WIND TUNNEL

We continue our discussion of designing for safety.

By Barnaby Wainfan

As we continue our discussion of how designers help make airplanes safer, we turn our attention to the pilot/airplane interface. The design and functioning of the cockpit flight controls have a major impact on the safety of the airplane. In a properly designed cockpit, the controls let the pilot fly the airplane and operate its systems simply and without confusion.

In a poorly designed cockpit, controls can cause incidents or accidents for a variety of reasons. Sometimes they produce an unexpected result when the pilot operates them. Sometimes they confuse the pilot. Controls can provoke errors or, in a few cases, create unexpected pitfalls due to poor mechanical design. Some of the more serious problems a flight-controls designer can cause (or prevent) are our subject.

Confusing-Cue Controls

When a pilot flies an airplane, there are many sources of feedback between the pilot and controls. These include control displacement, control pressures, and angular control position. These cues help tell the pilot what the airplane is doing and what control inputs he is making. This information is used to determine the pilot's next control inputs. It is often difficult to tell in advance which of these cues are the most significant, and their relative importance varies depending on the flight condition.

Periodically, someone builds an airplane with an unconventional layout of the primary flight controls. The two most common reasons for this are mechanical simplicity, and/or the belief that the new controls are somehow "better" than the conventional stick/yoke and rudder pedals. Unconventional flight controls seem to show up more often on unconventional airplanes and are often more at fault for the failure of the machine than the radical aerodynamic configuration. You have to pity a poor pilot faced with an entirely new airframe, combined with flight controls that don't look or work like a conventional stick and rudder pedals.

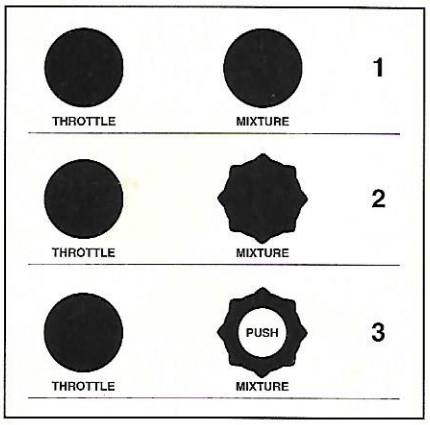


Figure 1. Two nearly identical controls like throttle and mixture in (1) are easily confused. Making them feel different (2) provides tactile feedback. Adding a lock with a release button (3) or requiring twisting instead of push-pull action should prevent confusion.

Even if the airframe is conventional and well-behaved, using unusual flight-control layouts or kinematics can be tricky. Some new approaches succeed, but often they cause problems and even accidents. The primary reason for this is that pilots have all learned to fly in airplanes with conventional controls. They have programmed themselves to react in a certain way to each set of control position, angle and pressure cues they receive. Many of these reactions are subconscious.

If the new control system provides different cues, then much of the pilot's skill is rendered irrelevant. The pilot is placed in a position of essentially having to learn to fly all over again. This means that each control input requires conscious thought rather than being subconscious as is normally the case. The critical difference here is that a pilot flying normally thinks "turn" and automatically makes the proper control inputs to initiate and coordinate a turn. A new student pilot or a pilot faced with a new set of controls has to consciously think of each control motion: "stick over, press rudder, stick back, neutralize ailerons."

All of that conscious thought takes time, which is why a new student is always "behind the airplane." An experienced pilot faced with a nonstandard set of control has this problem, compounded by the fact that he already has a set of learned automatic responses to unlearn—a potential source of real trouble. As long as the air is calm and everything happens slowly, it is possible to consciously think of each control input, and correct if it starts going wrong. But when the pilot workload gets high, as it does in turbulence or low to the ground, there is a strong tendency to short-circuit conscious thought and revert to the learned automatic responses from one's original pilot training. That's where trouble begins.

If the cues the pilot gets from a nonstandard set of controls are significantly different than those of a conventional system, the pilot can quickly lose control in a high-workload situation. The sequence goes like this: Turbulence or a control input upsets the airplane. The pilot makes an instinctive control input based on conventional controls. When the airplane does not respond as expected, he makes a second, larger control input that only exacerbates the problem because it too is wrong. The situation rapidly gets out of hand because the pilot's inputs to the controls do not produce the expected effect, and the airplane feels out of control. Since the pilot feels he is losing control and wants to correct it quickly, he continues to react instinctively rather than consciously thinking about control inputs. He gets out of phase with the airplane and the situation deteriorates rapidly.

Example: Top-Mounted Sticks

The problems encountered by airplanes and helicopters that use top-hinged control sticks are a good example of this type of situation. Top-hinging the stick is usually done in the interests of mechanical simplicity. On a helicopter, gyroplane or high-wing airplane it is much easier mechanically to hang the stick down from above than to run linkages up and around the pilot from a conventional floor-hinged stick. Unfortunately these systems have caused sev-

eral accidents because they give the pilot mixed cues that lead to confusion and loss of control.

Typically, top-mounted sticks are set up so that the direction of travel and the control pressures operate in the same sense as a conventional stick. The pilot pushes forward for down, and pulls aft for up, which is standard. What is different from a conventional stick is the angular rotation of the handgrip and the torque on the pilot's wrist. On a conventional bottom-hinged stick, pushing forward rotates the pilots hand so that the front of the hand moves down and the back of the hand moves up. The reverse is true for a pull. The change in attitude of the hand relative to the pilots body is the same as the change in airplane attitude the pilot is tying to command with the control input. If you visualize an imaginary airplane rigidly attached to the stick, moving the stick changes the attitude of the model the right way.

On a top-hinged stick, however, the angular cues are backward while the stick-force cues operate in the normal direction. Pushing the stick forward rotates the hand (and the imaginary airplane on the end of the stick) nose-up, while commanding the real airplane nose-down. This conflict between angular cues and stick-pressure cues can cause the pilot to become confused as to which way to move the stick to command the needed attitude change if the workload gets high such as in turbulence or a crosswind landing. Any input to the stick provides a pressure cue that says *zig*, and an angular cue that says *zag*. In the absence of time to sort it out, the pilot may lose the connection between stick motion and airplane response...or get it backward.

The confusion leads to pilot-induced oscillations and loss of control. This is not a theoretical possibility. It has happened more than once, and on more than one type of aircraft.

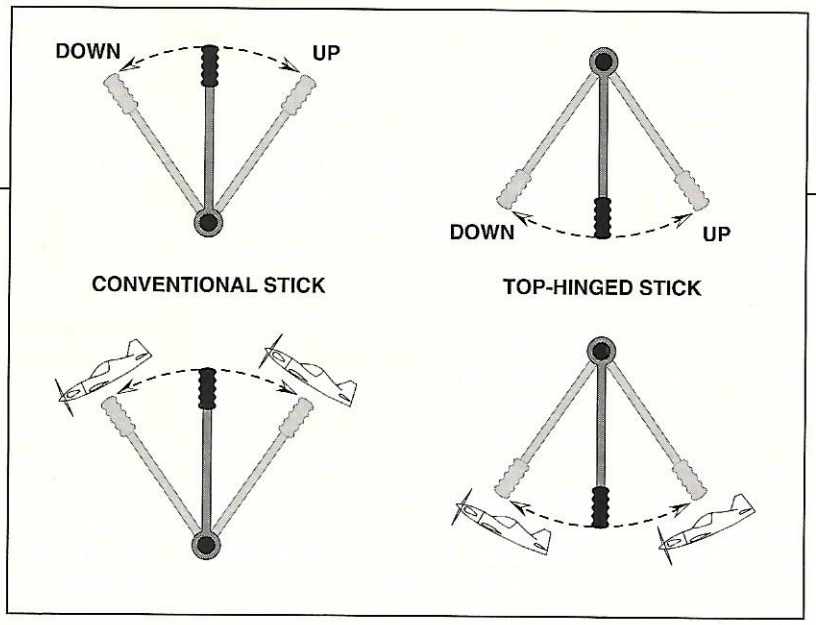


Figure 2. A top-hinged control stick may cause pilot confusion because although stick *position* is familiar, the *angle* of the stick is the reverse of a standard joystick when deflected.

The subtlety of the interaction between angle, position and pressure cues is illustrated by the fact that pilots manage just fine with no stick-angle cues in pitch. On most airplanes with yokes, the pitch attitude of the yoke remains essentially constant as it moves fore and aft, yet this does not seem to cause any problem for pilots—even those trained on airplanes with conventional sticks. It is only when the cue is reversed that confusion arises.

It is interesting to note that hang glider pilots, who move their control bars in the opposite sense to conventional airplane sticks, do not have difficulties similar to those encountered in airplanes with top-hinged sticks. They are trained to move the control bar so that its attitude change mimics the attitude change they want to command for the glider. Even though this means that the control forces are reversed relative to conventional airplane practice, the control motions are logical and, once learned, instinctive.

The importance of stick-position and stick-angle cues was not well understood until relatively recently. For a long time it was believed that pilots used stick-force feedback exclusively. They felt which way they were pulling or pushing on the stick, and this gave them the control cues they needed. The top-hinged stick problem was an early clue that this was not entirely true.

Example: Force-Only Controls

The early F-16s gave another indication that force feedback was only part of the story. The F-16 was the first production airplane to have a full-authority fly-by-wire flight control system. For the first time, the stick sent information to the flight-control computers, and the computers controlled the control surfaces without any direct connection between the stick and the control surfaces.

This made it possible to create a pure force-input flight-control system. The sidestick on the F-16 was set up so it did not move, or moved very little. It was mounted on sensors that measured the force the pilot was putting on the stick, and it sent this information to the flight-control computer. While pilots were able to fly the airplane using this system, they did not like it and complained about the lack of stick-position and stick-angle feedback from the airplane. The control system was revised, and the stick was mounted to a spring system that allows it to move in the conventional manner, although with relatively small throws. This revised system is much preferred by pilots.

The important lesson for homebuilt designers is to keep the control motions conventional. No matter what the control surfaces are doing to provide the proper aerodynamic moments, the pilot should be able to operate the flight controls like he would in a conventional airplane and get the expected response from the airplane.

Confusing Controls

There are some controls in a cockpit

ILLUSTRATIONS: BARNABY WAINFAN

that may be easily confused with others. The pilot may operate one control, thinking it is another, and get a response from the airplane that is totally unexpected and possibly dangerous. Proper design of the cockpit and controls layout can help prevent this.

One place where misidentification of controls has caused trouble in the past is confusion between throttle and mixture controls because of their proximity, size and shape. Pilots tend to reach for low-mounted controls without looking at them so they can keep their eyes focused outside the cockpit. It is easy to miss one knob and get the one next to it. A pilot who inadvertently pulls the mixture control to reduce power is going to get a larger and more permanent power reduction than he intended.

Rows of similar or identical electrical switches are the same kind of invitation to error. These errors may be more subtle and may ambush the pilot long after he has moved the wrong switch. A pilot who hits the wrong switch and turns on a light while thinking he has turned on pitot heat may never realize his mistake, and will be caught unaware if the pitot ices and causes false airspeed readings.

Cures for these problems are relatively simple. The first is to provide tactile as well as visual information to the pilot. In the case of the mixture/throttle mix-up, the pilot usually gets in trouble because he reaches for the control without looking at it. If the mixture control has a bumpy or prickly feel and the throttle is smooth, a pilot who grabs the mixture by mistake will get an immediate message that something is wrong because the control in his hand doesn't feel right.

Another aid is to make controls that can cause loss of power or similar dramatic events difficult to move without thinking about it consciously. Many modern mixture controls have a locking system that holds the control in a fixed position. To move it, the pilot must push a button to release the lock—a not-so-subtle way to get the careless pilot's attention.

Guarded switches are a way of doing the same thing for electrical systems. If a control requires two sequential actions to operate, the odds of an inadvertent action due to pilot misidentification of the control are dramatically reduced.

Another possible source of difficulty is controls that operate in a confusing, nonintuitive way. I recently saw an example of this in a nonaviation setting. I was having dinner with my family at a '50s-style diner that had jukebox controls at each table. The box had one row of buttons with letters "A" through "J" and below it a set of buttons numbered 1 through 10. To select a song, you push one letter and one number. My daughter wanted song A10. She pushed the "A" button, and then the "1" button, and was surprised and dismayed when the buttons popped out, indicating that she had made her selection.

What happened? How did she get the wrong number button? The "10" button was at the other end of the row, so she didn't just miss by one button. What caused Katie's mistake was that the vast majority of keyboard devices (computers, telephones, calculators) all have the digits 0 through 9 on the keyboard. To put in a 2-digit number like 10, we have all been trained by long experience to hit the first digit (1) and then the second (0).

This is what Katie tried to do. In this case nothing serious happened. We had to listen to "Woolly Bully" instead of "Why do Fools Fall in Love?" but that was all. A similar type of confusion on an airplane control could have serious consequences.

Facing Unusual Controls

Having flown a variety of strange and wonderful aircraft both before and during my time here at KITPLANES, I've been exposed to more than my share of unusual control systems.

Consider the B-7 Bensen Gyro-glider that I bought and (gasp! I've learned better since) taught myself to fly on a rig behind a car. This early Bensen used a top-pivoted stick in the form of an inverted T; the pilot held the horizontal bar with both hands like a bicycle and moved the control opposite the direction you would move a stick: left handle for right bank or turn and forward handle to flare for a landing!

At the time, I was actively flying conventional stick-and-rudder sailplanes and was surprised to find I could slip between the Bensen gyroplane and gliders without becoming confused. My conclusion is that the bicycle-like handle was different enough from a joystick to avoid transfer. To be fair, however, the initial training rig I installed may have saved my bacon and allowed learning with tiny, safe steps; I removed the nosewheel and bolted a 12-foot aluminum I-beam to the nose. A trailer hitch on the front end of the beam attached to the tow car. The advantage was that lifting off (forward handle) automatically reduced rotor disc angle of attack, resulting in reduced pitch authority at "altitude" (about 4 feet). The I-beam also reduced lateral excursions.

The Bede Truck-a-Plane (an engineless BD-5 mounted on a movable derrick on the front of a powerful pickup truck) offered first experience with the now-common sidestick control. Stick travel was no more than a few inches, and pilot-induced oscillation (PIO) was a concern. The solution was to keep your elbow down against the armrest and not think about it. It worked well enough that I was invited to fly the BD-5J the next day.

The early '80s offered more odd-control opportunities including some hang gliding (already described) and considerable time in the Lazair ultralights I built. They had top-pivoted sticks, and some people had trouble with that. But I read and reread the company's How to Fly It booklet before assuming the position in a factory single-seater, and it worked: no problem. But to make sure, designer Dale Kramer had me taxi as he ran at the left wingtip. With his hand, he moved the wingtip up or down and watched my reaction closely. I got to fly.

That's an example of the best advice on operating unusual controls if you must: Think about how they work and try them gently in an environment where you can't harm anything. Stay flexible!

—Dave Martin

Some problems of this type have popped up on airplanes with glass cockpits and multi-mode flight-control systems. There have been several accidents and incidents traced to mode confusion caused by poorly thought-out computer input setups.

This type of confusion is difficult to predict and prevent. In general, we should become wary when a control is moving in an unconventional way, or we are trying to improve control layout that is similar to a conventional control but does not operate completely conventionally.

Control Cliffs and Pitfalls

Some controls have cliffs or other pitfalls at the end of their travel that cause a seemingly normal control operation or a simple oversight to cause a problem. Most often, these arise from poor mechanical design.

If possible, controls should have stops so that the pilot cannot move them so far that something breaks, jams or disconnects. A control that uses a thread to make it move in and out when it is rotates should have stops to keep the pilot from unscrewing it all the way. It ruins your whole day to have a control suddenly come off in your hand in the air. Some mechanical linkages can go over center and jam or start operating backward if moved too far. Stops are prevent this.

Controls that can move themselves to an unexpected position, or that can be moved without the pilot's knowledge, can also ambush the pilot. As a student pilot, I found one of these. The trainer had electrically operated flaps. The flap switch could be pushed down from its neutral position to cause the flaps to extend and up to make them retract. The switch was spring-loaded so that it would move to the neutral position from the flap-down position, but it would remain in the flap-up position if placed there. This feature was to relieve the pilot from the need to hold the flap switch up until the flaps were fully retracted in a go-around situation.

In normal operation when the pilot wanted to add flap on approach, he pushed the switch down and held it until the flaps reached the desired position. Once the switch was released, the flaps would remain where they were. My problem was that instead of *placing* the switch in the center position after lowering flaps, I slid my finger off the end of the flap switch and allowed the spring loading to snap it back to neutral. On this particular airplane the spring was a little stronger than usual, and the switch snapped up with sufficient speed to overshoot neutral and end up in the "flaps up" position, where it remained. The flap motor dutifully retracted the flaps. Unaware that the flaps had retracted, I was most surprised to see my airspeed increasing rapidly as I tried to fly a steady approach.

The offending switch was replaced in later models of the same airplane with a preselector switch that works very well.

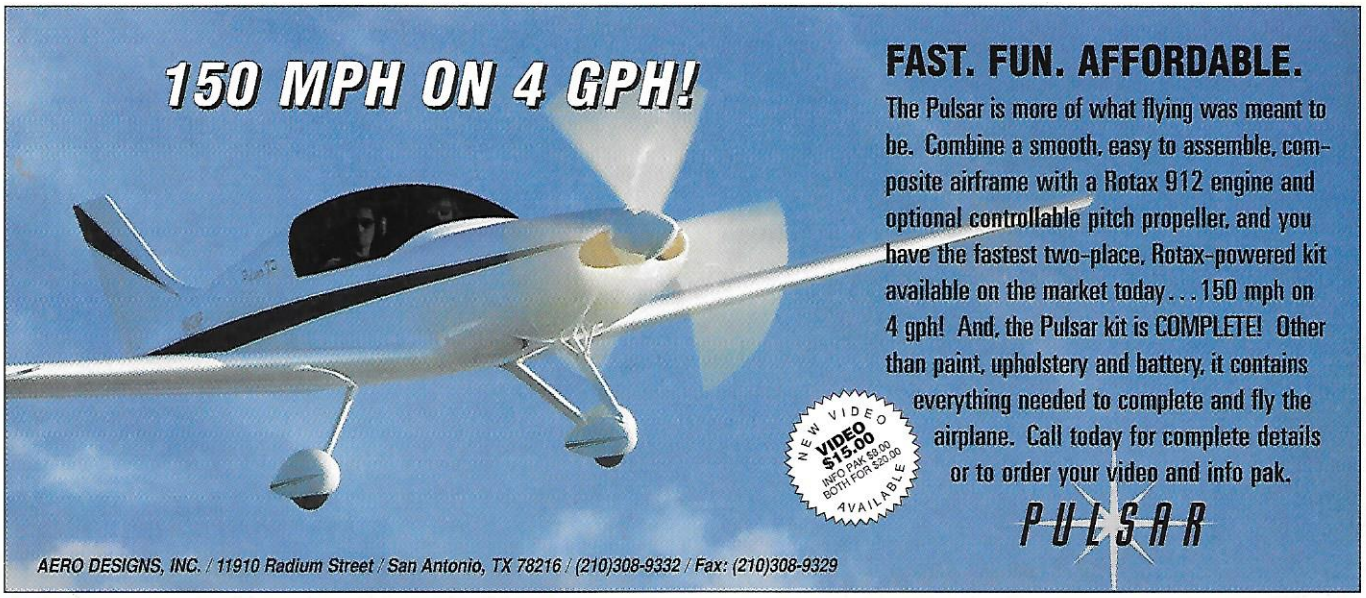
The danger in controls like this flap switch is that they can move themselves to a position the pilot did not intend. A similar problem can arise with controls that are easily bumped by normal movements in the cockpit, or that can be driven to change position by engine vibrations.

Some of these can be dangerous. If the flap switch had been a fuel selector that could pop to "off" unexpectedly, I could have had a much worse problem than a messed-up approach on my hands.

In Summary

With proper controls design, we can eliminate most of the worst pitfalls of human confusion and help the pilot fly safely. If we do things right, we can even create controls that help prevent pilots from committing common errors.

One good example of this is the control lock found on the Cessna 152 and 172. The lock fits through a hole in the control column and has a sheet-metal sign on the end that says "control lock." The shape of the lock is such that the sign blocks access to the ignition keyhole when the lock is in place.

It is this type of careful, safety-oriented thinking that we should all put into the cockpit design and layout in the aircraft we fly. ***KP***

Aerodynamic questions of a general nature should be addressed to "Wind Tunnel" c/o KITPLANES, P.O. Box 6050, Mission Viejo, CA 92690.