A VARIOMETER FOR DYNAMIC SOARING

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In the paper *Dynamic Soaring and Sailplane Energetics* we looked at how a sailplane can get energy from wind shear, gusts and turbulence. Some of that material is repeated here for background. The paper *Calculations on Soaring Sink* explains how even downdrafts can power a sailplane.

This paper discusses some ideas for a new type of variometer. An inertial based instrument that may enable glider pilots to fly faster and farther by using efficient dynamic soaring techniques.

Before getting into the design of a "dynamic vario" let's take a quick look at the history of variometer technology and the current state of the art. In the early days of soaring most flying was done along ridges and fairly near to the ground. In this situation pilots could tell if they were climbing or descending by looking out and noticing their vertical motion relative to the hills and trees. This kind of "visual variometer" still works well when near mountains and is also quite effective in reference to other sailplanes working the same area of lift.

As soaring developed and pilots began to utilize convective lift far away from the ground the "visual variometer" proved to be ineffective. Studying the altimeter to see how the needle was moving became a more practical approach. In combination with an astute "seat of the pants" the altimeter is a fairly good indicator of lift or sink. Some shortcomings of using the altimeter as a vario are that: it sticks (unless tapped constantly), it is difficult to quantify rate of climb or descent, and the careful needle watching required can produce a bad case of instrument fixation.

The flow meter variometer was then developed for gliders. By measuring changes in air pressure, rather than just pressure altitude this new type of instrument revolutionized soaring. The flow meter variometer determines changes in surrounding air pressure by detecting the airflow in or out of an insulated reservoir. With a quick glance at this instrument pilots could learn their rate of rise or fall over the previous few seconds. This made it possible to soar effectively far from any visual reference points. We should note that balloonists had been using a similar instrument for many years; they would observe air bubbles passing through a fermentation trap as the air in their reservoir expanded.

All was well until sailplanes began to use a greater speed range. The basic flow meter vario still showed the rate of climb or descent, but this information proved to be of limited value because so much of the short-term variation in instrument reading was caused by "stick thermals." These were changes in height caused not by the movements of the atmosphere, but rather by the diving and zooming of the glider as it changed speed.

The answer to this problem was the total energy variometer, which at least in uniformly moving air, compensates for the glider's changes in height that are due to speed changes. The total energy vario is so called because it measures the glider's total energy relative to the surrounding air mass, the sum of kinetic and potential energy, the energy components due to both speed and height. This represented a great improvement in variometer design. The addition of a flight computer interpreting the total energy system brings us more or less up to date in variometer technology.

Unfortunately a total energy variometer generally gives misleading results while dynamic soaring, at least in the short term. On average the total energy vario works okay over a complete dynamic soaring cycle (once one is back to the original air mass motion), but in the short term its readings are inaccurate. The total energy vario shows the glider's energy gains at the wrong parts of the dynamic soaring cycle. It shows the gains when the glider crosses the wind shear; the energy actually gets transferred from the atmosphere to the glider while maneuvering within the different air masses. The total energy vario shows the dynamic soaring energy gain only after the glider has moved on to the next air mass and after it is too late to modify one's flight path through the gust. A new type of variometer is needed for dynamic soaring.

Let's step back for a moment and take a general look at sailplane energetics to better understand how to build a dynamic soaring variometer. An understanding of vectors can be very helpful when working in this area, but we'll try to keep the math discussions from getting too "hairy."

First of all, how does a glider get energy from the air? A glider (or any other object) gets energy by being pushed *in the same direction that it is moving*. The opposite is true; an object loses energy by being pushed (or pulled) in a direction opposite to its direction of motion. As examples: a glider loses energy via drag which pulls it backwards (opposite to its motion), a glider in a thermal gets energy from the upward lift force on the wing as it climbs (both the force and the glider's motion are upward).

The rate that energy is gained or lost can be called power; which can be positive or negative. When the glider is getting more energy let's call that positive power and when it's losing energy let's call it negative power or loss.

To calculate power we multiply the force in the direction of motion by the speed of motion. The units can be a bit messy here, but if we take the speed in MPH, multiply by the force in Pounds and divide by 377 we get Horsepower.

As examples: an 800 lb glider with a 40:1 L/D has 20 lbs of drag, if we multiply by a true airspeed of 60 MPH and divide by 377 we find that the glider is losing energy at a rate of about 3.2 HP. The same glider being pushed upwards in a thermal at a vertical speed of 1000 feet/minute (about 11 MPH) is getting energy at a rate of (800 x 11) / 377, or about 24 HP.

Metric units can be simpler, in the MKS system no con-

stant numerical factors are needed, but it's less familiar. A glider with 100 newtons of drag flying at 30 meters/second loses energy at a rate of 100 x 30 = 3000 watts.

In vector math terms the power going into the glider is the "dot product" of the glider's velocity vector and the force vector pushing on the glider. A dot product is a measure of how much two vectors point in the same direction, if they point in opposite directions the dot product is negative. If the vectors are perpendicular the dot product is zero.

Now back to soaring. To get the most energy from the atmosphere we want the air to push our glider along in its direction of motion as much as possible. In conventional soaring this means using updrafts to push the glider upward. We normally do this by spending as much time as we can in updrafts where the air is pushing the wing upward and the glider is moving upward. The faster we are moving upward the greater the power or rate of energy transfer. In stronger lift, our energy uptake is limited by the air's lift force on the wing. The average upward force of the air on the wing equals the weight of the glider. This is why we put water ballast in our gliders. A heavier glider gets more energy from the atmosphere by pushing harder on an updraft while climbing. This extra energy allows the heavier glider to fly faster. Another way to get a bigger aerodynamic push is with additional g force. This is the key to dynamic soaring.

To better understand dynamic soaring strategies, we can look at the challenge of getting atmospheric energy in another way. The conservation of energy law tells us that instead of concentrating on how much energy the glider is getting; we can look at how much energy the atmosphere is losing. The two are equal (when we consider the glider's drag losses). The second way of looking at the situation can be more helpful to understanding dynamic soaring maneuvers.

How do we make the atmosphere lose energy? According to physics — by pushing on the air in a direction opposite to its motion. This slows the air motion and extracts kinetic energy.

We should clarify our terminology; the energy we are talking about is large-scale kinetic energy, which is the kind of energy a sailplane generally uses. Heat energy and micro-turbulence are of little use (that's where the glider loses energy via drag).

To make the atmosphere lose some of its kinetic energy we want to slow the air by pushing on it opposite to its direction of motion. Then according to conservation of energy, as the atmosphere loses energy, the sailplane gains it. In what direction can a sailplane push on air? Well, pretty much in any direction. The wing of a sailplane is designed to push on air in a direction perpendicular to the wing surface and towards the landing gear. The wing can also push in the "negative g" direction (away from the landing gear), but the airfoil is less efficient used that way. By banking and maneuvering the glider we can orient the wing to push air in any direction: up, down or sideways.

But what about gravity? Oh, yes, the wing has another job besides extracting energy from the atmosphere and that's holding the glider up, opposing the force of gravity. This limits our maneuvering somewhat, but we can work around these limitations. In fact it is the dual job of the wing that makes upward moving air such a good source of energy. To hold the glider up the wing needs to push air downward. Upward moving air loses its energy when pushed downward. This is very convenient; the glider can gain the energy lost by the upward moving air and hold itself up at the same time. We know that both gliding and regular soaring of updrafts rely on weight and gravity. If we were to "fill the wings with helium" until the glider had no weight; we would just float around like a balloon, with no power for forward flight. When we want more power to go fast, we add ballast. Dynamic soaring requires no weight, but it does require mass.

Getting energy from upward moving air is thus relatively easy for a glider; it just needs to stay in the "lift." What about getting the kinetic energy from sideways and downward moving air; what are the opportunities and what are the limitations? Because of the dual duty of the wing (holding the glider up as well as extracting energy from the air) it is more difficult to get energy from sideways moving air and especially downward moving air, yet it is still possible. In some circumstances these may prove to be very important energy sources.

To make use of the energy in upward moving air we can use the downward force of gravity to push on the air. To push on air that is moving in other directions and get its kinetic energy we can make use of the glider's inertia. Inertia is the property of mass that causes a body at rest to remain at rest and a body in motion to remain in motion. When a massive body's velocity changes a push (a force or impulse) is exchanged between the body and its surroundings. When a body's inertia carries an impulse over a distance it is in the form of momentum. To push on air in an energy getting direction we need to have a clear idea of the forces acting on a glider.

There are three kinds of forces on a flying sailplane: gravitational forces, which act between the glider and the earth; aerodynamic forces, which act between the glider and the surrounding air; and inertial forces, which appear when the glider changes speed or direction. The gravity force is constant and acts to pull the glider downward with a strength equal to the glider's weight. The aerodynamic force is more complex and depends on air speed, angle of attack, and air density. Inertial forces vary with the glider's motion and can be measured by accelerometers or "g meters."

The aerodynamic and inertial forces are the ones we play around with when dynamic soaring. By pulling back on the stick we can increase the aerodynamic force on the wing; by pushing the stick forward we can reduce or reverse the force. By banking the glider we can tilt the aerodynamic force sideways. As we maneuver, the inertial force varies in magnitude and direction so it always remains opposite to the glider's acceleration. Centrifugal force is a good example of an inertial force (which, by the way, the hard core physicists would call a "pseudo-force"). The total vector sum of these three types of forces on a flying glider is

always equal to zero. That is to say that; the three forces continually cancel each other out.

More about inertia... by using the glider's inertia we can push on air in any direction at least for a short length of time. When we use glider inertia as a basis for pushing air the glider accelerates in a direction opposite to the push. This is in accordance with Newton's famous law $F = m\,a$ (Force equals mass times acceleration). Acceleration is a change in velocity. An acceleration of one g corresponds to a change in velocity of 32 feet per second each second (or a change of 22 MPH per second). So if we want to limit our velocity change to 88 MPH we could use our inertia as a basis for pushing at one g for 4 seconds in a particular sideways direction. If we wanted to use our inertia to push upward on downward moving air we would be limited to two seconds, because then both the aerodynamic force on the wing *and* gravity would be accelerating the glider downward.

Note that a velocity change of 88 MPH does not mean a speed change of 88 MPH. When we make a 180 degree turn at a constant speed of 50 MPH we experience a velocity change of 100 MPH (50 MPH to 50 MPH in the opposite direction). When we talk about velocity the *direction* of motion is important.

How much energy (or power) is available from moving air and how efficiently can a wing extract the power? To answer this question we first must clarify what we mean by "moving." Motion is relative; and in order to get energy we must be able to push on both parts that are moving relative to each other. For example, we could be inside a sealed up train speeding along at 100 MPH and yet not be able to get any energy from the enclosed 100 MPH air, unless we could somehow connect a force to the outside stationary world. This is similar to drifting along in a glider on a stable windy day; there is lots of kinetic energy in the sideways motion of the air, but we can't make use of it. A kite, on the other hand, can do fine, because the string provides a force connection between the ground and the air, which are in relative motion.

Gravity provides a sort of downward pulling string that enables us to get energy from upward moving air. Inertia and momentum can provide a sort of temporary dynamic string that allows us to get energy from the relative motion of air masses in any direction, so long as the distances involved are not too great. How do we figure what distances will work and what is too far? That depends on how "clean" our sailplane is. A high performance ship can use its inertia to carry momentum over longer distances (for the same energy loss) compared to a draggy ship. Lift to drag ratio is a measure of momentum carrying ability. Faster ships are relatively less effected by the constant 32 ft/sec² acceleration of gravity and can carry momentum more effectively over vertical distances.

The distance that a particular sailplane (at a particular speed) can effectively carry momentum before the drag losses eat up any potential dynamic soaring gains defines an area of operation, which can be specified in terms of distance or in terms of a time interval. If one is circling, dis-tance may prove most significant; when flying cross country, time period or cycle frequency may prove most significant; when flying cross country, time period or cycle frequency may prove to be a better parameter. The (possibly weighted) average motion of the air inside the dynamic soaring operations area defines *a local inertial reference frame*. An immediate measurement of the glider's energy in this inertial reference frame is needed for effective dynamic soaring.

Before figuring out how to measure this energy, let's look for a moment at the sailplane's energy losses; for the energy we can extract from the air by dynamic soaring is of no benefit unless it is greater than the additional losses (negative power) caused by the extra maneuvering required. Sailplane energy losses can be divided into three categories: basic friction drag (also called parasite drag), basic induced drag (drag due to lift), and control drag (a combination of extra friction and inducd drag due to control surface deflection, etc.). Drag times true airspeed equals power loss.

The negative power (or loss) due to friction is approximately equal to a constant times the glider's airspeed cubed. The loss due to induced drag approximately equals a constant times the lift force on the wing squared divided by the glider's speed, which means that induced drag increases with g force. Control drag losses can be measured experimentally by wiggling the stick and observing the increase in sink rate (we don't have a simple formula for that one).

Now let's get on with the design of a dynamic soaring variometer. We've seen how the power extracted from the atmosphere is equal to the velocity of the air (in a local inertial reference frame) "dot product" multiplied by how hard we can push against the air with the wing. The net power gained is the power extracted from the air minus the glider's losses.

The other way of looking at the situation is that the power that the glider gets from the air is equal to how hard the air is pushing on the glider in the glider's direction of motion. Where the air's "push" includes both lift and drag forces. All velocities are best measured in the local inertial frame.

We'll use the second way of looking at the energy exchange to design the dynamic vario. This is because it automatically accounts for the glider's drag losses. If we used the first approach, the losses could pretty well be calculated from lift force, control deflection and air speed, but that would involve a lot of assumption. In the second approach the losses can be measured directly by a sensitive fore and aft oriented accelerometer in conjunction with speed information. We should note that the first approach can be good for figuring out the theoretical benefits of dynamic soaring.

The dynamic variometer needs to detect the necessary inputs, such as glider position and speed, do the appropriate calculations, and give us a moment by moment signal about how much net power the sailplane is getting from the atmosphere. We would also like the instrument to show us the outside air's motion relative to a local inertial frame. This is so that we can position the glider's wing at an angle

that is suitable for pushing on the air correctly (that is, opposite to the air's motion).

This seems like a lot of work; and it is! But the potential for improved soaring performance is vast; this kind of information properly used, could totally revolutionize soaring. Dynamic soaring can give sailplane speeds far greater than conventional techniques. The high g forces often used when dynamic soaring act like a temporary, very heavy, form of water ballast.

Is building a dynamic vario possible? To do all this detecting and computing thirty years ago the dynamic variometer would have been the size of a refrigerator and probably heavier, but now the combination of GPS, piezo gyros and microprocessors make the dynamic variometer a practical possibility.

What inputs does the dynamic variometer require and how do we detect them?

The vario wants to know:

1) Glider attitude: pitch, bank and heading (a vector)

2) Glider ground speed in three dimentions (a vector

3) G force or acceleration (a vector)

4) Relative wind direction

5) True airspeed (combines with relative wind direction to give a vector).

Gee whiz what a lot of vectors. And how can we measure all this stuff?

1) To get glider attitude we can use attitude gyros or three GPS units, one on each wing tip and one on the tail.

2) To get three dimensional ground speed we can use GPS (perhaps assisted by an altimeter, acceleration sensors and piezo gyros; to speed up the response time and get better accuracy).

3) G force can be measured by accelerometers (the fore and aft component and the component perpendicular to the wing are important, the lateral (sideways) component is probably not needed).

4) To determine relative wind direction we need a sort of electronic, three dimensional, yaw string (which could be of a vane type, or better yet a multi-port pressure probe). Because of the flow patterns induced by the glider, relative wind may prove difficult to measure accurately.

5) True airspeed is fairly easy, a pitot-static system can detect it.

Now if we've got all this information, how do we process it and display the information desired by the dynamic soaring pilot?

The first thing our dynamic vario wants to compute is the local air motion. It does this by subtracting the glider's ground-based velocity vector from the glider's "true airspeed vector" (the true airspeed vector is the reverse of the relative wind vector). Before doing the vector subtraction the two vectors must be expressed in the same coordinate system (by considering the glider's attitude).

The next step is to establish a local inertial reference frame by taking a running average of the local air motion over an appropriate time interval. The duration of the time interval can vary with conditions. It is determined by the glider's momentum carrying efficiency and the strength of the gusts. For today's gliders the time interval is probably on the order of a couple minutes or less. The running average can be weighted so that the more recently encountered air movements are given greater influence on the average. The system can create a map of air motion with respect to position, then the average defining the local frame can be based on distance rather than time. Distance averaging may be appropriate when one stays working the same area and conditions are not changing significantly.

With a local inertial frame established and the calculated local air motion we can display some very useful information to the pilot. Remember that we want to know how the air is moving relative to our local inertial frame; so we can position the wing and push on the air in an energy extractng direction. The variometer computer does this by subtracting the inertial frame motion from the local air motion. The result of this calculation is the dynamic (changing, gusting) part of the air's motion. This gusting air motion can be displayed as an arrow on a screen or better yet by some non-visual means (there's lots of room for creativity here). When we have the gust information, we want to orient the glider's wing perpendicular to the gust arrow and pull appropriate g force. The stronger the gust the higher the g force desired.

So far we've got information about how to position our glider, but no evaluation of the energy flow or just how many g's to pull. To find out how much energy we're getting (or losing) we need our variometer computer to do a few more calculations. To calculate energy we need to know how hard the air is pushing us in our direction of motion relative to the local inertial frame and also how fast the local inertia frame is moving up or down. If the frame is moving upward that is good news whether we do any dynamic soaring or not (for it means that we're in a general area of updraft).

To calculate the energy flow (power) relative to the inertial frame the computer uses the glider's attitude and acceleration (g forces both normal and fore-aft) to determine the aerodynamic force on the glider. The aerodynamic force is figured by using the fact that the vector sum of the aerodynamic, gravitational, and inertial (g) forces is always equal to zero. We measure the inertial forces and know that gravity pulls constantly downward with a force equaling the glider's weight; therefore the aerodynamic force is opposite to the sum of the measured inertial and gravity forces. (An accelerometer measures both gravity and inertial forces at the same time).

The computer calculates the dot product of the aerodynamic force vector and the glider's velocity vector in the inertial frame. This calculation gives the dynamic soaring energy we are getting from the atmosphere. Add to this dynamic part the energy we are getting due to the (hopefully) upward motion of the inertial frame and we have the total energy flow of the glider. This calculation generates the output signal of our dynamic soaring vario. The signal can be both audio and/or visual. This total power we're getting from the combination of dynamic and steady state sources is what we really want to know to soar most effectively.

These are some ideas on how to make a Dynamic Soaring Variometer. It's a complex instrument, but provides us with some very useful information. It could make soaring possible under conditions never before practical. It can also tell us how to get extra power under normal soaring conditions, thus increasing climb rates and boosting cross country speeds.

Rather than develop the complete dynamic system in one shot, we can consider some simpler versions. If we eliminate the dynamic air motion (gust) display and have only the energy flow indication then we don't need the relative wind sensor and the calculations are simpler. Instead of using the air's motion to define a local inertial frame we can use the glider's averaged motion.

A sailplane equipped with a dynamic variometer will have a substantial advantage over its less well-informed cousins.