Wrestling With the Beast

Working With, Instead of Against, A Powered Harness for Easier Handling

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Newcomers to a powered harness are often surprised to find that the glider handles very differently under power than it does while the engine is off. In the course of numerous discussions, ponderings and experiments I believe I have come to understand at least some of the key factors involved. Much of what I base my understanding of hang glider flight characteristics on are a series of books by Dennis Pagen (http://www.lazerlink.com/~pagenbks/). Dennis's books are well written and provide a wealth of information. If you want to learn more about the general flying concepts discussed here I highly recommend them.

This will be roughly grouped in two parts. In the first part I'll review the aerodynamics of turning a hang glider. The second part will be my best understanding of what effects adding the thrust force have.

How A Hang Glider Turns

Lift and Drag

Much of how a wing performs can be described by the Coefficients of Lift and Drag, and how they change with angle of attack. These can be written as $\mathbf{C_L}(\alpha)$ and $\mathbf{C_D}(\alpha)$ where α is the angle of attack and the parentheses mean "function of". For most of the flying range, increasing α increases both lift and drag, but they are not linear relationships - which is why there is only one angle of attack at which $\mathbf{C_L}/\mathbf{C_D}$, or L/D, is a maximum. The full equation for Lift (**L**) is:

$$\mathbf{L} = \frac{1}{2} r \mathbf{V}^2 \mathbf{A} \mathbf{C_L}(a)$$

where ρ=air density, $\mathbf{V}^2$ is the airspeed squared and **A** is the area of the wing. Replacing the **L** with **D** and $\mathbf{C_L}$ with $\mathbf{C_D}$ gives the equation for drag. It is the decreased ρ of hot days and higher altitudes that requires us to have a larger **V** (run faster) in order to achieve flight.

For unaccelerated flight, lift must equal the total weight (**W**) of the pilot, harness and glider. The $\mathbf{C_L}(\alpha)$ is determined by the glider design, and α is controlled by the pilot via bar position. Increasing the angle of attack, α, (pushing out) increases $\mathbf{C_L}$ which means that less of **V**-squared is needed for **L** to equal **W**, and we fly slower. Drag also increases with α. If you were to suddenly change the weight of the system (say, dropping ballast) but made no change in bar position ($\mathbf{C_L}$ does not change), then after a slight readjustment the glider will be flying slower because **V**-squared does not have to be as high for **L** to equal the reduced **W**. As a side note, the dreaded 'stall' is really more of a large increase in drag than it is a decrease in lift. That large drag quickly slows the glider to where the velocity is too low to generate sufficient lift, which is why you sink rapidly.

Assumptions and Conventions

I am going to use the convention that all forces are those acting on the glider. While it is pretty obvious that the Lift force acts upward, there has been some confusion about the direction of the Thrust force. My convention for thrust is that it acts on the glider in the FORWARD direction, as that is the direction of the force that the harness applies to the glider.

In order to avoid spending too much time trying to sort out "inside" and "outside" wings versus left and right turns, ALL TURNS WILL BE LEFT TURNS for the sake of this discussion. That way when "left" wing is used in one sentence and "inside" wing in the next one, it will be obvious that they are one and the same.

A lot of complex factors, all working together, come into play when turning a glider, but I'm going to start out taking them each as a separate part. Once we have looked at all the pieces I'll put them together again. Everything I am going to talk about now applies to our standard "flex wing" hang gliders. Rigid wing models are quite different in their design and I will discuss those differences at the end.

Roll

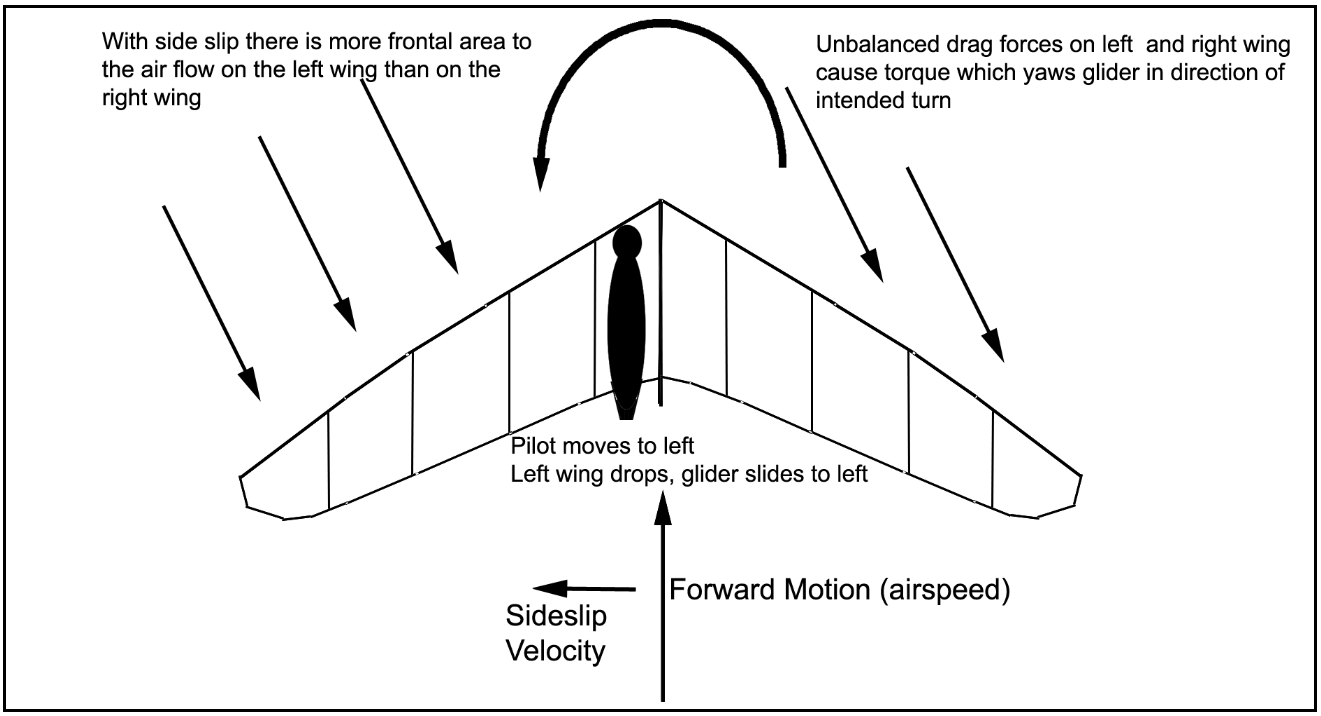
We control roll by shifting our weight sideways (for this part we are not pulling in or pushing out on the bar - strictly a sideways movement). Prior to our roll input the glider is flying straight ahead and stabilized, with each wing carrying half of the total weight. By moving our body to the left we have put more weight on the left wing and less weight on the right wing. Because the left wing was only moving fast enough to support half our weight it begins to sink, while the right wing is now carrying less than it had been, and begins to rise. That is what we wanted. But the two sides will try to stabilize with the new weights, which means that the more heavily loaded left wing will now want to fly faster, while the lightly loaded right wing will want to slow. This is definitely NOT what we want! This effect is called "adverse yaw", and it is a problem with all aircraft, not just hang gliders.

Let's think about using ailerons to roll a conventional aircraft. To roll left, the right aileron moves downward (to increase lift by effectively increasing the camber of the wing - therefore increasing $\mathbf{C_L}$) while the left aileron moves upward to decrease lift. While this unbalance of lift forces serves to create the roll, the increase in lift on the right wing also causes an increase in drag, and vice versa with the left wing. Thus the "adverse yaw" problem exists here too. In fact this problem took a long time to solve. Many of the early aviation pioneers were able to fly in a straight line, but they could not figure out how to make controlled turns (and some died trying). The Wright brothers finally solved the problem by adding a rudder which could then be used to overcome the adverse yaw.

But hang gliders don't have any direct yaw control.

Yaw Stability

Hang gliders achieve directional (yaw) stability because of the swept wing design. If a glider is flying straight ahead, the air is meeting both wings at an angle (that angle being determined by the nose angle of the glider). If a bit of turbulence or something else causes one wing to get ahead of the other one, the airflow will be hitting the forward wing more directly, and it will also have a larger apparent frontal area (relative to the airflow). It will also have an increased apparent length which increases the effective moment arm of the drag forces on that side. The increased drag force on the forward wing (and reduced drag force/moment arm on the rearward wing) produce a yawing moment that turns the glider back towards being straight into the airflow.



So far we have talked about yaw stability in straight-ahead flight, but how about that left turn? As we roll left the glider will start 'slipping' to the left as well. This is because the "lift" generated by an airfoil acts perpendicular to the wing - not necessarily "up". Thus the lift force is now acting up and to the left, while weight is still acting straight down. These unbalanced forces will cause the glider to move sideways (slip) to the left as well as continuing forward. This puts the left wing more directly into the airflow thus causing a yawing moment that slows the left wing and rotates it back. That is how our swept wing yaw stability comes into play to overcome the adverse yaw effect from our roll motion.

Of course there is a performance penalty for having a swept wing, since the airfoil is not as efficient as it would be if it were meeting the airflow at a 90 degree angle. That is why you will see higher performance (and generally more difficult handling) gliders with less of a nose angle than the lower performing but easier handling models.

Although it may seem intuitively obvious that by moving our weight to the left that we turn left, the physics of it don't necessarily agree with our intuition! It is only by careful design that what we think is obvious actually happens.

Billow Shift

Modern gliders allow the keel some sideways movement. When we move our bodies to the left for that left roll, we are also putting a sideways force on the keel. This sideways force on the keel has the effect of tightening the sail on the right side and loosening it on the left. For many years I thought this had the effect of changing the camber of the sail - that is, the $C_L(\alpha)$ of each wing. Under this scenario the right/tight wing would have decreased camber and C_L - resulting in lower lift and drag, while the opposite would apply to the left/loose wing. This (I thought) would be another effect to help overcome the adverse yaw problem. It was only very recently that Dennis set me straight on this point. While there might have been some billow shift/camber relationship on older (flexible batten) gliders, the shape of the airfoil on modern gliders with pre-formed battens will not change very much, if at all.

What does happen as a result of billow shift is that the relative angle of attack of the two sides changes. The left/loose side will allow the sail to rotate up slightly - thus α decreases because of the billow shift, and therefore creates less lift and drag, while once again the opposite applies on the right wing. Which also tends to generate adverse yaw!

But we are not done yet. As we are making the roll input (but before we are in a stable turn), the left wing is moving downwards, which increases the angle of attack on it while decreasing α on the right wing. The increased lift caused by increased α on the inside wing acts to oppose our roll input. But the billow shift decreases α, thus allowing the turn to be made easier. Now we can understand why the higher performance gliders with tighter sails can be more difficult to roll than easier handling gliders with looser sails.

Putting the pieces together

Let's summarize the points above when we put in that left roll input:
1. Left wing begins moving downward, increasing angle of attack
2. Sail shifts to loosen left side, very slightly decreasing the angle of attack
3. Higher load on left wing. This higher load is balanced partly by the increased angle of attack ($CL(\alpha)$ is larger) and partly by an increase in velocity (adverse yaw)
4. Glider slips sideways because the Lift and Weight forces no longer act to directly oppose each other.
5. Sideways slip creates a moment (because of the swept wing design) that yaws the glider to the left.

With a well designed glider these things will balance so that the glider will actually do what we expect it to. If nothing else we should have a finer appreciation for what has gone into designing our wings!

We are only discussing turn/roll initiation - which is most important when discussing "handling". There are a lot of other things that come into play once we are turning, but those have less of an effect on what we are talking about now.

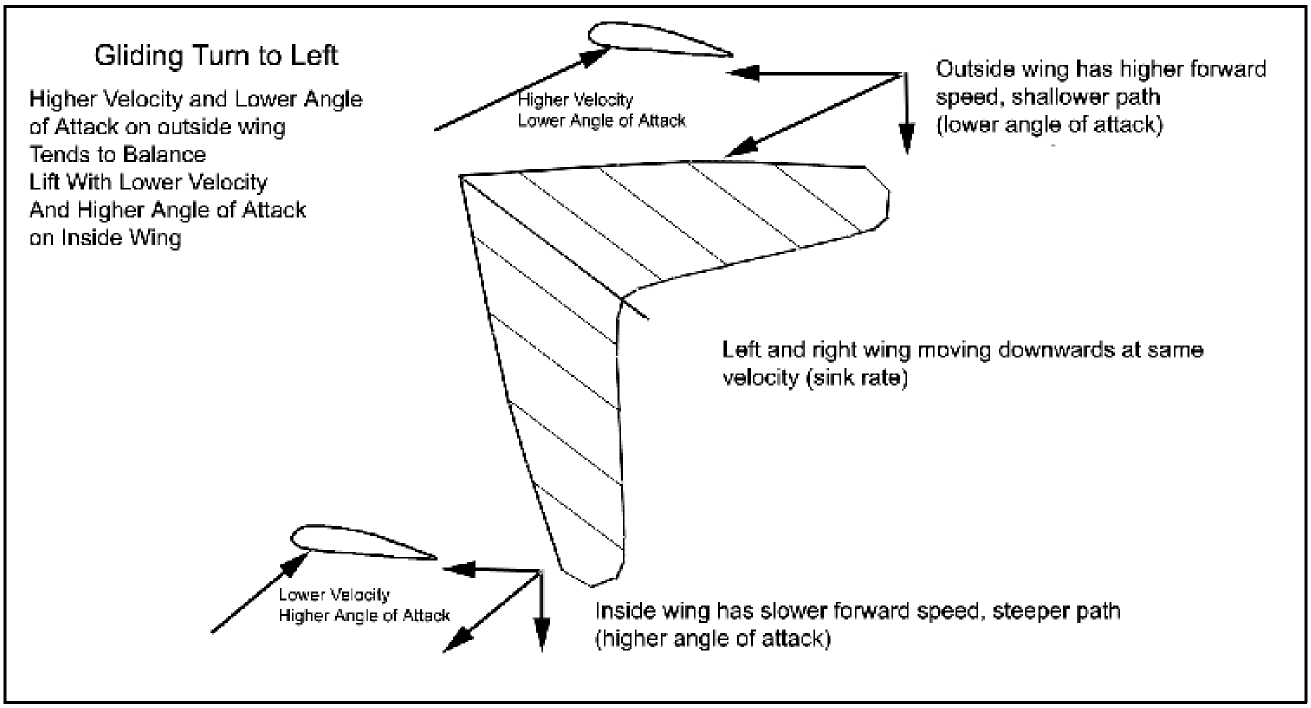
Adding Power

Adding power introduces another force acting on the glider. What follows is my best guess at trying to figure out all the ways in which that force affects our handling. One way is general to powered flight, while the others are more specific to our powered harnesses with their variable thrust directions.

Roll Instability

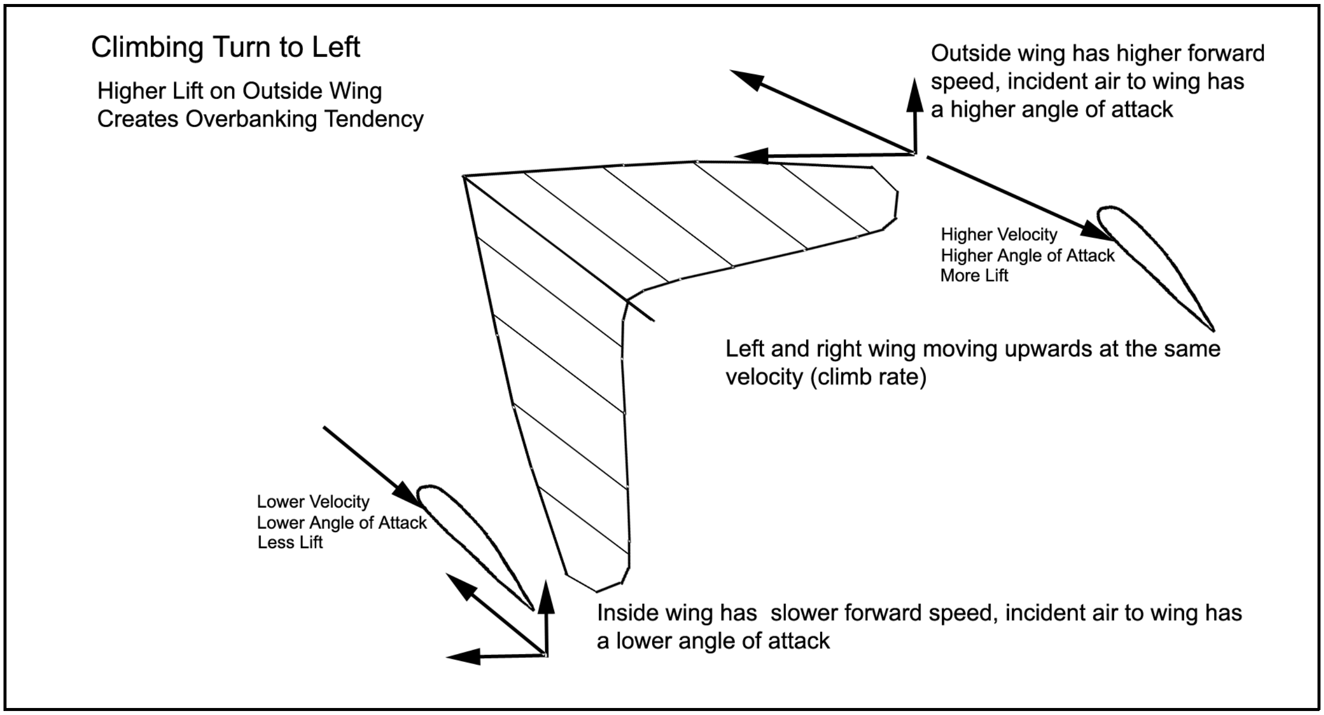
A gliding aircraft inherently has a higher degree of roll stability than when flying with power. For this

discussion we are talking about being in a constant turn, such as doing 360's. In our constant turn to the left our left/inside wing is moving through the air slower than the outside wing, thus we would expect it to have less lift. However, because we do not have any power, we must also be moving downward relative to the air we are in (even if that air is moving upwards, as in a thermal or ridge lift). Both wings will be moving downward at the same speed in a stable turn. Because the left wing is moving forward slower, this downwards motion causes it to have a higher angle of attack than the right wing.
If we add these two things together we have the potential for very nice roll stability: the left wing is moving slower (less **V**) but has a larger angle of attack (α) which increases $\mathbf{C_L}(\alpha)$. Putting both of those into the equation we see that it would not be hard to achieve a situation where these two effects exactly balance the higher **V** but lower $\mathbf{C_L}(\alpha)$ of the right wing.



Now we add power. To begin with, let's add just enough power that we are making our stable turn at constant altitude (air is not lifting or sinking). While the inside wing is still moving forward slower than the right wing, neither wing is moving downwards. Therefore the angle of attack is the same for both. The only thing in our lift equation that is different between the left and right wings is that **V** is smaller for the left wing. The right wing with the larger **V** will be generating more lift which creates a moment that wants to roll the glider ever more steeply.

In climbing flight the upwards motion reverses the relative changes in α for both wings. That is, α



increases for the right/outer wing - so now the right wing has both a higher **V** and higher $\mathbf{C_L(\alpha)}$ than the left wing, and the roll moment becomes even larger. Thus we can expect to do more "high siding" to maintain a stable turn under power than we do when gliding.

Thrust Line Direction

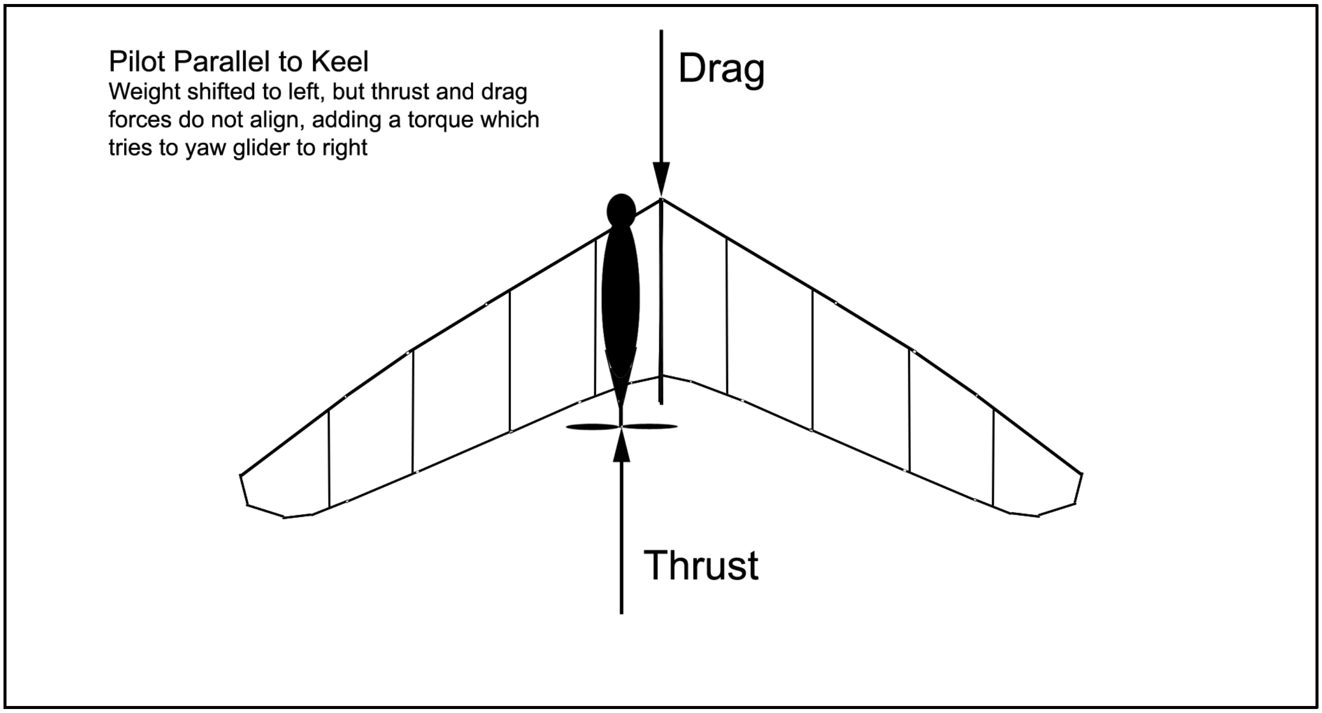
Everything up till this point has been rehashing things that are relatively well known. From here out I will be talking about my speculations and experiments about how the thrust line affects our handling in other ways.

When we make a roll input, we do so by moving our center of mass to the side. When flying an unpowered glider it mostly doesn't matter how our body is oriented (whether the body is parallel with the keel or not) - it is how far over our center of mass has moved. Many pilots do use a "feet first" method of turning which allows them to impart a small temporary yawing moment to the glider, but that is a secondary effect.

When we have power attached to our bodies we control the direction of the thrust force by our body orientation, so orientation becomes much more important than when just gliding. Let's look at all three possible orientations in turn (and recall the convention that thrust is acting on the glider as a forward force) The figures used in the following discussion will show primarily only the changes added by thrust, all other effects discussed earlier also still apply.

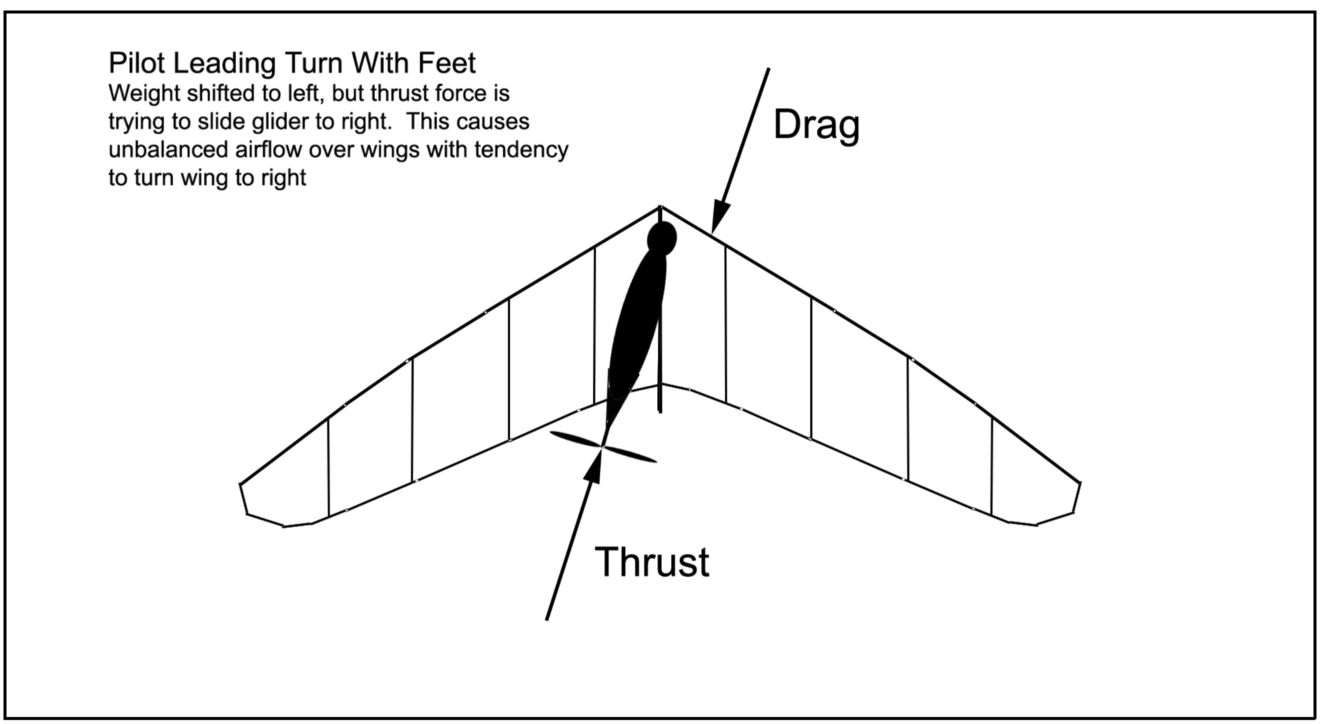
Body Parallel to Keel

The thrust line remains parallel to the keel, however it is now offset to the left. I have thought about



this in a lot of different ways, but the simplest one is to simply think of a twin-engine aircraft with the right engine dead - the thrust acting to the left of the centerline will tend to yaw the glider to the right, just the opposite of what we want.

Feet First Roll



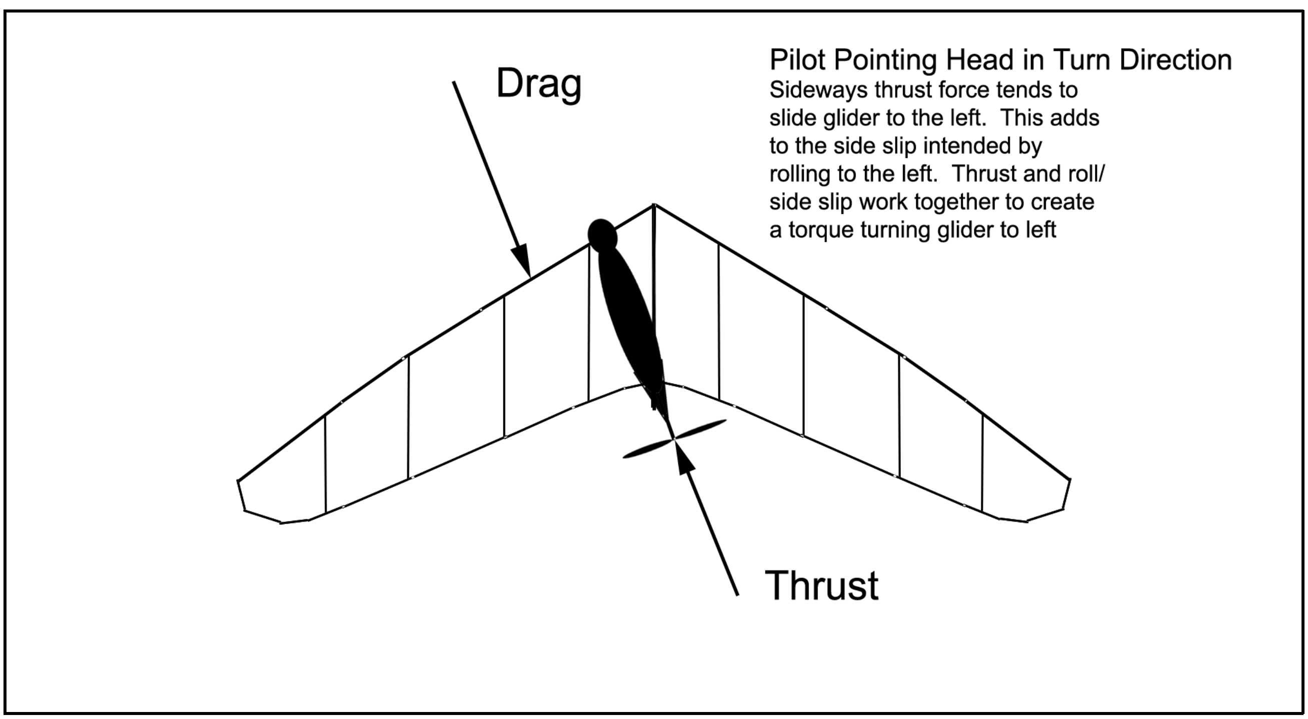
This is the standard method used by many hang glider pilots, myself included (for unpowered flight) -

the feet are moved farther in the roll motion than the shoulders. One good reason for doing this while free flying is that we are both moving the body sideways and rotating it about the hang point - the rotation causes a yawing torque on the glider which tends to turn it in the direction we wish. It is thought that this helps to produce "flatter" turns.

Now let's look at the thrust line direction. The pilots **CG** (center of gravity) is displaced to the left, but the feet/prop are further to the left, causing the thrust line to be twisted clockwise to the glider (when viewed from above). This clockwise rotation of the thrust line causes a component of force acting to push the glider to the right. However, in order for the yaw stability of our swept wing to come into action we need to be slipping to the left. Thus under power our feet-first roll technique becomes counter-productive because the angled thrust force is working in opposition to the desired side slip towards the inside of the turn.

Head First Roll

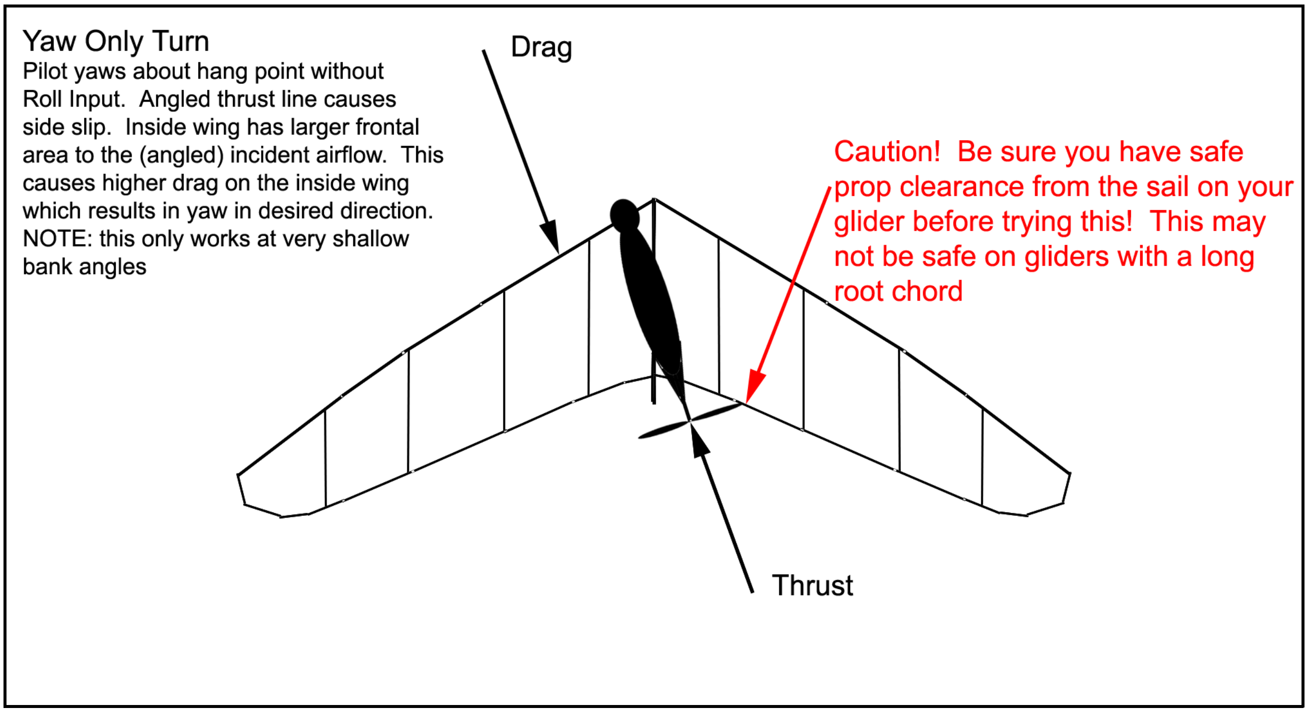
One of the first things new hang glider pilots learn is that if you simply move the upper part of your body sideways you will have very little control. That is because instead of moving your CG to produce a roll input all you have really done is twisted your body about the hang point. After a few panicked episodes of "the glider wouldn't turn and I was as far over on the bar as I could go!" the new pilot learns about keeping their body parallel to the keel (or even leading with their feet). Experienced pilots simply don't consider using a head-first rolling motion.



Let's take another look at that, except with thrust added to the picture. The pilot shifts his CG the same amount as with either the parallel or feet-first method, but rotated in the opposite direction from the feet-first method. That is, his head has moved the most to the left and his feet the least. The thrust line now has a sideways component to the left, which is the direction we want to turn and also the direction the glider needs to slip in order for the correct yaw to take place. It is my contention that this head-first method is the easiest way to initiate (or roll out of) a turn.

Experiments and Observations

On a number of occasions I have proven to myself that I can successfully turn the glider using only a yawed thrust line with no roll input. The way I have done this is to grasp the control bar with only 2 fingers on one hand, which I use to rotate myself about the hang point. Using those 2 fingers I am not able to create any significant sideways movement of my CG, thus I am not creating a rolling moment. I have been able to do a series of reversing turns using this method. What I believe is happening is this: when I yaw the thrust line (let's saw CCW viewed from above) I am introducing a sideways force to the glider. This sideways force creates a side slip which then causes the wing to yaw to left because of the swept wing yaw stability. In this case the mechanics work backwards because the yawing motion causes the left wing to slow (decreased lift) and right wing to speed up (increased lift) - thus creating the rolling moment to coincide with the yaw.



There are definite limitations to the thrust-only turn method - I have only been able to get it to work in smooth conditions and at shallow bank angles. It seems that at steeper bank angles the roll instability of flying under power is too great for this method to overcome. Once I am past more than about 5 or 10 degrees I have to add some roll force to the yawed thrust line in order to reverse the turn.

There are also limitations on how far I can yaw my body before I am blocked by the downtube. And if you are trying this with a glider that is not high aspect ratio (i.e., long root chord) - you will want to be very careful that you are keeping the prop clear of the sail!!! That does not appear to be a problem with my glider, but you should satisfy yourself that that is the case with your own glider before trying anything too radical!

Turning with only a yawed thrust line is a cute trick (and very handy for staying on course when you have one hand busy, such as while zipping up your harness) but useful mainly for demonstrating the effect of the thrust line on turns. However, if we can turn only with a yawed thrust line, then it should be apparent that we can use the angle of the thrust line to either help us or hinder us when turning. If the glider will turn under nothing but a roll input, and will also turn by simply yawing the thrust line, then it should be very easy when the two are combined. This has been my experience.

I have seldom found it hard to initiate a turn when flying straight ahead. What I have found to be harder is maintaining a constant bank angle turn, and even harder to roll out of that turn (especially under full power). Under thermally conditions much of our time is spent rolling out of unwanted thermal induced turns, and this is where it can become a real workout.

I have found the head-first roll method to make life much easier in all cases. My hang glider will coordinate a 360 very nicely when flying without power (that is, no roll force required to maintain a constant bank angle), but tend to spiral-in when flying with power. I have found that by simply yawing my body, so that the thrust line points slightly towards the upper wing, I can achieve a stable coordinated turn under full power without high siding. And the effort to roll out of the turn when directing the thrust towards the high wing is also greatly reduced.

When I first started flying with my NRG it was with an Airwave K4 - a relatively stiff glider in roll. Although on smooth days I had no real problems with it, the first time I flew it in thermally conditions I often found it nearly impossible to roll out of a thermal induced turn without reducing power. On one of those occaisions I later discovered my wife had taken a photo which allowed me to study what was going on at great length.

When the photo was taken I was under full power and in a turn towards the hill that I could not roll out of despite some strenuous effort to do so (once I reduced the throttle the glider responded immediately). Let's look at the points we've been discussing and how they relate to the photo. My body is nearly perfectly parallel with the keel, and I have definitely displaced my body well to the left - the glider should be rolling out of the turn, but it wasn't. You can see the billow shift effect towards the tips of the wings - more of the under-surface is showing on the left as would be expected (looser sail), although the sail on this glider is relatively tight and the billow shift is small. The looser sail on the left, taken by itself, would imply a lower angle of attack and therefore less lift. However there are two other factors to consider. One is the increased roll instability during climbing flight, which could effectively cancel the decrease in angle of attack caused by the billow shift. The second is that the left wing (on the outside of the turn) is moving faster and thus generating more lift. Of course the second point is always true, and does not normally prevent rolling out of a turn when power is not added. The best explanation I have been able to arrive at is the one described above for the Body/keel parallel case (twin engine aircraft with the right engine dead). The thrust line is not displaced that far to the left, but I think it may have been enough to play at least a partial role in locking in that turn. I've since been flying the Sting which is much friendlier in roll. But I still have the K4, and one day I plan to pull it out again and try it with my head-first technique...

A final argument in favor of the head-first roll technique (and one I have used repeatedly in the past) is the Doodle Bug. Pilots of the Bug tend to praise the easy handling of their units. I believe this is because of the way the limit lines are set up. Unlike a prone pilot, a supine pilot does not have an easy way to control the sideways location of the rear of the unit (since his feet are in front of him). The Bug design solved this by using relatively tight limit lines to maintain the rear of the unit in a nearly stationary position, at least as far as sideways motion. Thus when a Bug pilot rolls to the left he is automatically also directing the thrust line to the left, thus effectively using the "head-first" (for prone pilots) turning method.

Rigid Wings

Rigid wings have a different means of coupling roll and yaw. While a flex wing glider is controlled by rolling the glider (which creates a yawing motion because of the swept wing design), a rigid wing works just the opposite. A rigid wing is turned by inducing a yaw motion (creating higher drag on the inside wing via a control surface) which then creates the roll. That is because a rigid wing does not depend on having swept back wings to maintain yaw stability. Instead it uses dihedral to maintain roll stability (dihedral is what you get when the wings form a V, rather than being flat across the top - that is, instead of sweeping the leading edges backward at the tips as with a flex wing, they are moved upward).

To demonstrate how this works, take an envelope or something similar and fold it into a V. Hold it in front of you so that you are looking directly down the fold, and imagine that it is flying directly at you. Now turn it about the vertical axis in the CCW direction (as if it were yawed to it's left) and you will see that it's "right" wing (on your left) now has a much greater angle of attack, while it's left wing has had it's angle of attack greatly reduced - thus a moment has been created that tends the roll the glider to it's left.

To recap: a flex wing glider is controlled by roll where the swept back wings then create the necessary yaw. A rigid wing glider uses control surfaces to create a yaw motion which is then converted to a roll by dihedral.

I have no personal experience with rigid wings, but I can offer two observations that suggest how they will handle under power. The first is that the control surfaces out towards the tips of the wings are capable of producing large yawing moments by virtue of their long moment arms. This suggests to me that whatever effect a yawed thrust line has is very minor compared to the control afforded. The second is that the comments I have heard from rigid wing flphg pilots indicate that they seem to think handling is very easy, even under full power.

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