AOPA
your freedom to fly

Flight Control Forces

FLIGHT CONTROL FORCES
HOW AN AIRPLANE TRANSMITS ITS "FEEL"

FLIGHT TRAINING March 5, 1999 By Ed Kolano

Imagine...

You're driving down the road when the traffic light ahead turns yellow. Unlike those high insurance risks driving the cars around you, you decide to slow down for the ensuing red light and press on the brake pedal hard enough to achieve the desired deceleration.
Now imagine that it doesn't take any force to depress the brake pedal. It moves as soon as your foot touches the pedal. The farther you move your foot, the farther the pedal moves, but you can't feel it. If you withdraw your foot, the pedal comes back as well, but you still feel no force on the bottom of your foot. The car's reaction is your only cue to how much brake you're applying.

Think this might take some getting used to? Think you'd ever like it? What about a panic stop? Think there might be any tendency to over-brake?

Every time we physically interact with someone or something we rely on tactile feedback. More than a sense of touch, we use tactile feedback to know how hard to push, how tightly to squeeze, what feels good, and what hurts. You use this feedback mechanism, or cue, every time you fly.

Flying Forces

Most general aviation airplanes have "reversible" flight controls, which means you have a direct physical connection - push-pull tubes, cables, torque tubes, etc. - between the cockpit controls and the control surfaces. Therefore, the pilot feels the air load on a deflected control surface.

Actually, the amount of force feedback the pilot feels depends on mechanical engineering factors - the hinge moment of the deflected control and the gearing of the linkage, but the important point is the pilot feels a force proportional to the air load on the control surface.

Generally, the larger the cockpit control displacement, the larger the control surface deflection, and the higher the force needed on the stick, or yoke, and pedals. That works out nicely because the farther the pilot flies from the airplane's trimmed condition, the stronger the control-force feedback should be. Let's say you're trimmed for 100 knots in straight and level flight. You expect to hold back-yoke to fly at 80 knots, assuming you don't re-trim or adjust the throttle. You also expect to hold more back-yoke at 70 knots than at 80 knots.

Holding back-yoke lets you know that you're flying off-trim. The increasing control force requirement for progressively slower airspeeds gives you an idea of how far off-trim you're flying. Wait a minute - that's the airspeed indicator's job. Yes, and the control-force feedback is another source of information you can use to corroborate or suspect the indicator's reading. It's just like pitch attitude and wind noise and engine-propeller noise and probably a half-dozen other cues so subtle we don't realize we use them.

Initially, this example of yoke force as a cue to an airspeed change might sound a little far-fetched. Then again, pitot-static systems have been known to become blocked by ice, and pilots have been known to focus on VASI lights or the glideslope and localizer needles and let the airspeed indicator fall outside their scan. Having these inadvertent airspeed deviations channeled through the yoke is a nice back-up, but you have to be aware of this channel and what this force information is telling you.

Control-force feedback has other advantages. Once you get the "feel" of an airplane you can make better initial control displacements. Because you know how much force it takes, you can apply that force without the experimentation you had to go through the first time you flew the plane. You know how much yoke pull it takes to rotate for takeoff, flare for landing, compensate for lowering the flaps, etc. This predictability allows you to make those smooth transitions you're known for to everyone at the FBO.

Cockpit control-force feedback is not limited to airspeed changes. You may have heard of "stick force per G," an expression associated with maneuvering flight. Although this specific longitudinal stability term is often misused, the basic force-feedback idea generally comes through. The issue is how hard you have to pull to pitch the airplane to the attitude you want.

All three control axes are fair game for control feedback. Rolling out on a heading following a turn, you stop the roll when the wings are level. There's no disputing that the real or artificial horizon is your primary cue for achieving the wings-level goal. But the disappearance of lateral yoke force is another significant information channel that tells you where to place the yoke when you want no more roll rate. To begin the rollout you turn the yoke, and as you approach wings-level you turn the yoke toward its pre-roll position. Have you ever actually looked at the yoke during this task? Probably not, but you rely on the reduction of force you must apply to tell you when the yoke is back at the neutral position - force feedback.

Size Matters

How much force is the right amount depends on several factors. Should airliners have higher cockpit control forces than general aviation airplanes? What about the Airbus A-320, which uses a side-stick instead of the traditional yoke? Should the touch of the control stick in an aerobatic airplane be different from that of a similar airplane not designed for aerobatics? Should a trainer feel different from a business jet?

Generally, you can expect higher cockpit control forces in larger airplanes. This isn't because their larger control surfaces require more force to deflect. A better explanation for designing these higher cockpit control forces is solidly rooted in the whole feedback idea. Higher forces are there to continuously remind the pilot to be smooth and deliberate when flying this airplane. The hundred or so passengers on board want to peck at their laptops, watch the movie, or savor the in-flight cuisine, and blistering roll rates and two-G turns seem to extract some of the enjoyment from these activities. Designing the stick force per G on an airliner to be around 50 lb/g helps ensure non-aggressive normal maneuvering while preserving the pilot's ability to perform emergency maneuvers when necessary.

Let's take our cockpit control force example in the other direction. It's possible to design a reversible control system that requires very little force to deflect the control surfaces. That can translate into tiny cockpit control forces needed for flying far off-trim, or for pulling a lot of G or for achieving a very fast roll rate. We might classify these control systems as sensitive.

Of course, airplanes designed to produce high-G, dizzying roll rate maneuvers should not have the same cockpit control-force feedback as an airliner. These specialty aerobatic machines still must provide feedback to their pilots, but the forces should not be so high that the pilot is exhausted after just a few minutes of maneuvering. Keep in mind also that these airplanes are usually flown by experienced and accomplished pilots who may be more attuned to subtle cues than the rest of us.

Cockpit control-force feedback varies widely among the hundreds of homebuilt airplane designs on the market. They range from two-hands-required-for-a-full-stick-roll to a single finger stick pull for a three-G pitch-up. You won't see this variety among modern general aviation airplanes because the certification regulations specify some cockpit control-force requirements. Another reason is that the manufacturer wants to produce an airplane that "feels" like it should be flown a certain way. You should not be flying loops in a Cessna 172, which is, perhaps, one reason why the 172's stick force per G is more than 20 lb/G. Usually, pilots start a loop with at least a three G pull, which means the yoke force for a 172 (40 pounds) would be discouraging.

The type and location of cockpit controls are other things that vary in homebuilt aircraft. Side-sticks are popular, particularly in small or narrow cockpits. These control sticks are short - usually less than 12 inches from the top of the grip to the pivot point. That means they have a lot less mechanical advantage than a conventional center stick, which has its pivot on or beneath the cockpit floor.

By design, a side-stick is for one-hand use. So is a center stick, but at least the pilot has the option of grabbing the stick with his other hand. Naturally the stick force requirements for a low-mechanical-advantage, one-hand, limited-displacement side-stick should be different from the yoke of the four-place, single-engine, general aviation airplane. Yoke forces are usually higher than stick forces. The reasoning here is the two- versus one-hand operation.

Relative size matters, too. How much force it takes to pull, push, and move the stick left and right, and how these forces compare to each other, also affects the airplane's handling qualities. Imagine flying an airplane that requires a 25-pound pull to flare to land. That's about the weight of three one-gallon jugs of water - a pretty hefty tug. Next, imagine it only takes a few ounces of force to begin rolling the airplane. Do you think it might be difficult to keep the wings level during the flare?

Control harmony is the compatibility between cockpit control forces in the different axes. It can be quite challenging to modulate ounces of yoke force in roll while applying dozens of pounds of yoke force in pitch, particularly if a gust of wind hits you from the side.

The generally accepted ratio of reasonable control forces among roll, pitch, and yaw is 1:2:4. Pitch control force should be about twice the roll control force, and pedal force should be twice the pitch force and four times the roll force. This relationship makes sense. Our leg muscles are huge compared with our arm muscles. Any effort exerted by a pilot's legs should be heavier. We are also stronger pulling toward and pushing away from our chest than we are exerting an extended arm effort side to side. Most pilots are happy with the 1:2:4 ratio, which has been around for about 50 years now.

Force Shapers

When the original airplane design doesn't have the desired cockpit control-force feedback, designers resort to gadgets. You've seen them. Aileron spades, servo tabs, and aerodynamic balance horns are a few of these force-altering devices attached to various control surfaces. These fixtures all reduce the amount of force you must exert on the cockpit control. They all provide a hinge moment opposite to the hinge moment caused by the air on the deflected surface. What you feel in the cockpit is the difference between these two moments, and it is less than it would be without the device installed.

Not all force-altering devices are designed to reduce the cockpit control force. Some are intended to increase the feeling. Using an anti-servo tab is a common way to increase the cockpit control force. This trailing edge tab deflects in the same direction as the surface it's attached to. It sticks farther into the air flow, which means you must apply more muscle to deflect the surface.

Some force-shapers are internal. Springs are commonly used in airplane control systems. These can be helping or opposing springs whose function is to decrease or increase the cockpit control force, respectively.

A bob weight is another internal force-maker that is used in the longitudinal, or elevator, control system. The bob weight adds or subtracts stick/yoke force based on its location in the control system and the airplane's pitch rate and acceleration. Because the bob weight has mass, it has inertia that opposes any change to its motion.

Picture a mass attached to the end of a rod that extends forward from the control stick. When the pilot pulls the stick back the airplane pitches nose-up. As the airplane pitches nose-up the bob weight pulls downward - trying to pull the stick forward - because of its inertia. The pilot has to pull harder on the stick to overcome this forward pull of the bob weight in addition to the normal pull force associated with the deflected elevator.

If the bob weight were on a rod that extended aft from the control stick, it would tend to lighten the pull force needed. Bob weights are usually incorporated somewhere along the longitudinal control system other than the control stick, but the effect is the same.

Breakout and Friction

For all the stick force per G, hard maneuvering, and full-stick rolls we talk about, most of us spend most of our flying time in one-G flight. Whether we're climbing, cruising, or descending, we're always trimming the airplane for hands- and feet-free flight. Whenever we change the flight condition, we move the stick/yoke and pedals first. The minimum cockpit control force necessary to make the airplane pitch, roll, or yaw is called "breakout."

To see how breakout might affect your flying, imagine a flight control with no breakout in the pitch axis. The tiniest force exerted on the yoke causes the airplane to pitch. Even keeping a hand on the yoke is likely to cause inadvertent control inputs, and each of these inputs results in an unwanted airplane response.

Now let's crank up our imaginary breakout to six pounds, or the weight of a six-pack of 16-ounce soft drinks in plastic bottles. No inadvertent inputs here. Anything short of a substantial and intentional effort won't change the airplane's attitude.

Think you might have some difficulty with precision in this scenario? Too much breakout makes it hard to fine tune a control input. Depending on the control forces after the breakout, you might be pulling or pushing way too hard.

For example, suppose it takes six pounds to start the airplane pitching nose-up, but only seven pounds to generate a two-G pitch-up. Chances are good you'd be in for a less than comfortable flight. Fortunately most airplanes are not this extreme.

The right amount of breakout is enough to preclude unintended control inputs, but not so much as to make small control inputs difficult. Like the harmony between pitch and roll control forces, the relationship between breakout and control forces beyond the breakout must be compatible. Too much of one and not enough of the other makes for predictability problems and sabotages your efforts to be smooth.

Friction is everywhere, including flight control systems. Friction is the force that opposes the motion of one object relative to another. Bearings, cables in pulley channels, and hinges are a few of the flight control components where friction occurs. Most things are fine in moderation, but friction in a flight control system is not. Generally, we pilots like as little friction as possible.

Too much friction can prevent a displaced flight control from returning to its pre-displaced position. If this happens, the airplane is no longer in trim, and you're deprived of the force cue that tells you the control is in the wrong place. Re-trimming the airplane is one way to deal with this, but all you'd be doing is trimming through the friction band. You can reposition by trial and error until you happen upon the correct position. Either way the friction wins. You'll be distracted, off-trim, and probably frustrated.

Time for another imaginary airplane. This one has a generous amount of friction in the roll control system. The breakout is extremely low, and aileron spades compensate almost completely for the air loads. Got it? You've just rolled out on final approach. You return the yoke to where you think it was on base leg before the turn to final, but the airplane still rolls. You turn the yoke slightly to arrest the roll rate, and now it is rolling slowly the other direction. Again you adjust the yoke position, and again a persistent residual roll rate remains.

You have no force feedback, because the friction allows you to leave the yoke anywhere within a range of positions, and only one place within that range is the correct zero-roll-rate position. Your only recourse is trial and error. Had there been less friction and a more definitive force required when you displaced the yoke, you might have been able to converge on that correct position more expeditiously by simply returning the yoke to the zero-force position.

We pilots use all sorts of feedback channels every time we fly. All senses are working all the time even when we're not consciously feeling, listening, or looking. We can't ignore the big ones - the fumes in the cockpit or the sudden change in engine noise. But we might miss the more subtle ones if we're not prepared to observe them. Cockpit control forces fall into both categories. You're already aware of the high forces - now start feeling for the subtle ones.

Ed Kolano

GO TO ED KOLANO'S PROFILE ›