by Chuck Beaty

Gyroplane Stability

Understanding PIO, Buntover, and How Gyroplane Rotors Work

Introduction

To a person standing on the ground, especially here in Florida, the Earth seems, intuitively, to be flat. To many experienced pilots, a tailless gyroplane seems, intuitively, to be stable.

Intuition doesn't always coincide with fact. Much depends on the point of view. An astronaut in the space shuttle has an entirely different view of the Earth than a person on the ground. A person who has flown a tailless gyroplane with helicopter-type cyclic pitch control gets an entirely different impression than one who has flown only with a Bensen-type tilt head cyclic control. With a Bensen-type offset gimbal rotor head, a component of rotor thrust is fed back into the control system in a direction which serves to mask the instability of a tailless gyroplane and gives a misleading impression of stability.

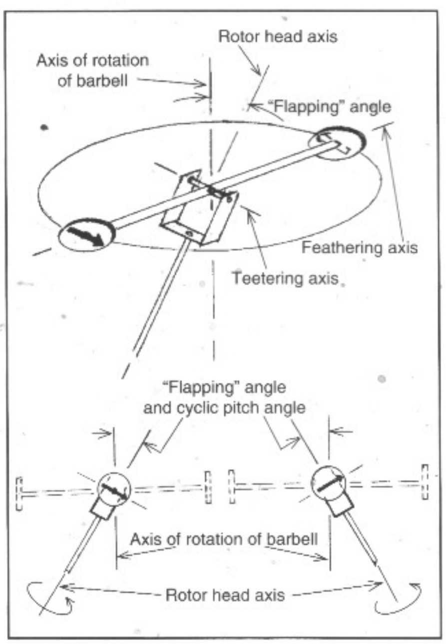
The following article is an attempt to present the facts of gyroplane stability comprehensively but with a minimum of mathematics.

Rotor kinematics

The single greatest obstacle to understanding rotorcraft is the difficulty of the spatial visualization of rotor blade motion. The common terms used for describing blade motion, "flapping" and "lead-lag", are inaccurate and misleading.

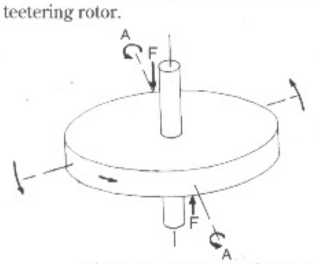
Imagine a barbell equipped with a teeter pin and mounted on some sort of rotor head. If we start the assembly spinning, we discover that we have a gyroscope and that its axis remains fixed in space, no matter which way the rotor head is tilted, so long as we don't run into mechanical interference. If an observer rotated with and viewed the barbell along the rotor head axis, the barbell would indeed appear to flap but there would not appear to be a cyclic pitch change. If the rotating observer viewed the barbell along the barbell axis, there would be a cyclic pitch change but no flapping.

The barbell, in fact, doesn't flap in the sense that a bird's wings flap; the combination of teeter pin and barbell axle is simply a universal joint which allows the barbell to rotate about a different axis from the rotor head, and permits a cyclic pitch input by tilting the rotor head. The arrows painted on each face of the barbell weights always remain parallel to the teeter pin.



If the barbell weights are replaced by airfoils, aerodynamic forces are produced which tend to force the rotor axis into alignment with the rotor head axis.

The kinematics of an articulated rotor are not fundamentally different than a teetering rotor.



The axis of rotation of a gyroscope remains fixed in space in the absence of external forces. Forces applied at arrows F in the illustration cause a counterclockwise precession about axis AA. The left side begins to fall and the right side rises. Precession is such that displacement of the gyro wheel lags applied force by 90°.

The rate of precession of a gyroscope depends on the ratio of precessing torque (force) to the moment of inertia and speed of the gyro wheel.

$$\text{Angular velocity of precession} = \frac{\text{torque}}{\text{angular velocity of gyro wheel} \times \text{moment of inertia of gyro wheel}}$$

Precession will be in radians per second when torque is in foot-pounds and moment of inertia is in slug-feet^2.

One radian = 57.3°, there are 2π radians in 1 revolution (360°).

One slug = 32 pounds, the English unit of mass (W/g).

A typical gyrocopter rotor weighs 37 pounds and has a diameter of 22 feet. Its moment of inertia is 46.6 slug ft². It turns, typically at 360 rpm, and its angular velocity is 37.7 radians per second. How much torque would be required to precess (tilt) the rotor at a rate of 10° per second (10°/second = .1745 radians per second)?

Torque = angular velocity of precession x moment of inertia of rotor x angular velocity of rotor

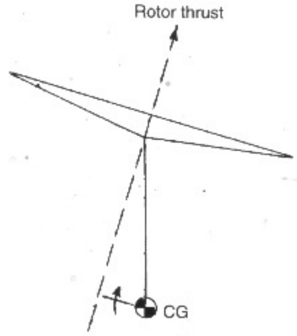
Torque = .1745 x 46.6 x 37.7
= 306.6 feet-pounds

The center of lift of the rotor blade is about 70% of radius—one-half the rotor disk area is inside 70% radius, the other half is outside. The lift differential between the advancing and retreating blades for the gyrocopter under discussion would be $\frac{306.6}{11 \times .7}$ = 39.8 pounds to tilt the rotor at a rate of 10°/second in forward flight.

An understanding of the mechanics of precession is essential to some of the discussion to follow.

Control by thrust vector orientation

All rotorcraft with flap hinges located on the center of rotation, whether teetering or articulated rotors, whether swashplate controlled or tilting rotor head controlled, are controlled by orientation of the rotor thrust vector about the pitch and roll axes.

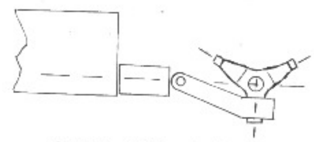


Rotor thrust is concentric with the tip plane axis. In the illustration above, the rotor is tilted to the right and the rotor thrustline is offset to the left side of the machine's CG. This offset generates a moment (or torque) which begins to roll the machine to the right.

The rotor aligns with a cyclic stick displacement within, typically, 2 or 3 revolutions of the rotor, 1/3 to 1/2 second at 360 rpm rotor speed but the airframe does not. Since the airframe has inertia about the roll axis, the torque which results from displacing the rotor thrust vector begins to accelerate the machine about the roll axis. This angular acceleration equals the applied torque divided by the roll axis moment of inertia.

Stick displacement in a fixed-wing machine controls roll or pitch rate. Stick displacement in a rotorcraft controls roll or pitch acceleration.

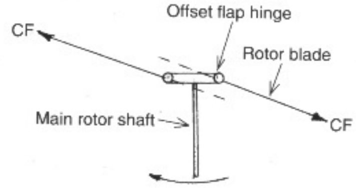
Control by thrust vector orientation is dependent on the presence of rotor thrust. No thrust, no control.



Sikorsky S-51 rotor head

Early helicopters such as the Sikorsky S-51 generally had flap hinges located on the center of rotation and were controlled by thrust vector orientation, exactly the same as teetering rotors.

Newer helicopters have offset flap hinges which provide some additional control moment. This is called the "T-bar" effect.



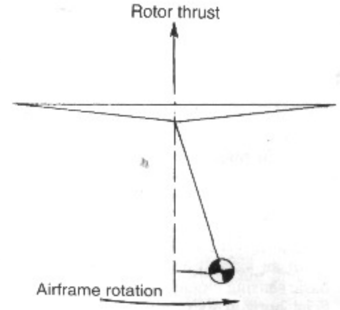
The Hughes 269-300 helicopters have a flap hinge offset of about $1\,^3/_4$" which provides a control moment of about 50 ft-lb per degree of rotor tilt independent of rotor thrust—not much when compared to the mass and bulk of the fuselage. Considerably more flap hinge offset is required to make a machine controllable during zero-G maneuvers.

Thrust vector displacement in a Hughes 269 generates a control moment of about 120 foot-pounds per degree of rotor tilt.

Dampening

An automobile with coil spring suspension and worn-out shock absorbers is a good illustration of the effects of inadequate dampening.

The only source of dampening in a rotorcraft without fixed aerodynamic surfaces is the rotor itself.



With the cyclic control stick locked in neutral, the rotor lags behind a rotation of the airframe and the moment so produced opposes airframe rotation. The faster the rotation, the greater the lag and the greater the opposing moment.

The dampening so produced is not large. If the airframe of the gyrocopter of the previous example was rotated at 10°/second, the differential lift required to precess the rotor would be 39.8 lbs. as before and the required cyclic flapping would be 0.15° (also the cyclic pitch). A rotor lag of 0.15° would generate a moment opposing airframe rotation of 4.7 ft-lbs.

The control sensitivity of an aircraft is governed by the ratio of control power to dampening.

An aerobatic biplane with four ailerons has high control power but it also has high dampening from four wings.

Rotorcraft controlled by thrust vector orientation have low control power and even lower dampening. The control sensitivity of rotorcraft is often greater than that of aerobatic airplanes.

Pilot induced oscillation

All closed-loop systems can become unstable under certain conditions.

Consider a rotary lawn mower with an engine speed governor. The speed sensing device is often weights which move in response to centrifugal force (engine

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speed) and which movement is opposed by a spring. As the engine slows down, the weights resist the spring pressure less and a linkage opens the throttle, tending to increase the engine speed. However, the rotating parts of the engine have inertia and the engine doesn't instantly respond and may slow down even more, resulting in a greater throttle opening. Eventually the engine does respond, and as it accelerates, may overshoot the governed speed. We then have surge or hunting. A rotary lawn mower doesn't need precise speed regulation, so the loop gain can be reduced until the system becomes stable. Loop gain is controlled by the linkage ratio between centrifugal weights and the throttle.

In an aircraft autopilot, the basic sensing element is an artificial horizon gyro which controls elevators and ailerons, but with gains set high enough to maintain close control of attitude, the system would hunt or oscillate with attitude signals alone. Fortunately, it's quite simple electrically to derive rate of change of attitude (roll or pitch rates) and rate of change of roll or pitch rates (roll and pitch acceleration). These derived signals are mixed in the proper proportion to dampen out overshoot.

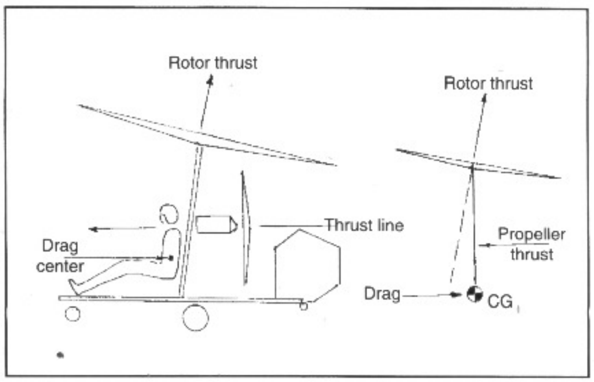
The human pilot closes up the loop and does the same things as an autopilot without even being consciously aware of doing so.

The things which cause pilot induced oscillation are lag in response to control movement, inertia and insufficient dampening.

A rotor in forward flight is unstable with angle of attack because of the dissymmetry of airspeed of the advancing vs. retreating rotor blades. If the cyclic stick is moved in a nose-up direction, the angle of attack of the advancing rotor blade is increased by the same amount as that of the retreating rotor blade is decreased, but the increase of lift of the advancing blade is greater than the decrease of lift of the retreating blade because of the airspeed differential. To compensate, the flapping angle of the rotor must increase, the result being that the angle of attack of the rotor increases more than commanded by the cyclic stick movement.

Upon encountering an upward gust, the same thing happens—the rotor moves in a nose-up direction. A stable aircraft noses down in an upward gust, always heading into the relative wind.

Most gyroplanes which follow the Bensen pattern have a built-in flaw because the propeller thrust line is above the center of fuselage drag.



In order to compensate for the resulting nose-down pitching moment, the rotor thrust line is forward of the machine's center of gravity, which is equivalent to a tail-heavy airplane. With the rotor thrust line passing in front of the CG, an upward gust torques the fuselage nose up, adding to the angle of attack instability of the rotor.

When the pilot of a gyroplane moves the cyclic stick in a nose-up direction, the rotor responds rapidly, aligning with the new stick position within 2 or 3 revolutions, but the airframe, because of its inertia, does not. If the stick position is held, the machine begins to climb with the fuselage in a level attitude. The increased rearward tilt of the rotor exerts an increased nose-up torque about the machine's center of gravity which begins a nose-up pitch acceleration. This nose-up pitch acceleration will continue at a rate of:

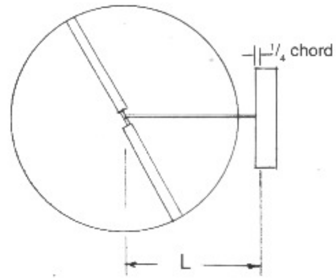
$$\text{acceleration} = \frac{\text{Torque}}{\text{airframe moment of inertia}}$$

until the dampening torque equals the accelerating torque. As mentioned previously, the only source of dampening in a rotorcraft without fixed aerodynamic surfaces is the rotor itself. As the pitching rate increases, the rotor lags farther behind the airframe rotation, providing dampening. But as discussed previously, rotor dampening is quite low which leads to very high pitch and roll rates.

When the cyclic stick is returned to its former position, airframe rotation does not stop because of its momentum, but starts to slow down as a result of rotor dampening. Reverse cyclic stick movement is required to arrest airframe rotation and prevent overshoot. The pilot must supply most of the dampening.

Horizontal stabilizers - Early helicopters without horizontal stabilizers were quite unstable in pitch and several were lost from pilot induced oscillation in the late 1940's through the early 1950's. The NACA investigated the problem and concluded that a horizontal stabilizer volume equal to 10% of rotor volume would provide a solution. Modern helicopters generally follow this rule.

Cierva began the development of his direct-control autogiro, a gyroplane controlled by rotor head tilt (thrust vector orientation) in the early 1930's with no aerodynamic surfaces except for a vertical stabilizer. He installed a horizontal stabilizer after only a few test flights and [illegible] lizer volume in the range of 12% to 15% of rotor volume for all subsequent production autogiros.



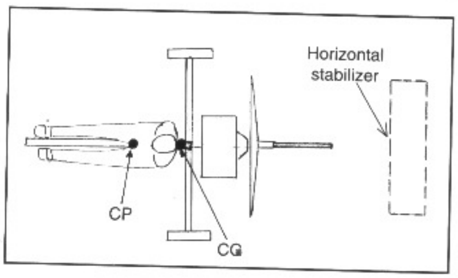
Rotor volume =
Rotor blade area x Rotor diameter

Horizontal stabilizer volume =
Horizontal stabilizer area
x
Moment arm length (L)

An adequate horizontal stabilizer reduces both control lag and overshoot.

As discussed previously, a nose-up cyclic input has no immediate effect on the fuselage attitude without a horizontal stabilizer. With a horizontal stabilizer, upward velocity of the machine produces aerodynamic forces which more quickly align the fuselage with the flight path. The maximum pitching rate is limited by the horizontal stabilizer, which reduces overshoot.

Stability - In a typical Bensen-type gyroplane without a horizontal stabilizer, the aerodynamic center of pressure leads the center of gravity, in effect, a tail-first arrow.



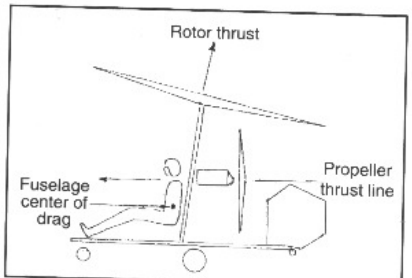
The aerodynamic center is approximately the centroid of area, the point at which a cardboard cutout would balance. A horizontal stabilizer of suitable dimensions will ensure that the C of P trails the C of G.

Gyroplanes have never had control problems in the roll axis.

Buntover

Of the several hundred fatal accidents to occur in homebuilt gyroplanes since the Bensen Gyrocopter first appeared, probably 95% have been due to a single cause, namely the unloading of the rotor and the resulting forward tumble. Surprisingly few fatalities have resulted from mechanical failures.

The propeller thrust line typically passes about one foot above the center of fuselage drag, as illustrated at the top of this page. Engine thrust is about 200 pounds for a typical 450-pound-gross-weight gyro in level flight, creating a nose-down moment of 200 ft-lbs. To counter this nose-down moment, the rotor thrustline must pass 5 1/3 inches (.444 ft) in front of the machine's center of gravity.



A reduction in rotor thrust can initiate a self-sustaining, irreversible forward tumble or buntover. A strong downward gust can reduce rotor thrust to the extent that it is no longer able to counteract the nose-down moment which results from propeller thrust being above the center of fuselage drag. As the machine begins to rotate nose-down, the rotor follows—a tilt of the airframe being no different than a tilt of the rotor head—and the resulting reduction of the angle of attack of the rotor further reduces rotor thrust which increases the nose-down pitch rate, etc. The action very rapidly becomes self sustaining and irreversible.

An action by the pilot which tends to unload the rotor, whether deliberate or not, can also initiate a catastrophic buntover.

A typical gyro has a moment of inertia about the pitch axis of about 40 slug-ft². With the rotor completely unloaded and a pitching moment (torque) of 200 ft-lbs, the angular acceleration about the pitch axis would be:

$$\frac{200 \text{ ft-lb}}{40 \text{slug ft}^2} = 5 \text{ radians/second}^2$$

or 286° per second/per second.

The time required for the machine to invert or rotate 180° would be:

$$\text{time} = \sqrt{\frac{\text{angle}}{.5 \times \text{angular acceleration}}}$$

$$180^\circ = \pi \text{ radians}$$

Therefore

$$\text{time} = \sqrt{\frac{\pi}{.5 \times 5}} = 1.12 \text{ seconds}$$

There is no way the rotor can generate enough force to precess 180° in 1.12 seconds, an average rate of 161° per second.

From the section on gyroscopic precession:

Torque = angular velocity of precession x rotor moment of inertia x angular velocity of rotor

Angular velocity of precession = 161°/sec = 2.8 rad/sec

Rotor moment of inertia = 46.6 slug-ft²

Rotor angular velocity = 37.7 rad/sec

$$\text{Torque} = 2.8 \times 46.6 \times 37.7 = 4900 \text{ ft-lb}$$

$$\text{Differential lift} = \frac{\text{Torque}}{.7 \text{ rotor radius}}$$

$$= \frac{4900}{.7 \times 11} = 636 \text{ lbs.}$$

The rotor can't develop this much lift differential between advancing and retreating blades and stalls.

The same thing can happen with helicopter tail rotors if the machine is yawed too fast. The tail rotor can overrun the flap stops and strike the tail boom. This phenomenon is called precession stall.

With precession stall, the rotor of a gyroplane can no longer follow airframe rotation. The airframe rolls up and into the rotor, past the rotor flap stops. The rotation is so rapid that the rotor blades are rotated about their pitching or feathering axis broadside to their plane of rotation and often make a loud bang or cracking sound, similar to the surface of water being slapped with a canoe paddle.

The signature - All buntover accidents, without exception, leave their signature. This signature is in the form of rotor strike marks on the vertical tail, as shown at the top of the next page.

The first strike, near the top of the vertical tail, produces a sharp, well-defined crease which indicates the rotor is turning at near normal speed.

From the spacing of the strike marks, it's clear that the airframe has rotated 24° while the rotor has traveled 1/2 revolution. If the rotor has slowed down to 300 rpm, 1/2 revolution requires 0.1 second, which would mean that the airframe is tumbling forward at the rate of 240° per second. This is good correlation of tumbling speed estimates based on propeller thrust and moment of inertia.

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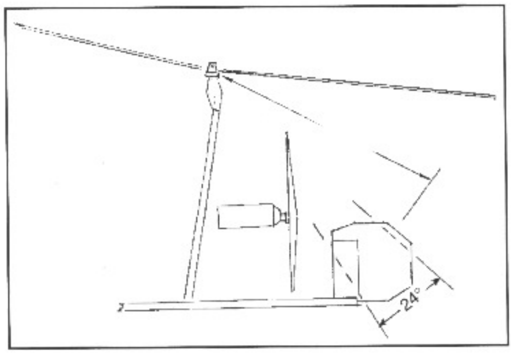


The solution - The solution to this problem is obvious. A seaplane with the engine mounted on a pylon above the wing does not tumble over when the wings are unloaded because the horizontal tail is of adequate size to prevent a loss of control. A gyroplane with a horizontal stabilizer volume equal to 12% of rotor volume won't tumble over either, even with propeller thrust offset from fuselage drag center. A gyroplane without a horizontal stabilizer won't tumble if the propeller thrust line passes through both the fuselage center of drag and the airframe center of gravity.

From the standpoint of controllability and ease of flying, it's highly desirable that the propeller thrust line pass through both the center of drag and center of gravity and that the horizontal stabilizer volume is equal to at least 12% of rotor volume. When these conditions are met, the fuselage pitching tendency with change in throttle opening is minimal and fuselage attitude stays more constant with change of airspeed.

Dampening required

The dampening supplied by the horizontal stabilizer is proportional to the square of the moment arm length—if the length of the moment arm is doubled, the dampening is four times as great. The ratio of dampening to moment of inertia of the airframe needs to be held constant.

As the masses of the airframe are spread out, for example in a tandem-seat two-place machine, the moment of inertia increases as the square of the distance. A two-place tandem machine requires a horizontal stabilizer to be on a longer moment arm than a two-place side-by-side machine.

A somewhat related situation exists for fixed-wing light twin-engine airplanes, most of which carry a warning placard against spinning. With engines mounted on the wings, the moment of inertia about the yaw axis is so great that without very large vertical stabilizers on long moment arms, spin recovery by pilots of average skill is unlikely.

Tandem vs. side-by-side - All other factors being equal, a tailless tandem gyro is more lethal than a tailless side-by-side machine, even though initial impression and intuition may make things seem otherwise. All tailless gyros have a built-in bobble in pitch and the bobble frequency of a tandem machine is lower than that of a side-by-side machine.

The best illustration of the lethal qualities of a tailless tandem gyro is an accident which occurred in Florida several years ago. An instructor in the rear seat had his hands off the controls while the student in the front seat was flying the machine. The student evidently overcorrected for a gust and the machine bunted over and tumbled to the ground before the instructor could take any useful corrective action.

Horizontal stabilizers

Mounting - Vestigial shingle-size horizontal fins stuck on the vertical tail are, no doubt, better than nothing, but don't come close to the 12% tail volume requirement. The problem for a pusher gyro is providing sufficient moment arm length. Tractor machines have no such problem and any reasonable-size horizontal stabilizer can be accommodated.

The choices for pusher gyros are:

1) twin tail booms straddling the propeller,

2) tail boom coaxial with the propeller,

3) tail boom under the propeller, and

4) tail boom over the propeller.

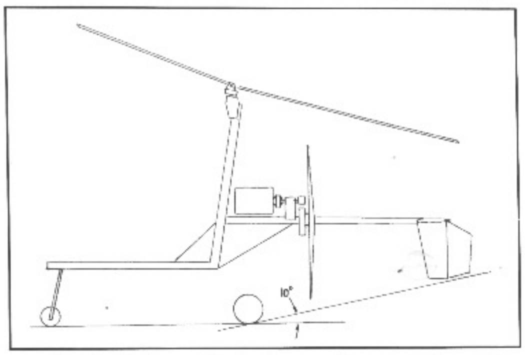
Any tail boom configuration used must permit the machine to rock back about 10° or the takeoff run will be too long.

Choice 1, twin tail booms straddling the propeller, seems to be the oldest. The Buhl pusher autogiro was first flown in 1931.

A somewhat more modern pusher machine was the Pitcairn XO-61, first flown in 1943. It had tilt-head cyclic control and jump takeoff.

Pitcairn XO-61

Twin tail booms are structurally inefficient and engineering the loads back into the main airframe adds considerable weight. The relatively modern McCulloch J-2 does not appear to have sufficient horizontal tail volume, among other things.



Choice 2, propeller mounted coaxially with the tail boom (above), is structurally efficient but causes some mechanical complications.

A coaxial propeller is an obvious choice where a belt reduction drive is part of the design. The small sheave must be supported by its own bearings to maintain correct belt alignment and tension and coupled to the engine by a rubber donut such as a Lovejoy "Saga" coupling. High-power gearbelt drives, namely the Gates Poly-Chain, have Kevlar tensile members and are torsionally as stiff as gears so that a torsionally soft coupling is necessary in any case. The same function is accomplished in automobiles by windup of the quillshaft in the transmission or by windup of the axle shafts.

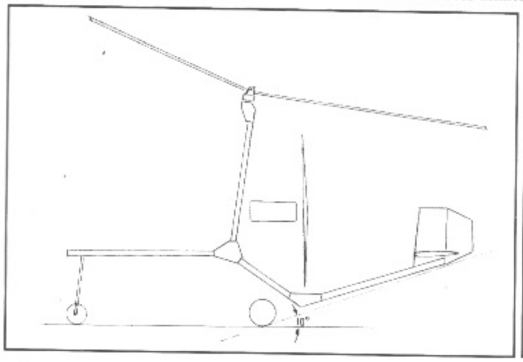
Choice 3, tail boom under the propeller (below left), requires a dogleg which is a structural weakness.

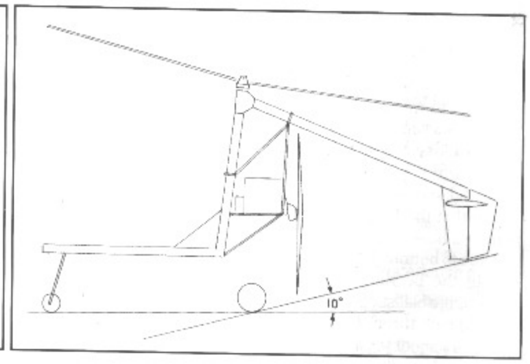
Choice 4, tail boom over top of propeller (below right) is simple and structurally efficient, but creates some problems when used with a see-saw rotor.

This layout results in a very rigid rotor pylon in a fore-and-aft direction. See-saw rotors in conjunction with their supporting structure must be very carefully tuned if severe rotor shake is to be avoided.

Design - The design of the horizontal surface itself is important. Flat plates can produce only about 1/2 the aerodynamic lift of a 12% thick airfoil and very nearly as much drag. A thick airfoil with a sharp leading edge is no better than a flat plate.

The horizontal surface should be of the highest aspect ratio which can be conveniently accommodated; that is, wide span and narrow chord.





Closure

The buntover phenomenon—sometimes identified as PIO, porpoising or negative G—has, until recently, been quite mysterious and has engendered a number of spurious theories, all of which can be easily dismissed:

1. Negative G and reverse coning. To begin, a normal cambered rotor blade can produce very little negative lift, and even if it could, the rotor would flap forward and chop off the nose, not the tail.

2. Unloading rotor causes it to slow down and flap into tail. An unloaded rotor can't flap. In order for a rotor to flap, it must stall while supporting a load.

All the other theories are a variation of theories 1 and 2.

The main problem is that so few qualified engineers have taken an interest in gyroplanes; otherwise the buntover mystery would have been solved long ago. Most present-day gyroplane designers, many of whom may be skilled mechanics of machinists, don't have any formal scientific or technical training. R