THRUSTLINES and HORIZONTAL STABILIZERS. ETC.

- Greg Gremminger

(Published in *Rotorcraft* magazine, February, 2003)

What's right? Here's how to tell!

I'm going to start out with the ANSWERS first. Here are three easy flight tests that can help you evaluate if you have the proper Horizontal Stabilizer "balance" for your propeller thrustline and fuselage aerodynamics.

CAUTION: The following tests and especially tests at higher airspeeds should only be conducted by a pilot who is experienced and proficient in that particular gyro. Higher airspeeds are a common precursor to PIO and bunt-overs in many gyro configurations.

Test 1: Sum of Static Pitch Moments test:
(A "Pitch Moment" is a torque on the airframe that tends to make it pitch nose up or nose down)

- Perform this test only in calm, no wind conditions at an altitude of at least 2000 ft.
- At your typical trimmed cruise airspeed (about 50-55 mph to start with), set the power to establish level and steady airspeed. This is the airspeed which is maintained without the pilot having to add stick forces in any direction - trim spring set for hands-off flight at 50-55 mph.
- Note your "trimmed" airspeed.
- Slowly reduce engine power to idle. Allow the nose to drop to establish a descent.
- With stick force if necessary, adjust the gyros airspeed to the same as was noted in level flight above. Ideally, no additional stick force, fore or aft, should be required to maintain airspeed within 10 mph of the original "trimmed" cruise airspeed.
- Slowly increase engine power to full throttle. Allow the nose to rise to establish a climb.
- With stick force if necessary, adjust the gyros airspeed to the same as was noted in level flight above. Ideally, no additional stick force, fore or aft, should be required to maintain airspeed within 10 mph of the original "trimmed" cruise airspeed.
- If stick force is required to maintain the original "trimmed" cruise airspeed within 10 mph, the "balance" of the Horizontal Stabilizer with the propeller thrustline and other aerodynamic static moments is less than ideal and suggests possible stability/safety issues.

  CAUTION: DO NOT proceed to testing at higher airspeeds if the initial criteria above are not satisfied. This would be an indication that possible stability concerns are present and the test should not be conducted at higher airspeeds where those concerns might be worsened.

- If the initial test above is passed, repeat the same test at an initial “trimmed” cruise airspeed 5 mph higher than the original “trimmed” airspeed.

  CAUTION: DO NOT conduct additional tests if any of the above tests do not meet the airspeed criteria.

- Repeat the test at increased airspeeds – 5 mph increments of increase. DO NOT exceed Vne of the gyro.

Test 2: Maneuvering or “G”–Load Static Stability test:

CAUTION: Do not perform this test, if the Test #1 above was not completed satisfactorily.

- Perform this test only in calm, no wind conditions at an altitude of at least 2000 ft.
- At your typical trimmed cruise airspeed (about 50-55 mph to start with), set the power to establish level and steady airspeed. This is the airspeed which is maintained without the pilot having to add stick forces in any direction - trim spring set for hands-off flight at 50-55 mph.
- Note your “trimmed” airspeed.
- Slowly bank the aircraft into an approximate 30 degree bank.
- Maintain the original “trimmed” airspeed noted above and allow the gyro to stabilize in a spiral descent at a steady bank angle of approximately 30 degrees.
- If AFT stick force is required to maintain the original "trimmed" airspeed, this indicates a dynamically stable condition where the CG of the aircraft is forward of the Rotor Thrust Vector (RTV) – the desired condition.)
- If no stick force, or a forward stick force, is required to maintain the original “trimmed” airspeed, this indicates a dynamically NEUTRAL or UNSTABLE condition where the gyro CG is on or aft of the RTV – the horizontal stabilizer is not properly “balancing” the other static moments on the airframe – propeller thrust, airframe drag, etc.

  CAUTION: DO NOT proceed to testing at higher airspeeds if the initial criteria above are not satisfied. This would be an indication that possible stability concerns are present and the test should not be conducted at higher airspeeds where those concerns might be worsened.

- If the initial test above is passed, repeat the same test at an initial “trimmed” cruise airspeed 5 mph higher than the original “trimmed” airspeed.

  CAUTION: DO NOT conduct additional tests if any of the above tests do not meet the stick force criteria.

- Repeat the test at increased airspeeds – 5 mph increments of increase. DO NOT exceed Vne of the gyro.

Test 3: Static Speed Stability test:

CAUTION: Do not perform this test, if the Test #1 and Test #2 above was not completed satisfactorily.

- Perform this test only in calm, no wind conditions at an altitude of at least 2000 ft.
- At your typical trimmed cruise airspeed (about 50-55 mph to start with), set the power to establish level and steady airspeed. This is the airspeed which is maintained without the pilot having to add stick forces in any direction - trim spring set for hands-off flight at 50-55 mph.
- Note your “trimmed” airspeed.
- Slowly increase airspeed to 5 mph higher airspeed. Allow the airspeed to settle out at this higher airspeed.
- Forward stick pressure and a further forward stick position must be required to maintain that higher airspeed. If aft stick pressure or stick position is required to maintain the higher airspeed, the aircraft is not statically speed stable and further testing should not be continued.

  CAUTION: DO NOT proceed to testing at higher airspeeds if the initial criteria above are not satisfied. This would be an indication that possible stability concerns are present and the test should not be conducted at higher airspeeds where those concerns might be worsened.

- Perform the above test at incrementally **increasing** 5 mph airspeed increments and allow the airspeed to settle out at each higher airspeed. In all cases, further forward stick pressure and stick position must be required at each successively higher airspeed. If stick forces or stick position direction changes or reduces at any of the increasing test airspeeds, the aircraft is not statically speed stable and the testing should be discontinued.
- Repeat the above tests starting at the initial trimmed cruise airspeed, but with **decreasing** 5 mph airspeed increments.
- At all points the stick forces and stick position must be incremental increases in aft forces and position. If forward stick pressure or stick position is required to maintain the lower airspeeds, the aircraft is not statically speed stable and further testing should not be continued.

  NOTE: Stick forces and stick position from “trimmed” condition must always be in the direction of speed changes – Positive slope of the control curve. If the stick forces or stick position reverse direction – negative slope of the control curve – at any point in the test above, the discontinuity can leave to difficult control and possibly to PIO or bunt-over.

CAUTION: DO NOT conduct additional tests if any of the above tests do not meet the stick force criteria.

NOTE: Successfully passing the above three STATIC tests does not ensure that that particular gyro is stable and safe to fly in turbulent winds or at high speeds. Nor do the tests above assure that the gyro is not capable of Pilot Induced Oscillations or a Bunt-Over. DYNAMIC stability is not assured from the tests above. The tests above are intended only as a baseline to determine if the Horizontal Stabilizer is properly applied to STATICALLY "balance" the effects of an offset propeller thrustline or an offset Center of Drag and other aerodynamic static moments on the airframe (windscreens, sloping enclosures, etc.)

The above three tests would additionally have to be verified at all loading conditions of the gyro. The CG of the gyro varies with weight of pilot, fuel load, etc. The loading limits of the gyro are determined by the designer according to cyclic pitch control range as verified by a Hang Test.

TECHNICAL DISCUSSION:

The nose-up or nose-down flight attitude of the gyro essentially determines the in-flight orientation of the Rotor Thrust Vector (RTV) relative to the Center of Gravity (CG). As in any aircraft, it is a critical stability criterion that the Thrust Vector be aft of the CG.

Test #1, the Sum of Static Moments:

Several STATIC pitching moments, nose-up or nose-down forces, add together to determine the airframe attitude and therefore the relative location of the CG to the RTV of the gyro in flight. These static moments include any offset propeller thrustline (vertically relative to the CG), any offset Center of Drag (CD or "Dragline") vertically relative to the CG, and any other aerodynamic forces on the airframe that might tend to raise or lower the nose such as a sloping windscreen or enclosure lift forces. These static moments also include the (up or down) lift of the Horizontal Stabilizer (HS) – which has the duty of balancing the other static moments in flight – so as to hold the RTV in the stable location aft, of the CG.

The HS has the duty to maintain this flight attitude, CG/RTV relationship, at all conditions of engine power – this relationship should not change significantly at different power settings. If there is any propeller thrustline offset, the HS must react to propwash with a HS force moment that is proportional to the power setting (propwash). This would normally mean that the HS is somewhat immersed in or affected by the propwash so that the propwash would create the balancing HS moment proportional to the engine power setting. For any prop thrustline offset, high or low, some lift component, up or down, of the HS would be required. The location and angle of attack of the HS relative to the propeller thrustline would affect the propwash component strength, and HS force direction, and must be located and configured so as to properly balance the propeller thrustline static moment at all power settings. This condition would be indicated in Test #1 when little or no stick force is required to maintain “trimmed” airspeed at all power settings.

Test #1 is intended to verify that the HS is balancing the nose-up or nose-down tendencies of an offset propeller thrustline. If for instance, at higher power settings, an “unbalanced” high propeller thrustline tends to push the nose lower, an aft stick position and pressure would be required to hold the nose at the attitude to maintain the original trimmed airspeed. This would be indicating that the HS is not adequately balancing the nose-down tendencies of that offset propeller thrustline at that airspeed.

If Test #1 is not satisfied within some tolerance limits (10 mph), this would indicate that the stability and controllability of that gyro, and its safety margin from PIO or Bunt-Over is changing significantly with different power settings – the CG/RTV positional relationship is changing significantly. Generally, the condition that requires aft stick pressure would indicate the condition where there is less stability and safety margin. In some gyros, the safety margin, due to “unbalanced” static moments may be such that it is neutral of negative stability at any speed, and a change in the nose-down direction (aft stick forces) may indicate conditions which may too likely result in PIO or Bunt-Overs in adverse conditions or inadequate pilot proficiency.

Also, if Test #1 is not satisfied, the nose reaction of the gyro to a sudden change in power may excite an over-response from the pilot, especially a less proficient pilot. Such overreactions may be a precursor to Pilot Induced Oscillations (PIO). A pilot overreaction, a too rapidly large cyclic input can, in an extreme case might contribute to a precession stall and resultant fatal blade flap.

For the HS to perform this propeller thrustline offset “balancing” act, its size, moment arm (distance aft), position relative to the propwash and free airstream, and its incidence angle mounted on the tail boom may be varied to produce the desired “balance.” There are no “simple” answers to where the HS should be placed or how big it should be. There is no one simple answer to these questions. Qualified designers using standard engineering analysis tools can derive initial configurations that take these balancing requirements into account, but the final result is what counts and can only be verified by flight testing.

Test #2, Maneuvering or “G”– Load Static Stability test:

The HS has the additional duty to maintain the proper CG/RTV relationship at all conditions of airspeed – for good stability and proper reaction to g-load transients, the RTV should be aft of the CG. Airspeed would affect the static moments from the airframe drag and from any of the other aerodynamic moments on the airframe (windscreens, etc.) To balance those airframe static moments and to properly hold the

CG/RTV stable positioning, the HS must be reactive to the free air stream proportionally to the other drag and airframe lift moments. At a higher airspeed, where the nose might have more tendency to lower (pitch down), the HS, reacting to the same airstream, must hold the nose up in a balance so as to maintain the CG/RTV stable relationship.

Test #1 verified that the CG/RTV relationship is steady and "balanced" at all power settings. However, Test #1 does not verify that the RTV is truly located aft of the CG. Test #1 only verifies that the HS is holding this relationship steady with power changes.

Test #2 is intended to verify that the CG is indeed positioned forward of the RTV under all airspeed conditions. Together with Test #1, the HS will be verified to be both holding the CG/RTV in a steady positional relationship, and that the CG is forward of the RTV – a STATICALLY stable condition.

Test #2 makes this determination by effectively increasing the weight of the gyro by adding centripetal forces to the normal weight of the gyro. This additional "weight" acts at the CG location. If this CG location is properly forward of the RTV, the nose would tend to lower, requiring aft stick pressure to maintain the original airspeed. This would be similar to just increasing the load in the gyro (at the CG location), which would require aft stick pressure (or more aft trim) to hold the nose up to the same airspeed condition.

If, in Test #2, no stick force is required in the 30 degree bank when the aircraft "weight" is increased, this would indicate that the CG is located directly on the RTV – a STATICALLY neutrally stable condition. (A neutrally stable condition is a difficult aircraft to fly – similar to flying an aerobatic aircraft where the CG is purposefully located at or on the Thrust (lift and drag) Vector of the wing.)

If, in Test #2, forward stick forces were required under the additional "weight" of the gyro, this would indicate that the CG is located aft of the RTV – a negative stable condition that might be dangerous in any turbulence or in the hands on a non-proficient gyro pilot.

For the HS to "balance" the nose-up or nose-down tendencies with changing airspeed, its size, moment arm (distance aft), position relative to the propwash and free airstream, and its incidence angle mounted on the tail boom may be varied to produce the desired "balance." This time, the HS must be reacting to free airstream, not reacting to power change (propwash) influences. Probably, a VERY large HS placed well aft of the CG would have such overwhelming nose leveling tendencies that all other factors (static moments) are insignificant – i.e.: the Little Wing gyro. But, many gyros do not have the luxury of such very large and far-aft tail feathers. For such gyros, there is no single, "simple" answer. Again, engineering static moments analysis can derive configurations that take all these issues in account to start with, but the final result is what counts and can only be verified by flight testing.

Test #3, Static Speed Stability test:

Test #3 is the traditional aircraft static test to assure that the slope of the control curve is always positive. Reversal of this curve leads to pilot control input discontinuities that could result in pilot over-control or even a runaway divergence in speed control. For instance, if at higher airspeeds the pilot had to be pulling aft on the cyclic stick to prevent further increasing airspeed, this would be a control slope reversal and is especially disconcerting to less experience pilots. This criterion is a standard requirement for all aircraft to be safe with expected and normal direction of control pressures and responses.

In gyroplanes, failure of this test is often the result of a rotor design or rotor application deficiency. Certain rotor characteristics, such as insufficient airfoil reflex or rotor compressibility effects at higher rotor RPMs can result in increasing forward stick pressures at higher airspeeds requiring increasingly stronger pilot aft stick pressures to arrest the increasing airspeeds – a very disconcerting and dangerous situation. Often, this undesirable rotor tendency might have little to do with the HS or the propeller thrustline.

However, an improperly applied HS could cause the same negative slope control curve or a discontinuity in that control at certain airspeeds. This can result from too much positive lift or inclination of the installed HS – increasing tail **lift** at increasing airspeeds. Typically in all aircraft employing a HS for airspeed stability, the elemental function of the HS would be to increase **down** force on the HS as airspeed increases so as to maintain speed stability – Private Pilot Aerodynamics, 101! A significant uplift of the HS at any power or speed combination could cause an undesirable reversal of the control slope curve. Test #3 would identify deficiencies in either the rotor application or the HS installation.

Summary:

There is much discussion and often consternation these days on the subject of Horizontal Stabilizer, propeller thrustline, etc. Too often people are looking for magic “simple” answers to questions such as, “How big should my Horizontal Stabilizer be?” or “Where should my HS be located in the propwash?” The real answer is however big and wherever located to produce the proper statically balanced and stable results for your particular configuration of propeller thrustline, airframe drag and fuselage aerodynamic characteristics.

The principles described above can be used by a competent designer to estimate an initial configuration that may come close to meeting all the baseline static requirements, but the results can only be measured and verified by flight test. There are likely a number of configurations that can satisfy all the requirements above. The final answer will likely be a specific blend of many of the “simple” answers. For instance, a “fully immersed” (in the propwash) HS can certainly be superbly effective at balancing any propeller thrustline offset. But, the “enhanced” free airstream that the HS is reacting to (in the accelerated air of the propeller) may also be a function of power levels (propwash), and make it difficult to achieve a HS balance proportional to the fuselage drag and aerodynamic moments (that are a function of airspeed only.) For instance also, the incidence angle of the HS to balance the propeller thrustline offset may not be the same, or even the same direction, as that required to balance a nose-down tendency of the airframe or a windscreen.

One final CAUTION is appropriate. The tests and discussions above are only addressing issues related to STATIC pitch balancing and STATIC stability. Although assuring that the RTV is steadily positioned aft of the CG under all airspeed and power conditions is an essential prerequisite to a safe and stable gyro, other additional factors not addressed here may also affect the safe and stable characteristics of any particular gyro. The DYNAMIC reactions of the gyro to wind or pilot disturbances are significant factors that are not addressed or assured by the STATIC tests or discussion above. Dynamic reactions are the result of other factors such as Moments of Inertia of the airframe and rotor and how those Dynamic factors “harmonize” with each other.

For instance, a gyro which passes the above STATIC tests is not necessarily assured to have moments of inertia that might not “resonate” or “feed” each other at certain disturbance rates so as to make the gyro very difficult to fly - PIO. The DYNAMIC stability of a particular gyro configuration also does not have easy or “simple” answers. Assurance of DYNAMIC stability also requires flight testing. Unfortunately, although we know how to perform such dynamic stability flight tests, we are not sure what the “safe” criteria for DYNAMIC stability for a gyro should be – to be “safe”, does it need to be the same criteria as used for airplanes? Also, performance of such testing in a gyro which may have hidden dynamic stability issues may not be totally safe and must be approached cautiously. The airplane industry and military use professional Test Pilots for this all flight testing.

On top of all that, no gyro should be flown with such abuse (push over the top of a zoom, rapid stick movements, etc.) that could result in precession stall, blade flap, or even bunt-over. By design, we can do a lot to assure gyros have a large safety margin from PIO and other non-recoverable events, but there is also no substitute for good training, lots of careful practice, and a thorough knowledge and respect for all these issues.

Suffice it to say, that any gyro, whether it meets some “simple” rules or passes the static flight tests above, should not be considered to be invulnerable to pitch related non-recoverable events. Until we have total assurances that our particular gyro, at the loading and airspeed and power settings and maneuvers and wind and pilot proficiency levels that you are experiencing is proven to be safe, approach every questionable condition with a very large amount of respect. Certainly take any “over-simple” solutions or assurances with a large “grain of salt” until they have been proven to be safe by demonstrable and repeatable flight tests. That really means, at this stage of the technology, do not submit any gyro to abuse or questionable conditions beyond the unquestioned safe limits of the gyro or the pilot.

Have a safe day!

Addendum

Propeller Thrustline – High or Low?

There is much consternation and arguing and advice concerning whether the propeller thrustline should be above the CG or below the CG. Perhaps unfortunately, the prevailing current common paradigm is that a high propeller thrustline is bad and a low or "centered" propeller is good! I believe this is not supported by good aerodynamic theory. I believe that the "best" configuration, the configuration that results in smooth and stable and harmonious control, is with the propeller thrustline slightly higher than the CG. This might sound like blasphemy to many, but here are the real aerodynamic facts:

First, a large propeller thrustline offset in either direction is not good. A very high propeller thrustline makes the job of the HS (to balance that high nose-down moment) very difficult – and still do the other "balancing" jobs that the HS needs to do. A very low propeller thrustline, and actually any low propeller thrustline, requires an up-lifting HS and is inherently not statically airspeed stable. And, a very low propeller thrustline, with the required strong up-lift of the HS can result in a very significant nose-down response upon rapid power decreases – engine failure? Rapid nose-down reactions are highly undesirable in gyros and can easily lead to pilot over-control or even rotor precession stall.

Secondly, a low propeller thrustline requires the HS to respond with up-lift in the propeller propwash. This requires a positive incidence HS – or one that assumes a positive incidence when the nose is forced higher by the low propeller thrustline. An up-lift on the HS is not consistent with the down-lift require of the HS for airspeed stability.

Alternately, a high propeller thrustline requires a down-lift HS reacting in the propwash. This negative incidence HS is at least consistent in lift direction with that required for airspeed stability. Also, typically for gyros, the Center of Drag is below the CG (landing gear, seat, fuselage enclosure, etc.), presenting a nose-down tendency that must be "balanced" by a down-lifting HS. And typical windscreen configurations also impart a nose-down static moment that also requires a down-lift HS. This suggests that, for a high propeller thrustline, it is at least possible for one HS to do all the jobs it needs to do – at least the incidence angle for all requirements is in the same direction.

A high propeller thrustline configuration requires a down-lift HS consistent with the other aerodynamic requirements of the HS. A single positive-lift HS required to balance a low propeller thrustline would be difficult to arrange so that it would also present a down-lift for free airstream reactions. The three static tests above will identify the dilemma of this inconsistency presented by a propeller thrustline that is below the CG.

SIDEBAR

Talking Gyro Stability

- Doug Riley

Most of us would like to fly a pitch-stable gyro. Many of us think we already do. Once you start investigating stability in detail, though, you quickly discover that we don't all mean the same thing when we say a certain craft is "pitch stable." You have to tighten up your definitions of "stable" (and certain related words) if you are going to make much progress talking about stability. Here are some typical terms used in these discussions (including the accompanying article) and their common meanings in the rotorcraft design world.

Stable. A gyro pilot chatting at the bonfire may tell you his bird is "stable," meaning that he can handle it comfortably. However, engineers mean something more specific when they speak of stability. A bicycle, for example, is unstable in the roll axis, but not especially difficult to handle. In the engineering sense, a device is "stable" if it tends to return to its earlier state after being disturbed, without the assistance of the operator. A gyro that can only recover from a disturbance with control input from the pilot isn't "stable" in this sense, even if the pilot finds it simple to fly.

Balanced Moments. Imagine a gyro flying in a steady climb/glide/cruise. Each moment (that is, torque) acting on the airframe is being opposed by one or more other moments, so that they all net up to zero. This is a condition of "balanced moments." For example, if the engine's torque reaction on the frame is 75 foot-lb. clockwise, we know that something acting on the gyro is creating a 75 ft.-lb. counter-clockwise torque to balance things out (with engine torque, either a tall tail or a slight tilt of the airframe does the balancing). Note: Greg's flight tests examine whether the gyro, once disturbed from a state of "balanced moments", returns to a balanced state without help from the pilot. In other words, whether the gyro is stable with respect to moments in the pitch axis.

Bunt or Bunt-over. A catchall term for several kinds of unstable pitch behavior in a rotorcraft. In a bunt, the aircraft experiences a rapid, uncontrolled, tight forward pitching rotation. It occurs because the moments acting on the airframe have gone seriously out of balance. Power pushover (PPO) is the most common form of bunt in gyros, but it's not the only possible type. PPO can occur in any gyro whose prop thrust creates a nose-down pitching moment on the frame IF, for any reason, the usual counter-moment to this pitching effect suddenly weakens. Besides engine thrust, other possible causes of "bunt" include windshields that produce a nose-down "wedging" effect, large, draggy wheels or floats. A "bunt" from PPO or any other cause can't happen as long as a counter-balancing moment of adequate strength is present. In the case of drag or "wedge" effects, however, the counter-moment must automatically adjust its size as the airspeed changes. In the case of thrust effects, the counter-moment must automatically adjust its size as the pilot adjusts the throttle. Greg's tests help determine whether these automatic adjustments occur in the test gyro.

Pilot-Induced Oscillation or PIO. A rhythmic back-and-forth rotation of the airframe in response to the pilot's back-and-forth control inputs. Gyro pilots usually talk about PIO in the pitch axis (nose up-and-down bobbing), although it sometimes occurs in yaw or roll as well. PIO does not happen without push-then-pull inputs by the pilot. A gyro won't PIO when the stick is either held perfectly still or flown hands-off. A gyro that lacks stability, however, is much more likely to lead its pilot into PIO, because the pilot must actively "work" the controls of an unstable craft to keep it steady. If the pilot's timing is off, PIO will result. PIO is especially dangerous in a gyro that relies on its rotor to provide some of the moments that keep the gyro in balance. That's because one consequence of PIO can be a temporary loss of thrust from the rotor ("zero G") as the nose drops. Without that thrust, there are no balancing moments from the rotor. A horizontal stabilizer (HS) provides "damping" of rhythmic pitching, like a shock absorber, and so helps to keep PIO from developing. The HS also can be set up to provide balancing moments in the pitch axis, which makes it unnecessary for the rotor to provide them. This lessens the danger in the event of an accidental "zero G" (though it is still a hazardous maneuver that gyronauts should avoid).

Doug Riley began building and flying gyros in 1970. He took engineering courses while an economics student at Brown University in the 1970's. He operated AEROTEC, Inc., a gyro kit-and-material supplier, for 14 years. Doug has owned and worked on Bensen, Air Command, Gyrobee and Dominator gyros, as well as fixed-wing ultralights. He now teaches ultralight gyro flying as a part-time ASC BFI in northwestern Vermont. Doug can be contacted by email at ***driley@lisman.com***