The Role and the Use of the Rudder

Daniel L. Johnson, reporter

"It is interesting that we, as student pilots, are given several hard and fast rules, which, as we venture out on our own, aren't so hard and fast after all."
— *F. Bick*

Author caveat: I have done my best to be faithful to the science while clarifying control use. But like all inexpert writing, this is a precis. For detail, take a degree in aerodynamics.

Two summertime letters to the *Soaring* editor about the rudder seemed to be having a mild argument about the same truth. This caused me to inquire and study a bit. The basics:

We can say that 3-axis control, first understood by the Wright brothers, is the foundation of aviation.

Ailerons: roll control

Rudder: yaw control

Elevators: pitch control

In a level turn, all three are necessary; none can be neglected.

Ailerons tip the lift vector to the inside of the turn by inducing an acceleration around the roll axis.

Rudder initiates the rate of yaw that is necessary to turn.

Elevator increases pitch to create an increased angle of attack to increase lift so that both level flight and turning occur.

"Coordinated flight" simply refers to using the controls together. Aerodynamically, its goal is symmetrical attached *airflow* across the lifting surfaces.

Our challenge as pilots operating in the turbulent air that we seek for soaring is that this air is full of swirls that instantaneously change angle of attack and wind velocity on lifting surfaces. Different parts of the aircraft may be in quite different air. This causes uncommanded pitch, yaw, and roll changes, to which we respond swiftly with control movements. *The thermal tries to spit you out.*

There are two situations in which this is especially important: circling in a thermal and landing in turbulence. We also learn that we cannot correct every wrinkle in the air, and we must learn to "fly attitude," knowing when to let the little wrinkles average themselves out, and which big wrinkles demand quick response.

"Maughmer's Rule"

Rus Howard's letter in "Soaring Mail" (July 2020, p 4) quoted the didactic *Maughmer's Rudder Rule*: "... the thermal is trying to spit you out .... While circling in a thermal the nose should be traveling along the horizon at a constant rate. If the rate slows down, you use the corresponding rudder to speed it back up. If it speeds up, you use the appropriate rudder to slow it down." (Top rudder slows the rate of turn, bottom rudder speeds it.)

Walt Cannon responded (*Soaring*, October 2020, p 5): "A turn in any aircraft is initiated and maintained by the ailerons. The rate of turn is determined by the angle of bank. The rudder is used primarily to keep the aircraft in coordinated flight. Turbulence may require independent use of the ailerons or the rudder, but in smooth flight the turn is initiated and maintained by the ailerons and coordinated by the rudder."

Well, this is often taught by those of us without knowledge of aerodynamics. It's like all inexpert writing: It reflects truth and misses nuance. Maughmer is an aerodynamicist, Cannon is a surgeon. I write because many of us have ignorantly followed simplistic rules.

When the aircraft is in equilibrium flight, it is not accelerating in any direction or about any axis. It is only then that the attitude indicators are reliable. You know how long it takes for the airspeed indicator to catch up with a change in angle of attack. Such lags are present in all indicators, reflecting time needed for the aircraft to come into equilibrium after any change in a force or moment.

The primary purpose of the vertical stabilizer is to achieve yaw, or weathercock, stability. When the fuselage is yawed, the vertical stabilizer creates a restoring moment that realigns it with the airflow, in the same way a weathervane works. A larger vertical stabilizer drives spiral instability, a small one facilitates Dutch roll. The goal of the designer is to balance these two issues.

To be exact, it's *side force* that turns the aircraft. Yawing motion is *initiated* or *stopped* and *modified* by rudder. Tilting the lift vector with bank is best, and backstick is necessary to stay level, or a spiral descent will occur. Dirigibles and submarines don't turn by banking, they generate side force by yawing the craft. A forward slip involves a large bank angle, but does not create a turn because the yawed fuselage and vertical tail create a side force opposing the tilted lift vector of the bank. This is not aerodynamically coordinated, so it's draggy, but that's the point.

Coordinated flight corresponds to a steady turn rate, and *Maughmer's Rule* is simply a way of restoring coordinated flight when the steady state is disturbed by turbulence. You don't wait for the yaw string to find a new equilibrium; you respond instantaneously to the movement of the nose against the horizon. *We are not flying the yaw string, we are flying the aircraft.*

What Is Optimal Rudder Use?

I've been piloting aircraft, off and on, for 60 years. During most of this time, I was mystified as to the *optimal* use of the rudder. I found myself a slave to the ball and needle in airplanes and the yaw string in gliders. For example, almost 25 years ago, while flying a 1-26 on the downwind leg of the pattern, the cumulus that had been growing all afternoon over the gliderport suddenly dumped its water, and my yaw string stuck firmly to the wet canopy. I suddenly realized how dependent I was on keeping the string centered, and that I had no feel for how to fly the glider without the yaw string. I decided to fly fast, in case I failed to coordinate the turn. A couple of decades later, the elderly and frayed yaw string departed my Ventus one April afternoon, and I did not bother to replace it that summer. I was now flying mostly by feel, always using a little top rudder to decrease adverse yaw and to keep the stick off the top stop, which also helps avoid skidding turns.

Helmut Reichmann, in *Cross-Country Soaring* (p 11, top left):

"IMPORTANCE OF CLEAN FLYING WHILE THERMALING

"Naturally, clean and coordinated flying is a prerequisite for decent thermaling. The yaw string is an irreplaceable and ultrasensitive 'instrument' that immediately indicates even the slightest skid or slip. Nevertheless, it is more important to center the thermal rapidly; the most gorgeous textbook circle is of little practical use if only half of it is in the updraft. Therefore: first, center the thermal, *then* be sure you are flying in a clean and coordinated manner."

What Is Coordinated Flight?

Most of my piloting life, I thought that the ball defined coordinated flight. Well, no. The ball describes which way gravity + lift is pointing. That is useful, but it's a *proxy* for symmetrical airflow over the wings and is insensitive to gusts. Similarly, the yaw string only shows the airflow past the yarn. It is a *proxy* for aerodynamic coordination that is most accurate when it is least needed: straight flight.

In my early life as a soaring pilot, I was a slave to the idea that a centered yaw string is mandatory, believing this ensured "coordinated" flight. In steep turns, it merely indicates the flow of air past the *string*, not its flow over any part of the lifting surfaces or control surfaces.

Spanwise flow always occurs. Airflow across a wing is not parallel with the wing chord, but bends away from this, especially at the outboard end, where the ailerons tend to be located. The magnitude depends on wing characteristics and direction of incident flow and lifting load.

The banked turn *inevitably* induces asymmetrical spanwise flow, as the two wings are in different airflows and doing different work. The direction of the gravity vector and the direction of airflow across the canopy cannot be thought to portray airflow across wings. Now add turbulence that puts the wings in airflows of differing velocity.

Before the winglet was invented, in a steep turn, approximately the outboard 1/3 of the flow atop the wing is detached, and only a couple of feet of the inboard aileron have attached flow. Winglets cause this flow to be attached, decreasing adverse yaw and improving aileron authority.

Without winglets, slipping the turn points the up wing aft and increases the area of attached flow, increasing aileron authority and decreasing adverse yaw. This is the key to efficiently thermaling an older, long-winged sailplane.

What Does the Rudder Do?

The two key achievements of the Wright brothers, that created aviation, were a lightweight engine with a highly efficient propeller (I've read that it's difficult to exceed the 85% efficiency theirs achieved) and effective 3-axis control. They were the parents of the rudder.

The vertical stabilizer on the tail hinders it from swishing back and forth (Dutch roll, in which the wingtips make circles).

Movement of the rudder essentially warps the vertical tail to produce lift on one side or the other.

This lift induces acceleration around the vertical (yaw) axis to create the slow rotation needed for a turn. If a slip is wanted, the rudder is held over until the design forces that give an aircraft longitudinal stability – that cause it to want to fly straight forward – balance the lateral lift of the rudder. (A skid is dangerous when close to stall.)

A turn in an aircraft involves a slow, constant yawing that is best initiated and regulated by the rudder. After this is established, the rudder is held constant until it's used to stop rotation when rolling out of the turn or to correct the effects of turbulence.

The bank itself predisposes the airframe to yaw, so that continuous rudder displacement is not needed to maintain the rate of turn *in smooth air.* Aerodynamic coordination of a turn requires bank, initiated by aileron movement.

Altitude is *maintained* by up elevator – backstick pressure – so that the centripetal force that creates turning is added to the lift that holds the aircraft up.

Adverse Yaw and Overbanking

Initiating a bank with aileron induces *adverse yaw* (the tendency of the nose of the aircraft to deflect toward the outside of the turn when bank is initiated), which is countered with rudder movement that accelerates the tail in the correct direction for the intended turn.

In a coordinated banked turn, there is also an *overbanking tendency* that increases with bank angle and wingspan. Throughout my career, I received the standard instruction, "You may need opposite aileron to maintain your bank angle."

Well, yes, this maintains a bank angle, but if you think about it, this does *not* create aerodynamically coordinated flight. The lay-instruction explanations say that overbanking occurs because the lift is greater on the outside wing than on the inside due to speed. But there is also a difference in spanwise airflow that exacerbates this, which is *made worse* by maintaining the bank with opposite aileron.

Effect of Winglets

Whatever other good things winglets have done, they decrease spanwise flow and make airflow more symmetrical in turns. This creates *aerodynamically* coordinated turns and makes handling in steep turns safer and easier. Those of us without winglets should read on.

Standard Teaching

One of the finest of soaring instructors, Dale Masters, in the first edition of his excellent *Soaring Beyond the Basics* (not in print) said about thermaling technique on p 71:

> "Making the most of strong, narrow thermals requires walking the edge of a stall or spin in turbulent air. Some sailplanes can be turned so tightly that full rudder into the turn, full opposite aileron to counter the over-banking tendency (with the yaw string centered!), and full back stick, will produce the fastest climb. Remember that when you roll out of a very tight turn your high angle of attack will be too great for straight flight, and the cure for that is neutral elevator as the wings come level."

I believed this and practiced it for years, slavishly centering the yaw string; in steep turns frequently put into incipient spins by turbulence. Steep, slow turns had the stick hard against its limit; I had to learn to manage the nose attitude and yaw rate with rudder and elevator alone. This was awkward and tiring.

Then one day, watching video of a seminar, a famous racing pilot remarked that his open class ship climbed much better when he slipped turns 10° or 15°. I drew 15° angles on my canopy from the yaw string and began practicing this. The stick came off the top stop and I no longer fell into an incipient spin with thermal turbulence. Steep turns became as effortless as level flight.

When I've related this to pilots or instructors, there's often a vigorous defense: "You must realize that the yaw string is forward of the center of gravity, and in a turn the air flow across the canopy is at an angle."

Do the math, kids! The yaw string is 3 to 6 ft forward of the center of gravity (CG) or yaw axis. The angle it would make with the glider centerline is congruent with the angle between the CG and the yaw string attachment. The yaw string angle is therefore the arctangent of {the distance from yaw axis to yaw string} divided by {the radius of the turn}. At an extreme, if the yaw string is 6 ft ahead of the yaw axis in a turn 200 ft in diameter, the angle is 3.4°. If the yaw string is 3 ft forward and the circle 300 ft in diameter, the angle is 1.14°. This is trivial.

There is another effect that means that the yaw string angle will not follow this simple math – there will be upwash along the side of the cockpit, the exact amount unknowable, depending on cockpit shape and turn dynamics, that may exaggerate the deviation. Thus, the yaw string is a fluttering approximation.

The point is that some off-center drift toward the top wing – a slip – is the best way to reduce overbanking and allow full 3-axis control in the glider without winglets. A centered yaw string in a steep turn is not necessary or desirable; but it should *not* point toward the low wing!

Adverse Yaw Is Related to Wingspan

This effect is smaller in airplanes with short wings and greater in a long-winged glider. Regardless, overbanking eventually puts the stick to the stop and then only rudder and elevator are available to keep the nose level and yaw at a proper rate. Responding to thermal turbulence is complicated, and the risk of a turbulence-induced incipient spin is high.

The better way to correct overbanking is to use a little top rudder to slip the turn. This neutralizes the stick or yoke very nicely. Aerodynamically, this makes the spanwise flow more symmetrical (better *aerodynamic* coordination) and greatly reduces pilot workload. This has been a secret technique among racing pilots for decades. The advent of winglets has greatly reduced adverse yaw and removed the need to slip turns.

Slipping Turns Provides 3-Axis Control

My own experience is that, in airplanes, when the ailerons have been neutralized by top rudder in a steep turn, the ball is about 1/3 to 1/2 of its width off-center – and the airplane can be comfortably kept in the turn indefinitely.

For example, I read that greater than 3g causes mild hypoxia by collapsing the lower third of the lung and removing circulation from the upper third. I wanted to find out whether 2g could be problematic. So I filed IFR for a local flight, and with a recording oximeter, maintained a 60° bank for five minutes at each of 3 altitudes up to 12,000 ft. With a little top rudder, this was easy to do. (The oximeter record declared that no hypoxia occurred at 2g in one elderly male pilot, a very limited experiment.)

In the Ventus, enough top rudder to bring the stick well off the stop restores normal 3-axis control and makes steep turns relaxing and comfortable. Yes, the yaw string drifts toward the outside of the turn. But the spanwise flow is more symmetrical.

When I tell instructor pilots this technique, they get emotional, as if to let the yaw string go off center creates a near-death experience. No, only if it goes to toward the *low* wing, honey! To skid a turn at low speed – risking a cross-control stall – should be experienced and understood. The break happens in a flash.

Thermal Turbulence

In a strong thermal, the air is *never* calm or smooth. This requires continual responses with ailerons, elevator, and rudder to keep one's airspeed within a desired range, to maintain a bank that will ensure staying near the thermal center, and to manage yaw when the turbulence has stopped it or accelerated it.

Meanwhile, it's useful to remember where the safe boundaries lie:

Slipping turns is safe, skidding turns is not safe. Err toward the slip (top rudder) rather than a skid (bottom rudder).

Airspeed excursions due to thermal turbulence can often be more than 10 kt. Sink rate increases rapidly when airspeed is on the slow side of best glide for your chosen bank angle. In turbulence, a little bit fast is safer and more efficient than a little bit slow.

Slip the glider a bit in turns so that pilot workload is less, because fatigue impairs climb performance more than anything, by delaying and slowing responses, and impairing decisions.

Directional Slips

The rudder is useful in straight flight, to fly crosswise through the

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air, to adjust altitude or position, especially when landing. Coordinated flight is deliberately abandoned in straight-ahead slipping: The function of the rudder is then to *produce* uncoordinated flight. The slip is described as a *forward* slip when increased rate of descent is needed, as a *side* slip when a change of direction is needed. As always, reality is often a combination. Drag is increased, so descent rate increases versus straight flight. In a glider, carrying a steep slip to landing may touch the wingtip first, a danger to ship and crew.

A sideslip is the angle about the vertical axis between the nose of a sailplane or airplane and the flight path vector. A left rudder input yaws the nose left and causes the relative wind to come from the right, aka, in the flight test world, "wind in the right ear." When a sailplane has a sideslip, it experiences rolling and yawing moments. A stable sailplane will have a left rolling moment with "wind in the right ear" and a right yawing moment.

Rudder First? Aileron First?

I've read arguments about whether a slip should be established with aileron or rudder first. My experience in a small number of aircraft is that if a steep slip is desired, the rudder should lead before it gets blanketed by disturbed airflow, and that this depends on aircraft design. The aircraft slides toward the down wing. Bank affects sideways movement and rate of descent, and the rudder is modulated, as always, to adroitly manage the forward-motion vector.

To achieve a straight-ahead forward slip, it seems most effective to first use rudder to turn away from any crosswind and then promptly lower the upwind wing to slip into the crosswind while increasing descent to the rate needed, while using rudder to keep the aircraft on the rhumb line to the runway.

The desired response to increasing rudder pedal input is an increasing sideslip. If not, it can be a wild ride. For instance, in the 1980s, the Coast Guard's HU-25, a derivative of the Dassault Falcon business jet, was being tested at Edwards Air Force Base. The test pilots were doing sideslip tests at about 38,000 ft. When the pilot put in the last input to reach full rudder pedal deflection, the vertical tail stalled and the HU-25 swapped ends. The pilot, who was an A-7 departure pilot, said it was a 3g lateral departure, the worst that he had ever experienced. Fortunately, when they released the inputs, the airplane stopped yawing and recovered.

Increasing pedal deflection should also require increasing force. This is not a problem on sailplanes because the forces are low. On a big airplane such as a KC-135 (Boeing 707), the force to reach full rudder deflection can be up to 250 lb. If the force gradient reverses, a pilot might have trouble moving the pedals back to neutral. Some sailplanes, such as a Grob 103, can have rudder force reversals at full deflection (which the pilot can easily overcome).

In a "steady heading sideslip," the pilot moves the ailerons opposite the rudder input to balance the rolling moment due to the sideslip. In a sailplane with lots of side force due to sideslip, such as a Schweizer SGS 2-33, the bank angle required to balance the side force is significant. In a flying wing, which has a low side force due to sideslip, the required bank angle is low.

Ground Handling

Some gliders have a powerful rudder that works well even at low airspeeds. If the glider has a swiveling tailwheel, or if rollout speed is enough to lift a fixed tailwheel, turns can be made during the ground roll by using *opposite* aileron (to prevent a ground loop by touching a wingtip) and using rudder in the direction of the turn. This skill should be practiced on a wide runway so that you have it in your kit of tricks when a runway incursion looms.

Nuances:

The typical pilot does not understand that pitch attitude is not the same as angle of attack, that heading angle is not the same as yaw angle, or that bank angle is not the same as roll.

Attack angle, yaw angle, and roll angle reference the aircraft and *free stream wind direction.*

Pitch angle, heading angle, and bank angle reference the aircraft and *the earth*: the horizon and north.

For example, in a loop, an aircraft could have a constant angle of attack, perhaps 10°, while the pitch angle rotates through 360°. Similarly, the yaw angle is the crosswind component of apparent wind velocity, and is unrelated to heading.

What's the Point?

"Keep the yaw string centered" is a good rule and a useful didactic guide. Like all rules, it is based on a principle. Like all rules, it is a simplification that lacks nuance and has limits. There's an old aphorism, *the exception that proves the rule*, which means that the rule is tested or revealed by understanding its exceptions. In soaring, the steep turn is that exception, where the pilot should not rigidly follow the rule – and by understanding the aerodynamics that underly it, deviate intelligently.

Acknowledgments

My sources want to remain anonymous, so please do *not* send an email about this, especially if you feel like debating. John Updike once wrote, "Language is intrinsically approximate, since words mean different things to different people, and there is no material retaining ground for the imagery that words conjure in one brain or another." Failure to hold this in mind is a cause of futile debate.

The reporter. Dan Johnson is a retired internist and AME who likes writing term papers.