DYNAMIC SOARING AND SAILPLANE ENERGETICS

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Did you know that a high performance sailplane can stay up on a day with no lift, but only pockets of strong sink? Most sailplane pilots regard sinking air as an enemy and of no value, but there is just as much energy in downward moving air as in upward moving air it's just more difficult to utilize. A companion paper called *Calculations on Soaring Sink* goes into the details of getting energy from down gusts. Here we'll look at the basic energy picture.

There is a lot of energy in large-scale air turbulence and often we can extract this energy with a sailplane. A sailplane can get energy from the moving air. Using up and down gusts in opposition to each other is particularly effective. On days when the air is smooth and calm, then there is no way to stay up without a motor.

How are we going to stay up on "sink" anyway? Perhaps a parallel to basketball players will prove illuminating. The players want to get the ball up and through the hoop. There are two ways to do this; they can throw (lift) the ball up into the air so that it goes up and through the hoop. Or (if they are tricky) they can push the ball down so that it bounces off the floor then goes up and through the hoop. In the second case there is no "lift" involved, rather a downward push plus a bounce.

How can we do this in a sailplane? Assuming we are flying fairly fast in an approximately wings level attitude and hit an area of strong sink, we can push the stick forward and go into negative g so that the downward moving air pushes us downward. Then as we come out of the sink hole we "bounce" off the surroundng stationary air by pulling back on the stick and zooming upwards (at more than one g). Obviously this can only work if the "sink hole" is fairly small, because we can spend just a short period of time in negative g before building up excessive speed. (So there's a catch after all!) But the situation is not so far fetched as all that; often there is strong sink on the edges of thermals where we can get a bit of a downwards push and get right back into lift. The downward push can come from a bank angle of greater than 90 degrees rather than negative g and "bouncing" back off upward moving air is much more energizing than bouncing off still air. This is a dramatic and practical example of dynamic soaring. The bad news is that dynamic soaring can result in a rough ride and vigorous maneuvering, as its name would lead one to believe.

Let's take a general look at sailplane energetics. An understanding of vectors and vector math can be very helpful when working in this area, but we'll try to keep things 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 also 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 motion are upward).

The rate that energy is gained or lost can be called power; it 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. 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 60 MPH and divide by 377 we find that it is losing energy at a rate of about 3.2 P. 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.

In vector math terms the power going into the glider is the "dot" product of the velocity vector and the force vector. A dot product is a measure for 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 power from the atmosphere we want the air to push our glider in the same direction that the glider is moving as much as possible. The way that we normally do this is by spending as much time as we can in upward moving air, where the air is pushing the wing upward and the glider is moving upward. The faster we are moving upward the greater the power of energy transfer. The upward force of the air on the wing averages out to be the weight of the glider.

We can also look at the challenge of getting 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) and the second way of looking at the situation can be easier when understanding dynamic soaring.

How do we make the atmosphere lose energy? By pushing on the air in a direction opposite to its motion. But first let's clarify our terminology, the energy we are talking about is large-scale kinetic energy due to air motion, which is the kind of energy a sailplane can use. Heat energy and micro-turbulence are of little use (that's where the sailplane loses energy via drag).

Once again, to make the atmosphere lose energy we push on the air opposite to its direction of motion. As the atmosphere loses energy the sailplane gains it. In what direction can a sailplane push on air? Well, 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 when used that way. By banking and maneuvering the glider we can orient the wing to push air in any direction: up, down or sideways.

What about gravity? Oh yeah! 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 energy manipulations somewhat, but we can work around it. 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 down. Upward moving air loses its energy when pushed down. This is very convenient; the glider can gain the energy lost by the upward moving air and hold itself up at the same time.

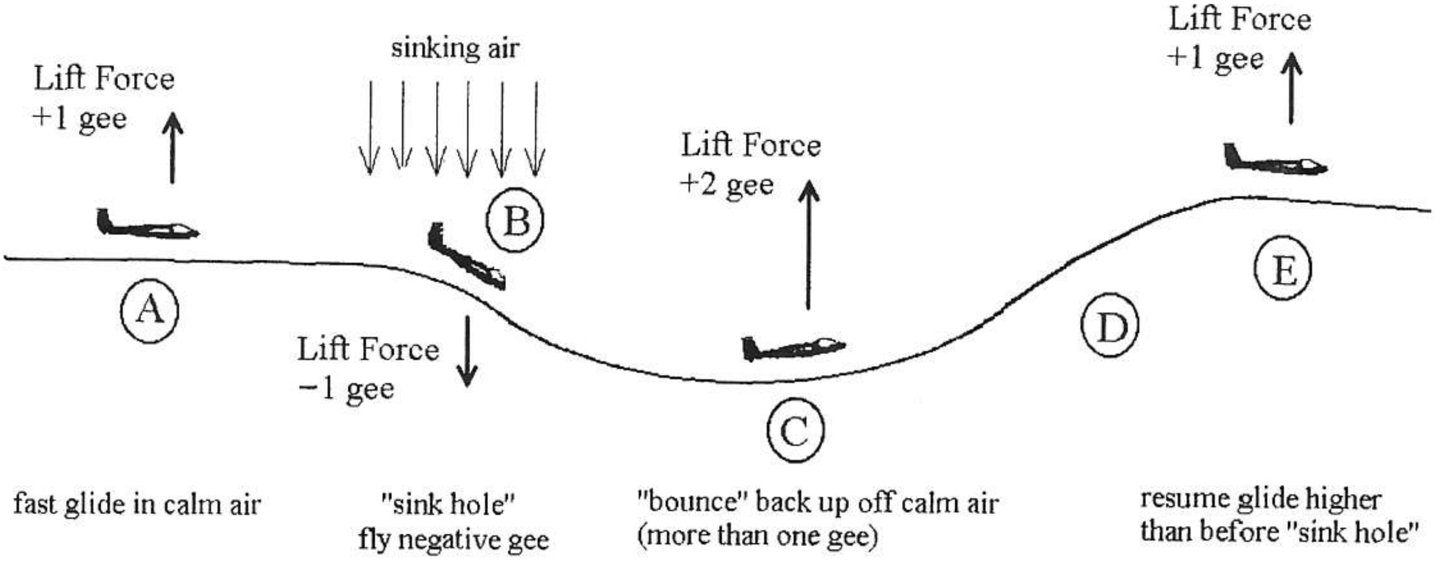
So getting energy from upward moving air is relatively easy for a glider, it just needs to stay in the "lift." What about getting energy from sideways and downward moving air; what are the opportunities and what are the limits? Because of the above mentioned dual duty of the wing (holding the glider up as well as extracting energy from the air) it is more difficult to get energy from sideways moving air and especially from downward moving air, yet it is still possible. And in some circumstances it may prove very useful.

To make use of the energy in upward moving air we can use the downward force of gravity to help us push on the air. To push on air that is moving in other directions 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 motion (velocity) changes, a push (force, 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.

In the case of a glider there are three kinds of forces in action: gravitational forces, which act between the glider and the earth; aerodynamic forces, which act between the glider and the surounding air; and inertial forces, which appear when the glider changes speed or diection. The gravity force is constant and acts to pull the glider downward with a force 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 can be meas-

Dynamic Soaring of Sink Pockets

How a Sailplane Can Get Energy from Sinking Air



Notes: Because of airspeed limits it is best if the glider spends less than 2 seconds in the sink hole.

Location Ⓓ is a good place to encounter another sink pocket and repeat the cycle.

Because a glider can quickly change gee loading, dynamic soaring of vertical gusts works well at high frequencies. Cahnges in airspeed limit low frequency technique.

ured by "g meters" (accelerometers) and vary with the glider's motion.

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; 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 forces vary in magnitude and direction so as to remain opposite to the glider's acceleration. Centrifugal force is a good example of an inertial force (which, by the way, the hard core physicists call a "pseudo-force"). The total (vector) sum of the three types of forces is always equal to zero. That is to say that; the three types of 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 see 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 access both parts that are moving relative to each other. For example, we could be inside a closed window train speeding along at 100 MPH and yet not be able to get any energy from the enclosed 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 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 and the relation of stored kinetic energy to the energy dissipation rate are both measures of momentum carrying ability. Faster ships are relatively less effected by the constant 32 ft/sec^2 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, distance may prove most significant; when flying in a moe or less straight line, time 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.

Let's consider dynamic soaring with horizontal wind shear and see how it is done. When we do this we are using our sailplane as a sort of dynamic windmill. A windmill is fixed to the ground on a tower and uses the earth as a basis for pushing against the moving air. A dynamic soaring glider transfer push (force, impulse, momentum) between fast moving air and air that is at rest, or air that is moving more slowly, or (best of all) air moving in the opposite direction.

The Albatross is famous for soaring the wind gradient over the open ocean in this way. How can we do it in a glider? First we connect with the fast moving air and push on it opposite to its motion. We do this by banking the glider belly into the wind and pulling back on the stick; this extracts energy from the moving air and gives the glider extra momentum in the direction of the wind. We then maneuver into the air that is not moving (often at a different altitude) and we bank to push on this air in a direction opposite to the initial push. This transfers the glider's extra momentum into the still air. Some energy may be lost in this second push (if the air is not at rest), but overall we can gain energy in the cycle. We then maneuver back to the fast moving air and repeat the process.

The energy gained is equal to three factors multiplied together: the force of the initial push opposite to the air movement (times) the duration of the push (times) the difference in velocity between the two blocks (or layers) of air. For example, say we bank the glider and can get a sideways push of 800 lbs. for 3 seconds and the velocity difference between the two air masses is 20 mph. $(800 \times 20 \times 3)/377$ equals 127 HP-seconds, which is the energy extracted (we need that 377 constant factor for these Pound and HP units) if one whole cycle takes 15 seconds we have an average power of about 8.5 HP, which could be a reasonable amount of power to sustain a maneuvering sailplane. This example is presented for illustration purposes only. Messing around with radical maneuvers near the ground or ocean (especially in high winds) is very hazardous and is, how you say? "for the birds." There are many instances of wind shear at altitude however, and these may prove to be a terriffic source of energy for the sailplane pilots of the future.

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 induced drag due to control surface deflection, etc.). Drag times true airspeed equals power loss.

The negative power (or loss) due to friction is equal to a constant times the glider's airspeed cubed. The negative power due to induced drag equals a constant times the lift force on the wing squared divided by the glider's speed.

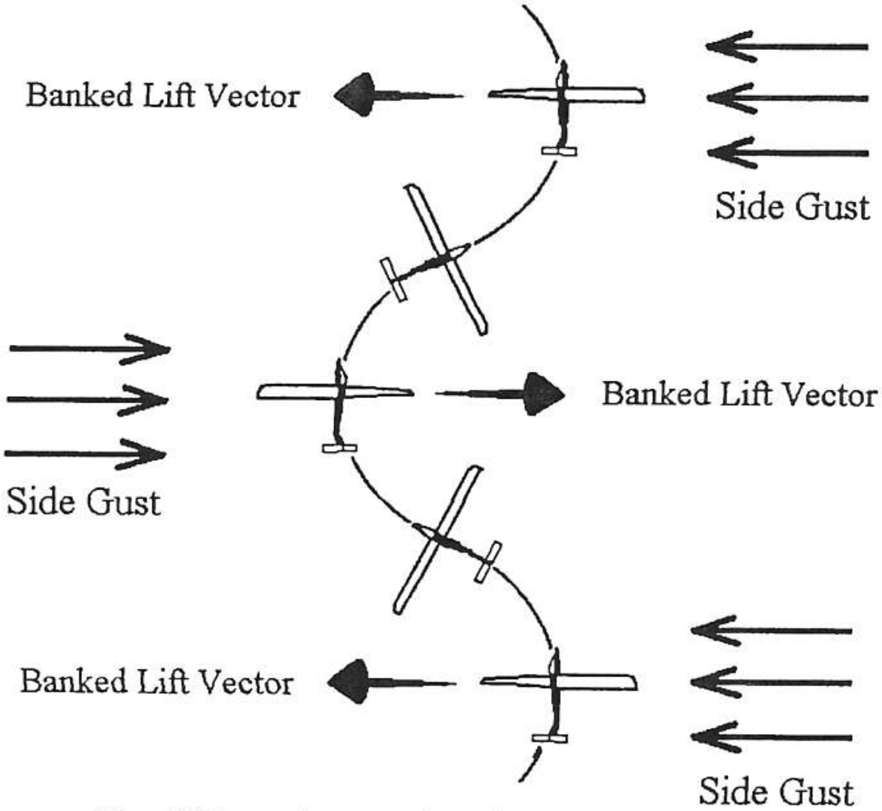
Control drag losses can be measured experimentally by wiggling the stick and observing the increase in sink rate (we don't have a simple formula for that one).

We've seen how the dynamic power extracted from the atmosphere is equal to the velocity of the air (in a local inertial reference frame) multiplied by how hard we can push against it with the wing. Or similarly, how the power of energy flow that the glider gets from the air is equal to how hard the air is pushing on the glider in its direction of motion times the glider's speed in the local inertial frame.

In the future there will be instruments designed specifically for dynamic soaring, but here, let's look at some

Side Gust Soaring

Dynamic Soaring with Side Gusts



The Glider makes a series of coordinated "S" tunrs, always turning away from the side gusts.

Note: Side gust soaring can work well with low frequency gusts as the changes in lateral velocity can easily be up to 200 f/s while keeping glider speed constant. High frequency response is limited by glider roll rate.

dynamic soaring techniques that we can use with standard instrumentation. Standard instrumentation in this case consists of: a total energy vario, an airspeed indicator, a yaw string, and a sensitive (g force sensing) "seat of the pants."

First let's look at vertical gust soaring. Thermals are often bumpy; how do we make the bumps work for us? As explained above, the general rule in dynamic soaring is to push on the air opposite to its motion. The faster the air is moving the harder we should push. This leads us to the first principle of dynamic soaring — increase the g force in lift, decrease or reverse it in sink. When we feel a bump of extra powerful "lift" we should pull back on the stick and increase the g force. Vice versa when the "lift" suddenly poops out we should reduce the aerodynamic force on the wing by pushing forward on the stick. One of the difficult aspects of this technique is figuring out what part of the g force is from the air's motion and what part is due to our control stick movements; experience helps a lot with this.

Working the bumps in this way can increase the power extracted from the air and thus increase our rate of climb or running speed. The technique produces a sort of roller coaster ride and probably will not be popular with passengers. Also extra care is needed if there is other traffic. How vigorously do we work the bumps in this way? We can "over do it" and waste more energy than the extra we're getting if we are not careful; this is because the average induced drag increases when the lift force on the wing is not constant. So some experimentation is necessary to see what works under various conditions. All things considered it is best to err on the gentle side.

As we fly faster induced drag is a smaller percentage of the total drag; this is one reason to fly faster in bumpy lift. If we are running a cloud street and flying fast we can work the bumps more vigorously without so much concern about increasing induced drag.

A situation where dynamic technique can be particularly effective is when we fall out of the side of a thermal. In this case we are suddenly in sink and know pretty much where the lift is (behind us). We want to get back into the lift quickly and lose a minimum of energy to the sinking air. We could lose a lot of energy in a hurry by pushing downward on downward moving air. So the first thing to do after entering the sink is to reduce the aerodynamic force on the wing by pushing forward on the stick, in an extreme situation perhaps even to somewhat negative g.

Next we can bank up to 90 degrees or so and perform a maneuver similar to the second half of a wing over (the low g state can enhance roll rate). Once banked up we can increase the g force, since we don't lose any extra energy by pushing sideways on downward moving air. This gets us moving back towards the lift. Our speed will increase substantially and hopefully we'll be back in the lift just as we start our pullout. As we pullout (at more than one g, back in the lift) we'll be getting more energy than usual and may actually be higher after zooming up than we would have been if we'd stayed in the lift in the first place. Obviously this maneuver is no good if there is other traffic below.

Now let's look at dynamic soaring with side gusts. This may or may not prove practical, but if we find ourselves in a situation where the yaw string keeps blowing off to one side or the other (and it's not due to uncoordinated flying) we may be able to work the side gusts. If the string blows to the left, that indicates a gust from the right and that we should bank left to extract the energy. One way to do this is to use the stick alone (no rudder) to initiate the bank, because that will also straighten out the string and restore the (low drag) nose into relative wind atittude.

This is the second principle of dynamic soaring — bank away from side gusts. As in the vertical gust case there is an energy cost to maneuvering, so the amount of bank must be tailored to the strength of the gust.

In an ideal case the gusts will oscillate side to side and we can make a series of "S" turns and get energy. In another case there may be a wind shear with altitude where we can create our own side gusts by diving and zooming in conjunction with "S" turns or a racetrack oval course.

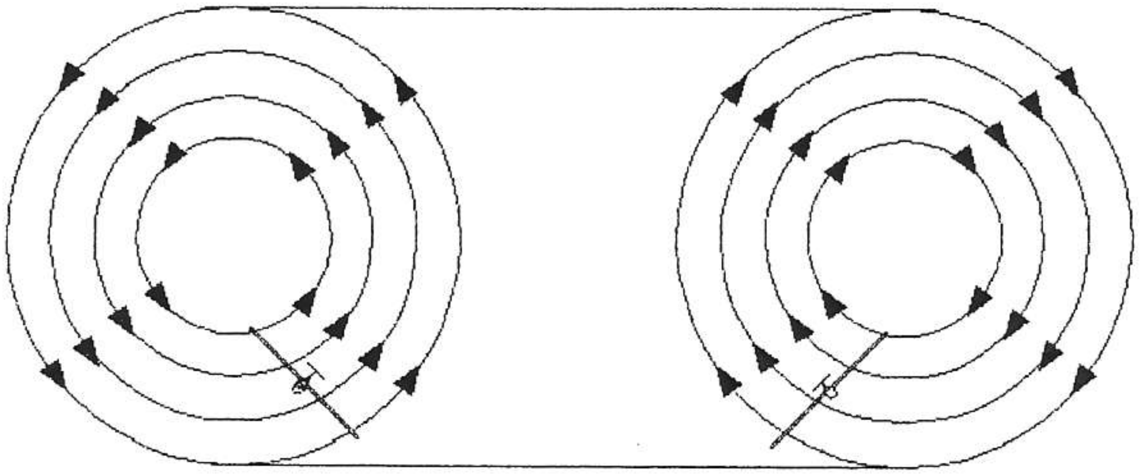
Another very interesting form of dynamic soaring is flying in a thermal vortex ring. A vortex ring is like a smoke ring, only without the smoke, and in the case of a thermal it is moving upward. This is an unusually smooth form of dynamic soaring and we may not even know that we're doing it.

On the bottom side of a thermal vortex ring there is an inward flow of air; on the top side the flow is outward from the core. If we are spiraling on the lower side our bank angle will cause us to be pushing outward or inward moving air, which, as we recall is in accordance with the general dynamic soaring rule — push the air opposite to its motion. The extra energy will show up in the form of forward impulse and we'll find ourselves gaining extra speed or spiraling with a more nose high attitude than is usual. This may be what's going on when we "core a thermal bubble" and find that a steep bank angle works better than steady-state upward-lift theory would predict. Another place to find inward moving air is near the base of a thermal. This leads to a third principle of dynamic soaring — seek out inward moving air to spiral in.

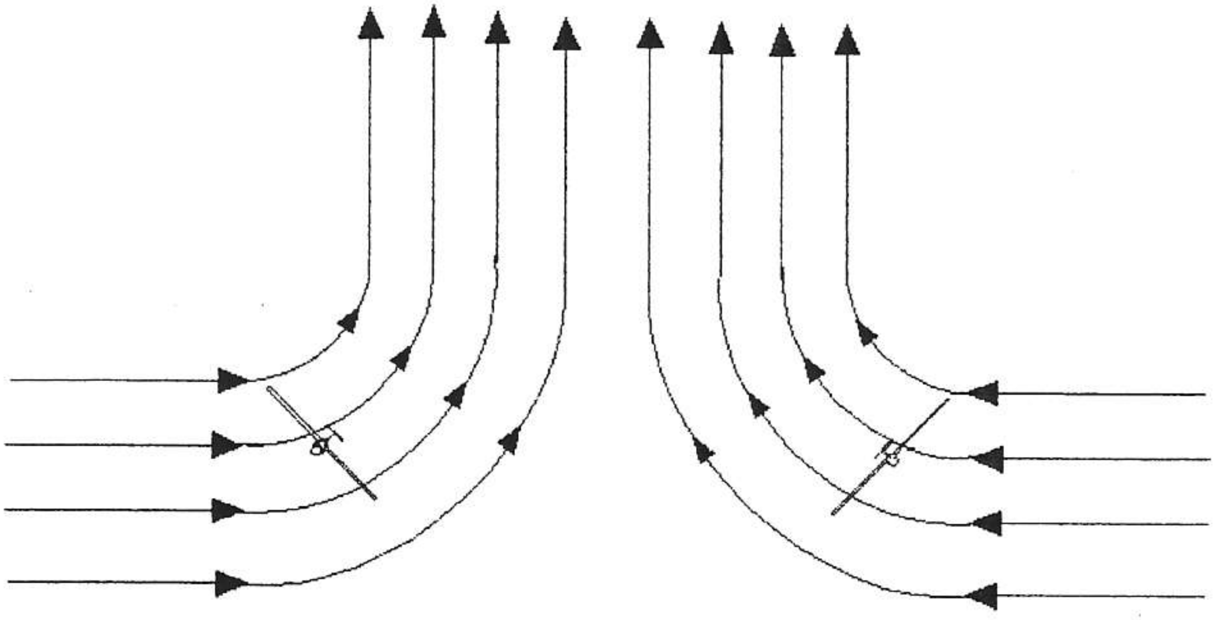
In summary, there are many situations where dynamic soaring technique can provide an extra source of energy for the glider pilot. The general rule for getting energy from the atmosphere is — push on the air opposite to its direction of motion, and remember — faster moving air yields proportionally more energy for the same amount of push.

This completes our discussion of dynamic soaring, hopefully the ideas presented here will advance the state of soaring art, producing longer, faster, and funner flights. Techniques for getting energy from the velocity fluctuations in the atmosphere may open a whole new era in motorless flight.

Two Cases of Smooth Dynamic Soaring



Thermal Vortex Ring



Inflow at Base of Thermal

(Danger of Wind Shear Induced Overbanking!)

Micro-Lift String Technique

Invented by Gary Osoba

Wing Rolling with Changing Wing Tip Loading Can Produce Thrust within a Spanwise Headwind Differential