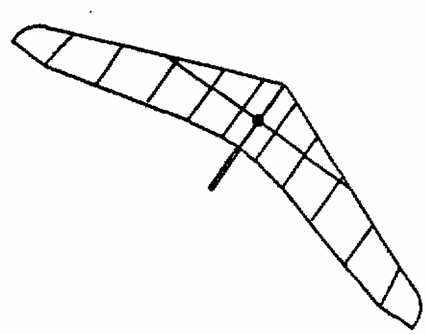
$$R_{L/D} = 1.14\, R_{min}$$

$$(L/D)_R = 0.87\, (L/D)_{max}$$

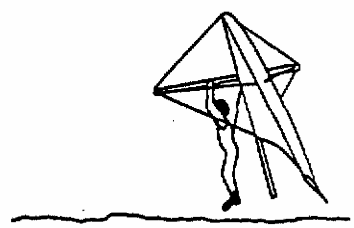
$$R_{min} = 0.88\, R_{L/D}$$

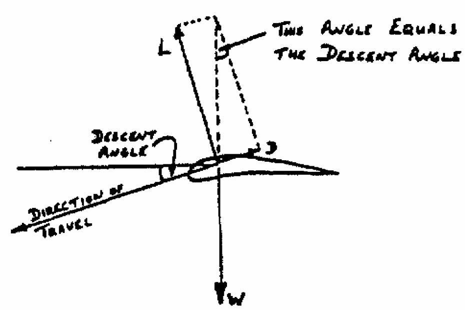
$$(L/D)_{max} = 1.15\, (L/D)_R$$

The Hang Glider's Technical Notebook



Finbar Sheehy





The Hang Glider's Technical Notebook

Finbar Sheehy

Faoilean Press

Pasadena California

Faoilean Press, Pasadena CA

Printed in the United States of America

WHAT THIS BOOK IS ABOUT

This book is not about hang gliding. It is about magic. Like many children, when I was young I used to dream I could fly. I would watch the birds and imagine what it would be like to do as they did. They had the power to do something that was clearly impossible. The air is so thin, and gravity so powerful, I could not imagine how they could be supported by air alone. Clearly the birds had some magical powers that enabled them to do this. I did not.

By the time I had grown up I had almost forgotten the dreams of flight and freedom. Almost, but not quite, because on a dull afternoon a stranger with Dacron wings flying along a mountainside brought them all back with a rush. I watched the stranger float overhead, silently, and knew, just *knew,* that this was impossible. I was witnessing magic.

This book is about that magic. It's not about how to use the magic. It's not about the art and skills of flying. All the air lore in the world would be useless without wings, and the magic that makes them work. The secrets, the ones the birds knew all along, are what this book is about.

Of course, we are modern, technical people. We do not speak of "magic". We talk about "physics", "aerodynamics", "stability", "control", "structures", "algebra", and so on. We talk about cold, hard facts. We are too hard-headed and practical for romantic ideas of freedom or magic, and you will find no such ideas here. This book tells you why hang gliders work, why the laws of physics actually demand that they defy gravity and fly, however unlikely it may seem.

This book is about physics and aerodynamics and why hang gliders fly, and why they fly the way they do. It's about how the ancient secrets of the birds have been turned into aluminum-and-Dacron wings. It's about magic.

<u>WARNING!</u>

This book is **FOR YOUR INFORMATION ONLY**.

It is **NOT** an instruction manual.
Do **NOT** use this book as instruction on how to fly.
The author is not a qualified instructor.

Do **NOT** modify **ANY** part of a hang glider or its equipment.
If the designer wanted it that way, leave it alone.

HOW THIS BOOK IS ORGANIZED

This book originally started as a series of notes I made to myself when I found the answers to questions I was asking. I wanted to know what determined the glide-angle, and why it was so poor compared to sailplanes, and why high-performance gliders were smaller and more difficult to turn, and why people couldn't get better performance with bigger gliders, and how fast to fly in a headwind, and how much altitude I would lose in a turn, and how much my sink-rate would increase in a turn...

I find I can grasp material best when there isn't much of it. When there's a lot of explanation and "too many words" I find I tend to miss the point occasionally. As a result, I've written these "notes to myself" in a fairly condensed form.

I've organized the notes so that each topic is explained on the left-hand page, with any corresponding diagrams or equations on the right-hand page. If there is no diagram corresponding to the topic on the left, then the right-hand page is blank. Where I've used equations I have summarized the results in the text, so that you can skip all the algebra if you like.

CONTENTS

1. WHY IT FLIES

---

1 (I) How to Use Air to Stay Above the Ground

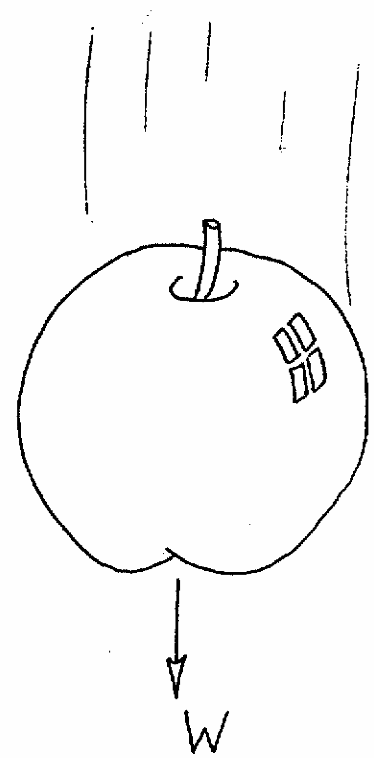
Newton's famous Third Law of Motion gives us the clue we need in order to fly. It says that if a machine tries to push some air down, the air will try to push that machine up.

In 1687 Isaac Newton published a book which contained some theories he had about mathematics and physics. This book, known to most scientists as the *Principia,* is widely considered the most important scientific publication in history. Newton is regarded as one of history's great geniuses. Although the book covers a lot of subjects, Newton was able to identify three facts that he felt were of really great importance. He wrote them in Latin, but in English they can be stated as follows:

1. An object at rest tends to remain at rest$_1$ and a moving object tends to continue moving at a steady speed in a straight line, unless acted on by a force.
2. When an object is acted on by a force, it accelerates in the direction of the force. The acceleration is proportional to the force, and is inversely proportional to the mass of the object.
3. When one object applies a force to a second, the second applies an equal and opposite force to the first, or, *"to every action there is an equal and opposite reaction"*.

These laws contain the clues we need to fly. If we can somehow build a machine that can push air downward, then the air will push the machine upward. If the force is equal to the Weight of the machine (which is trying to pull it down), then that force will cancel the Weight, the total force acting on the machine will be zero, and the machine will move in a straight line at a steady speed (as Newton's first law tells us).

Newton was a really smart guy, and used these simple rules to predict the motion of the planets. He also developed the mathematics, Calculus, (he called it Fluxions) which he used to make those predictions. Unfortunately Newton knew very little about aerodynamics (well, he was busy enough with gravity and mechanics) so his rules do not give us the details of how to fly, but they point the way. The basic mathematics needed to understand moving objects come from his ideas, which are over 300 years old!



As any apple knows,
Gravity Never Quits!

(with apologies to Sir Isaac Newton)

1(II) The Fundamentals of Lift

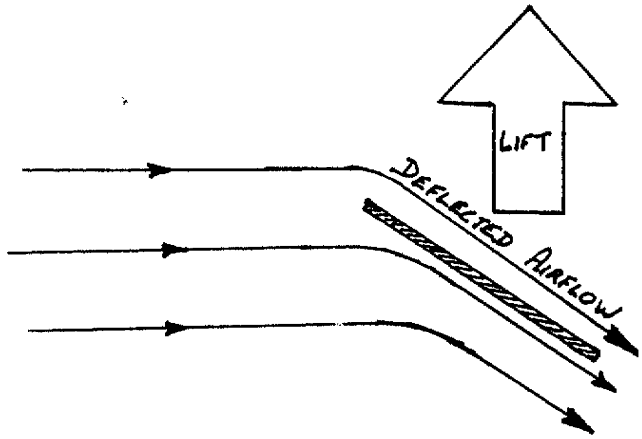
A wing in an airflow deflects the air downward. In doing so it pushes down on the air, so that the air pushes the wing upward. This is how the wing develops the necessary LIFT force.

We know that we need to push air downward in order to stay up. Suppose we have a flat plate and hold it at an angle to an airflow, as in the diagram. The plate deflects the airflow. If it deflects the flow downward, the air will try to move the plate upward, providing the LIFT we need.

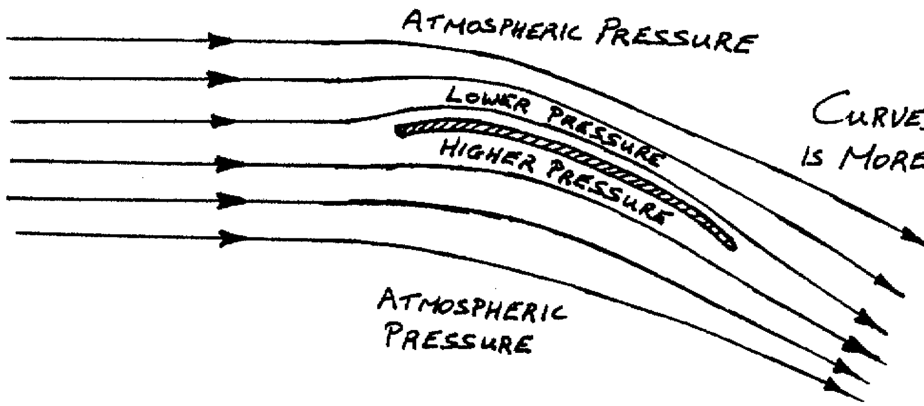
This actually works, but it is possible to get better results if the plate is curved. The way a curved plate works can be explained in a number of ways, none of them all that easy to follow, but the easiest is to get back to our friend Newton. His second law tells us that air molecules will flow in a straight line unless some force deflects them. If they are flowing in a path that curves downward then something must be pushing them down. In the case of a fluid the only thing that can "push" is the pressure. Quite simply, the pressure on the outside of the turn must be higher than the pressure on the inside of the turn. We know, in the case of the air flowing above the plate, that the pressure on the outside of the curve is simply atmospheric pressure, so the pressure on the inside of that curve (i.e. just above the plate) must be less than this. On the other hand, in the case of the air flowing below the plate, we know that the air on the inside of the curving path (well below the plate) is at atmospheric pressure, so the air pressure on the outside of the curve (i.e. just below the plate) must he higher. This all means that the pressure directly below the plate is higher than the pressure directly above it, so the pressure difference is trying to push the plate upward. Of course, we still get an equal and opposite reaction pulling the air downward as it flows past, following that curve.

There is another improvement we can make. The flat plate makes the air go around a very sharp corner at the front edge ("leading edge"), and air makes a big fuss about flowing around sharp corners. Things go much more smoothly if the leading edge is nicely rounded, for example if the plate is given an airfoil cross-section. Of course the two improvements can be used at the same time, by making a curved plate with an airfoil cross-section!

The angle of the wing relative to the airflow is called the Angle of Attack (pretty aggressive stuff, but don't blame me!). The bigger this angle is, the more sharply the plate pushes the air downward as it flows past, and the more lift force it develops as a result - up to a limit. Beyond this limit the air is being asked to turn too quickly. It refuses to do so, and lift decreases. The wing is "stalled". Obviously it is pretty important to know about this, so we'll get back to it again later. In any case, at any angle of attack the lift force varies as the square of the airspeed - double the airspeed to get four times as much lift. So, at higher airspeeds we can use a lower angle of attack to get enough lift.

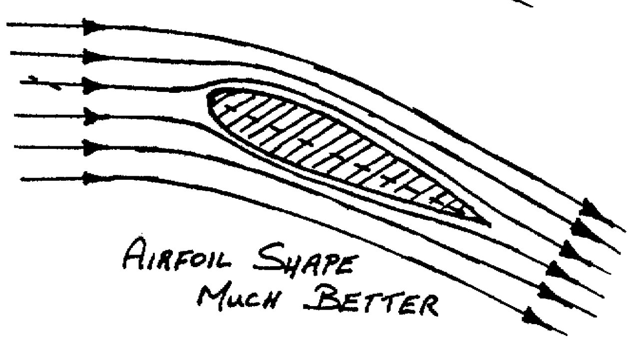


FLAT PLATE
DEFLECTS AIRFLOW TO
GET LIFT

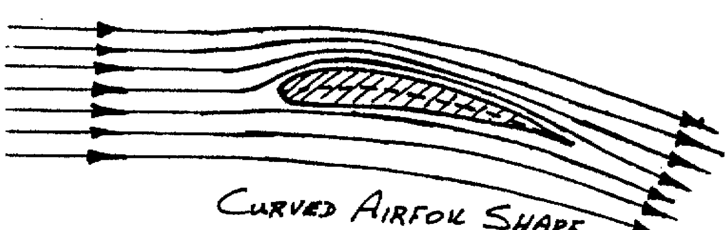


CURVED PLATE
IS MORE EFFECTIVE

FLAT PLATE NOT
SO GOOD ON UPPER SIDE



AIRFOIL SHAPE
MUCH BETTER



CURVED AIRFOIL SHAPE
IS REALLY GOOD

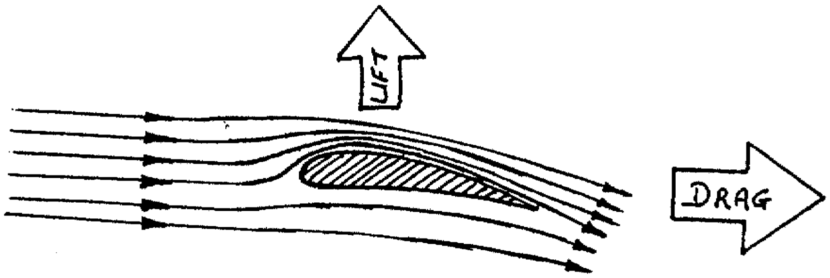
1(III) The Bad News, or, What a Drag!

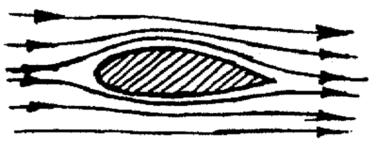
So far we have met two of the forces acting on the wing, Lift and Weight. Drag is a third force, and is the name given to the fact that the wing would drift along backways with the airflow if it could, rather than stay in position while the air flows past. There are two kinds of Drag; Parasite Drag and Induced Drag.

So far our lifting plate, or wing, has been stationary in the middle of each diagram while the air flowed past it to be deflected downwards. We haven't asked why the wing doesn't simply get carried along by the airflow and disappear off the page to the right. Actually, it would if something didn't stop it. The force trying to carry it along with the airflow is called DRAG. There are two kinds of drag, caused by different things.

The first kind of drag is usually called Profile Drag. I prefer the more colorful term Parasite Drag, and since I'm writing this, that's what I'll call it. Parasite drag is much like friction. Air resists anything moving through it. This includes not just the wing, of course, but anything attached to it. A hang-glider wing has a lot attached to it, such as the pilot, the wire rigging, kingpost and control frame. Airfoil shapes have low parasite drag. Round shapes have more drag, and anything lying flat across the airflow has a lot of drag. Rough surfaces cause more parasite drag than smooth ones. Anything that flutters or vibrates in the airflow makes a huge amount of drag, so loose clothing is very bad. So is the wire rigging. The whistle that comes from the rigging in flight is caused by the wires vibrating. This makes a lot of drag, even though the wire is very thin. The effects of parasite drag get worse very quickly as the airspeed increases. In fact, parasite drag increases as the square of the speed, i.e. if the airspeed doubles the parasite drag increases by four times, and if the speed triples the parasite drag increases by nine times!

The second kind of drag is called Induced Drag. It is the price we pay for lift. When the wing deflects air down, it turns some of the air's horizontal speed (left to right in the diagrams) into vertical speed (i.e. downwards). The vertical speed provides the lift force, of course, but the lost horizontal speed causes a drag force. The bigger the angle of deflection, the more horizontal speed the air loses and the bigger this drag force becomes. If the airspeed is low then the angle of deflection needed to make the lift big enough is big, and so the induced drag is big. On the other hand, if the airspeed is high then only a small deflection angle is needed to get the required lift force, and so the induced drag is small. This means that induced drag decreases when the airspeed increases, if the lift force is kept constant. Induced drag can also be reduced by making the wing longer. This is why high-performance gliders and many soaring seabirds have such long, thin wings.

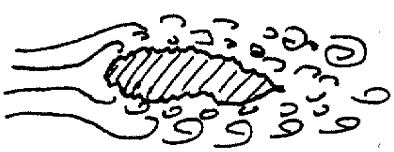




LOW DRAG

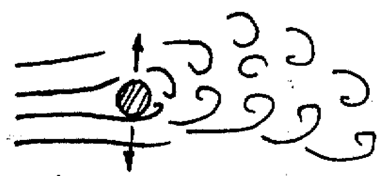
MODERATE DRAG

HIGH DRAG

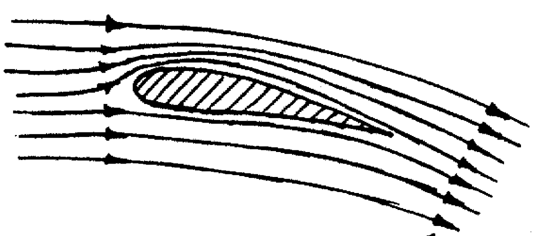


ROUGH - HIGH DRAG

FLAPPING
- HIGH DRAG

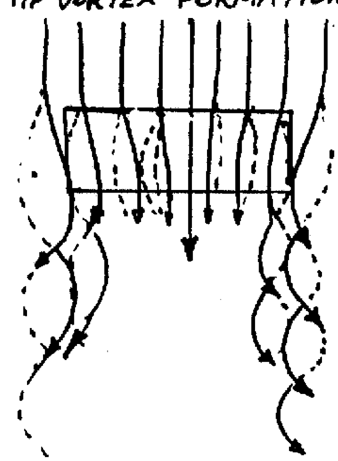


VIBRATING
- HIGH DRAG



AIR HERE IS
NOT MOVING TO THE
RIGHT AS QUICKLY AS
IT WAS - INDUCED DRAG

INDUCED DRAG IS OFTEN
EXPLAINED BY LOOKING AT
TIP VORTEX FORMATION



1 (IV) The Glider Equation, The Magic L/D Ratio, and Minimum Sink

Gliders have no onboard powerplant, so we have now introduced all the forces that act in flight. The glide angle through the air is determined by the ratio of Lift:Drag for the glider. Its sink rate is determined by its weight, drag and airspeed.

So far we have had the air flowing past the wing in all the diagrams. What if there is no wind? Well, of course it doesn't matter. The ground never showed up in those diagrams. It may have been moving along with the air. In other words, it may have been the wing that was moving all the time -it was just that the diagram was moving along with it, if you see what I mean. Only the relative speed of the air past the wing, or wing through the air, matters. Let's suppose that it is the wing that is moving, with the rest of the glider attached. From Newton's first law, if the glider is moving at a steady speed in a straight line, the total force acting on it must be zero. Since we know about three forces acting on it, Lift, Drag and Weight, these must all cancel each other out. The Lift is at right angles to the glider's path through the air (even if that means the Lift is not quite acting straight up) and Drag is acting back along the glider's path. Weight always pulls straight down. The Glider Equation is simply:

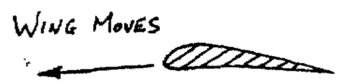
$$\text{Lift} + \text{Drag} + \text{Weight} = 0.$$

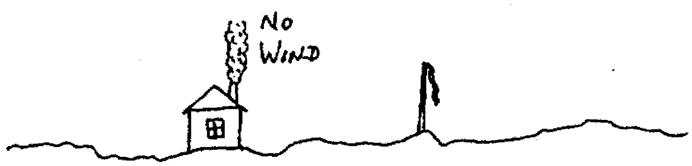
From the diagram we can see that simple geometry tells us that:

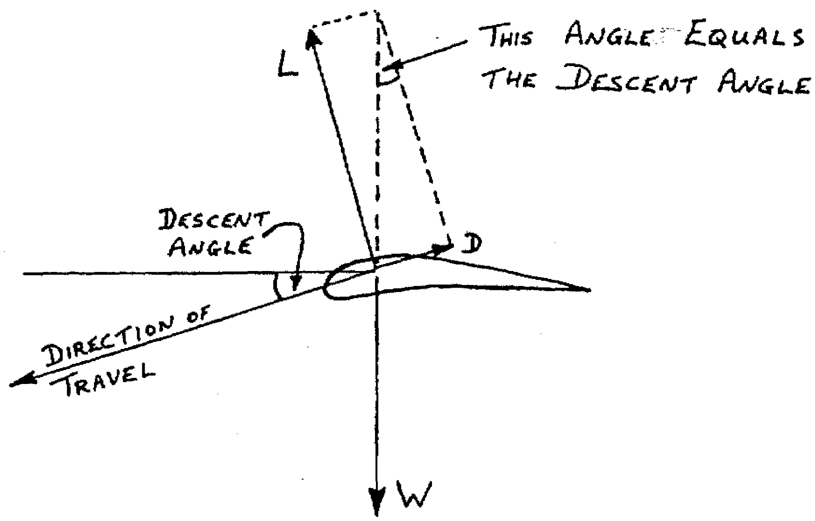
$$\frac{\text{Distance traveled forward by the glider}}{\text{Distance traveled down by the glider}} = \frac{\text{Lift}}{\text{Drag}}$$

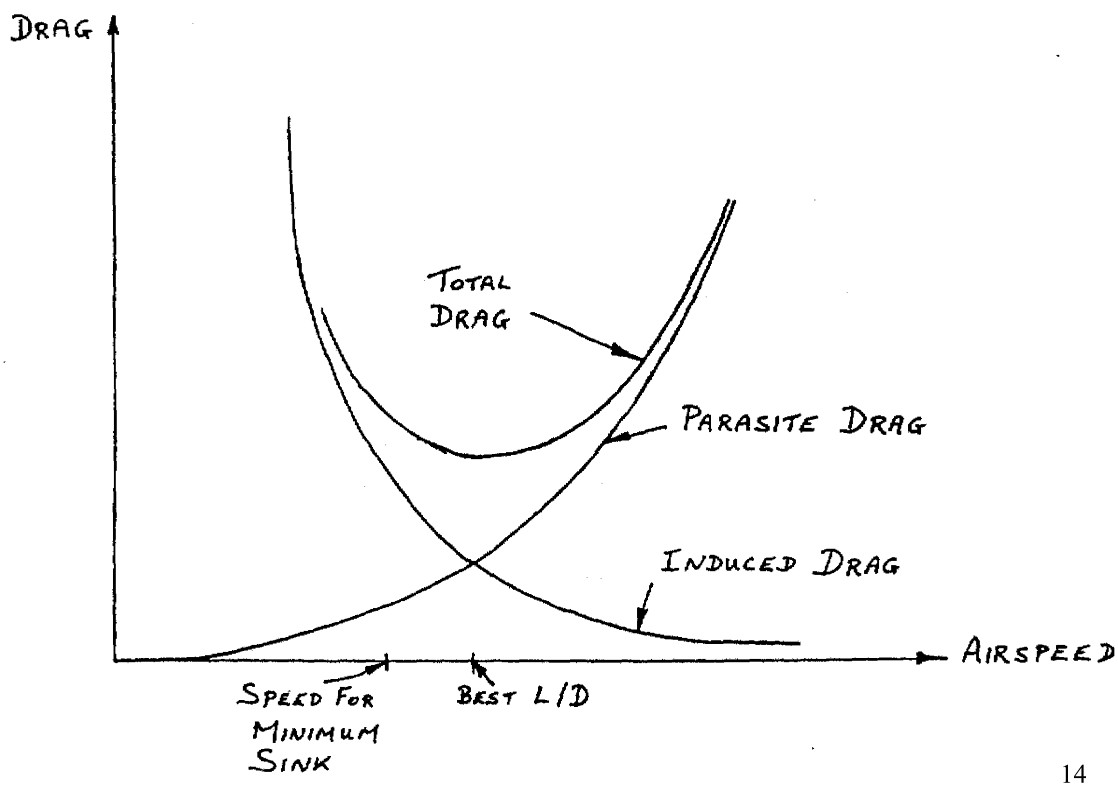
This is what is meant by the L/D ratio. For the glider to travel the maximum distance forward through the air for a given loss of altitude it should fly at whatever speed gives the maximum L/D ratio. Since the induced drag is highest at low airspeed, and the parasite drag is highest at high airspeed, there is an airspeed that results in minimum total drag. In fact this happens when the two kinds of drag have the same value. Any slower, and induced drag becomes the big problem. Any faster, and parasite drag takes over.

What about the sink rate? This depends on the airspeed. A good L/D ratio can still result in a high sink rate if the glider moves fast enough. The best sink rate happens at a lower speed than the one giving the best L/D ratio. This means that the wing is operating in the range where the induced drag is the main source of drag. It is here that the glider's aspect ratio is most important. All other things being equal, a glider with a high aspect ratio (long, thin wings) will have lower induced drag and will have a lower sink rate at a given airspeed. This will be especially important at the minimum sink speed, where the induced drag is the important source of drag.


WING MOVES


NO
WIND


L
THIS ANGLE EQUALS
THE DESCENT ANGLE
DESCENT
ANGLE
D
DIRECTION OF
TRAVEL
W


DRAG
TOTAL
DRAG
PARASITE DRAG
INDUCED DRAG
AIRSPEED
SPEED FOR
MINIMUM
SINK
BEST L/D

1(V) Performance

This will be our first run-in with Algebra. Don't let it bother you - I'll explain all the results in words. The performance of a gliding wing, in terms of L/D, sink rate and corresponding airspeeds can be computed mathematically. With some simple calculations we can learn some interesting things.

First I must define some quantities. They are listed on the next page. Since we will use them to do calculations, we must use consistent units. The usual hang-gliding units (mph, fpm, ft^2 etc.) are not consistent units. Worldwide, the most commonly used consistent set of units is the metric system. So, for your interest, I've listed the metric units with each of the quantities. Don't worry: I will list the results in familiar units.

Next, I want to explain about the assumptions. It isn't easy to write equations for the lift and drag of a real wing, but there is a kind of wing that makes it easy. If the wing is straight (that is, it has no sweep), and if it has an elliptical lift distribution (lift is evenly distributed near the center but the tips generate much less lift), and if it has no washout (the wing doesn't twist along its span) then it is easy! Obviously I've described something that is nothing like a hang glider, but it's not a bad place to start anyway. Later on we can look at the effects of taking out these assumptions one at a time to see how the results of the calculations should change. One other thing: I'm assuming that the angle of attack never exceeds a critical value, the *stalling angle of attack.* I'll explain this later in detail.

The first step is to start out by saying how the lift and drag are affected by airspeed and angle of attack, and nothing else. I am not interested (yet) in the wing area or air density or wing shape. I can write equations for Lift and Drag, and use them to get my Stage I Results. They're pretty cryptic, aren't they? With practice it is possible to look at equations like these and get a good idea what they mean, but to most people they don't mean much. Still, I can tell you a few things we can learn from these results.

First, the minimum sink rate depends on the square root of the weight. You can see that in the equation for R_{min}. This means that if the weight is doubled the minimum sink rate only increases by 41%. This isn't too bad. At least it didn't double, as we might have expected. The speed for best L/D is affected the same way (double the weight, increase the speed by 41%), and so is the speed for minimum sink.

Notice, as well, that the best L/D, that is, $(L/D)_{max}$, is not affected by the weight at all! That may be a bit of a surprise. A heavy glider gets the same L/D as a light one, it just has to fly faster.

Also, if the glider is flying at best L/D, it can reduce its speed by one quarter to get to minimum sink. If it is flying at minimum sink, it can get to best L/D by increasing speed by one third. The two speeds are "tied together" by this fact. You may be surprised that they are related at all!

The Performance Calculations - Part I

S	Wing Area (m^2)	b	Wing Span (m)
A	Aspect Ration ($A = b^2/S$ - no units)	α	Effective Angle of Attack (radians)
ρ	Air Density (kg/m^3)	V	Air Speed (m/s)
π	3.14159265…..	L	Lift Force (N)
D	Drag Force (N)	W	Weight (N)
R	Sink Rate (m/s)	K_L	"K Lift Coefficient" (Ns^2/m^2 per radian)
K_{DP}	"K Parasite Drag Coefficient" (Ns^2/m^2)	K_{Di}	"K Induced Drag Coefficient" (Ns^2/m^2 per radian^2)
$V_{L/D}$	Speed for best L/D (m/s)	V_R	Speed for Minimum Sink Rate (m/s)
R_{min}	Minimum Sink Rate (m/s)	$R_{L/D}$	Sink Rate at Speed for Best L/D (m/s)

Lift and Drag

Lift Force: $L = K_L \alpha V^2$

Drag Force: $D = K_{DP} V^2 + K_{Di} \alpha^2 V^2$ (Separate Parasite and Induced Drag Terms)

Stage I Results

$$L/D = \frac{K_L \alpha}{K_{DP} + K_{Di} \alpha^2}$$

$$(L/D)_{max} = 1/2 \; \frac{K_L}{\sqrt{K_{Di} K_{DP}}}$$

$$R = \frac{K_{DP} V^3}{W} + \frac{K_{Di} W}{K_L^2 V}$$

$$R_{min} = 4 \, K_{DP}^{\;1/4} \left(\frac{K_{Di}}{3 K_L^2}\right)^{3/4} \sqrt{W}$$

$$V_{L/D} = \sqrt{\frac{W}{K_L}} \left(\frac{K_{Di}}{K_{DP}}\right)^{1/4}$$

$$V_R = 3^{-1/4} V_{L/D}$$

1 (VI) Taking the Performance Calculations Further

So far we have not learned anything useful about wing size or shape, air density and so on. Here we go into more detail to learn more about these factors.

Now it's time to see what further information we can extract from those equations. To do that we have to do a little better than those K-coefficients I was using. They have served their purpose. I need to put down some equations that give some information about those K-coefficients so that they are no longer such a mystery. Unfortunately I can't get rid of coefficients altogether. There's no way to account for the drag caused by parasite effects (like the pilot, who insists on tagging along for the ride without being of any assistance to the performance) except to use - you guessed it - more coefficients. This time they show up as two drag coefficients. You can see them on the page opposite.

Well, what do the Stage II Results have to say?

The best L/D depends on the wingspan. Double the span, double the best L/D. It also depends on the parasite drag. Halve that drag, get the L/D improved by 41%. There's a slight influence due to wing area. As the wing area increases, so does its parasite drag. Nothing else affects the best L/D.

The equation for minimum sink rate is quite a complicated one. The minimum sink rate (or, for simplicity, I'll call it the sink rate) is proportional to the square root of the weight, as we saw before. On the other hand, it depends very much on the wingspan. Double the wingspan, get a 65% reduction in the sink rate (which is much more helpful). This makes sense. Remember, at minimum sink speed the induced drag is high, and a big wingspan helps to reduce induced drag. As we expect, it is affected much less by the parasite drag. Halve the parasite drag, get a decrease of only 16% in the sink rate (that's not very helpful). Finally, it depends on the air density, i.e. if the air density doubles (which is a big change!) then the sink rate decreases by 29%.

The equation for the speed to fly to get the best L/D (or, of course, best sink rate) is also complicated. It decreases with increasing air density just as the sink rate does. The effect of parasite drag is also quite weak. Double the parasite drag and get a 16% decrease in the speed for best L/D (remember this added drag would also produce a 29% reduction in the value of L/D itself). Finally, this speed depends on the *span loading,* the weight per unit wingspan. Doubling the span loading increases the speed to fly by 41%, but how it affects the L/D achieved or sink rate depends on whether the weight increased or the span decreased or there was a combination of the two.

Finally I've noted an equation for the angle of attack of the wing at minimum sink. At first it isn't obvious why. So far the only place where the wing area appears is in the parasite drag. This is always bad for performance. However, α_R is inversely proportional to the wing area. As the wing area gets smaller, α_R gets bigger. This cannot go on forever, because the equations are wrong if α is not kept small. Soon I will explain how this puts a minimum limit to the wing area.

The Performance Calculations - Part II

C_{DF} "Fixed" Parasite Drag Coefficient, caused by anything other than the wing surface (m^2)

C_{DW} "Wing" Parasite Drag Coefficient, caused by the surface of the wing - increases with wing area. This coefficient is a number, with no dimensions (e.g., m^2)

α_R Angle of Attack at Minimum Sink (radians)

$R_{L/D}$ Sink Rate at Airspeed for Best L/D (m/s)

$(L/D)_R$ L/D at Airspeed for Minimum Sink Rate

Lift K-Coefficient: $K_L = \pi \rho \dfrac{S}{1 + \pi/A}$

Parasite Drag K-Coefficient $K_{DP} = \dfrac{\pi \rho (C_{DF} + S\,C_{DW})}{2}$

Induced Drag K-Coefficient $K_{Di} = 2 \pi \rho \dfrac{S}{A (1 + \pi/A)^2}$

Stage II Results

$$(L/D)_{max} = \frac{b}{2 \sqrt{C_{DF} + S\,C_{DW}}}$$

$$R_{min} = 1.75/b \sqrt{(W/b)} \;\; \sqrt{2/(\pi\rho)} \;\; (C_{DF} + S\,C_{DW})^{1/4}$$

$$V_{L/D} = \sqrt{(W/b)} \;\; \sqrt{2/(\pi\rho)} \;\; (C_{DF} + S\,C_{DW})^{-1/4}$$

$$\alpha_R = \sqrt{3/4}\;\; b/S \;\; (1 + \pi / A) \sqrt{C_{DF} + S\,C_{DW}}$$

$R_{L/D} = 1.14\, R_{min}$ $\qquad$ $R_{min} = 0.88\, R_{L/D}$

$(L/D)_R = 0.87\, (L/D)_{max}$ $\qquad$ $(L/D)_{max} = 1.15\, (L/D)_R$

1 (VII) Conclusions - What we Know about Performance

This page will summarize what we have learned about performance, in a few easy-to-rememher (I hope) rules.

- A big wingspan is great for best L/D, and even better for the minimum sink rate.
- Low weight is a help with minimum sink rate but no help at all with best L/D.
- If we want the best glide to be fast we should have high span-loading.
- Parasite drag is always bad.
- Parasite drag is very bad for the best L/D.
- Parasite drag is not so bad for the minimum sink rate (but still bad).
- Parasite drag is not so bad for the best L/D speed (but still bad, i.e. reduces it).
- From best-glide speed, reduce speed by a quarter to get to minimum sink.
- From minimum sink speed, increase speed by a third to get to best glide.
- Minimum sink reduces the L/D by 13%.
- Best L/D increases the sink rate by 14%.
- In the equations, the wing area (S) only appeared in the parasite drag terms. These are always bad. So we have the curious result that a big wing area is bad for performance! However, we will see that small wing area brings a high stall speed, which we don't want,
- At high altitude, where the air is thin, the glide speeds and sink rates increase.
- At high altitude the best L/D is unchanged.

1 (VIII) Wing Loading and the Infamous Stall

So far I have said that the lift increases with increasing angle of attack. There is a critical angle of attack, however, the *stalling angle of attack,* and when the angle of attack exceeds this value the lift decreases. When the wing is operating at this angle it is developing its maximum lift at that airspeed. The only way to increase the lift is to increase the airspeed. This explains why there is a *stall speed.*

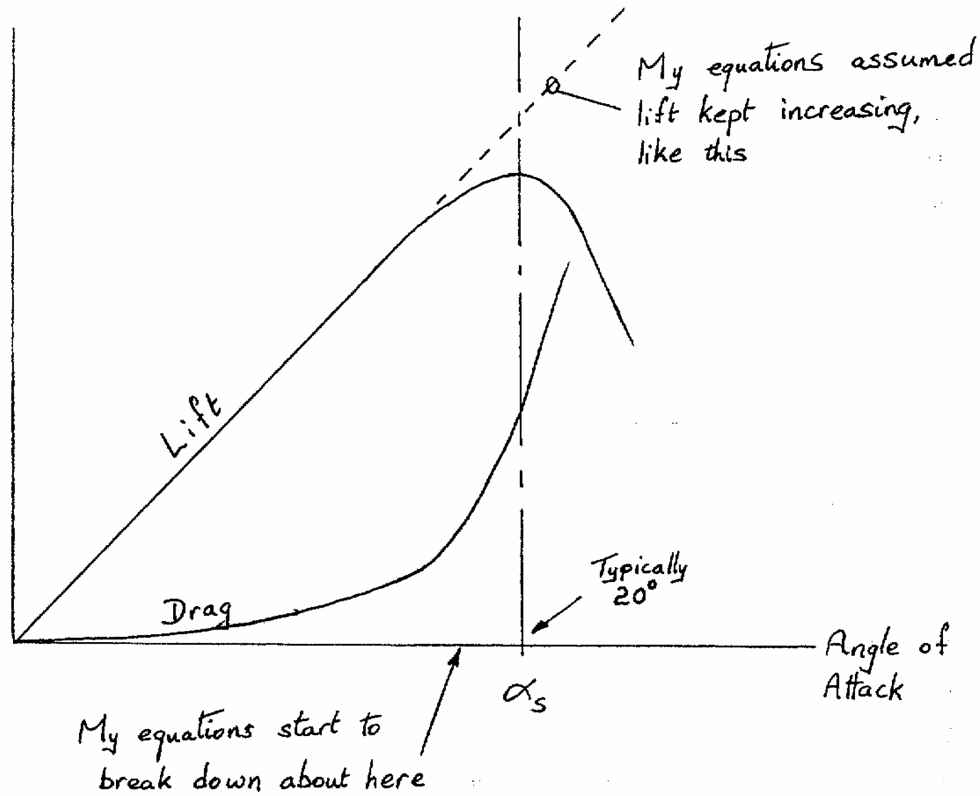
In the equations I used to examine performance I claimed that the lift increases with increasing angle of attack, and with increasing airspeed. However, there is an angle of attack, called the *stalliug angle of attack,* beyond which the lift begins to decrease again. At this angle of attack, too, the drag begins to increase rapidly.

As the glider is flown more slowly, it loses lift because of the decreasing airspeed. To compensate for this the pilot increases the angle of attack to recover the lift needed for steady flight. Eventually the angle of attack reaches the stalling angle. The airspeed at which this happens is called the *stall speed.* It is the lowest airspeed at which the wing can develop enough lift. As it slows beyond this, increasing the angle of attack further actually decreases the available lift. The wing begins to fall. Its increased downward speed causes the angle of attack to become higher, making the situation worse. Recovery is possible only by pointing the wing down, reducing the angle of attack and letting the speed increase as gravity pulls the glider downward. Once the speed is high enough the wing can again develop plenty of lift, and can recover from the dive.

When I looked at the performance I assumed that the wing was not stalled. I discovered that increasing the wing area did not help performance at all, but actually hurt it slightly by adding more drag. However, there is a minimum useful wing area. First of all, the wing area must be big enough to keep the stall speed below the calculated speed for minimum sink, so that the glider can actually get to that speed and still fly! Second, the stall speed must be low enough to allow safe takeoff and landing. A glider that lands at 60 knots is of no use to anyone, even if its performance is wonderful!

The stall speed depends on the square root of the *wing loading,* the weight divided by the wing area. Once we know the maximum acceptable stall speed, the stalling angle of attack of the airfoil used, and the aspect ratio of the wing, we can compute the maximum wing loading. Given the maximum weight to be carried, we can find the minimum wing area needed.

Hang gliders have always had their best L/D at very low speeds. This meant that the stall speed had to be low because the minimum-sink speed was low. This is why the speed for minimum sink was so close to the stall speed. As gliders have become "cleaner" (i.e. have lower drag), the L/D and minimum-sink speeds have become higher. This has made higher stall speeds acceptable, and so there has been a trend to smaller wing areas. However the higher stall speeds make takeoff and landing more difficult. In the future this may mean that stall speeds will be well below minimum-sink speed.



Lift Equation: $$L = \pi \rho \frac{S}{1 + \pi/A} \alpha V^2$$

Stall Equation: $$V_s = \sqrt{\frac{1 + \pi/A}{\pi \rho \alpha_s} \frac{W}{S}}$$

where

V_s is the stalling speed

α_s is the stalling angle of attack - value depends on the wing cross section

ρ is the air density

A is the aspect ratio - note if this is big then it has very little effect

S is the wing area

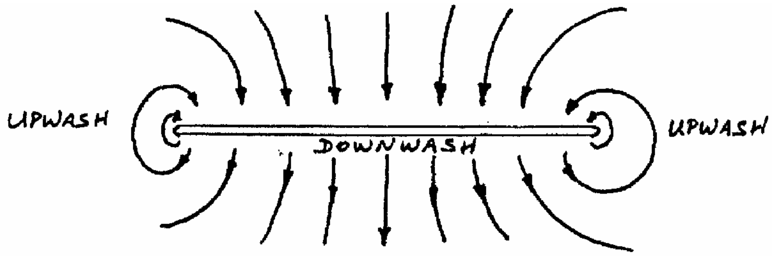
I (IX) Downwash, Tip Vortices and Other Cool Terminology

The wing pushes air down as it flows by, producing a region of air moving downward behind the wing. This is known as downwash. Where this downwash meets previously undisturbed air it causes vortex formation.

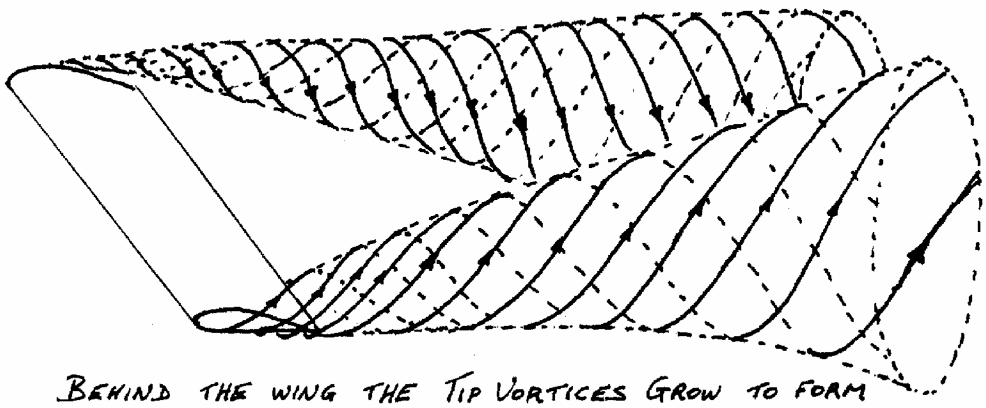
It's time now to look at some side-effects of generating lift. The wing pushes down on the air flowing past, so behind the wing there is a region of air flowing downward. This is known as the *downwash.* At the wingtips this downward-moving air meets air that is not moving. Furthermore, the pressure above the tips is low, the pressure below is high, so air tries to flow around the wingtips to get from the bottom to the top. These effects combine to make the air behind the wing rotate in the form of two large vortices rolling in opposite directions. They roll down behind the center of the wing, and up outside the wingtips. The vortex pair moves downward as well, because of the downwash. This disturbed air behind the wing, which is about two wingspans across, is called the *wake.* The wake from a large aircraft can be very powerful. Even a hang-glider wake can get your attention. This is why it is unwise to fly behind another aircraft without staying at least a wingspan above its flight path. Notice, too, how big the so-called tip vortices are. Sometimes aircraft manufacturers have tried to fit flat plates on the wingtips to keep air from spilling around the tips, so as to eliminate tip vortices. This is good advertising, but has very little impact on the vortex formation. Adding the same plate as extra wingspan would be more effective. It is possible, however, to design airfoil shapes that operate in the tip flow to extract energy from the tip vortex. Some new transport aircraft have such wingtips. The spread feathers at the wingtips of soaring land birds achieve this effect, and such birds have much larger effective wingspans than the actual lengths of their wings. This is why eagles and vultures have shorter, broader wings than seabirds like albatross - they achieve a high effective aspect ratio without such a long wing.

Just outside and behind the wingtip the tip vortex produces a region of *upwash.* A second wing placed here would be flying in rising air. This is why flocks of birds fly in a V-formation. If they flew in a line, the birds at the back would be flying in the combined downwash of all the ones ahead. The trailing birds would by flying uphill through the air just to keep from descending. By flying just off the wingtip of the one ahead, the trailing bird is flying in the tip upwash, which takes quite a bit less work than flying alone. I'm afraid the birds aren't displaying their artistic talents, just saving energy

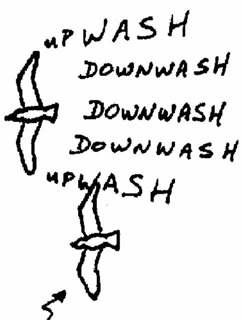
Having said that, let's think about a wing that is swept back at the tips. In the same way, the outward sections of the wing are flying in the tip upwash of the inside portions, so their angle of attack is higher. the angle of incidence of the whole wing increases, the tips are the first to reach the stalling angle of attack. We will see later that this is very, very bad. The solution is to build the wings with a twist so that the tips are at a lower angle of attack, even with the upwash effect.



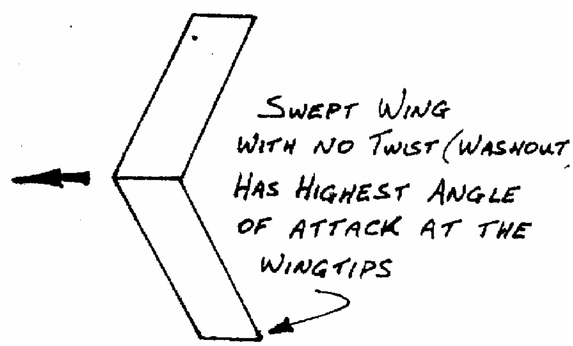
VIEW FROM BEHIND THE WING
– DOWNWASH, UPWASH AND TIP VORTEX FORMATION



BEHIND THE WING THE TIP VORTICES GROW TO FORM A PAIR OF ROTATING "TUBES" WHICH MOVE DOWNWARD – THE WAKE.



This bird benefits from the leader's tip upwash.



1 (X) Taking out the Assumptions

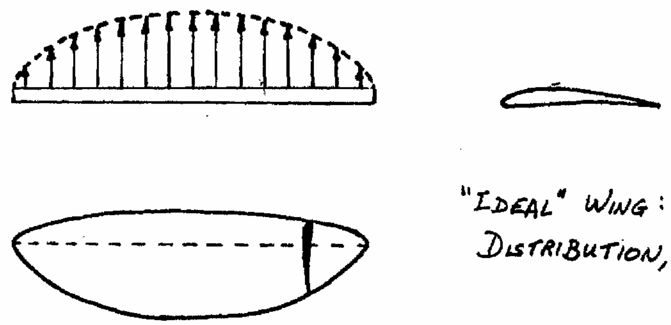
In the performance analysis I made a number of assumptions. Now I look at the effect of violating these assumptions to see whether any of the conclusions was wrong.

In the analysis I assumed that the wing was straight, had an elliptical lift distribution and had no washout. A hang glider wing is swept, is tapered and has washout. We have seen that if a wing is swept and is not to stall first at the tips, it must have washout. It turns out that if a wing is tapered, this also tends to make the tips stall first, so even more washout is needed! When we examine stability it will become clear that there is a third requirement, that the tips be the last to stall by a good margin. This calls for even more washout. Hang glider wings have enormous amounts of washout - older gliders have almost unbelievable angles of incidence at the wingtips

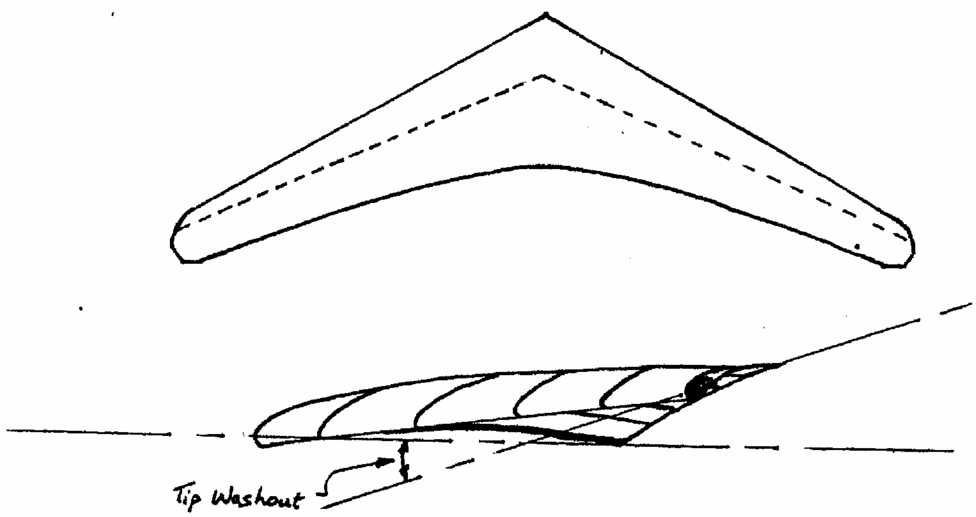
All this washout has two effects. First, there is no single angle of attack, since the angle of attack varies from place to place along the wing. However it is possible to define an effective angle of attack for the wing as a whole, and this gives results that are pretty close to the ones we had before. The second effect is that the lift distribution changes from one angle of attack to another. In essence, at low angles of attack the lift is concentrated too much toward the center of the wing, and becomes more correctly distributed at higher angles of attack. This means that the wing is less efficient at high speeds than my equations suggest. However, if the design is a good one, the error caused by assuming elliptical lift distribution is quite small, especially toward the lower end of the speed range

There is one assumption I made, though, which can be misleading. I assumed that the profile, or parasite, drag was not affected by the angle of attack. This may not be true. It the wing is very thin and curved so that the underside curves upward noticeably near the leading edge, then at low angles of attack the airflow will break away as eddies near the leading edge, on the underside. This increases the drag, and causes a loss of L/D at low angles of attack (high speeds) which may be quite severe. This is why single-surface hang gliders have noticeably poorer high-speed glide capability than double-surface gliders. The analysis I did (and will do later when I discuss speed-to-fly ideas) is closer to the truth for double-surface than for single-surface gliders.

To summarize, the assumptions I made, although not quite correct, gave results that were not too far from the truth, and saved a lot of algebra. The whole idea was to understand which details affect what aspect of performance, and how. This is best achieved by keeping things simple.



"IDEAL" WING: ELLIPTIC LIFT DISTRIBUTION, NO WASHOUT, NO SWEEP.



HANG GLIDER WING HAS SWEEP AND WASHOUT

SINGLE-SURFACE WING HAS EXTRA DRAG AT LOW α

DOUBLE - SURFACE WING WORKS WELL AT LOW α

2. WHY IT FLIES UPRIGHT - STABILITY AND CONTROL

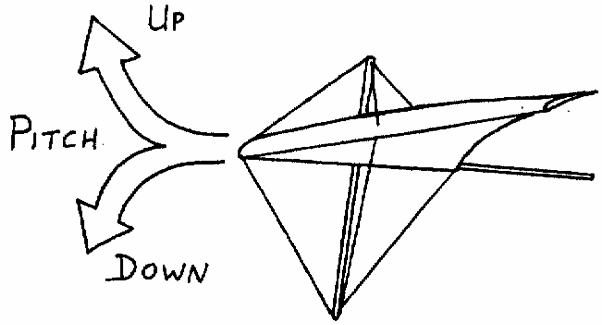
---

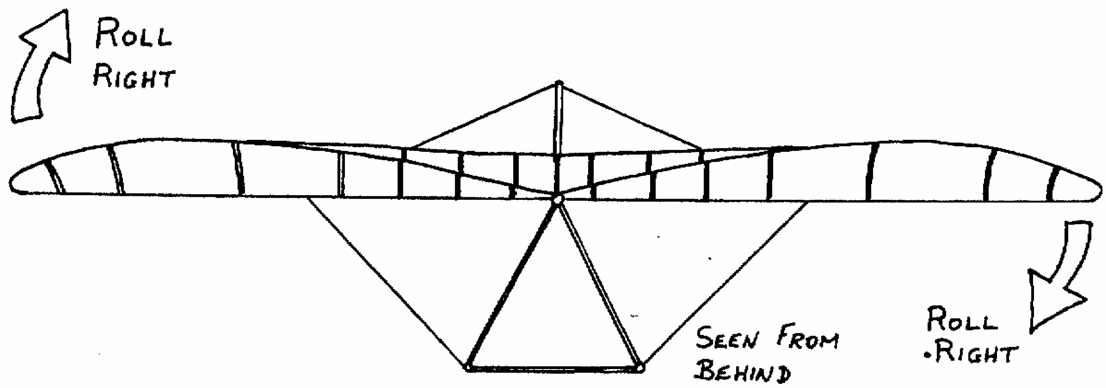
2 (I) Stable Relationships and Hang Gliding

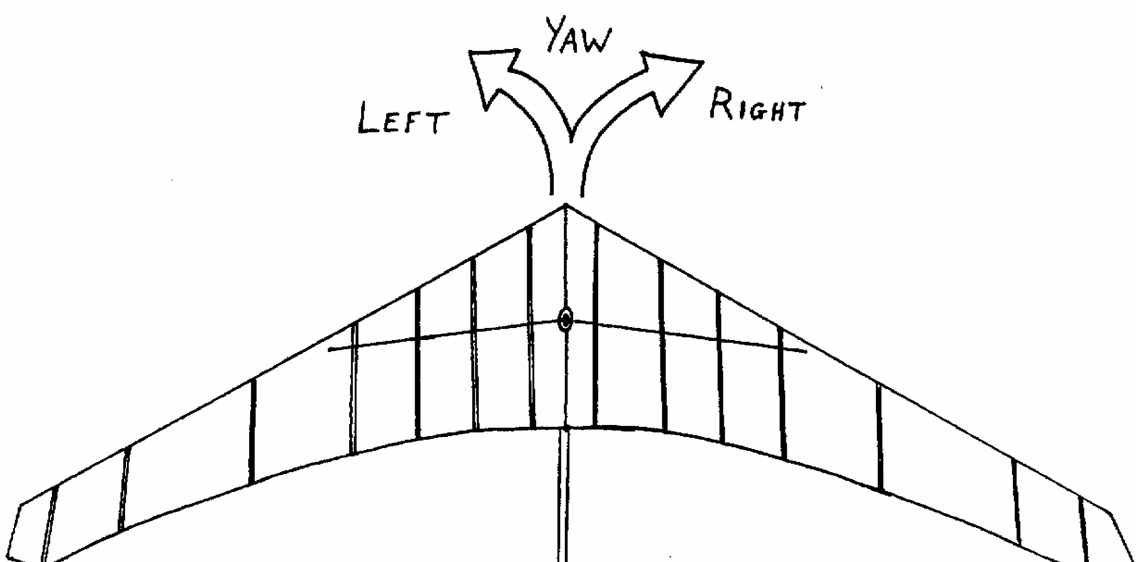
In part 1 we met the essential principles of lift and drag, and saw how to derive performance equations from them. But there was no mention of what holds the wing in the correct attitude. What does this is its stability, its tendency to position itself in the air so that it flies. This is not a natural tendency of wings. They must be designed to behave this way.

In part 1, I talked about the lift and drag of a glider, and about how they affect its performance. Of course, to develop lift with low drag the wing must have the correct angle of attack to the airflow. It must maintain this angle, must not roll over sideways and must not tend to turn to the left or right. A glider that tends to fly in a straight line at a steady speed, and that tends to return to this speed should anything disturb it, is *stabIe.* One that, if disturbed, tends to deviate farther and farther from its original course is *unstable.* If the glider is disturbed and simply settles down in this disturbed condition, neither getting any worse nor showing any tendency to recover, it is called *neutral1y stabIe.*
A glider that is stable will fly itself. This is rather nice, as it means the pilot really only needs to make corrections to what the glider would naturally do anyway. A glider that is too stable, however, will fly itself to such an extent that the pilot may have trouble influencing it! A glider that is neutrally stable may be flyable but will be a lot of work to fly. If the glider is unstable it may still be possible to fly it, but it will be a *very* unpleasant and dangerous experience. Anything more than the slightest instability will make the glider unflyable.

Of course, the glider operates in three dimensions, so it has three possible ways to be stable or unstable. The three dimensions we will be talking about are pitch, roll and yaw. If the glider's nose is rotating so that the angle of attack is increasing, it is said to be *pitching up.* If the nose is rotating so that the angle of attack is decreasing, it is *pitching down.* Usually these are the same as nose-up and nose-down respectively, but if the glider is upside-down the nose moves down when the glider pitches up. Pitch considers up and down to be related to the glider, not to the ground. Roll also comes in two flavors, right and left. If the glider is roIling to the right, someone looking from behind the glider would see it rotating clockwise. Normally a right roll would result in the right wing becoming closer to the ground than the left, but, again, it's the other way around if the glider is inverted. Yaw also comes in left and right varieties. Right yaw is when the nose of the glider swings to the right of the path through the air. Someone looking down on a glider that was yawing to the right would see it rotating clockwise.


UP
PITCH
DOWN


ROLL
RIGHT
SEEN FROM
BEHIND
ROLL
RIGHT


YAW
LEFT
RIGHT

2 (II) Take a Moment

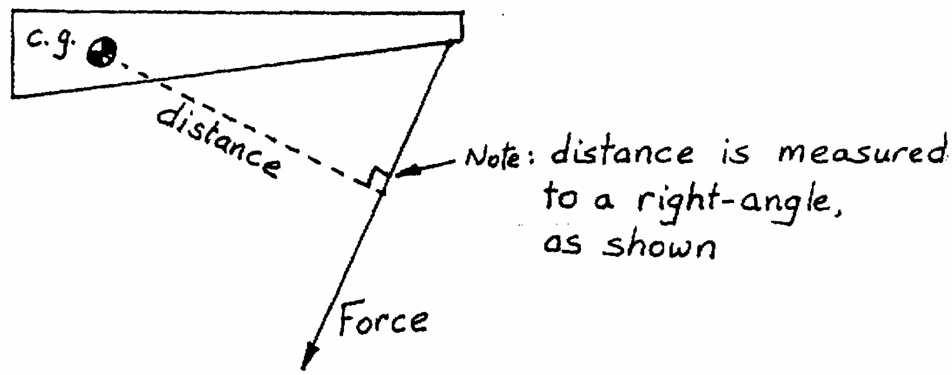
To discuss stability I will need to explain about *moments* first. When force is applied to an object it may try to rotate the object as well as move it. This rotating effect is called a Moment.

Since I am going to be talking about stability, I am going to be talking about things that tend to make the glider turn, or rotate. So far I have described how forces cause an object to move, or accelerate. There is also a way in which forces can make an object turn. Suppose a force is acting on an object, but the force is applied to one side of the object's *center of gravity (c.g.).* This force will not only make the object move, it will also cause it to rotate. (We're all familiar with this idea: we use it every time we turn something over.) We can divide the effect of the force into two parts: one part moves the object, and one part turns it. This turning, or twisting, force is called a moment. The bigger the moment about the c.g., the more the twist-force on the object.

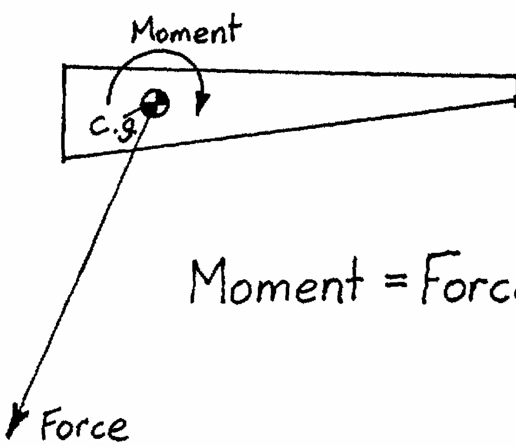
Moments may be calculated around any point. We will always use the c.g. as the point, but that isn't technically necessary - it just makes things much easier. The *moment of* a *force about a point* is the force multiplied by its distance from the point. The distance must be measured at right angles to the direction of the force, as shown in the diagram. Notice that if the force passes through the point, its moment is zero. (That's why I picked the c.g as the point - the moment of the Weight will always be zero.) Now we can calculate what happens to an object when a number of forces is applied to different places on the object. First we add all the forces to make one net moving force, which we say now acts at the c.g. Next we compute the moment of each of the original forces about the c.g., and add all the moments together to get a net moment (note that we must be sure to define moments in one direction as positive, and those in the other direction as negative, so that when we add moments in opposite directions they cancel each other). The effect of all the forces is the same as the net force plus the moment, i.e. it is the same as a single force at the c.g. trying to move the object and a moment trying to rotate it. An example of this with just one force is shown in the second diagram. Note that the net force may be zero, while the net moment is not. This would happen if there were one force on the right, pulling upward, and one force on the left acting downward. If the forces were equal in size, the net force would be zero, but the object would rotate to the left, indicating that the moment is not zero.

Stability is concerned with the moment rather than the net force. The net force on a glider is zero in steady flight (remember the glider equation L + D + W = 0?). If the glider is stable, then when it is flying in the correct attitude there will also be zero moment acting on it, and when it deviates from this attitude there will be a moment tending to rotate it back to where it should be.

MOMENTS



This is the same as this



$$\text{Moment} = \text{Force} \times \text{Distance}$$

2 (III) Stable Relationships and the Importance of a Good Attitude - Pitch Stability

Pitch stability is the tendency of a glider to try to maintain a steady angle of attack and airspeed. For pitch stability the center of gravity must lie ahead of the aerodynamic center.

If you look at a wing that is generating no lift you will see that it deflects air upward near the leading edge, only to pull it down again near the trailing edge. The equal and opposite reaction is that the air tries to push the leading edge down and pull the trailing edge up. The wing tries to twist itself nose-down, and, if allowed to, will do so. This is the kind of thing I have called a *moment*. By defining pitch-up as positive, aerodynamicists have come up with the term *negative pitching moment* for this effect. In English they are saying that something is trying to pull the nose down. There are other things that try to twist the wing. Suppose we increase the angle of attack so that the wing develops some lift. All the lift forces can be combined into one lift force, acting at a place called the *aerodynamic center* (a.c.). If the a.c. is behind the center of gravity (c.g.) then, since I am measuring moments about the c.g., the lift causes a nose-down moment, or another negative pitching moment. If the a.c. is ahead of the c.g. it causes a positive pitching moment, a pitch-up tendency.

There are, then, two sources of pitching moment about the c.g. One is the natural negative pitching moment of the wing itself, and the other is the pitching moment of any lifting surface whose aerodynamic center is not located at the c.g. The aircraft will fly at a constant angle of attack if all the pitching moments add up to zero. If they add up to a positive pitching moment, it will pitch up. If they add up to a negative one, it will pitch down. This gives the rule for pitch stability.

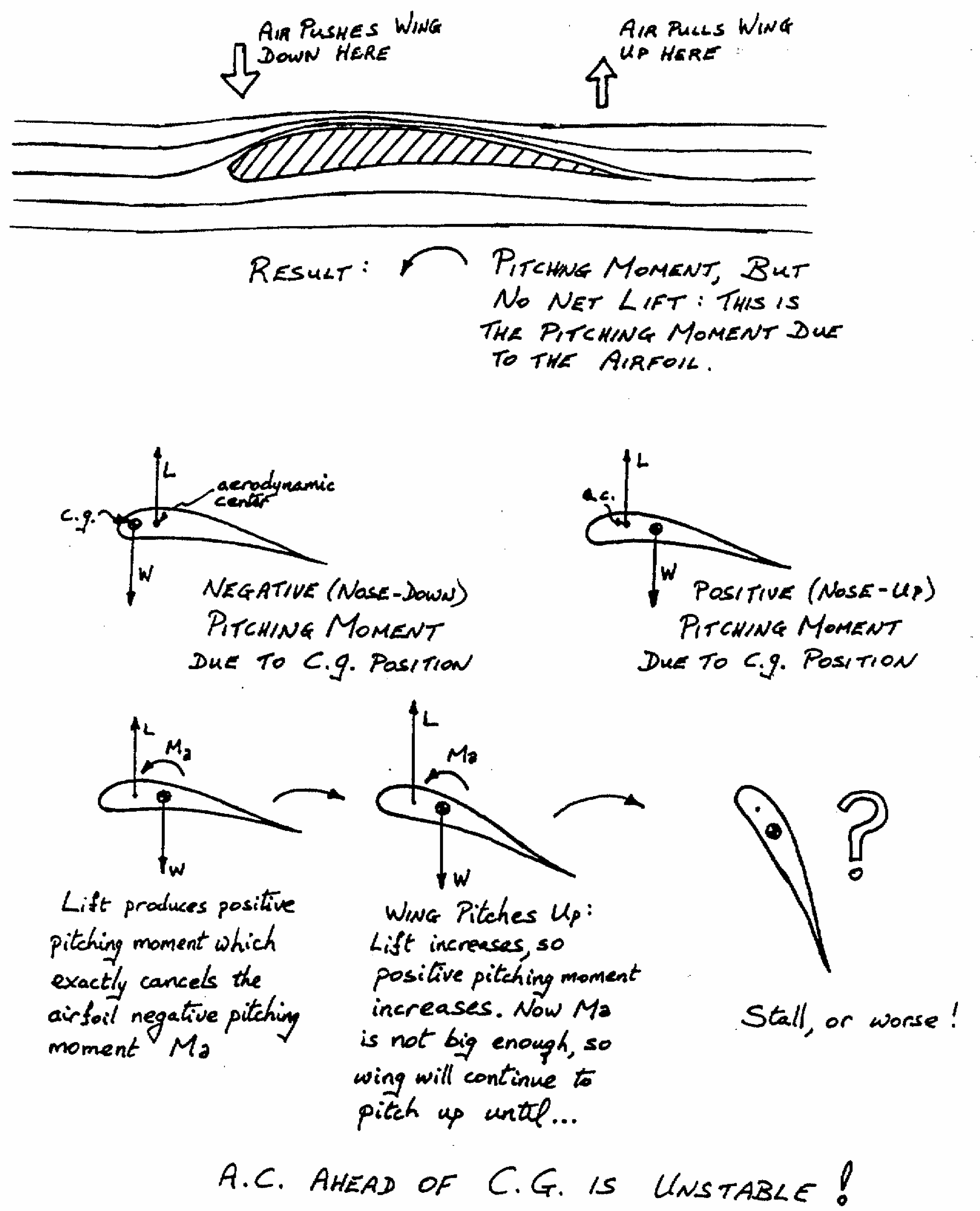
If the angle of attack is correct, the glider should have zero pitching moment about the c.g.

If the angle of attack is too low, there should be positive pitching moment about the c.g.

If the angle of attack is too high, there should be negative pitching moment about the c.g.

I have said that a simple wing has a negative pitching moment. We could cancel this by moving the c.g., as we can get a positive pitching moment by moving the c.g. behind the a.c. Unfortunately, this does not produce a stable aircraft. Here's why: Suppose we move the center of gravity back, far enough behind the a.c. so that the resulting positive pitching moment cancels the wing's built-in negative pitching moment and holds the nose up at the design angle of attack and airspeed. Now suppose that the nose pops up a little. This produces extra lift. This lift is ahead of the c.g. and tends to pull the nose up further - and so on. The glider will continue to pitch up until it stalls. It is unstable. If the aerodynamic center is behind the c.g., the extra lift tends to push the nose back down, which is what we need for stability . This is an important point.

If the center of gravity is behind the aerodynamic center the aircraft is unstable in pitch. For an aircraft to be stable in pitch the c.g. must be ahead of the aerodynamic center.

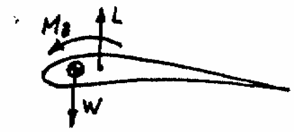

AIR PUSHES WING DOWN HERE
AIR PULLS WING UP HERE
RESULT: PITCHING MOMENT, BUT NO NET LIFT: THIS IS THE PITCHING MOMENT DUE TO THE AIRFOIL.
L
aerodynamic center
c.g.
W
NEGATIVE (NOSE-DOWN) PITCHING MOMENT DUE TO C.g. POSITION
L
a.c.
W
POSITIVE (NOSE-UP) PITCHING MOMENT DUE TO C.g. POSITION
L
Ma
W
Lift produces positive pitching moment which exactly cancels the airfoil negative pitching moment Ma
L
Ma
W
WING Pitches Up: Lift increases, so positive pitching moment increases. Now Ma is not big enough, so wing will continue to pitch up until...
?
Stall, or worse!
A.C. AHEAD OF C.G. IS UNSTABLE!

2 (IV) Pitching Moments and You - What about Hang Gliders?

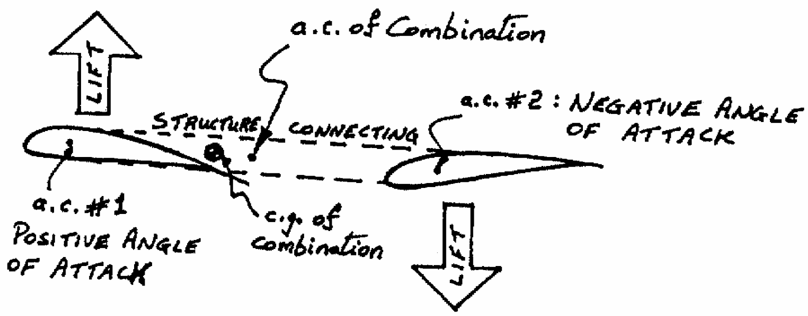
Hang gliders are tailless aircraft ("flying wings"), but must still achieve pitch stability. They do this by the use of swept wings with excess washout.

We have seen that for stability the c.g. must lie ahead of the a.c. However, this produces a negative pitching moment. The simple wing also has a negative pitching moment, so both effects are trying to pull the nose down. Notice that if the wing's pitching moment were positive there would be no problem. The wing's positive pitching moment would try to pull the nose up, so we could put the a.c. behind the c.g., producing a balancing negative pitching moment. In addition, we would now have a stable aircraft, with the c.g. ahead of the a.c. So, we need a wing with a positive pitching moment, that is, one that tends to pitch up when not developing any lift. A simple airfoil has a negative pitching moment, so we need to do something clever. The solution is to have two parts to the wing, one well ahead of the c.g., and one well behind the c.g. Since the two parts are connected together we consider them to be just one wing, with an effective a.c. somewhere between them. The part ahead of the c.g. should be at a higher angle of attack than the part behind it. Now when the total lift force is zero, there is an upward lift force ahead of the c.g. and an equal downward one behind it, which produces a positive pitching moment. If this positive pitching moment is big enough, it overcomes the negative pitching moment of the airfoil itself, and we have a wing with a positive pitching moment instead of a negative one!

There are four ways to build this modified wing. One is to attach a tail that actually develops lift downward behind the main wing - this is the conventional aircraft solution. The second is to put a small foreplane ahead of the main wing, at a higher angle of attack - this is sometimes done and is called a *canard* configuration. The third is to design an airfoil with *reflex,* i.e. an airfoil that deflects the airflow upward at the trailing edge, as if a conventional tail had been moved forward until it was attached to the trailing edge - this is not very effective, however. The fourth is to sweep the wing, and have washout so that the wingtips, which are behind the c.g., have a lower angle of attack than the center section, which is ahead of the c.g. Hang gliders usually combine the last two. In normal flight conditions the wing has little or no reflex, but under negative load the wing deforms and develops considerable reflex to increase positive pitching moment and get the nose up. The rest of the time the stability primarily depends on the sweep. Remember, swept wings tend to have higher angles of attack at the tips because of vortex effects, so the washout needs to be considerable to achieve the required lower angle of attack at the tips.

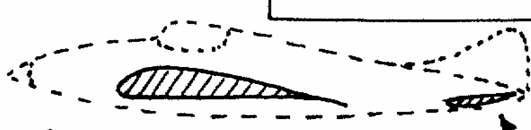


NEGATIVE PITCHING MOMENT DUE TO AIRFOIL M_a AND
NEGATIVE PITCHING MOMENT DUE TO C.G. POSITION
→ ALL NEGATIVE PITCHING MOMENTS → TROUBLE!
SOMEHOW MUST GET A WING WITH POSITIVE PITCHING MOMENT M_a.



FRONT AIRFOIL LIFTS UPWARD, BACK AIRFOIL LIFTS DOWNWARD. NO NET LIFT, BUT LARGE POSITIVE PITCHING MOMENT, ENOUGH TO OVERCOME THE NEGATIVE PITCHING MOMENTS OF THE INDIVIDUAL AIRFOILS. THIS "COMBINED WING" HAS A POSITIVE PITCHING MOMENT.

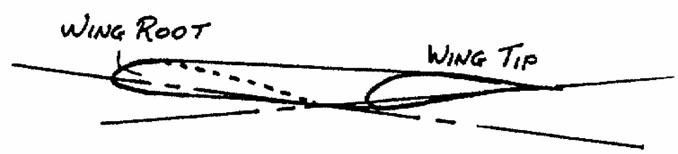
$\boxed{\text{EXAMPLES}}$



CONVENTIONAL AIRCRAFT WITH TAIL

CANARD AIRCRAFT

REFLEX AIRFOIL



SWEPT WING WITH WASHOUT

2 (V) Rolling with the Punches - Lateral Stability

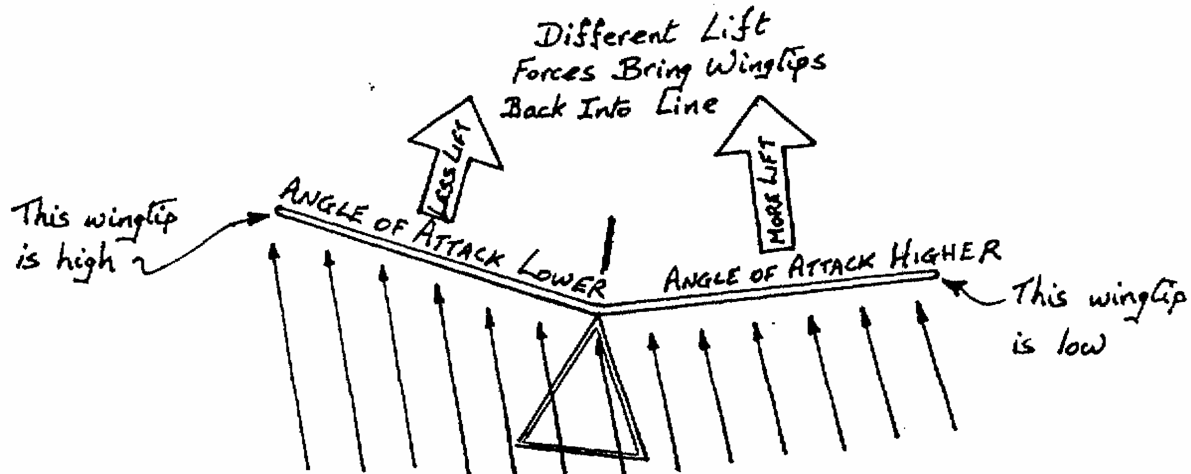
If the glider is in steady flight and is disturbed by raising one wing higher than the other, it should tend to return the wings to the same level. A glider that does so is LATERALLY STABLE, or roll stable. Swept wings and dihedral contribute to roll stability.

The second kind of stability I want to talk about is roll stability, or lateral stability. It is the tendency of the glider to fly with its wings level, that is, to resist having one wing higher than the other. If the wings are too stable they will be difficult to roll deliberately, however. In fact, hang gliders are relatively unresponsive in roll because of their long wingspan, as I will explain in a later section. Consequently newer hang gliders are designed with relatively little lateral stability. Nevertheless, it's worth looking at the things that affect roll stability.

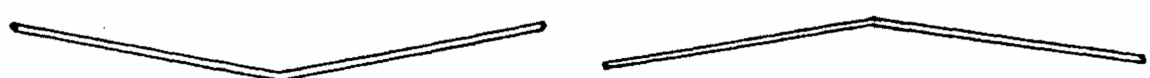
The most common technique used in aircraft to give roll stability is to design the wings with *dihedral.* Dihedral is the name given to the shape of wings that have the wingtips higher than the center of the wing. Low-winged light aircraft often have very obvious dihedral. When an aircraft has one wing lower than the other, the lift is inclined to that side and causes the aircraft to drift sideways, toward the lower wing *(sideslip).* As a result of dihedral, the angle of attack is then higher on that side. This causes the low wing to generate more lift than the high wing, and this creates a *rolling momcnt* that rotates the wings to the level position. Dihedral therefore increases stability. The opposite kind of design, with the wingtips lower than the center, is given the name *anhedral.* Anhedral causes unstable rolling moments, and decreases stability.

Swept wings also increase roll stability. At first this isn't very obvious. However, suppose one wing is lower than the other in steady flight. Because of the sideslip that results, the airflow meets the leading edge of the lower wing more nearly at right angles than it does the leading edge of the higher wing. The diagram should make this clearer. This means that the lower wing is effectively made longer than the higher wing, so the lower wing's lift is effectively moved farther away from the center of gravity. This creates a rolling moment that tries to rotate the glider so that the lower wing rises. If the wings were swept forward, with the tips ahead of the center section, the effect would be destabilizing.

Let me summarize. If the aircraft has dihedral or sweep-back or both then it will be stable. If it has anhedral or sweep-forward or both it will be unstable. If it has dihedral and sweep-forward or has anhedral and sweep-back it may be stable or unstable. There are examples of all of these designs in the aircraft world. Remember, the pilot may want to roll quickly on purpose, so only slight roll stability is required. Since hang gliders have wings that are swept back, which contributes to roll stability, there is very little use of dihedral. In fact, hang gliders commonly have a little anhedral to keep roll stability to a minimum.



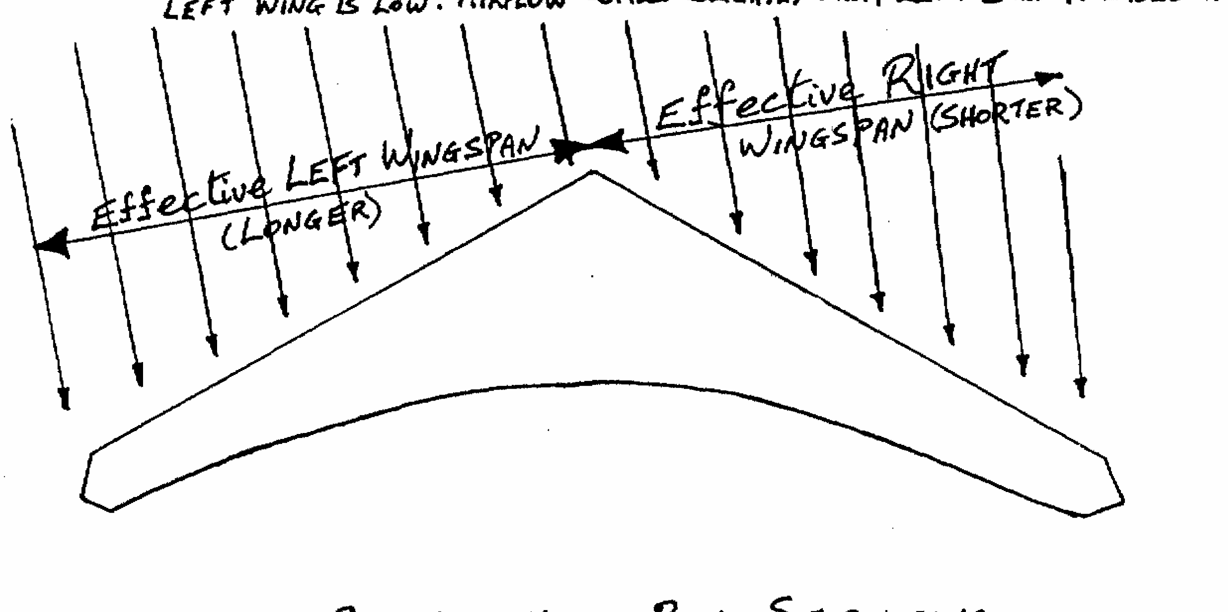
VIEW FROM AHEAD: AIRFLOW IS FROM AHEAD & BELOW AS USUAL, BUT ALSO FROM ONE SIDE DUE TO SIDESLIP



DIHEDRAL : STABILISING

ANHEDRAL : DESTABILISING

LEFT WING IS LOW: AIRFLOW COMES SLIGHTLY FROM LEFT DUE TO SIDESLIP



SWEEPBACK IS ROLL-STABILISING
(SWEEPFORWARD IS DESTABILISING)

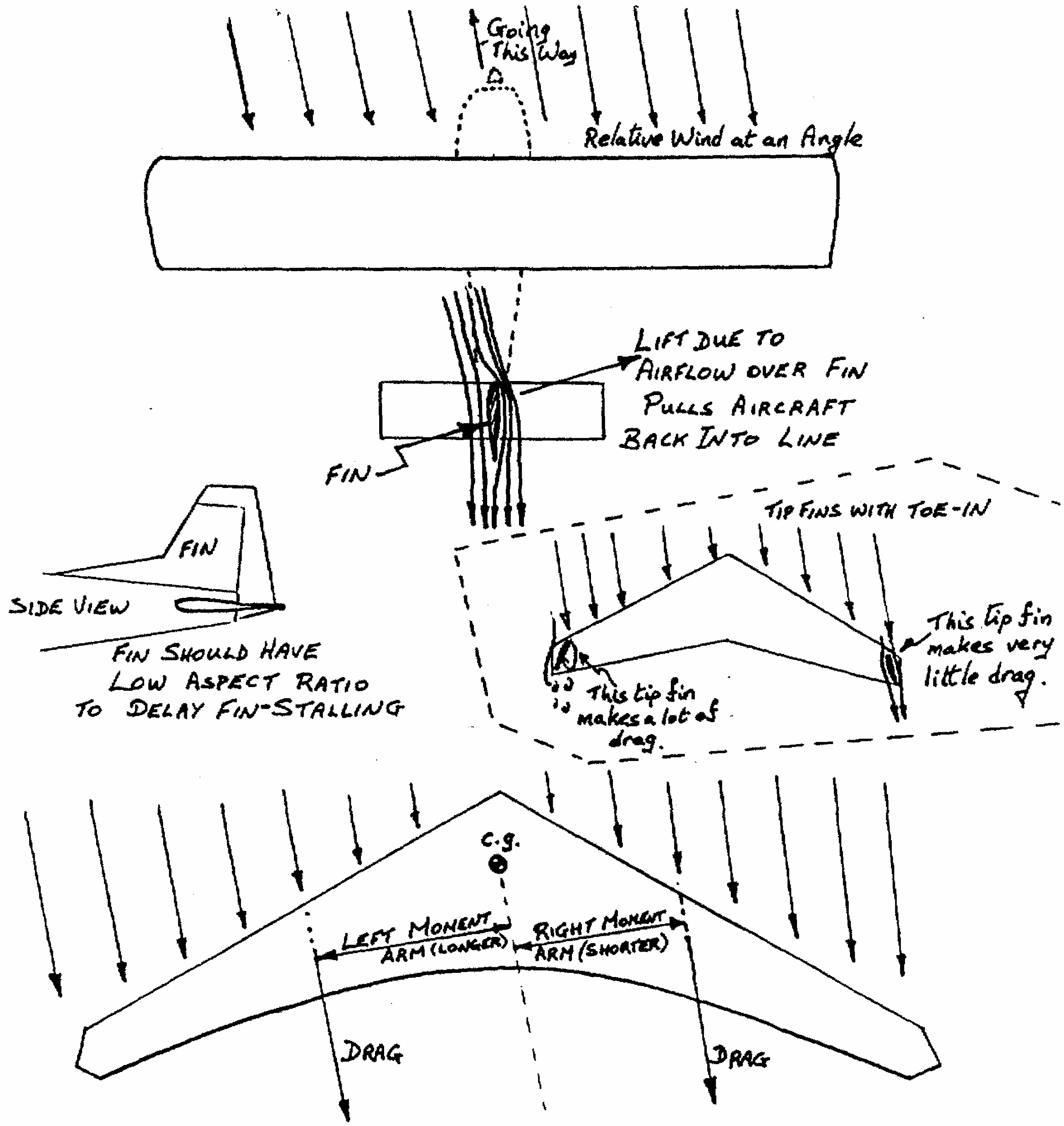
2 (VI) Yaw'll Come Back Now - Directional Stability

An aircraft is directionally stable if, as seen from above, it tends to point its nose in the direction in which it is traveling through the air. Swept wings and vertical surfaces affect directional stability, or yaw stability.

Finally we come to the third axis, the yaw axis. If an aircraft tends to yaw so that it is pointing directly into the airflow, it is *directionally stable,* or *yaw stable.* Swept wings and vertical surfaces affect yaw stability. In conventional aircraft there is a large vertical surface at the back of the aircraft, which is known as the *directional stabilizer,* and that provides directional stability. In other English-speaking parts of the world this is called the fin, which seems somehow much less intimidating. Normally the fin does nothing. If the aircraft yaws to the right, the fin develops an angle of attack due to the airflow coming from its left, and produces lift to the right. Since this lift force acts to the right and is far behind the c.g., it produces a *yawing moment* to the left, and brings the aircraft back into line. The fin, unlike the wings, may be called on to operate at very high angles of attack at times, and so must he designed so avoid stalling. One (the only?) advantage of airfoils with low aspect ratio is that they can operate at higher angles of attack without stalling, so fins are usually fairly short and squat, rather than long and slim.

Wings that have sweep-back also contribute to directional stability. When the aircraft yaws to the right, the "wingspan" of the left wing increases, while that of the right wing decreases. This moves the center of drag of the left wing farther away from the c.g., and moves the center of drag of the right wing closer to it. This produces a yawing moment to the left, bringing the aircraft back into line. There is a small destabilizing effect due to the fact that the left wing's effective aspect ratio increases, so that it develops a little less drag than the right, but this is not enough to cause problems. Of course, wings that are swept forward are destabilizing in yaw.

Hang gliders have wings that are swept back, and most of them rely on this to provide yaw stability. Some have fins, however. These may appear as keel-pockets, which provide very little yaw stability because they are so close to the c.g.; or as fins at the back of the keel, which are more effective because they are farther back; or as wingtip fins, which make use of the wing-sweep to position them behind the c.g. Sometimes designers have designed wingtip fins that are toed-in, so that they produce a little drag. If the aircraft yaws to the right, the airflow meets the right-side fin edge-on, which reduces its drag, but the toe-in of the left-side fin is increased, increasing its drag and pulling the left wing back. This is effective, but produces drag all the time and so is bad for performance.



SWEPT WING SLIPPING TO LEFT: DRAG ON LEFT SIDE ACTS WITH LONGER "MOMENT ARM" ABOUT C.G. THAN DRAG ON RIGHT SIDE: RESULT IS NET LEFT YAWING MOMENT, TURNING WING INTO LINE WITH AIRFLOW.

SWEEPBACK IS YAW-STABILISING
(SWEEPFORWARD IS YAW-DESTABILISING)

2 (VII) What about the Pendulum Effect?

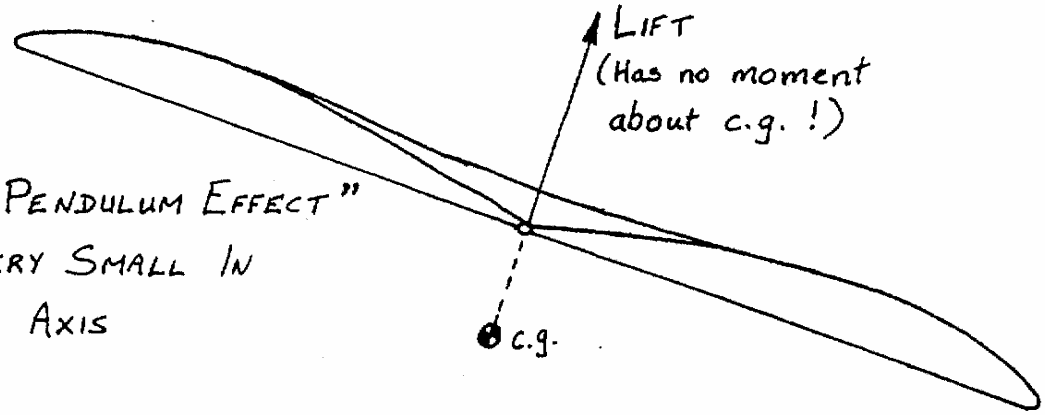
Many people have noticed that the pilot of a hang glider is heavier than the rest of the aircraft. It seems natural that the aircraft would fly so that the pilot is at the lowest possible point. This is the *pendulum effect.* In fact, the pendulum effect is not nearly as useful as it may seem.

Since the pilot is by far the heaviest part of a hang glider, it seems obvious that the glider would fly so that the pilot would be at the lowest possible point. This is known as the *pendulum effect* and should be a big contribution to the pitch and roll stability. Yet I never mentioned it. Why?

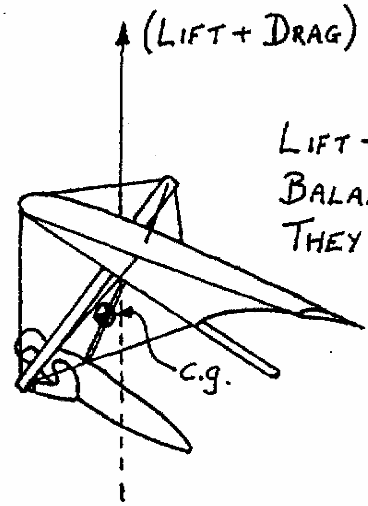
The reason is that the pendulum effect is not very important. To see this, we need to think about moments again. Let's consider roll stability first. Suppose we have a wing with no built-in aerodynamic roll stability. It does, however, have the center of gravity well below the wing. Since it has no aerodynamic roll stability, the two halves of the wing develop equal lift, so the center of lift stays at the center of the wing even in a sideslip. What is more, it continues to act at right angles to the wing. This means that the lift force acts along a line that passes through the center of gravity. A force that acts along a line passing through the c.g. has no moment about the c.g., so there is no rolling moment produced. It doesn't matter where the c.g. is, as long as it is on that line. It could be a long way above or below the wing and would make no difference. There is a small rolling moment from drag, however. Remember that the drag acts backwards along the direction of the airflow. In a sideslip the drag acts a little toward the higher wing. However, in a hang glider the pilot and control frame produce quite a bit of the drag, which moves the center of drag lower, nearer the c.g. The contribution of a low c.g. to roll stability is therefore quite small.

The situation in pitch is not so simple. If the c.g. is well below the a.c. and the nose pitches up, then the c.g. is moved forward relative to the a.c., which produces a negative pitching moment tending to pull the nose down again. This does indeed contribute to stability. However, at airspeeds below the speed for best L/D, the drag increases when the nose pitches up. The additional drag acts along a line that is above the c.g., and so has a moment that tends to pull the nose up more. Nevertheless, there is a net stabilizing pendulum effect in pitch at all angles of attack below the stall.

All of the above assumes the pilot holds on to the control bar very firmly. If the pilot lets go of the control bar the c.g. moves close to the hang point, which may even be above the wing, but the glider must still be stable if it is to be safe. So in fact the designer must assume there is no pendulum effect. Furthermore, most pilots learn to fly with a relaxed grip on the control bar, which allows the glider to move more independently, and reduces what little pendulum stability there was. Finally, the pendulum effect can be spectacularly destabilizing during a strong stall. When the wing stalls its drag increases sharply, while the lift decreases. The additional drag is above the c.g., and the overall effect is so unstable that the wing can exceed a 90° angle of attack temporarily during the landing flare!



THE "PENDULUM EFFECT"
IS VERY SMALL IN
ROLL AXIS



LIFT + DRAG TOGETHER
BALANCE WEIGHT. HOWEVER,
THEY MAY NOT ACT THROUGH
THE c.g., AS SHOWN.

THE "PENDULUM EFFECT" IS
STABILISING IN PITCH

2 (VIII) But I Want to Go That Way ! - Control

So far in this section I have been describing stability - what makes the glider fly "trimmed", that is, at the design angle of attack, wings level, pointing the way it is moving. Pitch control allows the pilot to choose a new angle of attack and airspeed. Pitch control is achieved by weight-shift.

The hang glider is designed to be stable so that, when left to itself, it will fly in "trim" condition, with the wings level and at an angle of attack that produces moderate airspeed. However, the pilot may not wish to do this! The pilot may wish to roll the wings, or change the airspeed, or fly the glider yawed to one side. Control is almost inherently at odds with built-in stability. The more strongly the glider is stable, the harder it is to change its behavior.

The simplest control on a hang glider is the pitch control. When the pilot's body moves forward, the c.g. moves forward. This makes the glider pitch nose-down. The glider must accelerate until the positive (nose-up) pitching moment of the wing, which increases with airspeed, balances the negative pitching moment caused by the forward c.g. position.

Some very alert readers may wonder how we know that the glider equation will be satisfied by the airspeed that produces this pitching moment. It's because we haven't yet specified the new angle of attack. The glider flies at whatever airspeed balances the pitching moments, and at whatever angle of attack gives the correct lift and drag at that airspeed to satisfy the glider equation.

We saw previously that the c.g. must he ahead of the a.c. for pitch stability. For this to work, the aircraft must have a positive pitching moment due to the wing configuration. The bigger the wing's positive pitching moment, the farther the c.g. must lie ahead of the a.c. to balance it, and the more stable the glider will be. To go 41% faster the pilot must move the c.g. twice as far ahead of the a.c., and if this distance is large then the pilot will have to pull the control bar back a long way. It is clear that a very pitch-stable glider will be a lot of work to fly, as the pilot will need to do much more weight-shifting.

Notice that when the pilot is flying faster, the c.g. is farther ahead of the a.c. This increases the pitch stability. Conversely, when flying slowly the pitch stability decreases. We will see later that variable-geometry systems make use of this phenomenon by decreasing the pitch stability, and so the control-forces, when the pilot wishes to fly fast.

2 (IX) It's in the Bank - Roll Control

"Oh, no!" you're saying. "Not more algebra!" Well, once again, don't worry about it. All will become clear. The pilot moving to one side effects roll control. This movement has two effects: first, it moves the c.g. to that side; second, it causes sail-shift that provides aerodynamic roll control.

At first glance it seems as if the mechanism for roll control is similar to that for pitch control -weight shift. To some extent this is true. When the c.g. moves to one side, the wing on that side is more heavily loaded than the one on the other side, so its sink-rate increases and the glider rolls to that side. The roll-rate can be computed from a knowledge of mechanics. There's a derivation on the opposite page, taking up much of the page, of the roll-rate that results from weight-shift.

Well, what does it mean? It means that, for constant wing area, the roll rate decreases as $1/b^2$, i.e. double the wingspan gets quarter the roll-rate. As glider wingspans have increased to improve performance, the roll-rate that can be achieved through weight-shift has suffered badly. On the other hand, the move toward smaller wing-areas has helped a bit. For a modern design the maximum roll-rate calculated from this equation is about 10 degrees per second. What's worse, this is the steady-state roll-rate. A longer wing also has a larger moment of inertia, so it takes longer to reach this roll-rate. It may be a surprise to see that the roll-rate due to weight-shift decreases with increasing airspeed. Most pilots are used to roll-rate increasing at higher airspeeds. It would seem that the reason for that must lie elsewhere. And, indeed, it does.

Some years ago designers realized that it was possible to improve on simple weight-shift roll control. When the pilot pulls across to one side of the control bar, the bar increases the tension in the flying wire on that side. The extra tension in the flying wire tries to pull the leading edge on that side closer to the keel. By having the crosstube "float" above the keel, designers allowed exactly this to happen. The leading edge on the loaded side moves closer to the keel, decreasing the sail tension on that side. On the other side, the sail tension increases. This alters the washout in each wing half. The twist in the loaded side increases roughly linearly along the half-span, reaching a maximum increase of α_1 at the wingtip. On the other side the twist decreases an equal amount. Then we have a roll-rate that increases with airspeed, as the second result on the page opposite shows. This is somewhat better, amounting to about 20 - 25 degrees per second for typical numbers. As a result, it's now the primary means of getting roll control. Although sail-shift is not as badly affected by increased wingspan as weight-shift is, it still suffers. To retain the same roll rate, the amount of wing-twist α_1 would also have to increase. "Stiffer" gliders$_1$ with less wing-twist available, are noticeably heavier and slower in roll response.

The Roll Control Calculations

Weight-Shift Only

If the wing has linear twist and taper the results are similar in form to those derived below. Only the actual rate of roll changes. In general, taper puts more lift near the wing-root, and the roll is quicker for a given wing-area. Twist (washout) makes the tips less effective, so requires more wing-area, and results in a slower roll than would result with no twist.

There are a few new variables in this derivation.

x: Position along the wing ω: Roll Rate W_p: The Pilot's Weight   c: Wing Chord = S/b

a: The Lift-Coefficient Slope (ideally 2π per radian)

δ: The Distance the Pilot's Weight Moves During Weight-Shift

Angle of Attack due to Roll-Rate ω: $\alpha(x, \omega) = \alpha_0 + \omega\, x/V$

Lift: $L(x) = \frac{1}{2}\, \rho\, a\, \alpha(x,\omega)\, c\, V^2$

$$\text{Rolling Moment} = W_p\, \delta = \int_0^{b/2} \rho\, a\, c\, V^2\, (\omega\, x/V)\, x\, dx = \frac{\rho\, a\, V\, b^2\, S\, \omega}{24}$$

Hence: $$\omega = \frac{24\, W_p\, \delta}{\rho\, a\, V\, b^2\, S}$$ - The Roll Rate due to Weight Shift

Wing-Twist Roll-Rate

There the wing twists linearly along the entire span. The downward-moving tip has its angle of incidence decreased by α_1, while the upward-moving tip has its angle of incidence increased byu the same amount. The steady roll-rate will restore the wing to the same angle of attach everywhere. This gives the equation for the roll-rate:

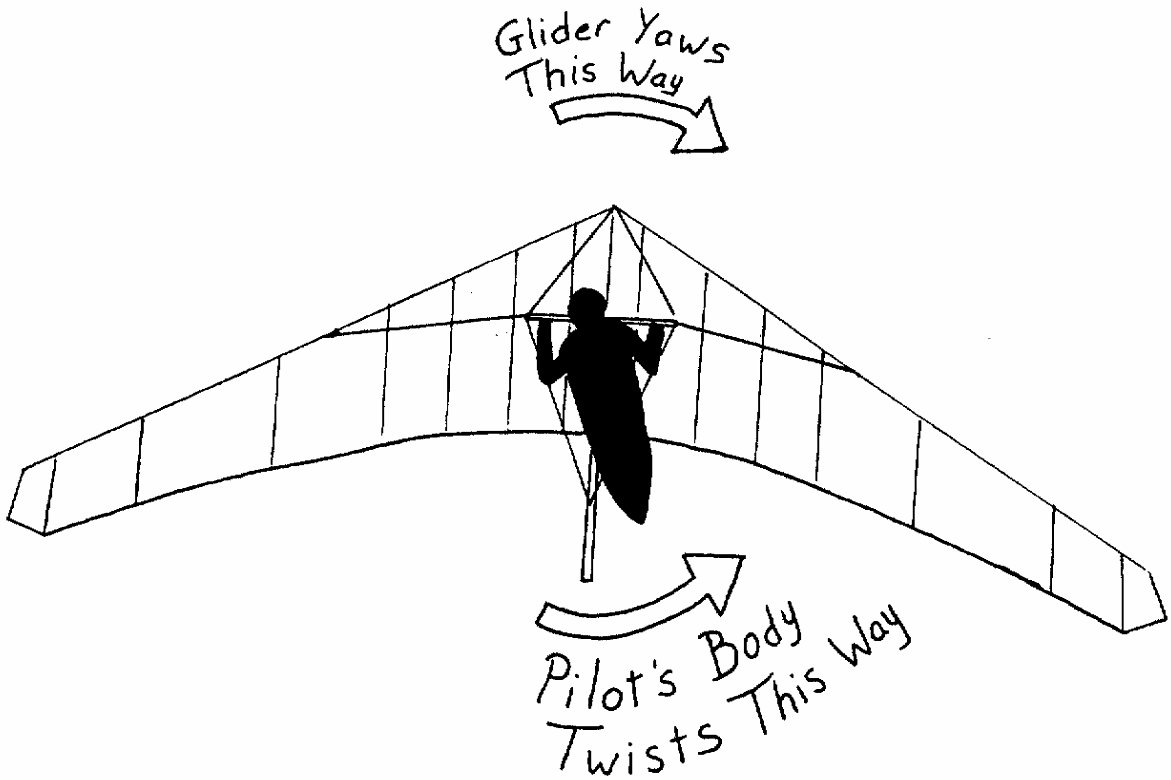
$$\omega = 2\, \alpha_1\, V/b$$

2 (X) Twist It All About - Yaw Control

The pilot of a hang-glider has no aerodynamic yaw control. However, it is possible to control the glider in yaw to some extent by twisting the pilot's body, and sideslipping turns are possible.

There is no aerodynamic yaw control fitted on a hang glider, and there is no way to fly the glider in a steady, straight line with the nose pointing anywhere other than straight ahead. However, it is possible to get the glider to yaw briefly, and this can be useful. If the pilot's body is forced to twist about the hang-strap in the yawing plane, the glider will yaw the other way. When the pilot tries to twist one way, this applies a yawing moment to the glider in the opposite direction (good old Newton again). As soon as the pilot stops turning by holding on to the glider to stop the rotation, the glider stops yawing also, and its aerodynamic yaw stability pulls it back into line. If the pilot wants to get a really big yaw, it is possible to pre-twist in the opposite direction (for example, to the left), with the pilot's c.g. staying at the center so no banking of the wings results. If the glider is now allowed to settle down with the pilot twisted to the left, then the pilot can twist a long way to the right before having to stop. This can provide a big yawing disturbance of the glider (to the left) if it should be required. We'll see soon why this might be a good thing to know.

There is a second way to get the glider to fly with the nose yawed to one side of the flight path. This is to do a slipping turn, which I will discuss later, in the section on turning. To give you a brief preview, if the pilot rolls the glider into a turn, then pulls the bar in (pitch-down) to increase airspeed, the lift will not be enough to pull the glider around the turn properly, and the glider will slip toward the lower wing. As the airspeed increases the glider will reduce the amount of slip. In the slipping condition the glider is flying so that it is yawed with respect to the airflow. This is an inefficient way to fly, creating additional drag. This drag increases the sink-rate by "throwing away" energy, which must be provided by the glider coming down. Sometimes the pilot will want to descend steeply, and will use this method to do so.


Glider Yaws
This Way
Pilot's Body
Twists This Way

2 (XI) You Can't Have One, But Not The Other - Roll/Pitch/Yaw Coupling

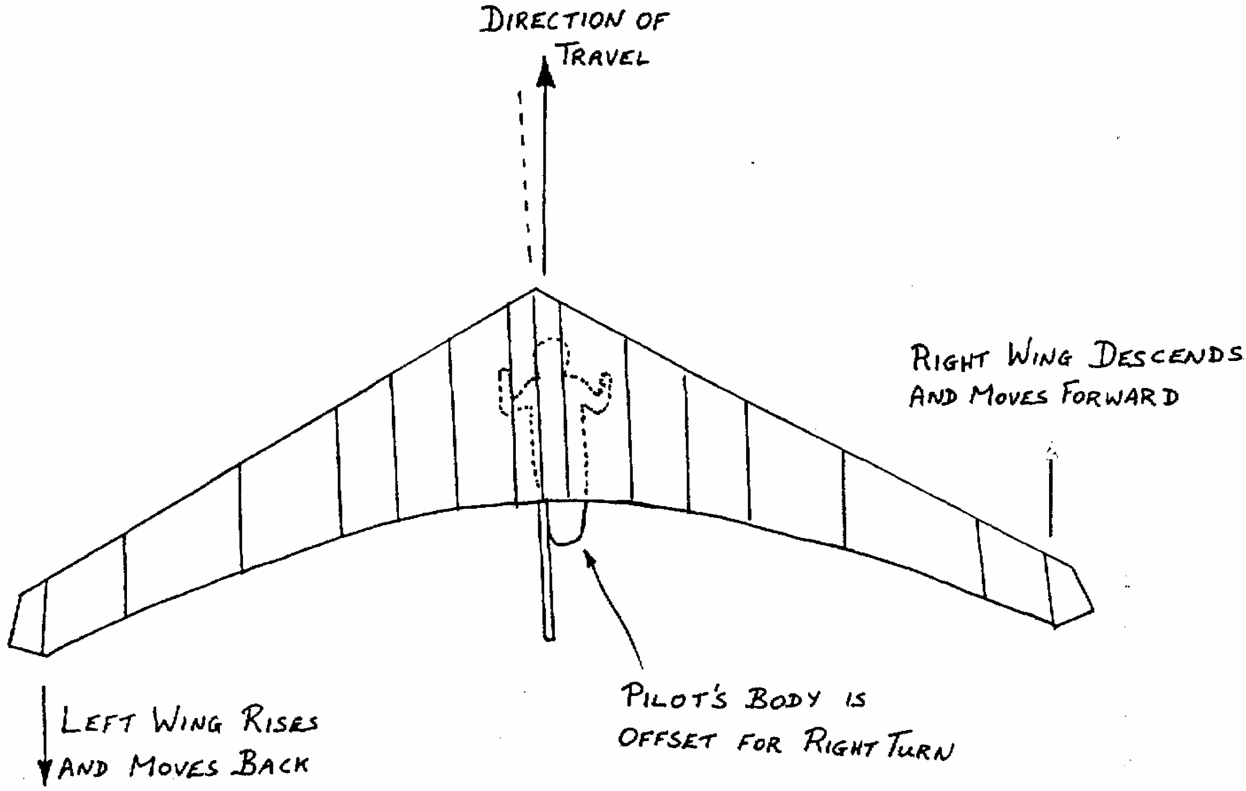
Control inputs in one axis may have effects in other axes as well. In turns, pitch inputs affect the glider in yaw and roll. Roll inputs affect the glider in yaw, and yaw inputs affect roll!

The various control axes are easy to think about separately, but difficult to separate in reality. The best-known example of coupling is called *advese yaw.* When the pilot makes the glider roll to one side, the down-going wing moves forward faster than the up-going wing, so the glider initially yaws toward the rising wing, away from the direction of the intended turn. There are two reasons for this. First, think about the case of weight-shift control. The downward-moving wing is going down faster because it is more heavily loaded. But its L/D doesn't change, only its airspeed. It moves downward faster, and forward faster. Now think about a wing controlled by sail-shift. The downward-moving wingtip is at a lower angle of attack, developing less lift. Therefore it is also developing less induced drag, so it moves forward relative to the other side. Eventually the glider's yaw-stability prevents the situation getting out of hand, but in both cases the effect is the same. When the pilot applies roll-control to begin a turn, the glider initially turns the wrong way, causing a delay before the turn begins in the right direction. This is where the trick of swinging the pilot's body to yaw the glider comes in: the pilot can yaw the glider into the turn while the weight-shift is rolling the wing, and in this way can reduce or eliminate adverse yaw.

If the pilot yaws the glider without deliberately rolling it, a small rolling motion will result anyway. When the glider is made to yaw, it has a sideslipping motion through the air. The glider's roll-stability works by detecting sideslipping, and so the wing that has gone ahead during the yaw will rise. The fact that the forward-moving wing has a higher airspeed also causes it to rise. This means that if the glider is yawed to the left, it will also roll to the left. A hang glider usually has very little roll-stability, so this effect is small.

If the pilot does a slipping turn (as I described on the previous page), the glider's usual efficient flight is disrupted by the pilot's application of pitch-down control during a turn. The result is that the glider does not point into the airflow properly, despite its roll and yaw stability. If the pilot now applies some pitch-up control, the added lift will pull the glider around in a turn, and as the airspeed stabilizes the glider becomes more properly aligned with the airflow.

Another example of coupling can be seen in high-speed "Dutch-rolling" behavior. When the glider is flying fast, it may begin to roll and yaw from side to side. This is usually made much worse by the pilot, whose attempts to stop the situation instead make things worse. This situation is called a *piIot-induced oscillation,* and can be a serious problem for inexperienced pilots. The solution is to slow down and stop applying control inputs! This kind of coupling is remarkable because it shows coupling between the glider and the pilot's reflexes!



ROLL - YAW COUPLING: ADVERSE YAW

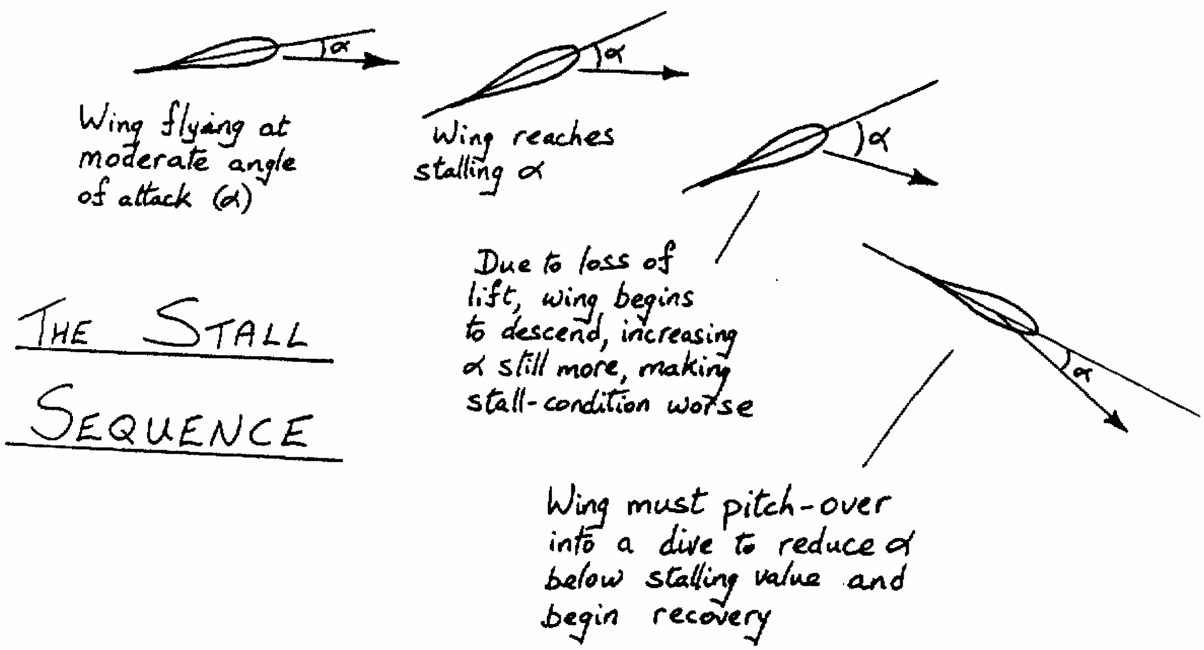
2 (XII) Control Effectiveness At Low Speeds

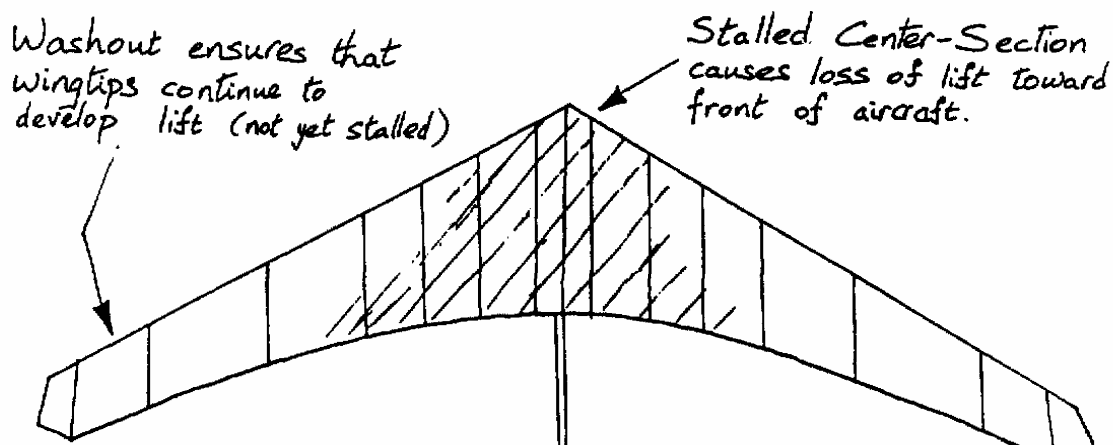
Hang gliders are controlled by weight-shift, so pitch control is effective as long as the wing is lifting the pilot. However, although roll control is controlled by the pilot's body position, it depends on aerodynamic effects and can be much less effective at low speeds.

When a hang glider is flown slowly, its wing is required to lift the same weight at a low airspeed. This requires a high angle of attack. Because the wing has washout which insures that the angle of attack is highest near the wing center and lowest at the wingtips, it begins to stall near the center first (actually the stall generally begins at about 1/3 span). The behavior of the glider at low speed is profoundly affected by the progression of the stall along the wing, and this needs to be considered.

Pitch control of a hang glider is achieved entirely by weight-shift. As long as the wing can lift the pilot's body, the relative positions of the c.g. and a.c. and the pitching moment of the wing control the pitch attitude. If the wing is developing no lift, then the relative positions of the c.g. and a.c. do not matter, and the wing will pitch up because of the wing pitching moment. However, if the wing is lifting and approaching the stalling angle of attack, the wingtips will be the last to stall. Over most of the wing the lift will decrease with further increase in angle of attack, while the lift of the wingtips will continue to increase. Since the tips are behind the center, this means that the wing's pitching moment is no longer constant. It begins to decrease, producing a pitch-down effect, and the changing pitching moment will prevent any further pitch-up motion' of the glider. However, at this stage the lift is insufficient to support the weight. The glider accelerates downward, causing the angle of attack to increase anyway. This causes the pitching moment to become more negative, and the glider pitches nose-down. If the glider is made to stall abruptly, the nose will pitch down so fast that the wing will recover from the stall, build up excess speed, and will then pitch up again because of the pitch stability, but if the glider is slowed gradually it will "mush", with part of the wing stalled, at a low airspeed and high sink rate.

Roll control depends partly on weight-shift and partly on sail-shift. With the inner part of the wing stalled, roll control becomes very difficult. Suppose a wingtip slows down a little for some reason. This causes the stalled region of the wing to grow on that side, slowing it further and causing it to drop, making the stall worse in a vicious circle. The pilot attempts to raise the wing by moving the other way. The weight-shift is helpful because it reduces the load on the stalled portion, but the sail-shift is unhelpful because it flattens the sail on the lower side, increasing its angle of attack and making the stall worse, moving it toward the tip. Out at the tips, however, the sail-shift is helpful because the tips are operating normally. The overall result is that roll control becomes ineffective as the stall begins to progress along the wing, and the roll stability of the glider goes away also.





How washout causes the stall to progress from the center-section outward. The tips are the last to stall, and help pitch the nose down to prevent the stall getting worse.

2 (XIII) The Lessons to Learn About Stable Relationships

Here is a summary of what we have seen in Part 2.

- The c.g. must be ahead of the a.c. for pitch stability.
- The wing must be designed with a positive pitching moment for stability.
- With enough sweep and washout a wing can have positive pitching moment.
- The more positive the pitching moment, the farther the c.g. is ahead of the a.c.
- The farther the c.g. is ahead of the a.c., the more pitch stability the glider has.

- Dihedral is stabilizing in roll. Anhedral is destabilizing.
- Sweep~back of the wings is stabilizing in roll. Sweep-forward is destabilizing.

- Vertical surfaces behind the c.g. are stabilizing in yaw. Ahead of it they destabilize.
- Sweep-back of the wings is stabilizing in yaw. Sweep-forward is destabilizing.

- Swept-back wings with plenty of washout are stable in all three axes.

- The Pendulum Effect has very little influence on lateral (roll) stability.
- The Pendulum Effect has much less influence on pitch stability than most people think.
- If the pilot uses a light touch on the control bar, the Pendulum Effect disappears entirely.
- BUT a rigid grip on the control bar is *damping* in all three axes (slows down any changes).

- Pitch control is entirely due to weight-shift.

- Roll control is partly by weight-shift, but mostly by sail-shift - an aerodynamic control.

- Yaw control is by swinging the pilot's body, and produces temporary yaw only.

- Roll and Yaw are coupled (affect each other), and, in turns, are coupled to Pitch also.
- Roll control inputs cause Adverse Yaw, which slows the entry to the turn.

- When the wing is partially or entirely stalled the glider tends to pitch nose-down.
- When the wing is partially or entirely stalled, roll stability and control go away.

3. <u>STRUCTURE</u>

---

3 (I) The Basic Structure, or Keeping It Together

The basic structural layout of a modern flex-wing hang glider is remarkably similar to that of the early Rogall~wing gliders. The structure has stood the test of time because it can perform its function while being light, simple and strong.

The modern flex-wing hang glider has a structure that is almost identical to that of the early Rogallo wings. This structure has been modified, certainly, and its shape has changed with the changing design of the gliders, but the basic layout remains the same. Complicated systems of deflexor wires have come and gone. In the end, the KISS principle (Keep It Simple, Stupid) has proven its worth yet again.

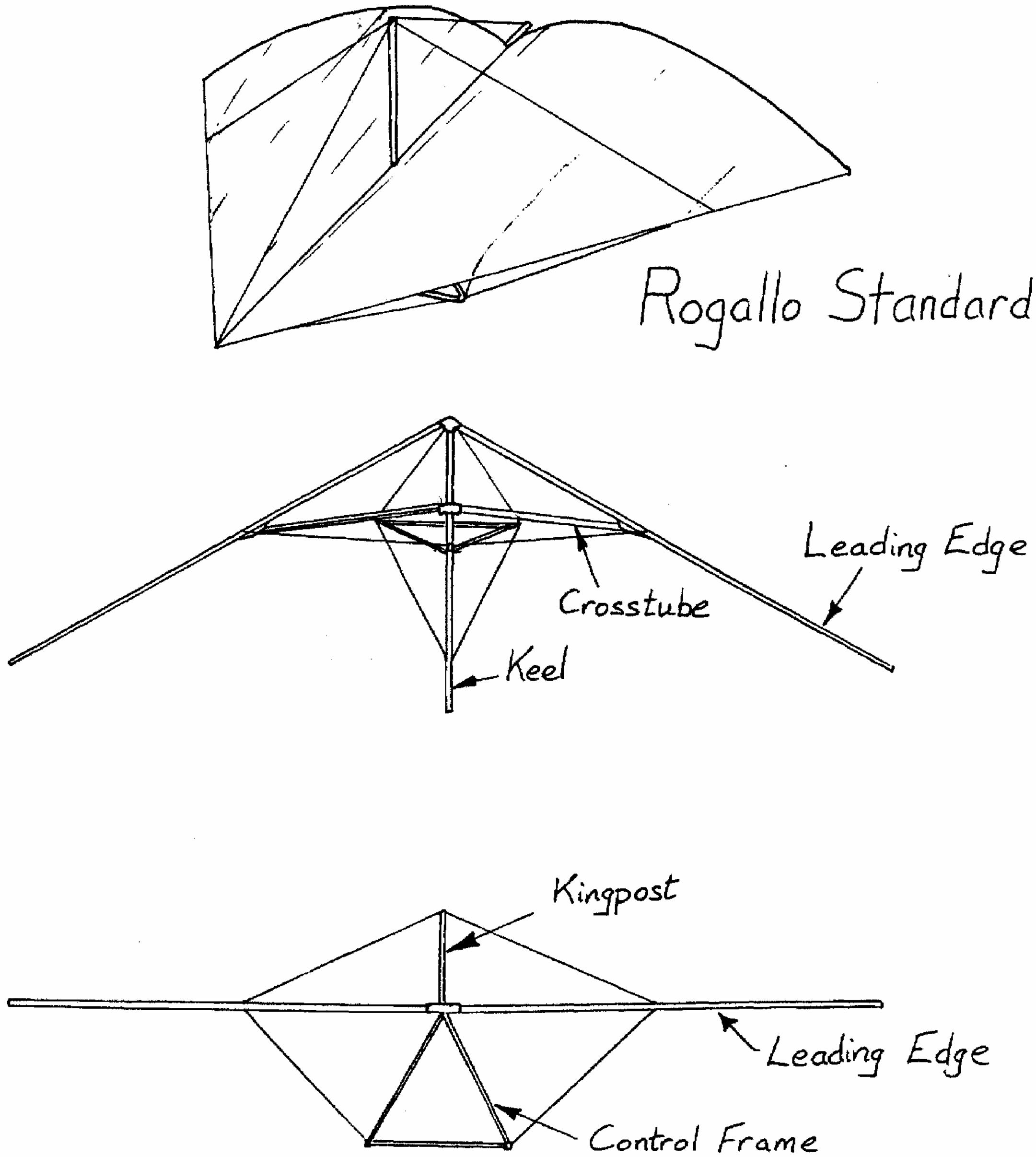
At the heart of the glider is the keel, an aluminum tube that runs down the centerline of the glider. Its main function is to keep the leading and trailing edges of the wing apart, and to locate the top of the control frame and the bottom of the kingpost. The keel extends some distance behind the wing to help protect the wingtips when the glider is on the ground.

Two leading-edge tubes are connected to the front of the keel. They are hinged so that they can be folded alongside the keel for storage. These tubes are the longest on the glider, and are made in two parts because the tubing is manufactured in lengths that are too short. They are joined by fitting an internal "sleeve", which has a diameter that just allows it to slide inside the leading-edge tube parts. The sleeve is held in place by a rivet through each leading-edge part. The leading edge tubes must be very stiff, because the lift on the wing tends to bend them.

A cross-tube holds the leading edges apart. The sail tension, which is quite high even on the ground, is much higher in flight, and tends to pull the leading edges back alongside the keel. The cross-tube hinges in the middle, again to allow folding for storage. Originally the cross-tube was anchored to the keel where it crossed it, but in modern gliders the cross-tube is allowed to "float" from side to side. This allows for sail-shift in flight, which helps with roll control.

Underneath the wing there is a triangular control-frame, or control-"bar". The control frame is anchored to the nose and tail of the glider by wires from each corner. It is also attached to the wing on each side by "flying wires". These wires anchor the control frame in position from side to side, but also transfer flight loads from the wing, as the leading edge by itself would not be strong enough.

Above the wing, a "kingpost" is similarly connected to the nose, tail and wings. The wires it supports keep the wing from collapsing under down-loads.


Rogallo Standard
Leading Edge
Crosstube
Keel
Kingpost
Leading Edge
Control Frame

3 (II) Secondary Structure, or, I Said Simple, Not Crude!

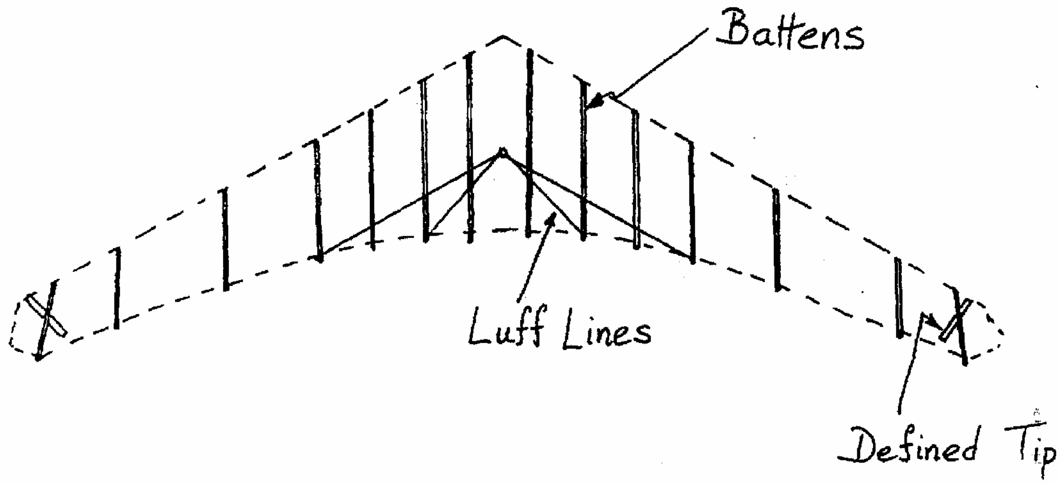
The primary structure is enough to keep the glider in one piece, and is all there was to a hang glider at one time. To give the wing a better shape, however, there is secondary structure.

The primary structure of a hang-glider is very simple, as we have seen. However, a glider with only this much structure would not fly very well, and would be unsafe for aerodynamic rather than structural reasons. The first major modification to the simple structure is the addition of battens. These are pieces of small-diameter aluminum tubing bent to an airfoil shape. They slide into pockets sewn into the sail, and hold the airfoil shape in the sail. Double-surface gliders will also have battens in the lower sail-surface, but usually these battens are flat. One batten near each wingtip is made much sturdier than the others, and the sail is pulled tight by an elastic cord that goes over the end of this tip-batten. Since there are so many battens, gliders now take quite a bit longer to set up than was the case before their introduction, but the performance improvement is very well worthwhile.

Out at each wingtip, there may be a strut that sticks out of the leading edge at an angle backwards. In normal flight it does nothing, since it is below the sail. However, if the sail comes under negative load, the wingtips will tend to collapse downward. The strut, which is known as a "defined tip" or "washout strut", prevents this. The idea is to ensure that the positive pitching moment that results from washout at the wingtips is retained at all times. If the tips were allowed to collapse, the positive pitching moment would become very much smaller, possibly even become negative, which would cause the glider to go inverted.

Another design modification that improves stability under negative load is the use of reflex lines, or "luff lines". These are lines running from the kingpost to the trailing edge of the sail. There is always at least one on each side. When the sail comes under negative load, it tries to collapse, but the trailing edge is held up by the luff lines. This gives the sail a dramatic reflex-type airfoil shape, which causes a large positive pitching moment, bringing the nose up. The use of luff lines and defined tips has made an enormous contribution to safety. It is important to keep them in good order. Since they do nothing under normal circumstances, any problems will only become apparent when the glider will not recover from a dive. In the "bad old days", such death-dives were all too common.

Newer gliders often have systems that allow the pilot to vary the cross-tube compression in flight. This alters the sweep of the leading edges slightly, increasing or decreasing sail tension. A loose sail has more washout, and can shift more from side to side. This increases pitch stability, improves stall behavior, and makes roll-control lighter. At high speeds, however, this much washout is excessive, the tips develop little or no lift, and the wing is inefficient. With the sail tight, the high-speed glide is noticeably better, at the expense of pitch stability, roll control and stalling behavior. Pilots are supposed to alter the tension to correspond to the speed at which they wish to fly.



Hang-Glider Secondary Structure

3 (III) Forces and Loads - How Strong Does it Need to Be?

The structure of the hang glider must be strong enough to carry the loads imposed in flight. Just how big are these loads, and what does it matter anyway?

The major structural elements of the glider are the leading edges, the crosstube, the control frame, flying wires and keel. Failure of any of these is catastrophic.

The crosstube, which holds the leading edges apart, takes a very large compression load. As long as the crosstube is straight, it can take a very large load indeed, but any deviation from straight, or "column", can be disastrous. There's a good way to show how this works. A soda-can, standing on end, should support your weight (that's a lot, for such a thin can). Now have someone tap the side of the can, just enough to dent it a little, while you are still standing on it. It will collapse instantly - just like a dented crosstube would! Never fly a glider with any dents or bends in the crosstube. While I'm on the subject, the wire that holds the center of the crosstube back needs to be in good shape, too!

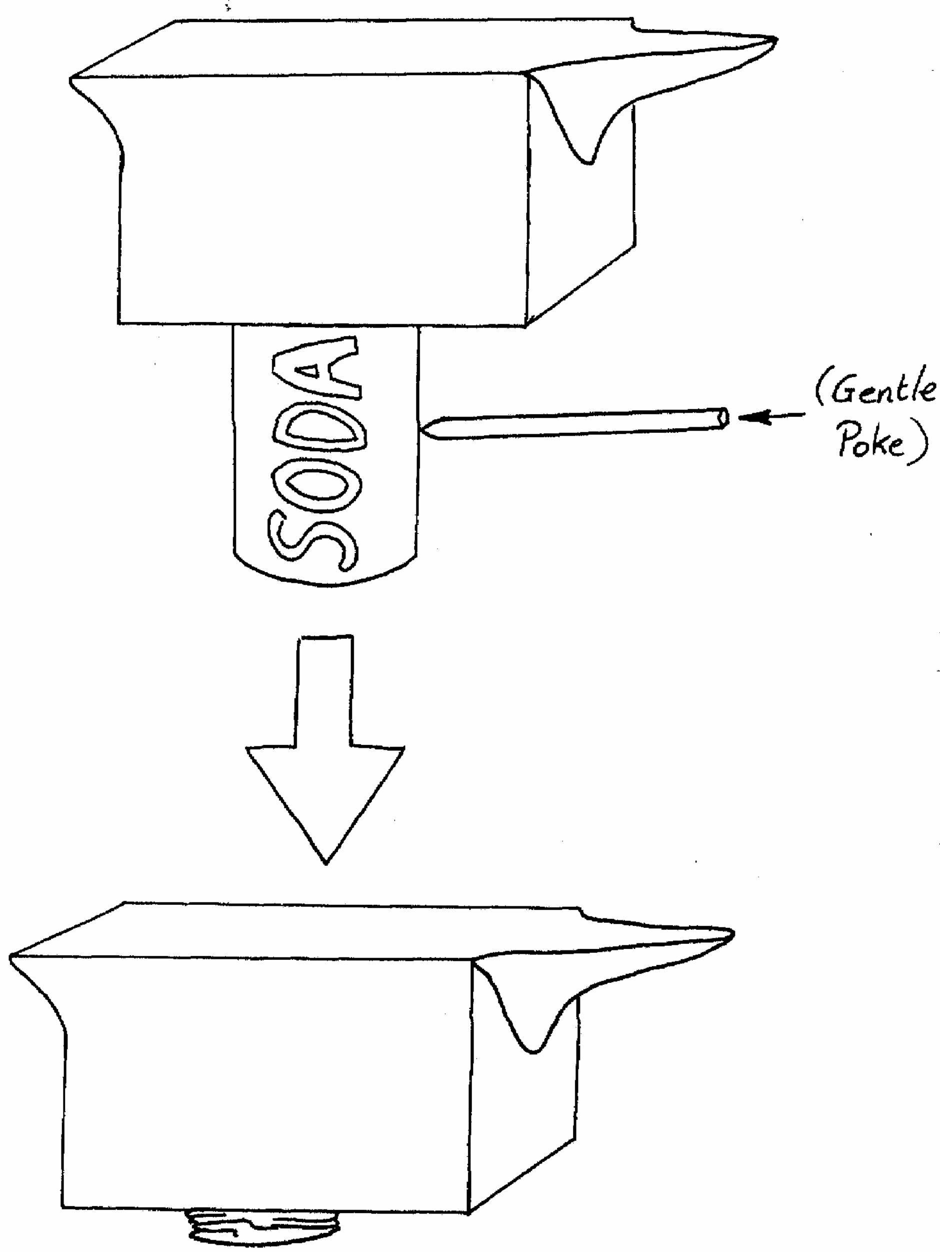
The leading edges are subjected to a large bending load. The lift on the sail tries to pull the leading edge up and back, but it is held down where the side wires attach and is held forward by the crosstube. The result is that the leading edge bends backwards and upwards, especially just outside the junction with the crosstube. This bending compresses the leading edge on the inside of the bend. Tube under compression is very sensitive to dents, as we've seen. There must be no dents in the leading edge$_1$ especially at the back. Minor damage near the wingtips may be okay, as the forces there are smaller.

The downtubes of the control frame also take compression loads, and must be straight, too. Each downtube is taking about half of the flight load, so at 6 g the load would be about 750 lbs on each one! This is much, much less than the crosstube has to put up with, but you are also much more likely to bend or dent your downtubes. Many people simply "straighten" their downtubes and fly again. Think about that soda-can, and the 750 lbs. Make sure those tubes are dent-free, and straight! If the bend was at all significant in the first place, toss the tube. Replace it.

The basetube of the control-frame is under tension-load. It doesn't need to be straight, just strong. "Speed bars" are possible for this reason. Under load, the bar may straighten a little, but problems with basetubes are uncommon.

The sidewires, too, are in tension. They take about 70% of the flight-load - each! At 6 g the load is about 1050 lbs. This is quite a lot, so the sidewires must be kept in perfect condition. Again, the word is perfect - nothing less is good enough.

The nose and tail wires take much smaller loads, and are unlikely to fail. Keep them in good condition anyway. Keels, also, are usually more than adequately strong - but they need to be!



Reminder: Dented Tubes Fail Under Compression !

3 (IV) Forces and Loads Again - What About the Other Bits?

The "minor" structural elements are also important, of course. What about them?

I've covered the forces acting on the major structural elements of the glider, and pointed out that parts under compression load must be straight, with no dents.

The kingpost does nothing most of the time, and if the glider could be launched without one (which it probably couldn't) there would probably not be any problem. However, under negative load (as often happens before launch) the wing would collapse. The kingpost and upper wires serve the same structural purpose as the control-frame and flying wires, but are in use during those negative-load moments we all love. For this reason, they need to be kept in good condition too. The kingpost must be straight, with no dents, and the upper wires - the upper side wires in particular - must be damage-free.

The luff-lines never really have to perform any truly heroic acts, hut do take a look at them every time because when you need them, you really need them. One of the elegant things about hang-gliders is that there isn't much on them that isn't really necessary. On the other hand, that means there isn't much on them that you don't need to be really sure is in working order!

The defined tips are like the kingpost. They do nothing unless you get into trouble. But then, they'd better work. The defined-tip strut comes under bending load, with the most likely point of failure where it attaches to the back of the leading edge. No dents, as usual, is the rule. These struts are much stronger than they need to be, so a failure here would be a big surprise and would mean the pilot really hadn't been paying attention during set-up!

The tip-battens control the sail tension. They are under a good-sized compression load, and should be straight and dent-free (yes, that again). If one fails, it will bend, and the glider will develop a natural turn to that side. Flyable, probably. Comfortable, no.

The other battens are a bit less critical. People have flown with some missing, with bent ones, the whole array of possibilities. However, it isn't good for the glider's handling or performance, and is definitely not recommended. Battens that are inserted wrongly so that they deform the mylar insert at the leading edge can have serious effects on trim-speed as well as on stalling speed and stall behavior. Bent battens, especially near the wingtips, can give you a bad fright. Do check your battens against the batten-pattern occasionally, and be careful with them. T hey are there for good reason.

Another apparently minor item is the nose-cone. On some gliders the nose-cone must be present for the glider to handle properly. If it is not present the airflow through the hole in the nose where the leading edges and keel meet allows air into the double-surface, which can inflate the sail. Again, this may affect handling and stability to a surprising (and unpleasant) extent.

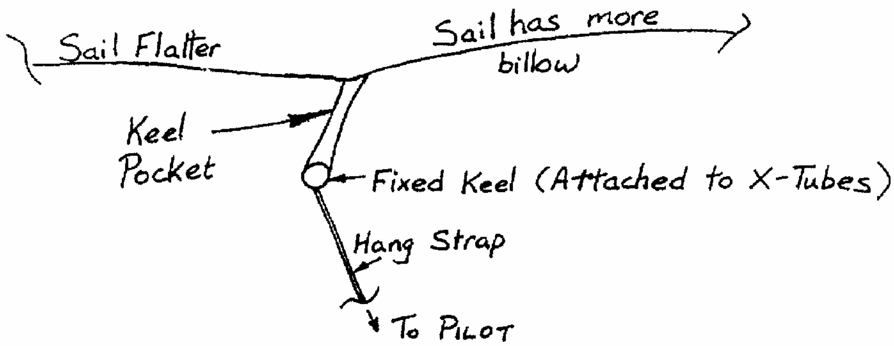
3 (V) Sail Shift, Floating Crosstubes, and the Mysterious Vanishing Keel-Pocket

This page is about how the sail can be twisted for aerodynamic roll-control - and a curious little bit of design history.

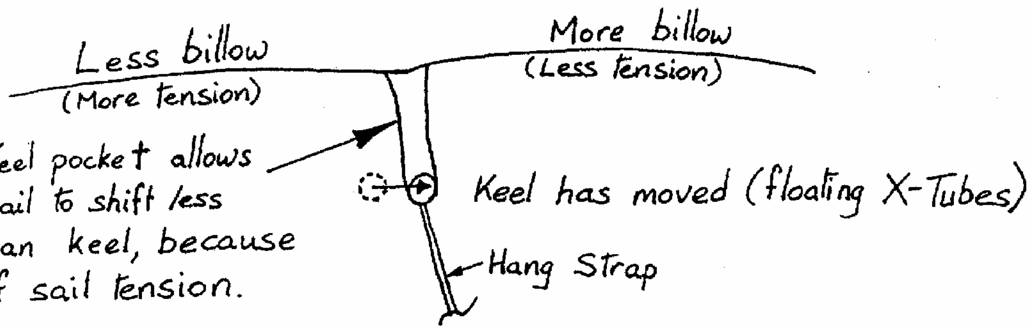
Back in section 2 (IX), I discussed roll-control. There are two forms of roll-control in hang-gliding. One is the direct effect of weight-shift, which increases the load on one wing and so causes it to sink faster. Unfortunately this becomes much less effective as the wingspan increases. The other form of roll-control, I said, was produced by twisting the sail. In early hang gliders the sail was firmly attached to the keel and leading edges. Then designers realized that they could allow the sail to move relative to the keel by adding a keel-pocket. This meant that when one side of the sail had a higher load (due to the pilot moving to that side) the sail would shift to that side, producing sail twist and improved roll response. After a while there was a further innovation. Since the sail-shift was limited by the fact that the keel was fixed, the thing to do was to allow the keel to float from side to side. The keel was anchored by the cross-tube, but the cross-tube could be allowed to float above the keel, so that the keel could follow the sail. When designers realized that they could improve the roll-control in this way, without adding any extra controls for the pilot to operate, they did it. The innovation was known as the "floating cross-tube", and it worked well.

Unfortunately, it wasn't quite right. With the keel no longer anchored to the cross-tubes, there was nothing to stop it following the pilot from side to side. So, when the pilot pulled to the right, the keel moved to the right also. If the sail had been firmly anchored to the keel, it would have moved the same distance. This would produce sail-twist, with more washout in the right wing, less in the left, just as required. However, the keel-pocket now allowed the sail to shift a little *less* than the keel! As newer gliders appeared, with tighter sails, this fact became important because it took more force to displace the sail to the side, and the keel-pockets disappeared. A major benefit of getting rid of the keel pockets was better control feel. Previously the sail was relatively free to shift as it pleased, which made the glider's behavior somewhat less predictable. Now, however, the pilot is more directly in control of the sail position, so the glider is more predictable and gives better feedback to the pilot, all of which adds up to better control feel.

There was one other use for keel-pockets, in that they provided some vertical surface toward the back of the aircraft, and helped with yaw-stability. Their effect is very small, however, because the keel-pocket is not very far back at all, and their absence doesn't cause any directional-stability problems.



Keel-Pocket Originally Allowed Sail to Shift



Floating Crosstubes made the Keel Pocket Counterproductive

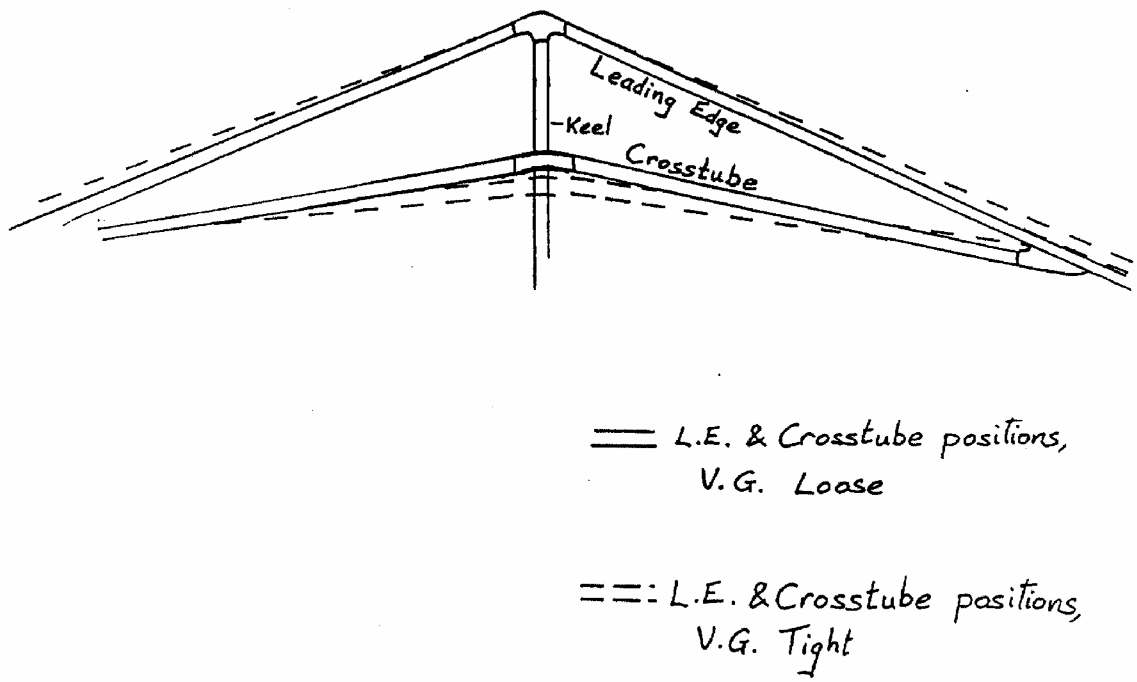
3 (VI) Variable-Geometry Systems - What They Do.

Hang gliders, like some jet fighters, often have variable-geometry swept wings. That is, it is possible to vary the amount of sweep in flight. Why is this done, and what other consequences does it have?

Variable-geometry (VG) systems have been very popular in medium and high-performance hang gliders in recent years. The systems work by using a system of pulleys to allow the pilot to adjust the tension of the wire that holds back the cross-tube at its center. When the wire is tighter, it pulls back the cross-tube and pushes the leading edges of the wing farther apart. The change in the angle of sweep is small, too small for anyone on the ground looking up at the glider to notice. However, when the leading edges are pushed out, the sail tension increases. The washout decreases, and this makes the wing more efficient at higher speeds. Remember, the swept wing must have washout to have the same angle of attack everywhere, because the sweep tends to make the angle of attack increase toward the wingtips. If the wingtips are to be the last to stall, the washout must be even greater. The effect of wing-sweep decreases with increasing airspeed, however, and so the amount of washout needed decreases. If the washout is kept the same, the wingtips develop too little lift, and the wing becomes increasingly inefficient.

The pilot should be aware of the effects of having the VG tight. There will be less washout, so that when the wing stalls, more of it will stall at once, making stalls more abrupt and more likely to result in spins or partial spins. On the other hand, the stall speed will be a fraction lower than with a loose VG, and the minimum sink-rate will be somewhat lower because the wing is producing lift more efficiently. With less washout, the positive aerodynamic pitching moment of the wing is decreased, too. This means that the pitch stability will be reduced (so control forces will be smaller). The new trim-speed may be higher (smaller pitching moment) or lower (due to moving the area of the wing forward slightly) - it depends on the design details. With the sail tight, the sail will twist less for roll control, causing the glider to be difficult or even impossible to control in roll.

With the VG fully loose, the sail may be too loose for aerodynamic efficiency at any speed. Some pilots use this position anyway, especially in turbulent conditions, because it makes the glider much more responsive in roll. On some gliders, the choice of VG position may cause a noticeable change in handling when landing. With the VG loose, the wingtips may be slow to stall, even in a landing flare. If the tips do not stall, they tend to push the nose down, of course, and so fight the pilot's attempt to flare for the landing. Some high-performance gliders land not unlike training gliders when the VG is loose, needing a gentle, gradual flare at first, with a quick finish as the stall begins to progress along the wing (training gliders will still be more forgiving). With the VG tight, the same glider will require a sharper, more rapid flare, because the stall will move along the wing very rapidly, once it starts.


Leading Edge
Keel
Crosstube
L.E. & Crosstube positions, V.G. Loose
L.E. & Crosstube positions, V.G. Tight

4. <u>STRAIGHT AND LEVEL WITH ME!</u>

---

4 (I) The Minimum-Sink Controversy (Where is it, Really?)

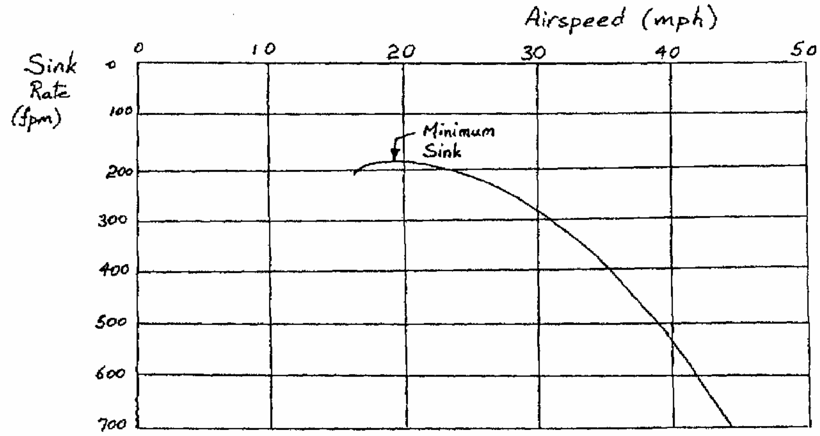
The speed for minimum-sink is always a good subject for hangar-flying. What is it? How do you get to it? How do you know when you've got it wrong?

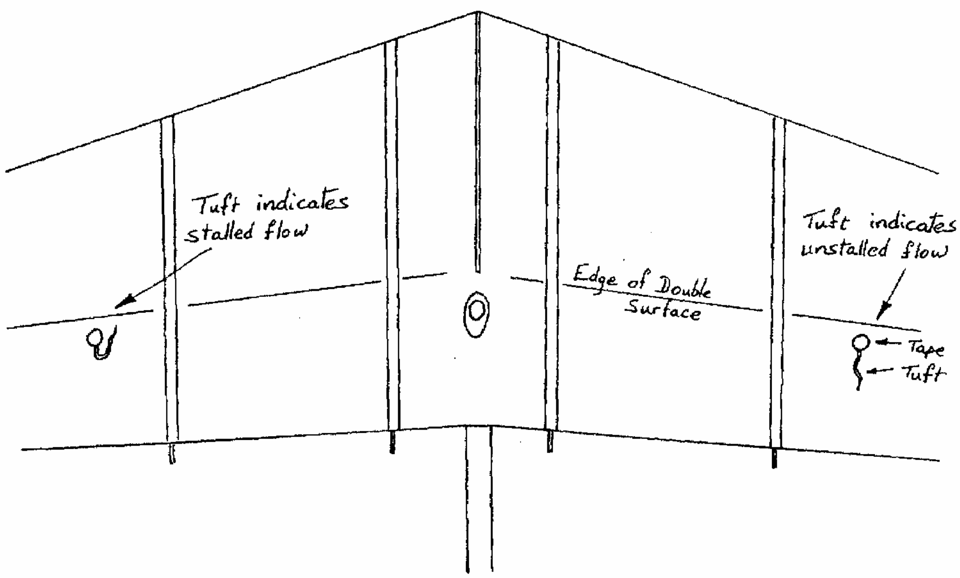
As we discussed in part 1, there is an airspeed for any glider which gives the minimum sink rate. Actually, to be more precise, there is a minimum-sink angle of attack, which depends on the shape of the glider but not its weight. It's important for the hang glider pilot to know how to fly at this speed, because hang gliders have a pretty high sink rate, and spend most of their time in the air looking for enough lift to stay up. So, how do you do that?

The most common advice given is, "it's a little faster than the stall speed". Personally, I didn't think this was very helpful. The wing stalls gradually, starting at the center and moving outward. It isn't easy to know just when this process starts. But, anyway, why should it be just above stall speed?

Well, there is an indirect connection between the two. There are two things that limit stall speed. The first is that it must be low enough that the pilot can run that fast! The second is that the stall speed should he lower than the minimum-sink speed. But, if you remember, the stall speed is kept low by increasing the wing area, which is bad for high-speed performance because of the added drag, so the stall speed will he kept no lower than necessary. The designer will put the stall speed at a fast sprint, coincidentally a little below the speed for minimum sink.

But, that still doesn't help the pilot to fly at that speed. Well, first I want to point out that it's really only necessary to fly *near* that speed. It's well known among mathematicians that if something is near a minimum, it isn't very sensitive to small variations in whatever controls it. If the sink rate is near its minimum, the airspeed can be a little too high or low without hurting much. So, simply trim the glider to fly just a little above minimum-sink speed, and fly at trim! Trim speed is controlled by the position of the hang-point: move it forward to go faster. The speed you want is the roughly the lowest speed where you have good, effective roll-control of the glider. More precisely, you can attach wool tufts to the upper surface of your wing, at about 1/3 span, just behind the point where the lower and upper surfaces meet - in fact at least one major glider manufacturer sells gliders with tufts on the wings. Now fly on a sunny day and watch the tufts' shadows on the wing. As you slow down, note at what speed some of the tufts curl around and stream the wrong way, with the free end ahead of the attached end. At this speed the wing has begun to stall. Set your trim-speed a bit faster than this speed, so that the tufts all stream out properly. Be very careful about decreasing the trim-speed!


Airspeed (mph)
0
10
20
30
40
50
Sink Rate (fpm)
0
100
200
300
400
500
600
700
Minimum Sink


Tuft indicates stalled flow
Tuft indicates unstalled flow
Edge of Double Surface
Tape
Tuft

4 (II) Are You Flying Too S-L-O-W-L-Y?

Many pilots, in an attempt to minimize their sink-rate, fly too slowly. This is bad. Very bad. Are you one of them?

Since the speed for minimum sink is just above the stall speed (everyone knows that, right?), many pilots try to minimize their sink-rate by flying as slowly as possible. After all, if they fly too slowly the glider will stall. Everyone knows what a stall is like - the nose drops and you fall a little way and you know you've overdone it.

WRONG! Try this sometime. Fly straight, and very gradually start to fly slower and slower. Work as hard as necessary to keep the wings level, and keep slowing down gradually. On my glider it's possible to push all the way out, arms straight, without anything dramatic happening. No g-break, no nose-drop, nothing. The wings are hard to keep level. The airspeed is oh, so low. The glider is very, very stalled. The sink rate is enormous. But I can do it. I can "fly" much, mush (sic) too slowly. This is not a good way to find minimum-sink!

The effectiveness of wing-twist for roll-control goes away at low speeds, and in a stall may help or hinder by making the stall worse on the wing the pilot is trying to raise. Weight-shift is more effective, but it is never all that effective in the first place. And if anything even remotely disturbs the glider, especially in yaw, the unstable tendency to spin may be too powerful for the pilot to prevent. The only way to regain control is to break the stall - fly faster. Of course, this means a short dive to build up speed, which costs altitude too.

Aside from the loss of control, flying a little too slowly is much worse for the sink rate than flying a little too fast. As the center section of the wing starts to stall, it produces lots and lots of drag, which is very bad news. Also, induced drag increases really quickly at lower speeds. It really is much better to risk being a little too fast (better control, less risk of stalling, less impact on the sink rate) than a little too slow (loss of control, partial stall possible, bigger increase of sink rate).

The lesson? Well, use one of the methods from the page before this one to set the glider's trim-speed. Then fly the glider no slower than trim-speed. This is far easier and more reassuring than setting the trim-speed between the minimum-sink speed and best L/D speed, which is another popular method. That method requires the pilot to spend a lot of time trying to guess how much to "push out" to get the minimum-sink speed. Pilots have better things to be doing near a mountain-top than constantly risking a stall. It makes life simpler if the glider flies at the right speed all by itself!

4 (III) Best L/D and Best Glide - Do You Know The Difference?

There seems to be a lot of confusion around about the notion of "Best L/D". People are really talking about "Best Glide" most of the time. Here's the difference.

Far too many articles have been written on the subject of calculating the speed for "Best L/D over the Ground". It's time to set the record straight. For a particular glider, at a particular weight and air density, there is only one airspeed that gives Best L/D. From section 1, remember that the L/D is the ratio of the Lift produced by the glider to the total Drag produced by the glider and all the stuff attached to it. At some airspeed this ratio has its maximum value. At that speed, the glider will travel a maximum distance forward through the air for a given loss of altitude. That's all there is to it.

So, where does the confusion arise? It arises when we introduce the subject of WIND. The glider pilot really isn't all that interested in how far the glider flies through the air, but rather wants to go a maximum distance over the ground. But the air is moving over the ground because of the wind, so this complicates matters. Suppose the wind speed is equal to the glider's best L/D speed. Then if the glider flies into the wind at that speed, it will stay over one spot on the ground and never go anywhere. It is flying at its Best L/D, but it gets a Terrible Glide. If it went a bit faster, it would make some headway. It would get a Better Glide, but a Worse L/D. Eventually there would be a Best Glide speed, which would depend on the wind speed. No wind, it would be the same as the Best L/D speed. Going with the wind, the Best Glide speed is less than the Best L/D speed, while going into it the Best Glide is faster than Best L/D. To confuse matters, authors have been known to calculate the "Best L/D Over The Ground", which varies with wind speed. Well, since the L/D ratio is purely a matter between the glider and the air, the ground isn't involved, and so the speed of the air over the ground isn't involved, and so *ihe wind speed doesn't have any effect at all on the L/D.* I emphasize again, these references should be to the Best Glide, since the glide is the descent over the ground.

Just thought I'd get that off my chest. I hate to see perfectly useful, cool terms like "L/D" being thrown around with such careless abandon. If you want to use nifty terminology, please do, but it's very uncool not to know what it means!

I'm going to do some Best-Glide calculations in the next few pages. For the purpose, I'll be using the performance figures of an imaginary glider. It has a best L/D of 10 at 25 mph, a minimum-sink rate of 185 fpm at 19 mph, and behaves according to the performance equations I used when I discussed performance in section 1. Real hang-gliders are not too far off this, but many (or even most) of them have somewhat poorer performance at high speeds, so bear this in mind. Again, we're looking for general lessons, not total accuracy.

4 (IV) Best Glide, and the Effect of Wind

If there is a wind the Best Glide and Best L/D are different, and the Speed for Best Glide is not the same as the Speed for Best L/D. It is faster in a headwind, slower in a tailwind.

I've said that the Best Glide and the Best L/D are not the same thing, unless there is no wind. The Speed for Best L/D makes the glider move farther forward *through the air* for a given vertical descent than any other speed, but the Speed for Best Glide makes the glider move farther forward *over the ground* for a given vertical descent. The Speed for Best L/D is always the same, but the Speed for Best Glide depends on the wind.

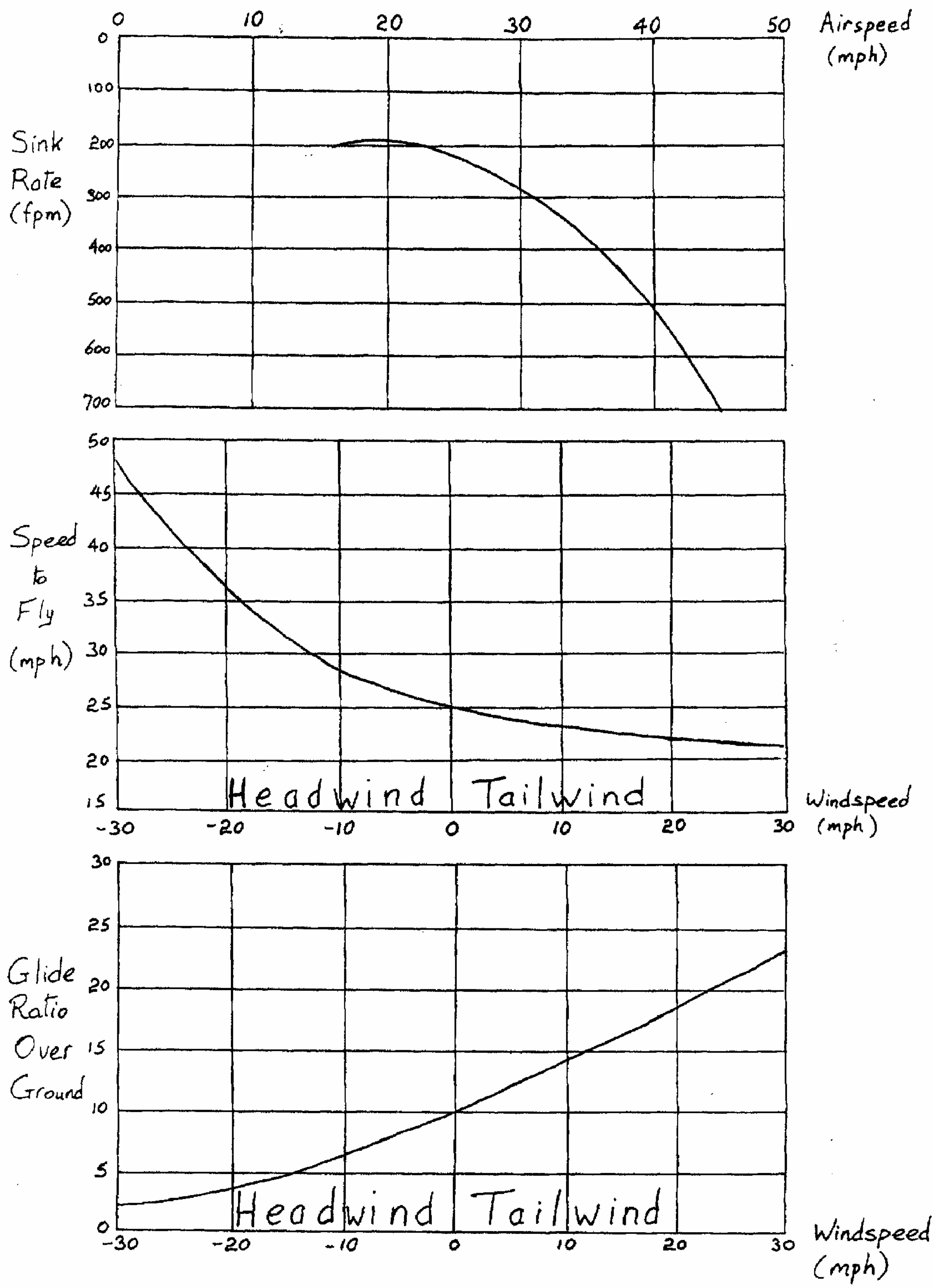
Of course the wind could be in any direction relative to the flight path, but I will look at only two directions: headwinds and tailwinds. Other directions involve trigonometry, and it's hard to do that in one's head, in flight. I will have a little bit to say about crosswinds.

On the page opposite I have three graphs. First is my "typical hang-glider" performance chart, showing sink-rate on the vertical axis and airspeed on the horizontal axis. It shows that the minimum-sink speed is about 19 mph. This kind of graph is often used, with some geometry, for illustrating how to find the speed to fly under various wind/lift/sink conditions - but instead I've got two more graphs to show the results of all this. The second graph shows the Best Glide Speed for a particular wind. The wind speed is on the horizontal axis, with positive numbers representing a tailwind, negative numbers for a headwind. The third graph shows the Best Glide achievable in a given wind.

Let's look at the second graph. In no wind, it says one should fly at 25 mph, which is the Speed for Best L/D. We know that already. For tailwinds (positive wind speeds) we should go a little slower - but only a little. In a 20 mph tailwind the pilot should slow down only 3 mph. For practical purposes there's no need to slow down at all. For headwinds we should go faster - quite a bit faster. A good rule, under normal conditions, is to add half the wind speed to the Speed for Best L/D. For light winds that's a little too much, in fact. For really strong winds it's not enough, but I, for one, don't plan to fly in such strong winds.

The third graph says that in no wind, flying at the Best Glide Speed (from the second graph), the glide ratio over the ground will be 10, which is also the Best L/D. If we have a tailwind (positive wind speeds) the glide ratio over the ground improves (remember, the airspeed is a little less than Best L/D Speed). The improvement is about 50% for a 12 mph wind. A headwind makes the glide ratio worse - about 50% for a 14 mph headwind - which is quite typical at ridge-soaring sites. If the headwind is 20 mph, the Best Glide is only 4:1, the correct airspeed is 36 mph and the sink rate is 400 fpm. The glide is surprisingly steep, and fast. Beware of headwinds any stronger than this!

If there is a crosswind, the pilot must crab into wind a little. This is like flying in a slight headwind, so the pilot should fly faster than the Best L/D Speed.



Airspeed (mph)
Sink Rate (fpm)
Speed to Fly (mph)
Headwind
Tailwind
Windspeed (mph)
Glide Ratio Over Ground
Headwind
Tailwind
Windspeed (mph)

4 (V) Best Glide, and the Effect of Lifting/Sinking Air

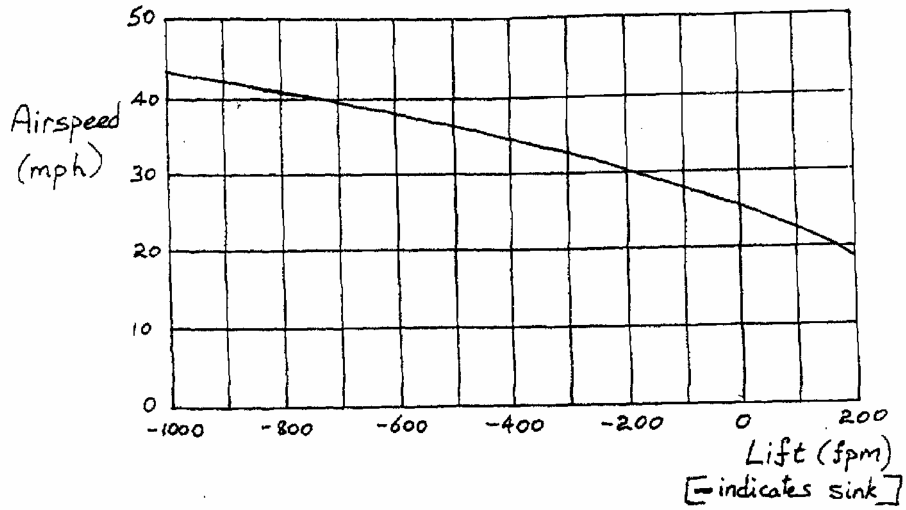
The Best Glide speed is also affected by whether the aircraft is flown in lift or sink. If there is lift, the Best Glide speed is closer to the Minimum Sink airspeed, while in sink the Best Glide speed is faster than the Speed for Best L/D.

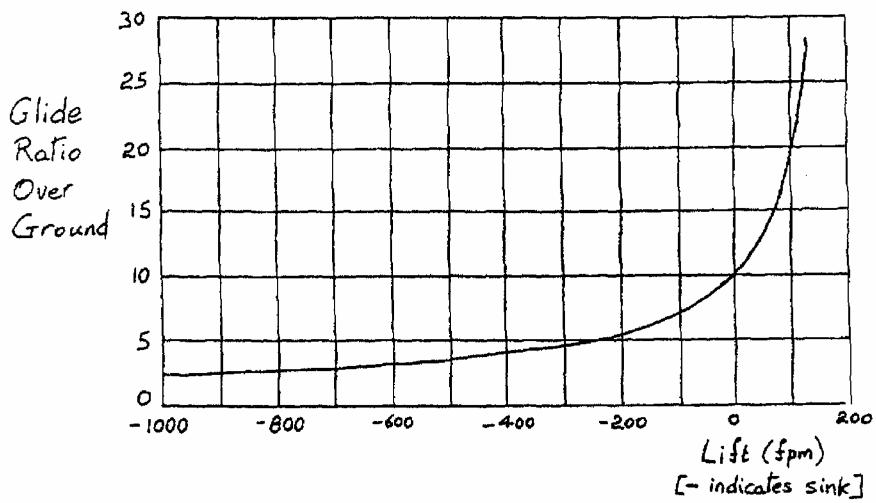
The glide ratio is simply the ratio of (distance traveled over the ground)/(altitude lost while flying that distance). In still air this is maximized by flying at the Best L/D speed, and I've explained how horizontal winds affect things. Now I want to look at how vertical winds affect the glide ratio. Vertical winds are known as *Lift* and *Sink* - Lift is a wind blowing upward and Sink blows downward. Unfortunately, Lift is also the name of one of the aerodynamic forces acting on the wing - that's not what I'll be talking about here.

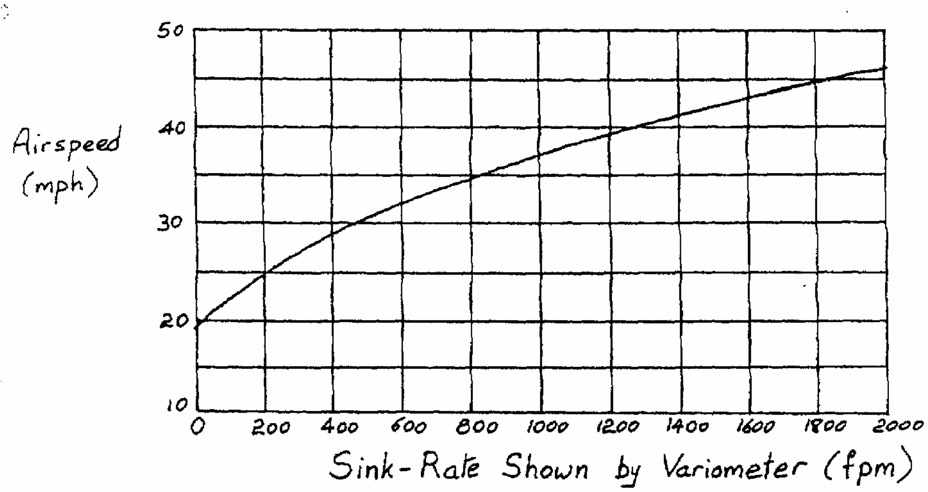
If there is lift, and if it is equal to the minimum sink-rate of the glider, and if the glider is flown at the speed for minimum sink, then the glider will not descend at all. In this case the glide ratio is infinite - the glider can go any distance without descending. This suggests that the glider should be flown at a lower speed than the speed for Best L/D when flying in lifting air - and indeed this is the case.

If the glider is flying in sink, it turns out to be better to fly faster. By flying faster the glider goes farther in any given length of time. Since the sinking air pushes it down some distance during that time, the glider gets better "value for altitude" by going farther. The top two graphs on the page opposite show the speed to fly and the glide ratio at that speed, given the lift - or sink - rate of the air. Lift beyond about 200 fpm is not shown, because the glider can be made climb in lift any stronger than that, and should be flown at minimum-sink speed to get the maximum rate of climb. The second graph shows that if the air is sinking at 250fpm the glide ratio is roughly halved -a serious loss of performance!

Of course, the pilot in flight has no way to measure how the air itself is behaving. Variometers measure the sink-rate of the glider, which depends on its airspeed as well. The third graph on the opposite page is a speed-to-fly graph. In flight, note your sink rate and airspeed. The two numbers define a point on the graph. If the point is above the curve, you are flying too fast, if below it, you are flying too slowly. Remember, this is for a "typical" hang glider. As an example, if you are flying at 30 mph and the variometer reads 800fpm down, you are at a point below the curve. Fly faster. If you speed up to 40 mph, the variometer will read 1000 fpm down. This is above the curve; it is too fast. The best speed is around 36 mph, with a sink rate of about 950 fpm. Dennis Pagen has pointed out that for a given glider and pilot, each airspeed corresponds to a particular control-bar position. The bar-position can be marked on the vario so that the pilot can achieve the correct airspeed-sink-rate combination. This is an excellent idea, but remember the pilot must still make an additional correction for wind.


Airspeed (mph)
50
40
30
20
10
0
-1000
-800
-600
-400
-200
0
200
Lift (fpm)
[- indicates sink]


Glide Ratio Over Ground
30
25
20
15
10
5
0
-1000
-800
-600
-400
-200
0
200
Lift (fpm)
[- indicates sink]


Airspeed (mph)
50
40
30
20
10
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Sink-Rate Shown by Variometer (fpm)

4 (VI) Closing Remarks on Going Straight

In the preceding pages I have listed some rules for straight flight. There are many more, but these are getting beyond the scope of this book.

In the preceding few pages I have given some advice on how to fly in a straight line. This advice is derived from looking at the performance equations of a typical hang glider. It doesn't take anything else into account, such as pilot ability, proximity to the ground or obstacles, or the fact that conditions are not the same everywhere. The graphs show the effects of flying in very strong winds and sink, but only the effects on the glider's performance. Whether the pilot and/or glider can actually handle such conditions is not something that can show up on a graph.

There are more complex speed-to-fly theories which serious competition pilots should know about. These are based on assuming that thermals will be of some known strength, and at some known separation from each other. Obviously if the thermals are very close together then there is no point climbing very high in the present one because the glider will not sink much en route to the next one. Also, if thermals are strong, the pilot may be willing to fly faster than the best-glide speed between thermals, losing a little extra altitude (and having to regain it in the next thermal) in exchange for a higher average speed over the ground. Pilots who would like to know more about these theories should get a copy of Helmut Reichman's book, *Cross Country Soaring,* which tells all. It was written with sailplane flying in mind, but applies just as well to hang gliders. The theories I have given are simpler, based on trying to get the best possible glide at all times. For the more conservative pilot, these are often the rules to use.

In summary, the best-glide rules can be stated simply as follows:

- Slow down in lift (but not below minimum-sink).
- Speed up in sink (to get out of there quickly).
- Speed up in a headwind by half the wind speed.
- Slow down a little in a tailwind - but only a little. Not slowing down is okay.
- Even at the best-glide airspeed, a 14 mph headwind will halve your glide performance.
- Even at the best-glide airspeed, sink of about 250 fpm will halve your glide performance.
- Find out which bar-positions correspond to what airspeeds. Then use the sink-rate/speed to fly curve to mark the bar-positions onto your vario. This will give a guide bar-position for dealing with lift/sink. Remember to make the correction for any headwind or tailwind.

5. <u>TURNING OUR ATTENTION</u>

---

5 (I) Banking, and What It Has To Do With Flight

Newton's First Law tells us that the glider will move in a straight line unless some force causes it to deviate. We use the Lift force to turn by tilting it to one side. Banking, of course, has a lot to do with flight. It's where we get the necessary money!

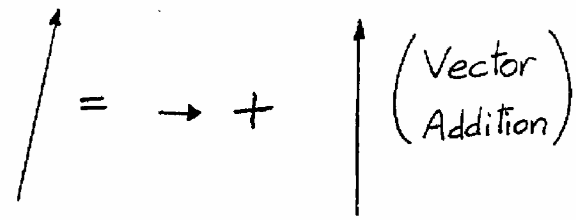
Okay, the bit about banking in the heading section is a little joke. Humor me. It's been said that aircraft do not fly because of Bernoulli's theorem: they fly because of the expenditure of vast sums of money! Enough of that. The truth about banking and turning is this: banking, in flying terms, is rolling the glider to one side, so that the wing's lift no longer acts straight up, but pulls to that side as well. Part of the lift force is upward, part of it to one side. Suppose the part that acts straight up is enough to support the weight. Then the sideways part is left to pull the glider to that side. Remember Newton's First Law: the glider will fly in a straight line at a steady speed if the sum of all the forces acting on it is zero. But now we have this force that seems to be "left over" - the portion of the lift force that is pulling to the side. This force makes the glider deviate from its straight-ahead path, and move to that side. Since the glider likes to point in the direction in which it is moving (remember Directional Stability?), the result is that it turns.

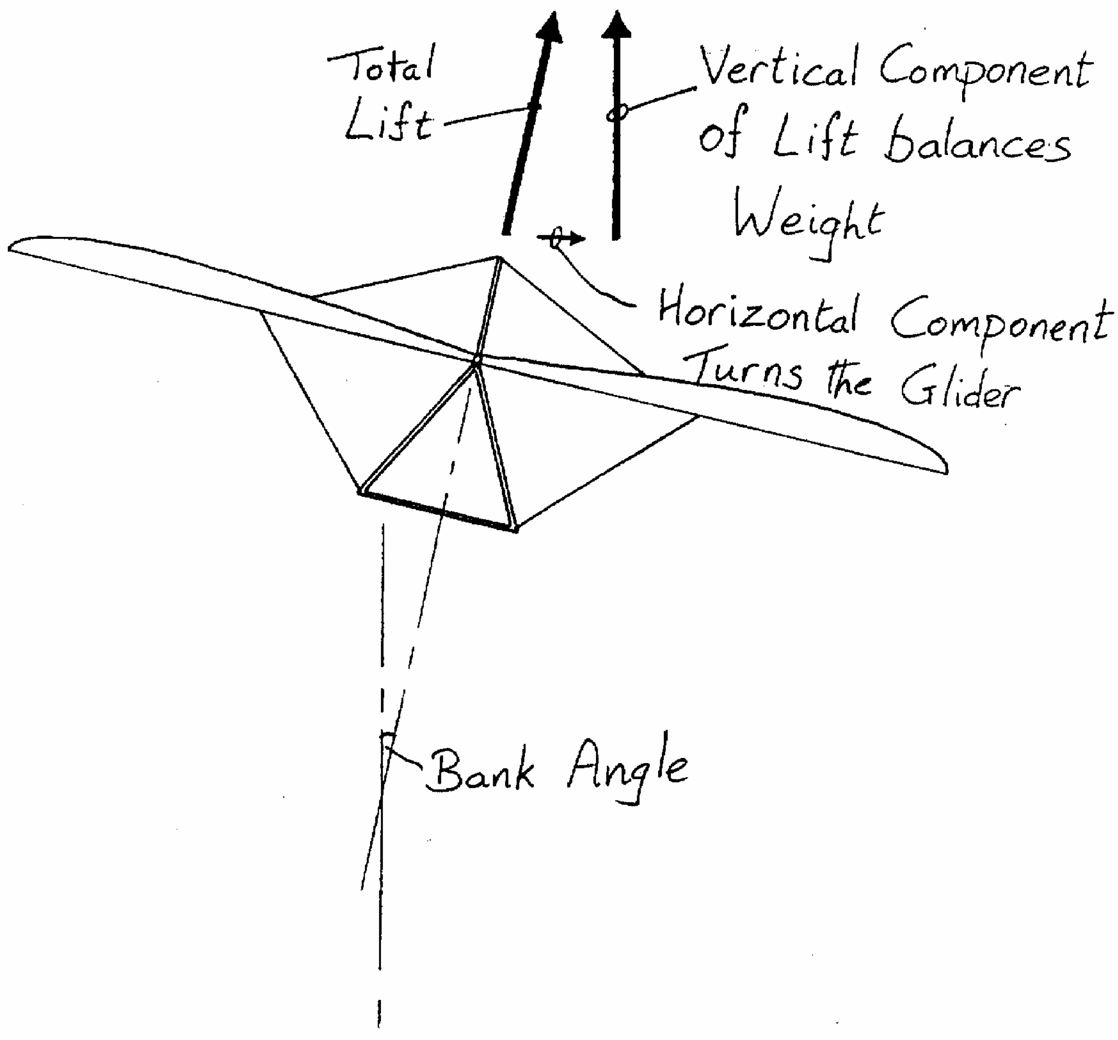
Why not do it the other way around? Why not turn the glider, and forget about this banking business?

Well, if we just turned the glider there would be no force to make it deviate from the original flight path, so it would carry on in a straight line. Since the glider likes to point in the direction in which it is moving, it would simply swing back to point in the direction in which it was traveling in the first place. We would achieve little or nothing from our efforts.

The point is, we must bank to turn. All fixed-wing aircraft do it. The birds do it, too, and they are the experts on these matters. If you don't want to take my word for it, at least take theirs.

Now I must admit that I exaggerated a little. It is possible to turn by yawing the nose to one side. The glider generates more drag when moving sideways through the air, and this produces a sideways force which can change the glider's flight path. However, the glider can produce the necessary force as lift much more efficiently, so this is a very bad way to turn - it is very inefficient. A pilot may try to yaw the glider around a turn by repeatedly swinging his or her body, in the belief that this produces a "flat turn" which gives a lower sink rate. Not true. The sink-rate depends on the airspeed and the drag produced. Yawing turns make more drag, which increases the sink-rate. It's that simple.


Vector
Addition


Total
Lift
Vertical Component
of Lift balances
Weight
Horizontal Component
Turns the Glider
Bank Angle

5 (II) Types of Turn: Steady Co-ordinated

The most common turn is the co-ordinated turn at a steady airspeed. This is the most efficient kind of turn.

The first kind of turn l want to look at is the Steady Co-ordinated turn. Steady means that the airspeed is constant through the turn. Co-ordinated means that the airflow is parallel to the centerline of the glider - the glider is not slipping to either side. Think about what this means. The glider is designed to fly so that the airflow is parallel to its centerline - i.e. straight from front to back, not flowing toward either side. This produces less drag than if the glider is slipping through the air to either side, and so is most efficient.

When the glider is turning, the lift no longer acts straight up, but is inclined into the turn. This means that additional lift is needed to balance the weight and stop the glider falling. This requirement for added lift reduces the glider's efficiency, and the polars for various angles of bank on the opposite page tell the story. Sink-rate becomes very high at steep bank-angles. Since the glider is not really going anywhere during a turn, it should be operated at the minimum sink speed for that bank angle. This corresponds to flying at the angle of attack for minimum sink, so the added lift must come from added airspeed. The speed to fly in a turn is shown on the opposite page, given the bank-angle θ. Once we know the bank-angle and speed, three other items are of some interest. These are: how long will it take to do a 360 at a given bank-angle; what is the minimum sink-rate at each angle; and how much altitude will I lose in a 360? The answers to these questions appear in the table opposite. (Of course, these numbers are based on my "typical" hang-glider performance figures again.) Note that the sink-rate is not the same as the straight-line sink-rate at the same airspeed. Since the wing is being operated at a fixed angle of attack, the drag coefficient is constant, and the sink-rate increases as the airspeed cubed!

The table shows clearly how hang-gliders can turn in very small circles. At 40° of bank, the turning-circle has a radius of only 42 ft, so the glider can turn entirely within a cylinder of 100 ft diameter. That's just 3 wingspans! It may also be a surprise to learn that the minimum height is lost in a turn at about 45° of bank! The sink-rate increases rapidly beyond 40° of bank, and this is important to know when flying in thermals. We will discuss thermal flying in part 7.

In a turn, the inside wingtip is at a higher angle of attack than the outside wingtip, so it is not possible to keep the whole wing at the minimum-sink angle of attack. What can be done is to have the wing at that angle of attack on average, to get a good compromise.

The table also shows why it is so hard to steer a hang-glider along a precise, straight line. A 10° bank angle will cause a complete turn in only 33 seconds. In the world of airplane flying a *standard rate* turn is a full turn in 2 minutes!

Glider Circling Performance

Lift: $L = K_L \alpha V^2$

Drag: $D = K_{DP} V^2 + K_{DI} \alpha^2 V^2$

Lift in a turn: $L = \frac{W}{\cos\theta}$

So $\alpha = \frac{L}{K_L V^2} = \frac{W}{K_L V^2 \cos\theta}$

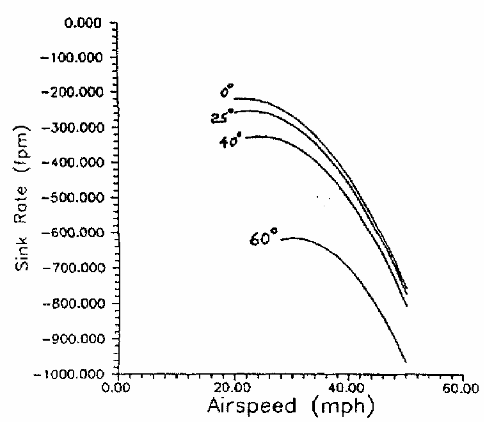
Then $D = K_{DP} V^2 + \frac{K_{DI} W}{K_L^2 V^2 \cos^2\theta}$

Sink Rate: $R = \frac{D V}{W} = \frac{K_{DP} V^3}{W} + \frac{K_{DI} W}{K_L^2 V \cos^2\theta}$

Typical Hang Glider: $K_L \simeq 31$ $K_{DI} \simeq 6.8$ $K_{DP} \simeq 0.36$

Making the appropriate conversion for units,

$$R(\text{fpm}) = 0.0055\, V^3(\text{mph}) + \frac{3490}{V(\text{mph})} \frac{1}{\cos^2\theta}$$



Example: (Mythical, but typical, glider performance.)

θ (°)	$V(\theta)$ (mph)	$r(\theta)$ (ft)	$s(\theta)$ (fpm)	t_{360} (s)	H_{360} (ft)
0	20	∞	193	∞	∞
10	20.2	154	197	33	108
20	20.6	78	212	16	57
30	21.5	53	240	11	44
40	22.8	42	287	7.8	37
50	24.9	35	374	6.0	37
60	28.3	31	545	4.7	43

5 (III) Types of Turn: Slipping

The slipping turn occurs when the pilot tries to increase speed in a turn. It is inefficient and causes a high sink rate.

Suppose the glider is turning and the pilot tries to increase speed by pulling in the bar. The lift generated by the wings decreases, so it no longer supports the glider's weight. (It also provides less turning force, so the turn becomes wider.) The glider's weight causes it to begin to fall. If the glider were level, this would produce an added component of airspeed from below and the glider would develop more lift, and fly faster (remember, lift is inclined forward a little, and so pulls the glider forward). However, the glider is banked over, with one wing lower than the other. When it falls, the added component of airspeed is partly from the side. The glider is side-slipping, or "slipping", and this is inefficient. The glider generates a lot more drag when flying somewhat sideways, like this. Remember that high drag causes a high sink-rate. It also causes the glider to accelerate more gradually, so that it takes longer for the lift to balance the weight again and re-establish a "proper" turn. Once the airspeed reaches a new (higher) steady value, the slipping turn is essentially over, and the turn should be considered a steady, co-ordinated turn.

Many pilots fly turns like these deliberately. When approaching to land it is usual to approach high, to avoid landing short. When the pilot is assured of reaching the landing area, there is a need for a technique to allow a steep descent to land. A simple dive would get the glider to ground level but at high speed. A slipping turn, however, from downwind to final approach, is a high-drag maneuver which loses a lot of altitude without adding as much airspeed. The technique is to set up the glider on the downwind leg with a little excess altitude. Toward the end of the leg, flying slowly, the pilot banks the glider into the turn. As it rolls, the pilot pulls in the bar substantially. It is helpful if the pull-in is timed to coincide with the moment when the glider has rolled but the adverse-yaw has not yet disappeared. The glider will drop - fast. If the approach is very high, the bar should be pulled in all the way through the turn. The glider will come out of the turn at fairly high speed. On the other hand, a more normal approach will need only a partial slip. Once the pilot feels the glider is low enough, the slip can be stopped by easing out the bar so that the glider can get into a co-ordinated turn, which is more efficient.

At other times, slipping turns are inefficient. In turns at altitude, don't speed up unnecessarily.

An inadvertent low-altitude slipping turn can be dangerous. Suppose the glider is flying low and slow on downwind. The pilot begins the final turn. Just then, a gust robs the glider of airspeed. To avoid stalling so near the ground, the pilot pulls in the bar. Surprise! The airspeed doesn't increase very rapidly, but the glider descends very fast. This can be dangerous, as everything happens very quickly. Unless you intend to slip the turn, keep the speed up on downwind!

5 (IV) Types of Turn: The Stalled Turn

The glider may be flown so slowly in a turn that the inside, or lower, wing is partially stalled. This is also an inefficient way to turn, and leads to a poor L/D and high sink rate.

As we saw before, the correct speed to fly in a turn is the minimum-sink speed for that bank angle. This speed, of course, is very near the stalling speed in the turn. If the glider is flown too slowly, the inside wing will begin to stall. This is because the angle of attack of the inside wing is higher. The whole glider is sinking at the same rate, but the inside wing has a lower forward speed, and this is why its angle of attack is higher. The washout of the wing should prevent the tip from stalling first, but the stall will begin at some point along the inside wing (which is also the lower wing). When this happens, the inside wing will lose some lift, and will develop more drag. The added drag will cause the wing to lag behind, so that the glider "skids" toward the outside of the turn. In addition, the loss of lift will tend to make the inside wing drop. The pilot will notice that it is necessary to move to the outside of the turn, or "high" side of the control bar, to keep the bank angle steady. Unfortunately this causes the wing to twist because of the "sail-shift", further increasing the angle of attack of the lower wing. It may or may not be possible for the pilot to keep the inside wing from dropping.

This kind of turn is inefficient, and reduces the L/D ratio, while increasing the sink rate. Unlike the slipping turn, however, it should not be used to lose altitude near the ground. Since the glider is partially stalled, any wind shear could easily lead to a more severe stall, with the inside wing dropping to a very steep angle. It might not be possible to recover from this before hitting the ground. In addition, if the pilot wishes to recover from the partially stalled condition, it means that the glider must accelerate. The glider always loses altitude more rapidly while accelerating than when flying at a steady speed, and so the pilot must throw away still more altitude to recover from the inefficient turn.

On the other hand, a temporary stalled turn may be useful at higher altitude. When flying in a steady co-ordinated turn, the pilot can push out a little on the control bar to stall the inside wing slightly. This will cause that wing to drop. This is an alternative way to make the bank angle steeper. It is inefficient, but much less work than shifting the pilot's own weight over and back. By saving the pilot's energy at the expense of a few seconds of inefficient flight, it may make a much longer flight possible. Many pilots use this method, especially when trying to "core" thermals. The idea is that when the glider reaches the core of the thermal the bank-angle should be increased to reduce the turn-radius and keep the glider there. This may be repeated many times in the same thermal as the glider goes in and out of the core. If the pilot uses the normal weight-shift method, it can be tiring. A small push-out will stall the inside wing, causing it to drop. Voila! Be careful: don't use this method near the ground!

5 (V) Yaw, Lag and Turning Technique

The pilot now knows about the different kinds of turn, and the various secondary effects that occur. I'll just take a page to summarize them.

We have seen the various types of turn, and want to consider them from the point of view of technique. What is the actual technique needed for a good turn?

Remember that for an efficient turn the pilot must not let the glider fly sideways. But a long time ago we saw that the glider has an adverse yaw effect that happens every time we try to change the bank angle. However, we also saw that the pilot has some yaw control. If the pilot's body is made to twist to the right, the glider will twist to the left for a moment. By combining weight-shift and body-twist, the pilot can get the glider to roll without adverse yaw.

To get a co-ordinated right-hand turn, the pilot should add a little speed, usually not much, then apply weight-shift to the right, twisting tbe whole body by swinging his (or her) legs even farther out to the right. As the glider begins to turn, the legs should be allowed to come into line with the upper body. Once the desired bank-angle is reached the pilot should be able to hang in the center of the control-frame. A small push-out of the bar will be needed, increasing as the bank-angle becomes greater. Roll-out should follow essentially the same technique. The rule is, "lead with the legs". Some people find it helps if they think of twisting the control-bar to the right to yaw the glider to the right.

To get a slipping turn, the pilot should fly slowly, then bank the glider by moving the upper body and legs to the right, but without twisting. As the glider rolls, it will develop adverse yaw. When the wings have rolled perhaps 30°, the pilot should pull in the bar quite hard. To recover, the pilot should roll the wings level and relax the bar pressure, in either order.

To get a stalled turn, the glider must first be turning to that side. The pilot should ease the control bar forward until the inside wing stalls and drops. When the desired bank-angle is reached the pilot should relax the pressure. It may take the glider a few moments to settle down, as it will need to accelerate to the proper speed.

At times it may he difficult to get the glider to roll into the turn, perhaps because there is lift under the inside wing. In this case many pilots find the *bump-turn* method useful. The glider should be flown a little faster than usual, if the pilot expects that this may be necessary. The pilot applies the usual turn input, and if nothing happens, pushes out the bar for a moment. This increases the apparent weight of the pilot as the glider accelerates upward. The pilot's higher apparent weight increases the control authority and gets the sail-shift and roll under way more quickly. The push-out need only apply for a moment, hence the *bump* in the name. Some gliders respond more readily to this technique than others.

6. Unusual Attitudes, Strange Behavior, and Other Special Situations

----

6 (I) Rowdy Conditions

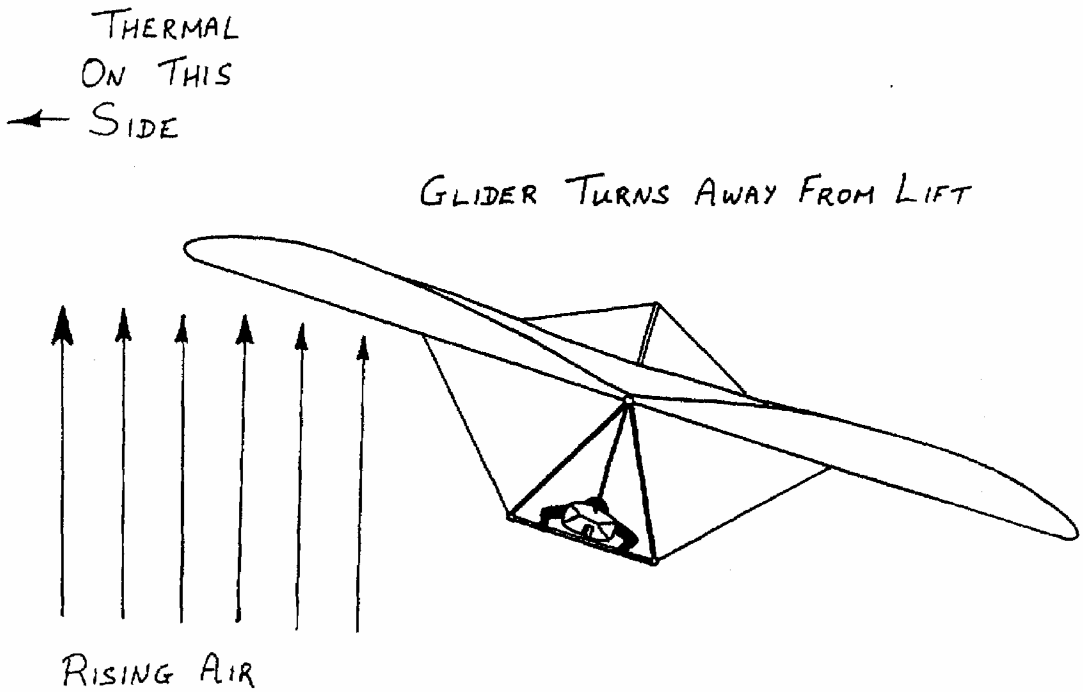
In strong turbulence, certain odd things happen. These include "zerog-loc", "thermal lock-out", "going over the falls", and "tumbling". Sometimes it's even difficult to get down!

A hang-glider is controlled by weight-shift (and the resulting sail-shift, in roll). Obviously there can be no weight-shift if the pilot has no weight. Well, actually the pilot always has weight, but if the wing generates no lift the whole glider, pilot and all, will free-fall. In free-fall the pilot and glider exert no forces on each other, and, as far as the glider is concerned, the pilot is indeed weightless. Ridiculous? No, it happens! All that is needed is a strong downdraft. Fly into it suddenly, and the angle of attack becomes zero or negative. The wing stops lifting. The pilot's harness-lines go slack. The pilot is in free-fall: weightless! When this happens, the glider is out of control. As long as the pilot's harness lines are slack, the pilot is a passenger. What's more, even if the lines don't go slack, a downdraft still reduces the pilot's effective weight, making control more difficult. This is a major disadvantage of weight-shift control compared to aerodynamic control. Jet pilots have their g-induced loss-of-consciousness, or "g-loc". We have zero-g loss of control, or, as I call it, "zero-g-loc"!

A second type of control problem involves strong updrafts. When one wing enters a thermal, but the other doesn't, the wing in the thermal rises and the glider turns away from the thermal. Obviously the pilot would prefer to turn toward the thermal. If the thermal is strong enough, full weight-shift to that side will not be enough to turn into the thermal, and the glider will turn away. The glider is "locked out" by the thermal. It's infuriating, and it happens all the time!

A more dangerous situation can occur when thermaling. As the glider comes out of the thermal, there is a moment when part of the glider is outside the thermal, in sinking air, while part is inside, in rising air. This will pitch the glider nose-down, so that it dives out of the thermal. This is known as "going over the falls", and is not that bad in itself. However, if the thermal is very strong, it can turn ugly. When the glider pitches nose-down, it may pitch beyond the vertical, and tumble end-over-end. I'll get back to tumbling in a little more detail later. It's a bad situation, and can damage the glider and/or hurt the pilot.

Finally, in strong conditions there may be so much lift that the glider cannot come down. I will address this in part 7, so I'll say very little about it for now. It is probably best to fly as fast as possible in a straight line. After all, if you don't want to go up, why are you turning in lift?



GETTING LOCKED OUT OF A THERMAL

6 (II) Final Approach

The final approach is a special situation because it happens near the ground. The objective is to get the glider set up for the landing flare.

The final approach deserves a mention as a special situation. It is the second-last stage of the flight, and allows the pilot to make the final adjustments to the glide path prior to the landing flare. At the end of the final approach, the glider should be flying level, just above the ground, wings level, into wind, in the right place, so that the flare will stop the aircraft and drop the pilot gently to earth on the target-point.

Early on in the final approach, the idea is to get the glider flying in a straight line, wings level and heading into wind, on a glidepath that would hit the ground a little short of the target point. The tricky part is getting that glideslope right. If the glider is too low, the pilot should remain prone and try to find the absolute best-glide speed. The way to do this is to find the "aiming point", which is where the glider is going, and to adjust the airspeed to move this point as far ahead as possible. To find the aiming point, think about how the landing area appears to be getting bigger. As the view "expands", every point ahead seems to move away from a center-point (i.e. points above will move up, those on the right will move to the right, etc.). This center-point is the aiming-point. Of course, if the glider is flying into wind, the airspeed for best glide will be the speed for best L/D, *or higher*. This means the glider will have good airspeed. The glider normally should not be flown at an airspeed below best L/D, since a low-altitude stall would be very dangerous.

If the glider is going to go long (i.e. the approach is too high), the pilot needs to decide what to do about it. If the glider is very high, and needs to lose 50 or 60 feet, then a 360 or some S-turns may be needed. If the glider is a little high the aiming point will be at or farther away than the target-point. The pilot should get upright to produce drag, and increase airspeed to well above the best L/D speed. (In very strong winds the best glide may occur at high airspeeds, but then the glider is unlikely to land long in these circumstances.) If the glider is a single-surface design, high speeds will give a very steep glideslope. Double-surface gliders will come down less readily, and build up more speed in the process. The goal should be to get the aiming-point to be closer than the target-point so that the glider will have room to "bleed off" the excess speed.

Once the glider gets to ground level (with the pilot now upright and clearing the ground by a couple of feet) the pilot should ease the back-pressure and allow the glider to "round-out" and float along over the ground, slowing down. Close to the ground there is an effect called "ground effect", which reduces the glider's drag. For perfection, the pilot can come low to glide farther, or round out higher to shorten the glide, then allow the glider to drift lower before the flare. The difference made by such perfectionism will be small in any case. After that, keep the wings level until it's time to flare.

6 (III) Do It With Flare! (sic)

The final moment of the flight is the landing flare. The flare slows the glider, ideally bringing it to a stop directly over the target point, with the pilot's feet not more than 2-3 feet in the air.

The landing flare is something that causes many pilots endless grief. This is because it is a tricky thing to get right. No two landings are ever the same, and even the best pilots get it wrong from time to time. It's worth noting that pilots of other aircraft, up to and including jet transports, have occasional problems landing. Practice is the only real solution.

First, what is the idea behind the flare? Originally it seems to have been a way to slow the glider until it would "mush" onto the ground, moving slowly enough for the pilot to keep up. However., as wing areas have been getting smaller, the "mush" landing is now still too fast for the pilot, who falls behind. The center of gravity of the glider gets ahead of the unfortunate flier, and the nose descends to earth with a resounding WHACK. The modern method is to slow the glider just above the ground to trim speed or a little less, then quite suddenly apply a large pitch-up control input, making the glider literally point straight up in the air. At the low airspeed, the glider makes very little effort to climb, but stalls. This leaves the pilot traveling forward, just above the ground, with the whole wing acting as a giant airbrake. The glider (and pilot) stops in the air for a moment, then drops the pilot a short distance to the ground. At this moment the wing is moving backwards (pointing up, going down), and the pilot is way back at the back of the aircraft. This is a perfect beginning to a tumble. The glider doesn't tumble because it touches down first. NEVER flare except when landing.

If the pilot tries to flare too early, the glider will have excess airspeed and will climb for a few moments before it stalls. The drop to the ground will be long and the landing heavy. The wingtips are very vulnerable, and the control frame may not survive. If the flare is far too early, the glider will climb a long way. The pilot may not be able to keep the glider from starting to tumble on the way down, diving into the ground, with unfortunate consequences.

If the flare is left until too late, the glider will stall the moment the pilot tries to apply pitch-up control. The wing will drop to the ground before the pilot can get it turned enough to act as an airbrake, so there will still be lots of forward speed. This often (usually) results in a WHACK, with damage to the downtubes being fairly common.

There is some room for error, and the details of the flare vary with conditions. If the wind is strong, the ground speed will be low anyway, so only a gentle flare (just a slight pitch-up) is needed. If the flare begins a little early, and the glider begins to climb, make the flare slower initially to keep the climb small, then finish the flare strongly as the glider begins to settle. If the flare begins late, so that the glider fails to climb at all, then make the whole flare strong to get as much braking as possible. In the "perfect" flare, the glider should climb a little before coming to a complete stop in the air.

6 (IV) Do it with a bit More Flare

Well, we've seen why a flare is needed, and considered the timing to some extent. How about the mechanics of the situation?

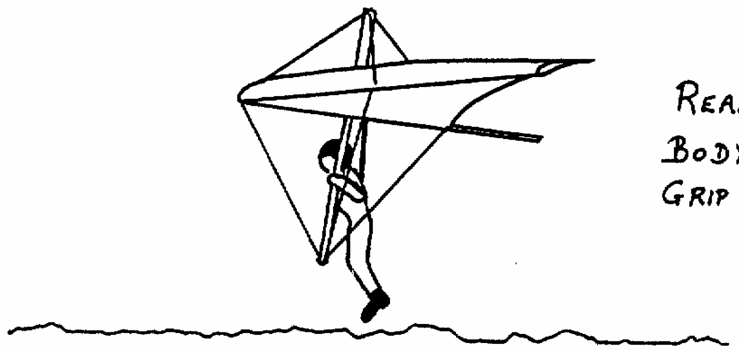
So far I've said what the flare is for, and what happens if the timing is off. I've also given some ideas on what to do if the timing is a little off. But how about the mechanics of the flare? How should the pilot go about making the glider point straight up?

I'm going to assume that the pilot will flare at about the right moment. Let's consider the final moments of flight. The glider is just above the ground, wings level. The pilot is upright, feet just off the ground. The pilot should now move his or her hands up the downtubes to a point at or just above shoulder-level. At the moment of flare, the pilot should push the downtubes almost straight up, so that the arms end up pointing straight overhead, while swinging the legs and feet back from the hips. Of course, the pilot's body will actually be tilted forward about 20° - 30° by the harness, so the push is really forward and up. It is important that the pilot's body should be held rigid at this time, so that the legs swing powerfully toward the keel. There are two reasons for this. One is that we want to get the weight way back, and legs are heavy. The other is that we want to use "conservation of angular momentum". When the pilot pushes out/up like that, and the pilot's legs swing toward the keel, the pilot's body is trying to go face-down. However, those legs are pretty heavy, and can't easily be made move in a hurry. Instead of the pilot going face-down and the glider staying still, more the reverse happens - the pilot stays still (or goes a little face-down) but the glider pitches up. This is not a good moment to touch down, since the pilot's feet are at the keel. However, the glider is now doing its airbrake impression, and stops. The pilot doesn't quite stop at once, but swings out ahead of the glider - which puts the pilot's body in an upright position, feet down, for landing. Of course, as the pilot's body swings out, the pilot keeps stiff arms so the glider pitches up even more! By far the most common mistake that causes landing problems is failure to keep the body stiff and get the legs back. Concentrating on this can produce a dramatic improvement in landings.

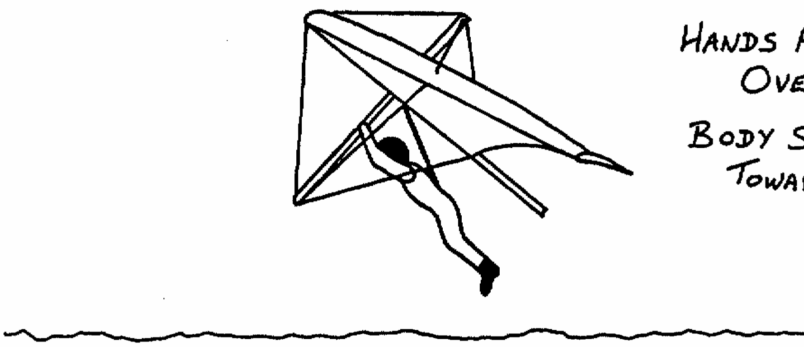
The speed of the push-out depends both on the glider and on the conditions. Large gliders, or looser gliders, like training gliders and gliders with a very loose VG setting, require a slow push-out initially with a more rapid finish right at the end. Tighter or smaller gliders require a more rapid flare: some need quite a snappy move. If there is a headwind, a slower and less complete flare will be appropriate. In zero wind, or at high altitude, or (especially) in a tailwind, a very full flare is in order.

So, the idea is: move the hands up the downtubes; wait for the right moment; stiffen the body *and legs*; push up (and a little out) all the way (unless it's windy); hold it like that until you land.

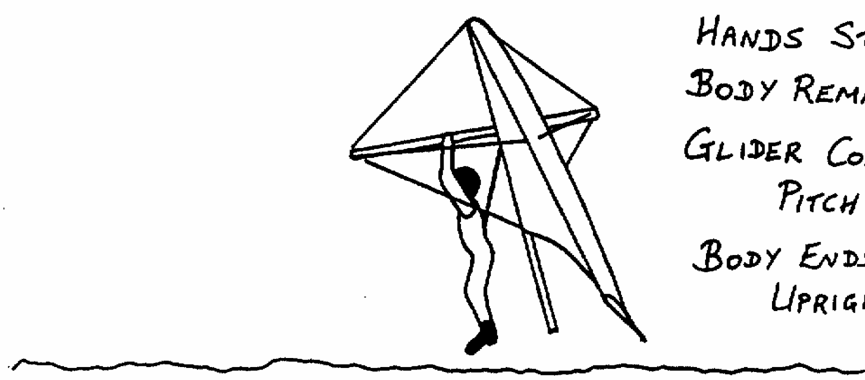
Well, there it is. Two pages on a maneuver that lasts one second. But remember, only hang-gliders and birds land this way. This maneuver makes us special among pilots!



READY TO FLARE.
BODY UPRIGHT.
GRIP HIGH ON DOWNTUBES



FLARE !
HANDS ARE NOW OVERHEAD.
BODY SWINGS BACK TOWARD KEEL



TOUCHDOWN
HANDS STILL OVERHEAD.
BODY REMAINS STRAIGHT
GLIDER CONTINUES TO PITCH UP
BODY ENDS UP IN UPRIGHT POSITION

6 (V) Spinning: The Tale.

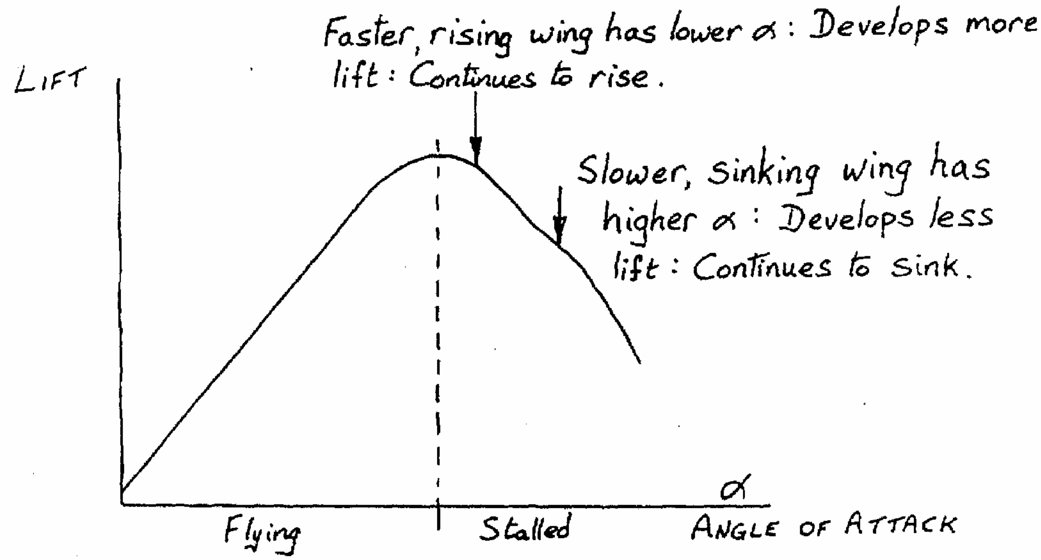
The Spin is a well-known phenomenon, but often poorly understood. It is a real hazard to most aircraft, and can be a problem in hang-gliding too.

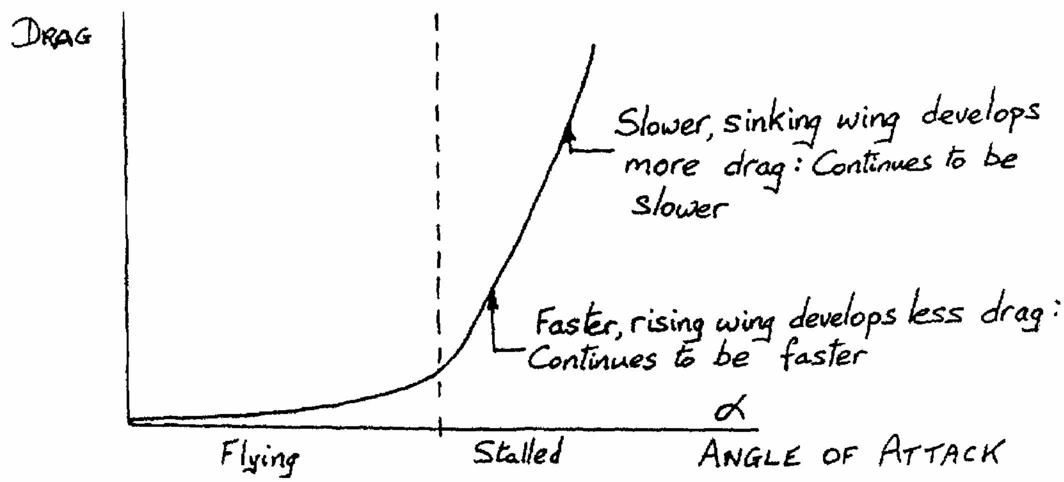
The infamous Stall\Spin accident was the number-one killer of airplane pilots for years, and the spin has its fearsome reputation as a result. In fact, the spin was not understood until the middle of World War 1, when the mystery of how to recover from one was finally solved.

Suppose an aircraft stalls, and yaws to the left as it does so. Since the right wing is moving forward as a result of the yawing motion, its angle of attack is a little lower than the angle of attack of the left wing, which is moving back somewhat. Although both wings are stalled, the left wing generates more drag and less lift than the right, because of the greater angle of attack on that side. The extra drag on the left causes a yaw to the left, helping to keep the angle of attack higher on that side. The higher lift on the right causes a roll to the left, also helping to keep the angle of attack higher on the left side. The result is that the aircraft falls from the sky, rolling and yawing to the left. The wings are stalled, but the nose may point steeply downward, perhaps as much as 70° or as little as 20° below the horizon, while the aircraft rotates around a near-vertical axis passing through,or near, its center. The natural tendency is to try to pull up, but this makes the stall worse and does nothing helpful at all. Instead the pilot must stop the yawing motion with the rudder, then *push the nose down to break the stall*. This puts the aircraft in a steep dive, with a "normal" dive-recovery to follow.

Hang-gliders do not have rudders. This means that the glider must be designed so that it will not stay in a spin if put in one. In fact, modern hang-gliders will recover if left to themselves. The problem is that the recovery takes time, and still leaves the glider in a dive, with a dive-recovery to follow. But, you say, if the glider will recover by itself, how did it get into a spin? Simply: by stalling one wing before the other. If the glider is yawing or turning and stalls, there is a fair chance of its going into an "incipient spin". This involves a sharp wing-drop on one side, with a rolling/turning maneuver to that side, followed by the nose dropping quickly. The glider will now begin to recover, and the recovery will typically be a dive heading 90° - 180° from the original heading. If this happens shortly after takeoff…

Hang-glider pilots are fortunate in that they don't have to know much about spin-recovery - just center on the bar and pull in. In fact, only the aerobatic types can *keep* the glider spinning. But the incipient spin can happen, and it can be very bad news near the ground. Once again, the message is the old, important one. *Keep the speed up near the ground.* This will prevent the stall, and without a stall there can be no incipient spin.





THE AERODYNAMICS OF SPINS

6 (VI). Tumbling, Whipstalls and Loops

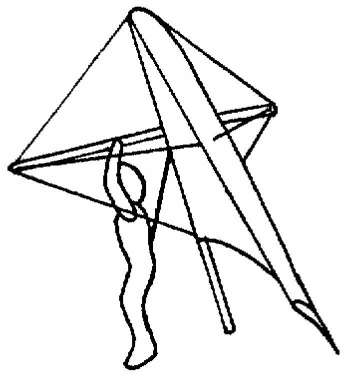
Let's get to some exotic stuff here. Let's look at tumbling, whipstalls and the world's most famous aerobatic maneuver: the loop.

Let's imagine hanging a glider from its nose, then dropping it. Let's also imagine that the pilot is attached, and is pushing out hard (pitch-up control input) when the glider is dropped. At first the glider will slide backways, but it is designed to fly forward, and will eventually figure this out. The glider will pitch over (usually pitch-down) into a dive. The pitch-over will be very quick, in fact so quick that the glider will not stop when it reaches nose-down. The nose will start to come up again on the other side. By this time the pilot will have been swung around pretty hard, and may well have hit the back of the keel. The pilot's weight will then help the tumble by pushing the back of the keel over. The diagram on the other page says it all, really. You can watch a tumble quite easily. Cut a hang-glider-shaped piece of paper, and put a little washout in the tips. Now drop it backways. Ugly, isn't it? By the second time around a tumble will have become rapid and violent, and the pilot will be bouncing off the structure. Structural failure is very likely. The pilot may not fare too well either!

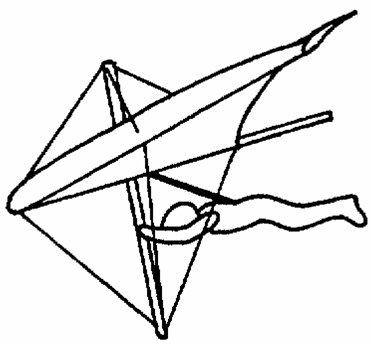
If it seems that the glider may be about to tumble, the conventional advice is to pull in as much as possible (curl up in a hall to get those legs up) and hold on to the bar as if your life depends on it. It may. This advice is based on the idea that the glider is more pitch-stable with a forward c.g., and may stabilize in the dive. The pilot is less likely to hit the back of the keel, which is a good thing! Finally, it helps to get the center-section rotating pitch-down a little earlier, before the wingtips get too bent out of shape.

A whipstall is a stall that happens while the glider is climbing. The stall is dramatic, since it takes the nose longer to get down for the recovery. If the climb is steep, the glider will come to a near-stop in the sky, nose up, with the pilot pushing out hard... Haven't we just talked about this?

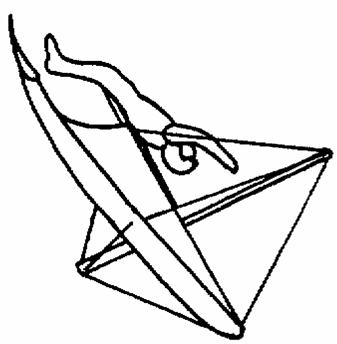
The loop, of course, is the most famous aerobatic maneuver in the world, and hang-gliders have been able to do loops for over a decade. That said, looping a hang-glider is very risky. If the glider runs out of airspeed in the first part of the loop, it will end up stalled in a steep climb, with the pilot pushing out hard... There's that "tumble" word again! If the glider runs out of airspeed near the top of the loop, the pilot will fall into the sail. Falling into the back of the sail will cause a big-time inverted stall. Good luck getting out of that situation in a hurry! Finally, loops involve speeds well in excess of the glider's VNE, so over-stressing the structure is on the cards. Can *you* say "structural failure"? Oh, perhaps you're wondering how a weight-shift-controlled glider can do a loop - after all, shouldn't the weight be on the bottom? In fact, the glider doesn't care which way is down as long as the pilot "hangs" from the wing. If the loop is fast and tight, the pilot will "hang" above the wing, just as water can stay in the bottom of a bucket when the bucket is swung upside-down quickly.



WHIPSTALL !
GLIDER BEGINS TO
PITCH NOSE-DOWN
RAPIDLY



GLIDER STILL STALLED.
RAPID NOSE-DOWN
MOTION
PILOT HAS FAILED TO
PULL IN



GLIDER GOES
BEYOND VERTICAL.
FIRST TUMBLE
HAS BEGUN

6 (VII) The Great Wingover

The Wingover is a popular aerobatic maneuver, less risky than the loop. It involves getting the glider to bank angles in excess of 90°

Since loops can get a bit too wild for comfort when they go wrong, the *wingover* is a more popular aerobatic maneuver. The idea is to get the glider to a bank-angle greater than 90°. Just as with the loop, it seems at first as if this should not be possible for a weight-shift glider (how call the pilot get above the hang-point?), so it impressed me quite a bit when I first saw it. It's popular with spectators, too. Normally a hang-glider with its pilot pulled all the way over to one downtube will not exceed about 60°, so the wingover takes a little more technique than that. What the pilot does is to dive for some speed, then apply pitch-up and roll-control inputs at the same time. The pitch-up gives that water-in-the-bucket effect, and "cons" the glider into "thinking" that the pilot is still "below", even though the roll-control input has rolled the glider over so that the pilot is now higher than the hang-point. As the airspeed dies away the glider begins to slide sideways toward the ground, and yaws to that side, ending up in a dive. Because the glider is in a steep bank instead of a steep climb, and should not stall at all, there is little risk of tumbling.

There are still some risks. Some pilots can get a wingover to near-inverted, at which point it may be possible to end up too slow, upside-down, with the pilot falling into the sail for good measure. If the wingover is very steeply banked but the wings are not kept loaded throughout, perhaps because of a stall or poor technique, the recovery will involve a dramatic sideslip. This can put large structural loads on the wings, and/or cost a great deal of altitude (hundreds of feet).

As a final remark on this subject I want to point out that the glider-manufacturers, who have your health (and their own best interests) at heart, recommend that the glider never be banked more than 60° nor pitched up or down more than 30° in flight. I would encourage pilots to follow that advice. I thought you might like to know how the more daring among us can even achieve these feats in the first place. Before you go out and try it, though, do you really want to be a test-pilot?

7. CAN YOU KEEP IT UP? - SOARING

----

7 (I) Slope Soaring

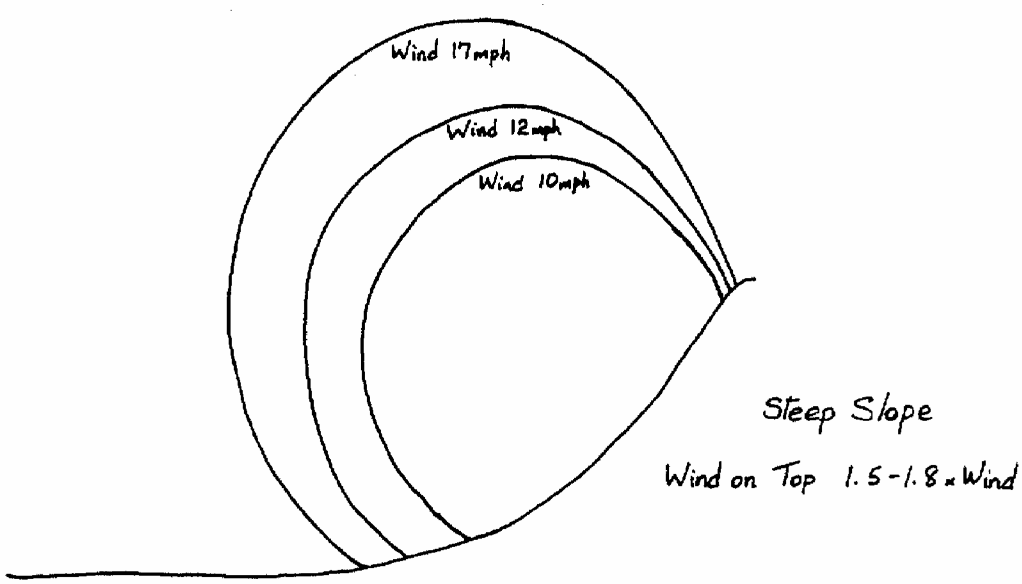
Slope soaring is the act of keeping a glider from descending, or actually making it climb, by flying in the wind blowing up the windward side of an obstruction.

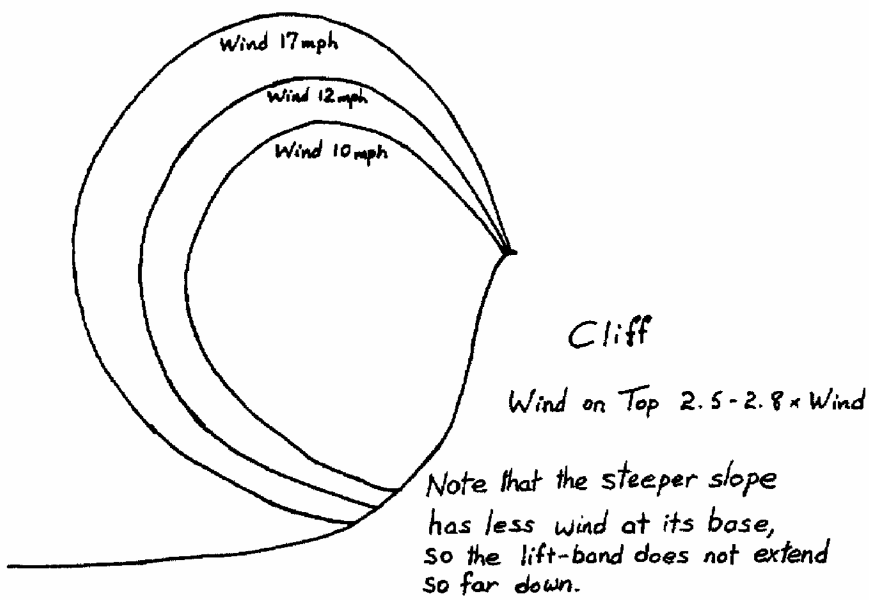
There is not a lot of mystery about slope soaring. When wind finds its path blocked by an obstacle, it must go over or around the obstacle. Usually it will do both. To soar, the pilot must fly in wind that is going over the obstacle, where the vertical component of the wind is greater than or equal to the glider's sink rate. If it is easy for the wind to go around the hill, it will do so rather than go over. Hence a long ridge, aligned at right angles to the wind, produces much better lift than a simple hill. If the ridge curves so that the ends are upwind of the center, the lift will be better than for a straight ridge. Pilots often refer to this kind of lift-producing hillside shape as a "bowl".

The airflow is compressed as it goes over the top of the hill. This compression is associated with an increase in the wind speed and a drop in pressure. The steeper the slope, the bigger these effects will be. Simple theory suggests that on a moderately steep slope the wind speed on top of the ridge can be double the wind speed well away from it, and the pressure drop can cause an altimeter to mis-read by 15 - 20 feet. There is no lift directly over the ridge, and the wind is strongest there, so it may be difficult to penetrate into wind just above the top, even if it is easy to do so in front of the ridge. Opposite I show lift contours for a steep ridge and a cliff. These lift contours show that as the glider climbs it is necessary to move out in front of the ridge somewhat to get the best lift. The strongest lift will be found just below the shoulder of the hill, which would normally be just below launch. This is where the last gliders will hang on as the lift dies at the end of the day. Earlier, the highest gliders will not be directly over the ridge, but some distance out in front of it. When you are climbing in ridge lift, try moving gradually away from the ridge in the search for the best lift. As you sink, move back toward it.

The simple theory does not account for the real conditions that may exist because it does not consider the stability of the airmass. In an unstable airmass the existence of the hill may be sufficient to start thermals forming, and there may be unexpectedly widespread lift in front of the hill. On the other hand, if the airmass is stable the lift band will not get as high as might be expected.

Hazards associated with ridge soaring include the risk of hitting the ridge when "scratching" below the top in weak lift, or of getting into the rotor behind the ridge (being "blown over the back"). If the ridge is crowded, as they often are, there may also be a midair collision hazard.





Contours show where ridge lift = min. sink-rate.

7 (II) Thermal Soaring

Thermal soaring depends on finding warm air rising as fast as or faster than the sink-rate of the glider. Thermals are usually temporary phenomena, localized to a small area, which requires the pilot to fly in circles in order to climb.

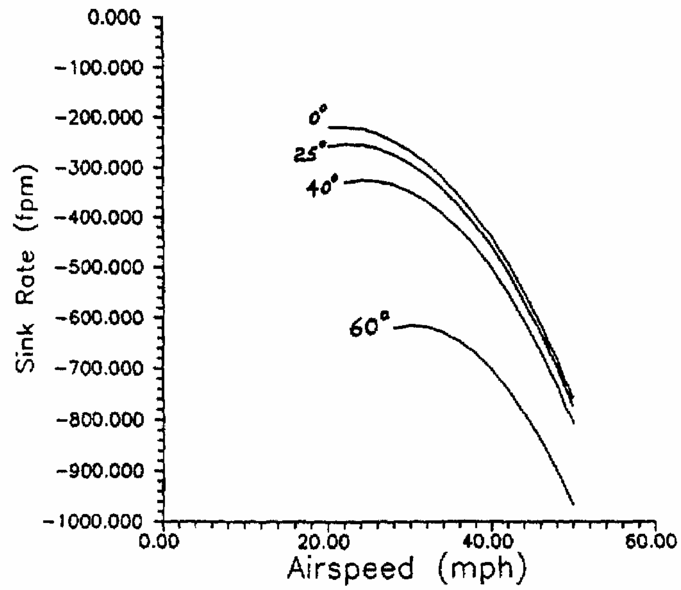
Thermal soaring is considered more difficult but more rewarding than ridge soaring. The location of the ridge provides all the information necessary to find the ridge lift, which will be there as long as the wind blows in an appropriate direction. Thermals, on the other hand, are localized and often temporary, and may or may not be associated with any obvious ground feature. Their advantages lie in the fact that thermal lift can often take a glider much higher than ridge lift, and there are thermals in places where there are no ridges. The art of guessing where thermals are likely to be is beyond the scope of this book, but the analysis of flying in one is not.

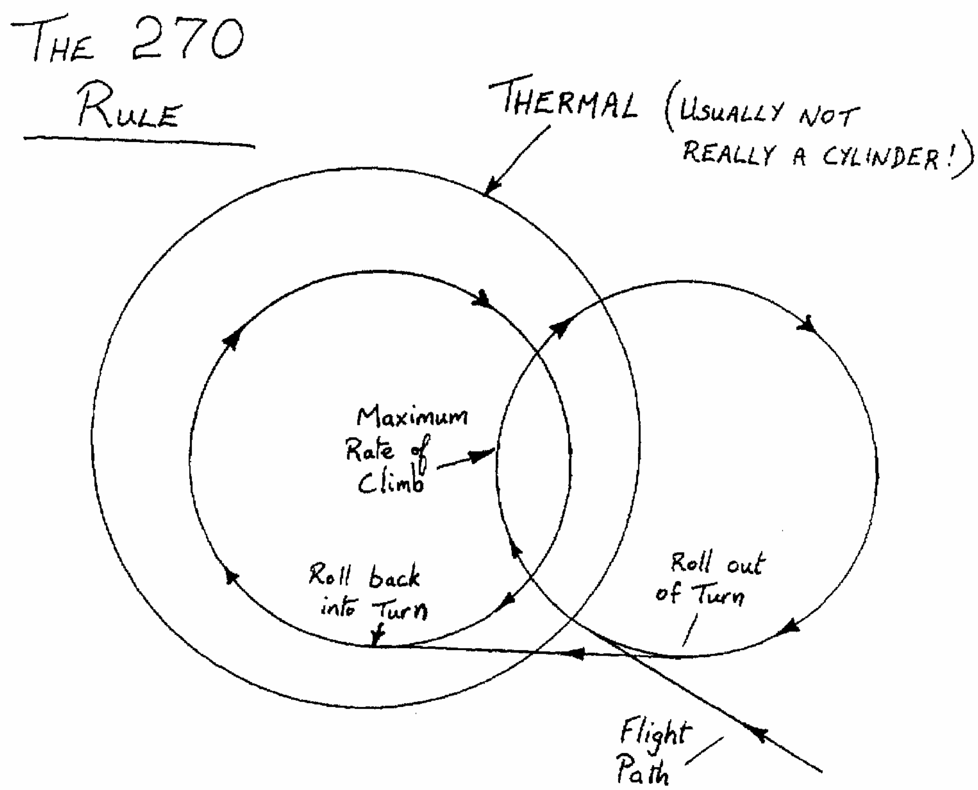
In order to use a thermal, the pilot must fly in circles, to avoid flying through the thermal and out the side. Many pilots instinctively feel that the angle of bank in the turn should be kept small because the sink-rate of the glider increases with bank-angle. However, this also increases the turn radius, which often makes it impossible to keep the glider in the core of the thermal. Consequently it is often a better idea to make tight, steeply-banked turns to stay in the core. One of the features that often distinguishes expert pilots from novices is the bank-angle they use when thermaling.

How steeply-banked should the turn be? We saw in chapter 5 that the sink-rate of the glider increases in a turn from about 200 fpm in straight flight to about 300 fpm at 40° bank-angle. At this point the turn radius is a mere 42 feet, which is little more than a wingspan. Beyond this the sink-rate increases very rapidly while the turn radius decreases only slowly (if it decreased much more the inside wing would have very little airspeed). At 50° the sink-rate is almost 400 fpm while the turn radius is 35 feet, about 1 wingspan. Only in light, widespread lift, should the bank-angle be less than 25° while only in very strong, small cores should it be more than 40°.

As for finding the core, the best rule is probably the "270 rule". Note where the outside wing points when the rate of climb is highest, then continue the turn until heading toward that point, and roll out on that heading for a moment before resuming the turn. This amounts to rolling out of the turn for a moment after 270° of turn, which explains where the rule gets its name. Once the glider is in the core, it should be kept there by making the turn tight enough to do so. More than 40° bank should not be needed - this seems very steep in flight. A full turn at 40° will take about 8 seconds - it seems like less.

The importance of staying in the core is illustrated by the fact that expert pilots will often momentarily stall the inside wing on entering the core. This causes the wing to drop, tightening the turn. The lost efficiency is made up for by the tighter turn, which keeps the glider in the thermal core.


0.000
-100.000
-200.000
-300.000
-400.000
-500.000
-600.000
-700.000
-800.000
-900.000
-1000.000
Sink Rate (fpm)
0°
25°
40°
60°
0.00
20.00
40.00
60.00
Airspeed (mph)


THE 270 RULE
THERMAL (USUALLY NOT REALLY A CYLINDER!)
Maximum Rate of Climb
Roll back into Turn
Roll out of Turn
Flight Path

7 (III) Getting Down

Occasionally the lift is so strong that it becomes difficult to get down. The two options are a straight dive, which moves the glider to a different area where there may be less lift, or a spiral dive, which produces a higher sink-rate but does not get away from the area of lift.

Although most of the time a hang glider is airborne the pilot is searching for a way to get high and/or stay high, sometimes the pilot finds it difficult to get down! This can happen in strong thermal lift, which tends to be quite turbulent, or in "glass-off" conditions, in which the lift is widespread and stronger with altitude, but is usually quite smooth. The glider may even be flying in wave lift, which is also widespread and smooth.

Pilots should always be aware that a hang glider's maximum sink-rate is unlikely to be more than 1000 fpm under any circumstances (except structural failure). If the glider is climbing faster than about 800 fpm it will not be possible to get down without leaving the lift.

The biggest danger is of being lifted into a thunderstorm or towering cumulus. If the thermal is under a large cloud with a flat, dark bottom surface, and the thermal is very strong, it may be a bad sign. The lift may be very strong near the bottom of the cloud, the thermal may grow to be very wide, making escape difficult, and the cloud may be drawing air in from all sides, generating headwinds for the escaping glider in all directions! This situation may be EXTREMELY HAZARDOUS.

The pilot has a number of options to consider to get down. One is to fly fast, in a straight line. The high speed increases the glider's sink-rate to about 800 fprn at 50 mph. The glider may continue to climb, but at the high flying speed may eventually escape the area of lift altogether and begin to descend.

The second option is to make tight, high-speed turns at steep bank angles. On the previous page I showed a typical glider's polar for various angles of bank. Turning does indeed increase the sink-rate, having a large effect at low speed but a relatively small one at high speed. At 50 mph a 60° bank will increase the sink-rate by about 200 fpm. This would be a very difficult spiral dive to maintain, with large control-forces. This option is better if the additional sink-rate makes the difference between going up and coming down and if the lift is so extensive that it is unlikely that the glider will be able to escape by flying in a straight line. If the glider continues to climb in the turn, the pilot must roll out of the turn and fly as fast as possible in a straight line while looking for weaker lift, as circling in the strong lift is pointless and the only way down is to escape the lift, no matter how long it takes!

A third option is to do wingovers or other high-g maneuvers to increase the sink-rate. Tight turns are probably more effective, as wingovers apply high g only for a few seconds at a time.

Finally, if the lift is widespread, there may be a "sink-hole" in it, like an inverted thermal. If the glider turns in this sink-hole, it can come down. This is known as "coring sink".

Who wrote this stuff?

Finbar Sheehy did. I am an engineer by profession, and a pilot by avocation. At the moment I am a graduate student at the California Institute of Technology, working toward my PhD. I have a Master's degree in Engineering from the Institute. I have been an airplane pilot since 1986, and hold a Private Certificate. I took up hang gliding in 1991 and do most of my flying in southern California.