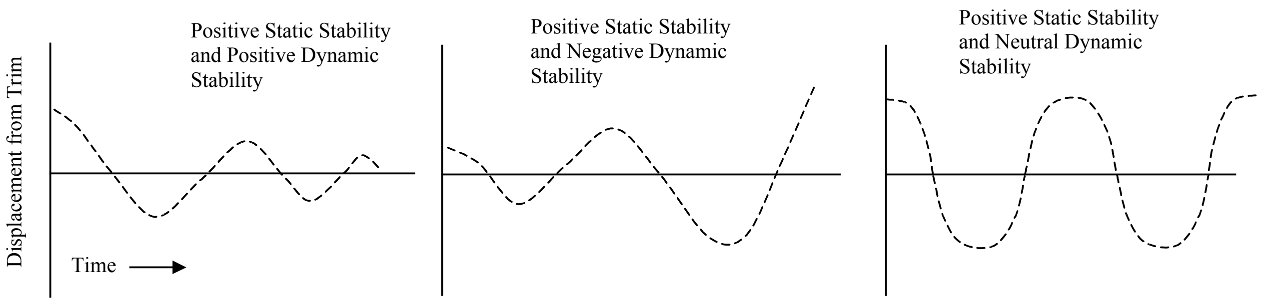
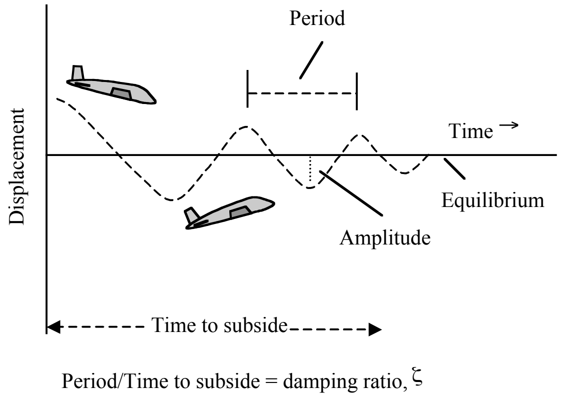


Figure 3
Positive Dynamic Stability



Dynamic Stability: Short Period and Phugoid

Figure 3 illustrates positive longitudinal dynamic stability: a series of damped oscillations of constant period, or frequency, and diminishing amplitude, that bring the aircraft back to the trimmed condition after a displacement.

Period is time per cycle. *Frequency*, which is inversely proportional to period, is cycles per unit of time. *Amplitude* is the difference between the crest or the trough and the original equilibrium condition.

Damping is the force that decreases the amplitude of the oscillation with each cycle. The *damping ratio*, ζ, is the time for one cycle divided by the total time it takes for the oscillation to subside. The higher the damping ratio, the more quickly the motion disappears.

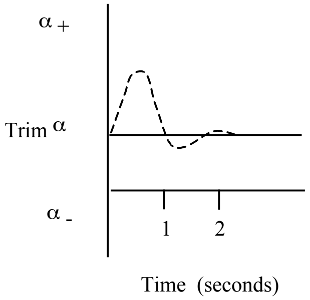
Damping defines much about the character of an aircraft. If damping is too high, an aircraft may seem sluggish in response to control inputs. If damping is too low, turbulence or control inputs can excite the aircraft too readily; its behavior appears skittish.

There are two modes of pitch oscillation: the heavily damped *short period mode* (damping ratio about 0.3 or greater), followed by the lightly damped, and more familiar, long period, *phugoid* mode. When you maneuver an airplane in pitch by moving the stick forward or back, you initially excite—and essentially just ride through—the short period mode. If you were then to let go or to return the stick back to the trim position, the aircraft would enter the phugoid mode. Instead, you normally hold the pressures necessary to prevent a phugoid from occurring.

Short Period

The short period mode is excited by a *change in angle of attack*. The change could be caused by a sudden gust or by a longitudinal displacement of

Figure 4
Short Period



the stick. Figure 4 shows the variation in angle of attack, α, over time. The aircraft quickly overshoots and recovers its original angle of attack, or its new angle of attack in the case of an intentional pilot input and a new stick position. The motion of the tail causes most of the damping, although other parts of the aircraft can contribute to damping (or to oscillation). There's negligible change in altitude or airspeed by the time the mode subsides. During the short period oscillation the aircraft pitches around its c.g.

Positive damping of the short period is important because catastrophic flight loads could quickly build from a divergent oscillation—suddenly the airplane has oscillated into parts. The short period mode is also an area in which pilot-induced-oscillations, PIO, can occur, because the typical lag time in pilot response is about the same as the mode's period (approximately 1-2 seconds). As a result, by the time a pilot responds to an oscillation his control input is out of phase, and he ends up reinforcing rather than counteracting the motion he's trying to correct.

At some point during our flights, we can perform a *frequency sweep* with the stick to try to isolate the aircraft's short period natural frequency, ω_n. (As a child you pumped a swing in rhythm with its natural frequency to make it go higher and terrify your mother.) We'll do this by moving the stick back and forth over a constant deflection range of perhaps three or four inches, but faster and faster until we find the input frequency that places us 90 degrees out of phase—meaning that the stick is either forward or back when the nose is on the horizon (although it can be hard to tell). We're then at the undamped short period natural frequency—undamped because we're driving it with the stick. Then we'll abruptly return the stick to neutral when the aircraft is at its trim attitude, and observe the damping of the short period oscillation. It subsides very quickly, as in Figure 4.

The frequency sweep is not occupant friendly, but it's a good way to assess an aircraft's pitch acceleration, or "quickness." The high pitch acceleration—the ability to quickly change angle of attack—is one of the first things you'll notice when transitioning to high-performance aerobatic aircraft. You can think of an aircraft's natural frequency in terms of its ability to "follow orders"—how rapidly you can tell it to do one thing, then tell it the opposite, and still have it respond. The higher the natural frequency, the more response cycles you can coax from it per unit of time. As we do our sweep, you'll notice that past a certain point you can't coax any more. Then the faster you move the controls back and forth the less the aircraft responds. It's as if the aircraft figures that you can't make up your mind, and that you need to be ignored.

An aircraft with a low natural frequency may seem initially unresponsive to control input. A pilot may then over control, using a large initial input to get things going, only to find that the aircraft's final response is excessive. If the natural frequency is too high, the aircraft will feel too sensitive in maneuvering and too responsive to turbulence.

Aircraft with low short period damping ratios tend to be easily excited by control inputs and turbulence, and the resulting oscillations take longer to disappear. Aircraft with high short period damping can be slow to respond—they're sluggish, and the control forces seem high.

(We'll also look at our trainer's quickness in roll. The notion of a natural roll frequency doesn't really apply, because an aircraft isn't supposed to oscillate in roll. Oscillatory response is characteristic of "second-order" systems. First-order systems, like a rolling aircraft, are exponential and non-oscillatory. We'll do some "roll sweeps," anyway. You'll discover a similar fall-off in response.)

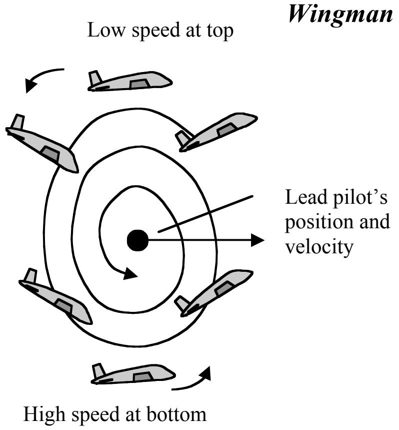
Long Period—Phugoid

The lightly damped, long period, or phugoid, oscillation can take minutes to play out. But it doesn't get to very often. Unlike the short mode, the phugoid period is long enough that the pilot can intervene easily and return the aircraft to equilibrium. We typically demonstrate the phugoid by pitching the nose up (thus exciting the short period mode) and allowing the aircraft to decelerate and stabilize some 15-20 knots below trim. Then we positively return the stick to its original trimmed position. The positive return overcomes any friction in the elevator system, and this keeps us from imposing an overall descent or a climb onto the phugoid. Usually it doesn't matter if you then hold the stick or let it go, since the difference between stick-fixed and stick-free is minor in the long period mode. But for consistency in response we want to keep the wings level. By using rudder for that job, we can avoid inadvertent pitch inputs. (On our flights we'll often enter a phugoid more theatrically, perhaps as the recovery from a spiral dive.)

From the nose-high attitude, the nose will begin to drop through the horizon into a descent, then pitch up and climb back up as speed increases. It then repeats the cycle, overshooting its original, trimmed airspeed/altitude point by less and less each time. *During the phugoid the aircraft maintains essentially a constant angle of attack,* α*,* while cyclically trading altitude and airspeed (potential and kinetic energy) until it again regains equilibrium as in (Figure 3). The pitch rate and the variation in maximum pitch attitude will diminish with each oscillation. Pitch attitude at the very top and bottom will be approximately the same as the original pitch attitude at trim. Minimum airspeed will occur at the point of maximum altitude, and maximum airspeed will occur at the point of minimum altitude.

The phugoid oscillation is typically damped and convergent, but it can be neutral, or even divergent, and the aircraft will still be flyable, because of the ease with which the pilot can bring the long period under control (you're controlling the phugoid whenever you hold altitude). But poor damping does increase the workload and complexity of the scan for instrument pilots when flying by hand, because the effort needed to hold altitude increases. Poor damping also makes it harder to trim an aircraft.

Figure 5 Phugoidal Wingman



The undulating lines back in Figure 3 suggest how the phugoid would appear to a stationary observer. Figure 5 shows the same from the point of view of another pilot flying level in formation, watching a "phugoidal" ("phugoiding?") wingman. The aircraft appears to rise and fall as airspeed changes produce lift changes. Excess airspeed at the bottom produces lift greater than weight and a resulting *upward* force. Diminished airspeed at the top produces lift less than weight and a resulting *downward* force. Remember, α stays the same.

As a result of the airspeed changes an aircraft in the phugoid would also appear to move back and forth, falling behind at the top of the cycle and scooting forward at the bottom, but less and less each time as the motion damps out.

Drag effects, rather than tail movement, damp the phugoid. Raising parasite drag increases damping. With both the short period and the phugoid mode, an aft shift in c.g., close to the neutral point, will begin to produce an increase in period and a decrease in damping (for *neutral point*, see ground school "Longitudinal Static Stability").

Propellers add a damping factor absent with jets. If brake horsepower is constant, propeller thrust increases as airspeed decreases, and vice versa. This adds a forward force at the low-speed top of the phugoid and a restraining force at the high-speed bottom. This changing thrust/airspeed relationship helps reduce the speed variation from trim and thus helps damp the motion.

The phugoid is sensitive to coefficient of lift, C_L. At slow speeds, thus at high C_L, both the period and the damping decrease. At high speeds, thus at low C_L, both period and damping increase.

Regulations

FAR Part 23.181(a) requires that the short period oscillation must be “heavily damped” with the control free and fixed. FAR Part 23.181(d) requires that “Any … phugoid oscillation … must not be so unstable as to increase the pilot’s workload or otherwise endanger the aircraft.”

Part 25.181, for large aircraft, says the same thing about the short period, but leaves the phugoid unmentioned.

The common element in the regulations is the recognition that a pilot can readily control the long phugoid mode, and it’s not a crucial factor in flying qualities.

In regulatory practice, “heavily damped” means in no more than two cycles. Test pilots for the Raytheon Premier I took the aircraft to 35,000 feet to evaluate short period behavior in gusts. After pitching up and releasing the controls (stick-free), they found that the aircraft took approximately 2.5 cycles and 5 seconds to return to level flight. The FAA agreed that this presented no safety issues, but refused to wave their criteria (2 cycles and 4 seconds). The designers fixed things by adding wedges to the trailing edge of the elevator to change the hinge moments, making the elevator’s response to vertical gusts more neutral and bringing the aircraft into line with FAA requirements. All of this happened after an earlier modification had slightly reduced the friction in the elevator control system, which in turn reduced the damping ratio. The strange protuberances you see on aircraft often have complex histories.