PILOT EXAM NOTES

FLIGHT THEORY AND INSTRUMENTS

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Lecture 3 : Flight Theory and Instruments

1. How lift is produced

1.1 Bernoulli and venturi

Lift is the major force that keeps us up in the air. It is produced by the wing moving through the air. In simple terms, Bernoulli's law explains the lift, or upward force that permits airfoils to generate lift. The upper surface of a wing is more curved than the lower; air, travelling across the wing is made to travel faster and thus its pressure on the upper surface is reduced. This effect is seen in such areas as car carburettors or atomisers and makes use of a thing called the venturi effect.

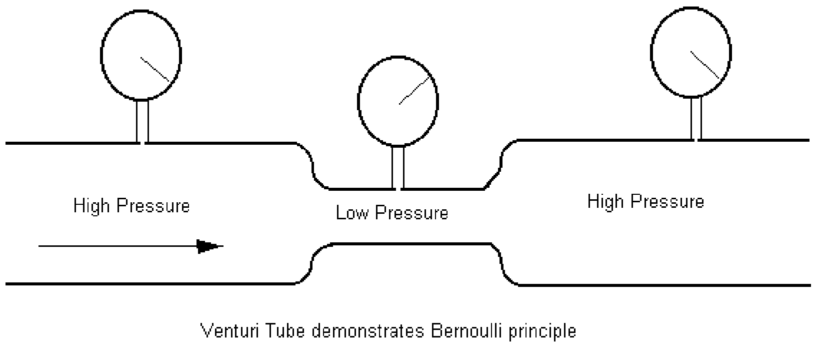


Figure 1 Venturi effect

The structure of the wing best demonstrates the principle of airfoil lift. In the 19th century a scientist named Bernoulli discovered that the internal pressure of a fluid (liquid or gas) reduces the faster the fluid flows. If you take a tube, and make the tube smaller in diameter in the middle, this creates a "necked-down" section called a venturi. When air is forced through the pipe, as much air has to come out the exit as goes in the tube entrance. The air in the venturi section must travel faster to get through. Bernoulli found that the pressure at the venturi section was less than at the two ends of the pipe. This is because the speed of the air through the venturi section is travelling faster than at the ends of the tube.

1.2 The Airfoil

The shape of a wing is called an AIRFOIL. Usually the bottom of the wing is flat or nearly flat. The top of the wing is curved, with the wing being thicker at the front edge of the wing, and tapering to a thin surface at the trailing edge of the wing

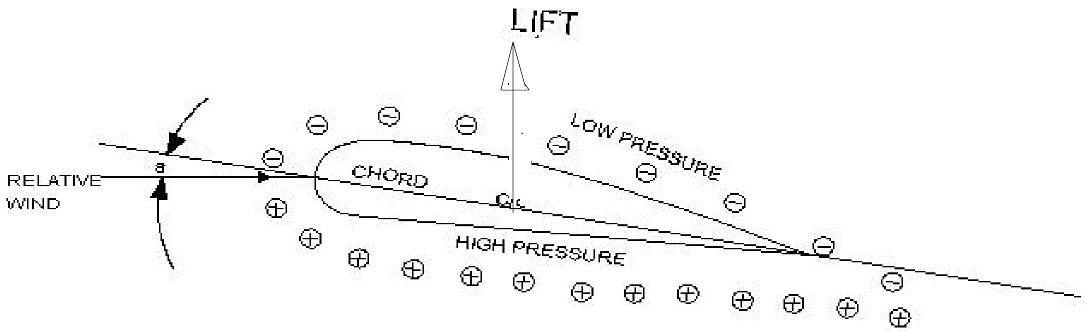


Figure 2 Lift on the airfoil

. When a wing airfoil surface passes through the atmosphere, the atoms of the air on the top of the airfoil (shown as minus) must travel faster than their cousins (shown as plus) passing along the lower and flatter surface, ref Figure 2 Lift on the airfoil on page 5. This occurs because the distance the air must pass over the curved top of the wing is longer than the distance along the lower surface. According to the Bernoulli Principle, the pressure above the wing is less than the pressure of air below it. Consequently, a pressure difference between the lower and upper surfaces exist. This results in LIFT being produced. The amount of lift depends on the airfoil design and the speed of the air over its surfaces.

Lift is a force generated at 90' to the angle of the undisturbed airflow or relative wind

About 2/3rds of the lift results from the reduced pressure above the wing and 1/3rd from the increased pressure below it. The majority of the lift being in the front top surface of the wing. The lift is proportional to the angle at which the airflow meets the wind, the angle of attack.

1.3 Angle Of Attack

As the aircraft passes through the air it traverses a particular line of flight. The air passing by the surfaces of the aircraft in the opposite direction of travel is called the Relative Wind. The angle which the wing [1]chord makes with this Relative Wind is called Angle of Attack. An increase in angle of attack increases both lift and drag. If the angle becomes to great, it will pass the Critical Angle of Attack. This is a point where the airflow over the wing becomes so disturbed that the wing ceases to produce lift. The wing then enters into a Stalled condition.

The amount of lift generated is proportional to the speed at which the airflow meets the wing and sufficient lift can be generated by high airspeeds with low angle of attack or low airspeed with high angle of attack.

1.4 Vortices

When the wing is started flying it produces a starting vortex which is left spinning gently behind as you fly off. Ref Figure 3 Vortices on page 6. The standing tubular vortex your wing carries wherever it flies is created as the wing flies through the air molecules. At the wing tips, there is no wing to keep the vortex captive so it rolls of the tips in 2 spinning tubes which extend outwards and downwards. These vortices are a source of drag which will be described later. Keeping the standing vortex trapped at high angles of attack is the problem, because the molecules are accelerated more fiercely and the

[1] The chord of a wing is an imaginary line from the leading edge to the trailing edge of the wing. The term is used in the definition of "Angle of Incidence" and "Angle of Attack"

vortex becomes unstable. Finally at the stalling angle, the vortex leaves the wing and forms the end vortex which dies away. The following which is taken from a back issue of skywings may explain it a little better.

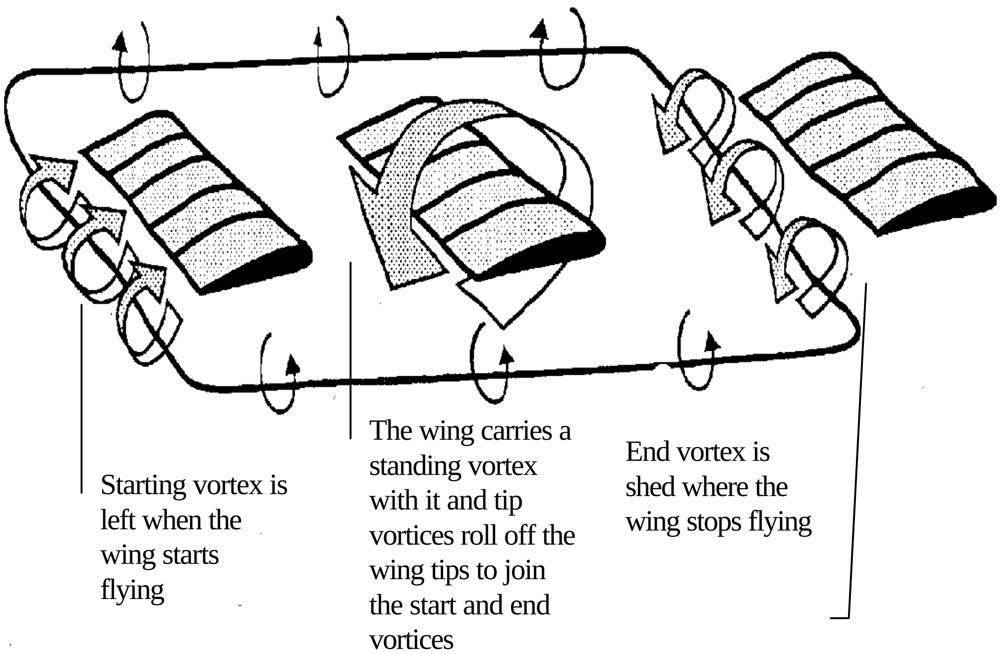


Figure 3 Vortices

Unfortunately the process of generation of lift cannot be accomplished without the generation of drag and the measure of the efficiency of the wing can be expressed as the lift generated (good) against the drag generated (bad). Dividing the lift by the drag gives a number, the bigger the number for us, the better.

2. Aeronautical Terms

Some useful aeronautical terms.

Angle of attack.

The measured angle between the airfoil chord and the direction of the undisturbed air in front of the airfoil.

Aspect ratio.

This is the ratio of the span of the wing divided by the chord. The glider wings are usually high aspect ratio wings **-** the reason for this is that for a given amount of lift produced by a wing, the lower aspect ratio wing disturbs a shorter width of air, but it must deflect it more vigorously. As a result, the tip area experiences larger losses in the form of swirls at the tip.

$$ASPECT\_RATIO = \frac{SPAN}{CHORD} = \frac{SPAN^2}{AREA}$$

Centre of Pressure

Even though the lift of an airfoil is distributed along its surface, the resultant force of all the lift forces can be considered to be at single point along the wing known as the Centre of Pressure. Centre of pressure can move depending on the angle of attack.

Centre of gravity.

The resultant forces of all the weight can be considered to be at the centre of gravity. Centre of gravity can move by the point weight shifting. The C of G is where the aircraft would balance. It can also be called the centre of mass.

Chord

The straight line drawn from the furthest forward point on the airfoil to the furthest rearward point on the airfoil.

Dihedral

When you stand in front of an aircraft, looking toward the tail, the wings are usually higher at the wing tips than at the wing root (where the wing attaches to the fuselage). This upward angle from wing root to tip is called DIHEDRAL. On an aircraft with dihedral, when one wing drops, it will produce slightly greater lift than the other wing. The aircraft tends to return to a level status providing lateral stability to the aircraft.

Washout.

A lowering of the angle of attack of the wing as it progresses from root to tip. Hang gliders have washout and the tips are held up by tip rods or other means.

Washin.

An increase in the angle of attack from root to tip.

3. Aerodynamics of the stall

A stall occurs because of the air's inability to make sudden changes in velocity. The air has mass. Therefore it wants to continue in its initial direction due to inertia.

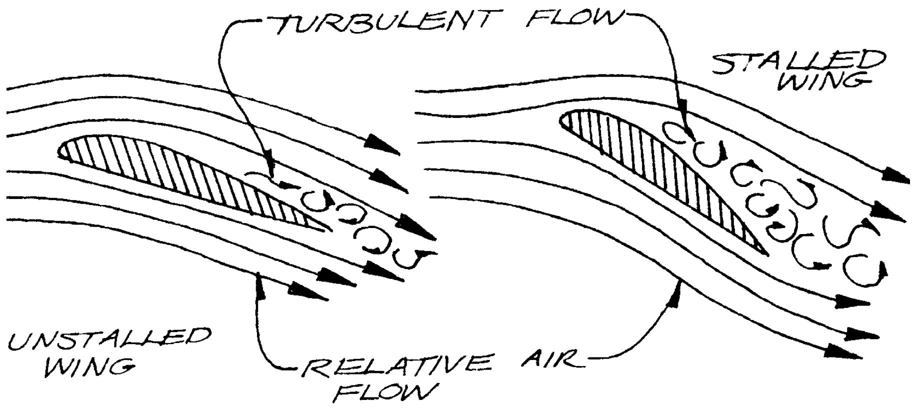


Figure 4 Stall effects

The air can no longer make sudden changes to flow smoothly over the upper surface. It breaks away at the rear and creates turbulence. The further the nose is raised, the more the break away point moves forward.

At the stall the drag increases and the lift decreases.

4. Stability

Stability is a tendency for a glider to return to normal level of flight after disturbance.

- Neutral **-** A glider is given a nudge and it stays where it is
- Stable **-** A glider is given a nudge and it returns to its trim point
- Unstable **-** A glider is given a nudge and it gets even worse.

For a glider this means that it must return to level flight after disturbances to the pitch, roll or yaw axes.

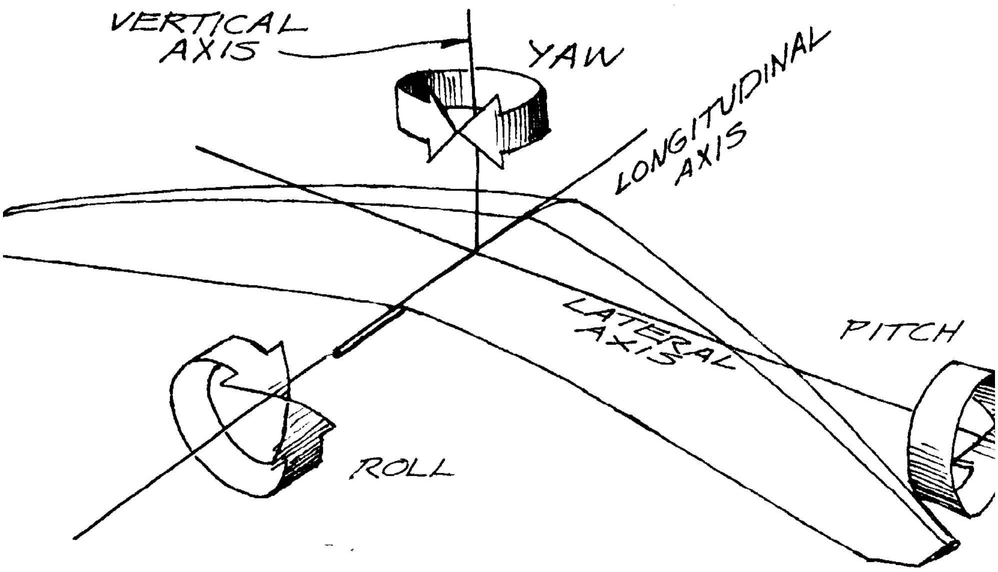


Figure 5 Axes of stability

A stable glider near stall will want to speed up, a stable glider flat out will want to slow down. An unstable glider near stall will want to slow up and an unstable glider flat out will want to go faster. (Not a very nice glider to fly).

The standard airfoil, if the angle of attack is increased (i.e. near the stall) then the centre of pressure moves forward with increasing angle of attack. The C of P also moves to the back of the airfoil as the A of A decreases. This is not a stable situation.

Unfortunately, all airfoils have the unwanted trait of instability so we have to do something to overcome the problem. Stability is a fine line for the designer between an overly unstable glider which would be a handful to say the least to fly and an overly stable glider which would not turn or be a real pig to fly.

4.1 Hang Glider

Hang glider stability is accomplished by several methods.

4.1.1 Pitch Stability

Pitch stability is the stability in the lateral axis.

4.1.1.1 Reflex

Reflex is the upward curving of the rear of the wing and is most often carried out by luff lines attached from the kingpost to the trailing edge of the sail. Topless gliders have some internal bracing to keep the reflex trailing edge in place.

What the luff lines do is destroy the lift at high speed so that the nose of the aircraft wants to pull up and slow down.

Luff lines are out of play during normal flight. With a VB system, the lines have to be loosened as the sail is tightened or they kick in too soon. Thus some gliders (Kiss for example) have VB compensators for the luff lines.

4.1.1.2 Sweepback

If the lifting surfaces are designed so that the lifting surface behind the C of G lose lift quicker than those areas ahead of the C of G, then more lift will be forward at high speeds to pull the nose up and more lift at the rear to force the nose down at low speeds. In other words, if we pull on speed, the tips unload more than the centre and thus the Centre of pressure moves forward to pull the nose up. If we push out, the tips lift more and tend to move the C of P back to pull the nose down . This is accomplished by a mixture of sweepback and washout. Sweepback is the V-shape given to the plan view of the wing and puts the tips behind the C of G.

4.1.1.3 Washout

Washout is the change in twist from the root to the tip. Washout is in one direction and washin is in the other direction. Moving from root to tip,, washout decreases the A of A. All hang gliders have washout. This combines with the sweepback and gives static pitch stability to hang gliders. Another advantage of washout combined with sweepback is the effect in a stall. As the glider stalls, the tips are at a lower angle of attack than the nose, and they tend to keep flying longer than the nose. In a shallow stall, if the nose is stalled and the tips flying, then the glider keeps on an even keel and the nose dips to pick up speed. This effect also helps during landing as the glider is flared, the tips stall last and help stop a wing dropping.

4.1.2 Roll stability

Stability along the longitudinal axis.

4.1.2.1 Dihedral/Anhedral

Dihedral is an upward tilting of the wings.

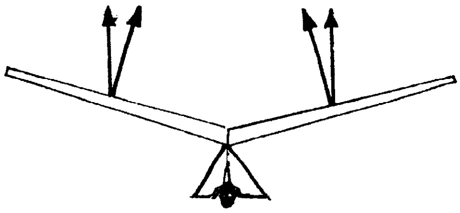


Figure 6 Dihedral

If a roll occurs, the lower wing will produce more lift and the higher wing will produce less lift. This will tend to counteract the roll effect and thus introduce stability.

Although dihedral assists roll stability, slight anhedral gives instability to assist turns. The amount of anhedral used is slight and since the leading edge is supported by the flying wires at about mid distance, during flight, the outboard sections would bend up and produce a small amount of dihedral. The original Kiss used an anhedral airframe but a relatively loose sail which when loaded assumes a dihedral shape, outboard of the flying wires. This mix of anhedral and dihedral is called a cathedral wing with the cathedral area being the part outboard of the flying wires.

4.1.3 Yaw stability

Stability in the vertical axis.

4.1.3.1 Sweepback

Yaw stability on a hang glider comes mainly from sweepback. As the glider yaws, one leading edge will present a larger frontal surface to the wind and therefore the amount of drag generated by this wing will be greater, similarly, the other wing will present a smaller frontal surface to the wind and the drag will be less. This effect will create a turning moment about the vertical axis which will tend to bring the glider back on course.

Yaw stability may also be helped by the addition of winglets on some gliders.

4.2 Paraglider

Stability for a paraglider is not such an issue since a paraglider is not a tail-less aircraft as a hang glider is.

4.2.1 Pendulum stability

Most of the stability comes from the pendulum effect. The weight of the pilot is great compared to the weight of the canopy. The lift comes from the canopy and the weight from the pilot. This effect means it is extremely difficult to dislodge the pendulum stability that a paraglider has.

Roll stability and pitch stability come mainly from the pendulum effect.

Pitch stability can be influenced by the aerodynamic section used, some are more pitch stable than others. The curve of the glider (viewed from the front) also affects the roll stability due to the direction the lift is acting in relation to the position of the pilot.

4.2.2 Washout

Paragliders can have a twist built in the wing as do hang gliders. Standard paragliders are built for stability and washin is often built in the tips. This has the effect of increasing the lift in this part of the wing and hence increase the tension in the sail across the span i.e. makes the wing feel more solid. It also tends to reduce the tendency for tip deflations. Advanced paragliders can have neutral or washout built in to increase the performance. This can also make the tips “loose” in turbulence.

5. Glide angle

Glide angle is not actually an angle but expressed as a ratio i.e. 8 to 1 glide angle. This means for every 8 units of length travelled across the ground, then 1 unit of length is descended. Obviously the greater the number, the better the glide angle.

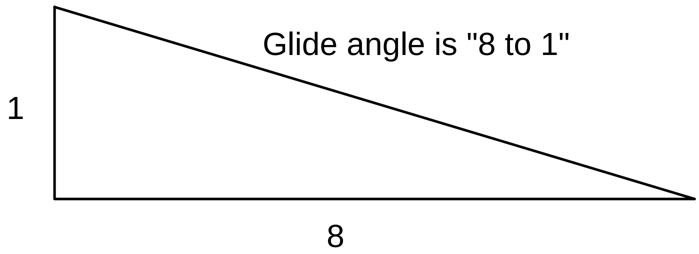
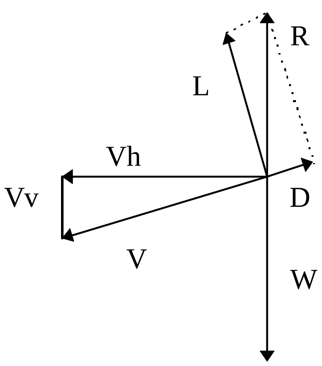


Figure 7 Glide angle

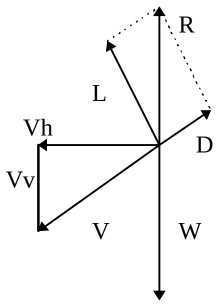
Glide angle also is the same is the LD ration (lift/drag). Glide angle is increased by increasing the lift (difficult) or reducing the drag (easier). Since as we will see on the section on drag, drag increases with airspeed, then at high speed, the reduction of drag is an important factor in glider performance. Sailplanes go to great lengths to reduce drag and have very smooth GRP surfaces and streamlining to reduce drag. For hang gliders, the reduction of drag has given rise to the topless glider. For paragliders, the number of lines has been reduced together with the introduction of microlines. The relationship between sink rate, glide ratio and flying speed is now explained. Some reference may be needed to the section titled “Forces on a glider”.

In the diagrams, L is the lift vector and is always at 90’ to the direction of flight vector V. D is drag and is always opposite to V. L and D combine to give the resultant R which is opposite and equal to the weight W.

V has been split into 2 vectors, Vh (horizontal speed) and Vv (vertical speed).
For clarity the airfoil has been removed

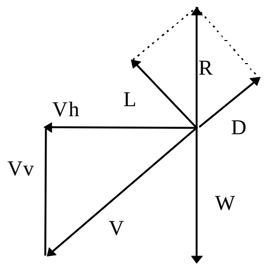


The diagram shows the forces acting on an airfoil. The wing is moving right to left in the direction of the arrow V. V is opposite in direction to the wind hitting the wing. The wing is flying with little drag.



The direction of travel is further down the wing is pointed in more of a dive.

The wing is travelling further in a dive. Note that the drag is always opposite to the travel and that the resultant R is the sum of the lift and the drag and counterbalances the weight.



The sink rate can be identified with the component of velocity Vv. To minimise the sink rate we must minimise Vv. The glide ratio is equal to Vh/Vv. This is simple the distance travelled divided by the distance fallen.

To maximise glide ratio we need to maximise Vh and minimise Vv.

By applying geometry rules we can find that the triangle of sides R,L and D (when D is shifted) is similar to the triangle defined by V, Vh and Vv.

Therefore L/D equals Vh/Vv which is of course the glide ratio.

6. Ballast

Ballast is another name for additional weight carried by the pilot. All gliders are certified to fly within a certain weight range. At the top of the weight range, the behaviour of a glider is different if weighted at the low end. As mentioned before, the design of a glider is a compromise, increase performance in 1 area such as glide angle and another area may suffer, such as sink rate.

Ballast can be used to increase the weight of the aircraft and thus increase the [2]wing loading” on the glider. This means that the aircraft will fly faster down the glide slope. The sink rate is increased slightly but the max glide ratio is not affected. The top speed of the glider is increased which may be helpful if flying on strong days in a paraglider. Performance and general handling of the glider may be better when flying at a certain weight. Performance paragliders seem to benefit from being well weighted.

Remember if you intend to take ballast that can be jettisoned in flight, then ballast is only allowed in the form of water or fine sand. Also, remember never to exceed the design weights of your glider.

7. Forces on a glider

Already touched on in an earlier section. There a 4 forces on the glider wing. Ref Figure 8 Forces on a glider.

[2] The surface area of the wing divided by the total weight.

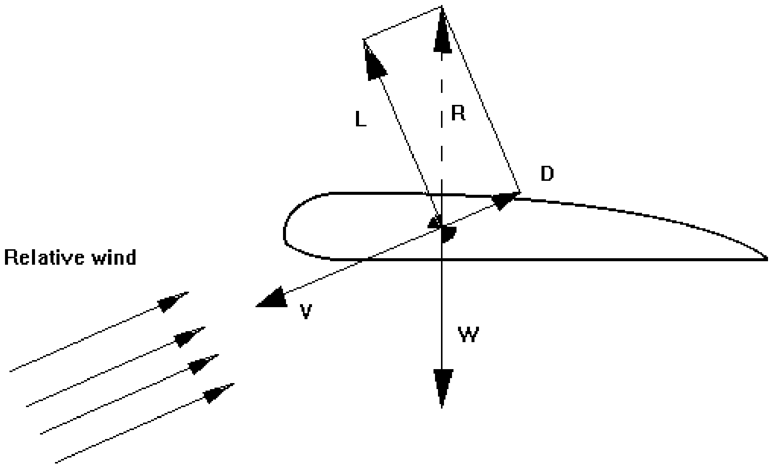


Figure 8 Forces on a glider

One difference between a powered wind such as a light aircraft and a glider wing. All flying objects without power get their energy from gravity. A glider converts some of its downward falling motion to forward motion shown as “V”. Once airspeed is established, the lifting forces build up to couple with the downward pull of gravity and lift the nose until equilibrium is reached.

The force of gravity is shown by “W”.

This is always balanced in steady flight by the sum of forces of lift “L” and drag “D” called the resultant “R”. If W is not balanced by R the glider will accelerate until both the lift and drag increase to a point of reinstating the equilibrium. i.e. if a take off run is too slow, the lift generated will not support the weight. The nose will dip and the glider pick up airspeed until enough lift is produced for the two to equalise. Hopefully this happens above ground.

The resultant force R always acts through the centre of pressure

The weight always acts through the centre of gravity..

Both the C of P and the C of G can move. The centre of pressure by changing the angle of attack and the centre of gravity by weight shifting. That’s how we can control the glider.

If a pilot pulls the bar in to gain speed, the lift decreases. This means that R is reduced and there the wing picks up speed until the lift is increased (and the drag) to match the weight.

The flying speed varies only with angle of attack for a given glider and flying weight.

8. Drag

Drag is result of us flying in a fluid (air) and cannot be totally removed. There are several types of drag. Refer to Figure 9 Total drag on page 14.

8.1 Induced

Induced drag is a by product of lift. The majority of induced is formed at the wingtips where the wingtip vortices are shed, as the area of low pressure above the wing and the high pressure below the wing slide off the wingtip and mix in a swirling trailing tip vortex.

The important thing is that induced drag reduced with angle of attack and hence airspeed. High aspect ratio wings reduce induced drag. Winglets on 747's reduce induced drag at slow speed. Condors have extended feathers at the tips that do funny things with tip vortices and they all help reduce induced drag.

8.2 Parasitic

Parasitic drag is a friction drag and varies with the square of the speed. i.e. doubling your speed quadruples your parasitic drag. There are a few types of parasitic drag

8.2.1 Form drag

Caused by solid non-lifting items in the airstream. i.e. You, wires, kingpost etc.

8.2.2 Profile drag

Caused by the lifting surfaces. It consists of skin friction drag and leading edge form drag. The more streamlined the airfoil shape, the less profile drag.

8.2.3 Interference drag

Interference drag is when the airflow around the aircraft interfere with each other. Not a big problem on hang gliders or paragliders.

8.3 Total drag

Add all the drag components up to get the total drag. Different parts of the drag are important at different speeds. We can plot a graph as below.

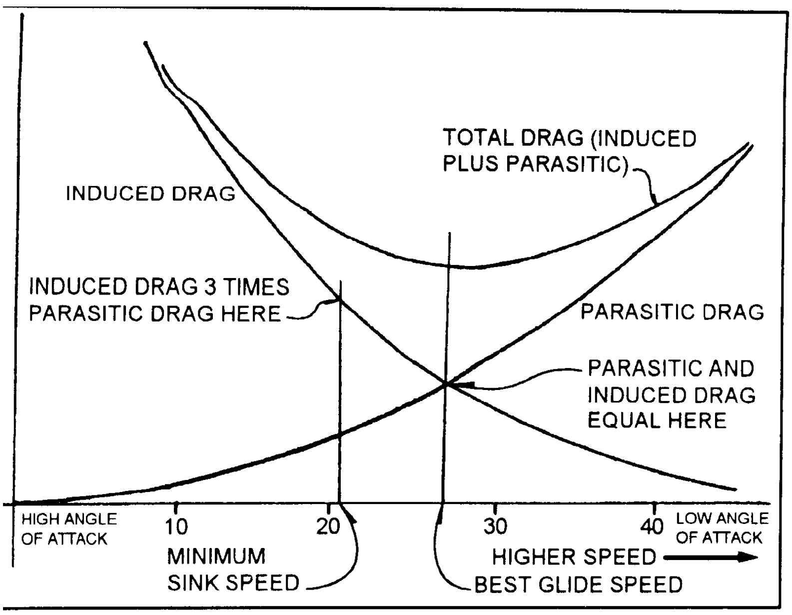


Figure 9 Total drag

The best glide occurs at minimum drag.

9. Polar curves

Polar curves are graphical representations of the performance of our wing. They can be used to determine what speed we should fly at for any given conditions to maximise our glide over the ground. They are drawn with airspeed along the x axis and sink rate along the y axis.

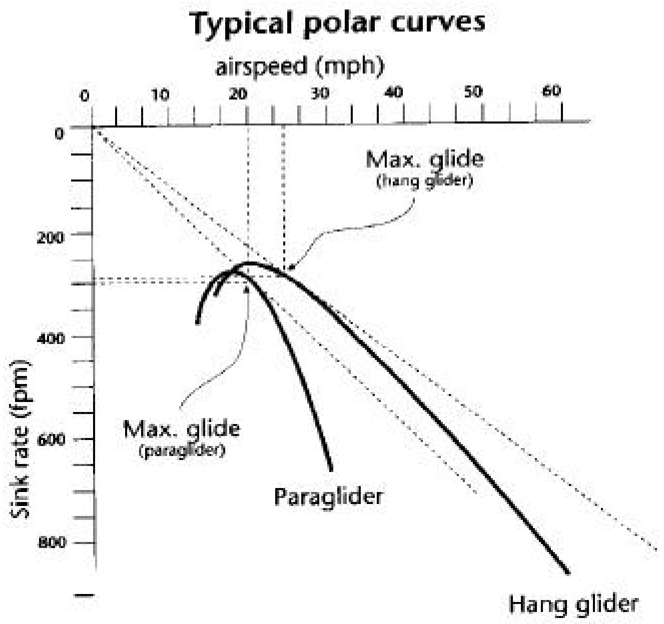
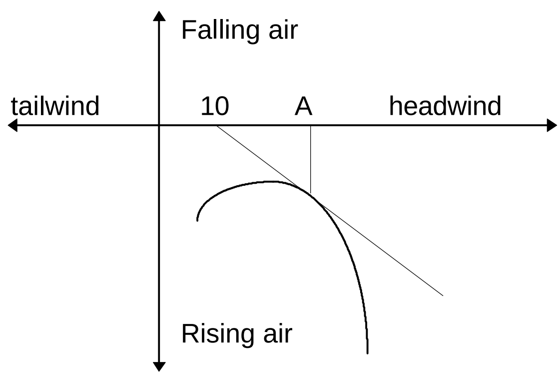


Figure 10 Polar curves

The curve is a series of plots taken for a particular aircraft and for a series of airspeeds. At each airspeed the sink rate is taken and then it is possible to plot the polar curve. The sharp increase in sink rate at slow speeds is the point just before the stall.

Min sink is the highest point on the graph.

Max glide in still air is obtained by drawing a tangent to the graph from the origin . The point of intersection can be read off in sink rate and airspeed. The graph can also be used in head winds and tailwinds and rising and sinking air for the same purpose.



If we want to find out the speed to fly at in say a head wind of say 10mph. Instead of taking our tangent line from the origin, we take it from the 10mph point on the headwind side of the line. The tangent touches the polar at a faster speed which can be read off at point A. Similarly if we are flying in a tailwind, the polar will tell us to fly slower.

Figure 11 Polar curve with headwind

In this example, we are flying in a 100fpm thermal. Our polar tells us to slow down a little to fly at speed indicated at A

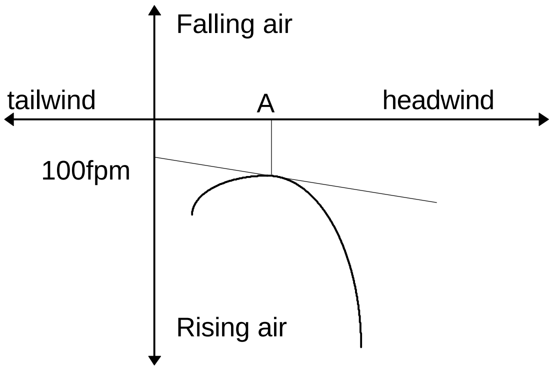


Figure 12 Polar curve with thermal

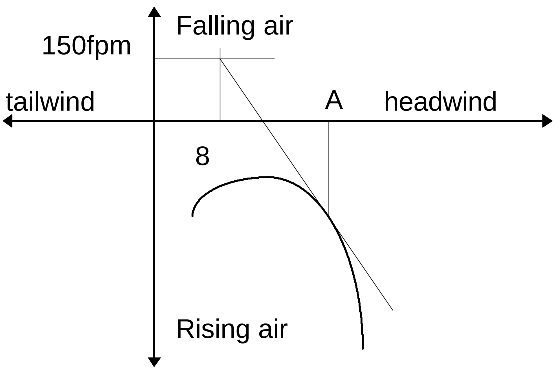


Figure 13 Polar curve with both

The final example shows a combination of flying an a 8mph headwind and a 150fpm sink area. The fast speed is shown at A

From the above we can deduce that we should speed up in sink and a headwind and slow down in thermals and a tailwind

10. <u>Instruments</u>

We all fly with instruments. The altimeter measures height above a reference. The variometer measures our rate of change of altitude. The Air speed indicator measures airspeed. The 2 or 3 are usually combined in 1 instrument.

10.1 Altimeters

Altimeters measure height against a reference. Most commonly they use the fact that air pressure reduces by 1mb for every 30ft we rise and the relationship is linear (at the levels we fly at). There are other means of measuring height (satellite navigation) but these are not as accurate for the amount of money we can afford.

10.1.1 Aneriod

The aneroid altimeter uses a small sealed capsule containing air. As the instrument goes up, the air pressure in the capsule increases and by the design of the capsule, it is allowed to expand in a certain direction. This expansion is coupled by mechanical linkages to a dial display. The dial can be adjusted by a knob to read say height above sea level (QNH) or height above the field (QFE). This altimeter is mechanical.

10.1.2 Electronic

The majority of altimeters are electronic. They use semiconductor materials to sense changes in air pressure. Once you have the sensor, then its relatively straightforward to design electronics around it to convert the signal to a display. Modern altimeters also have the ability to have temperature compensation and data links built in.

10.2 Variometers

Variometers also sense changes in air pressure, but in a different way. They display the rate of change of air pressure outside rather than the absolute air pressure. The faster the ascent, the faster the rate of change of air pressure.

10.2.1 Electronic

Once the pressure sensor is in the box of electronics, it can also be used to measure and display the rate of change of pressure.

10.2.2 Flask

A flask vario is more commonly found in sailplanes and is an early from of vario. It looks like below;

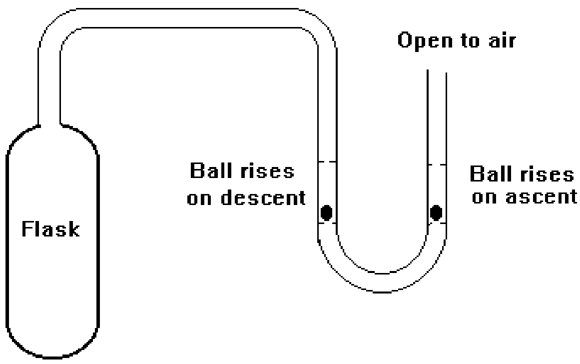


Figure 14 Flask vario

As the instrument rises, the air in the flask will try and rush out of the openings since it will be at a higher pressure than the surroundings. As it rushes past the pith balls, one is forced upwards in the draft. The same thing happens in descent but the other ball is forced upwards.

10.2.3 Total energy

False readings may be obtained by flying fast and converting this speed to height. This may be converted into an imaginary thermal as the vario senses the increase in height. This is called a “stick thermal” It is of course not a real thermal. Varios which take the airspeed into account when determining the air around are called total energy varios. Very important for sailplanes which have a lot of energy retention and can convert speed to a lot of height.

The solution to avoid false readings is to use a total energy vario. By total energy we mean the sum of the kinetic (moving) and potential (due to height) energy. They work since the dynamic pressure of the air increases with the square of the velocity. Our sink rate increases pretty much with the square of our flying speed. In we have some device to measure the airs dynamic pressure, and tie this into our varios detection circuits, we can compensate for the altitude change due to glider speed. The metal tube on LR3 varios is the total energy probe.

10.2.4 Airmass(Netto)

As we fly at different speeds, our glider has different sink rates. We have to mentally compensate for this when working out what the air is doing. Netto varios work this out for us and always indicate the airs "net" lift or sink.

10.2.5 Speed to fly

Speed to fly is a complicated area of theory, covered recently by Gordon Rigg in an excellent article in Skywings. Suffice to say for the exam, speed to fly is a theory that for every condition of lift/sink and headwind/tailwind, in order to achieve the greatest distance over the ground, then there is one specific airspeed to fly at. It can also be used to determine the speed to fly at to achieve the fasted speed to goal. It's a lecture in itself.

10.2.6 MacReady ring

A MacReady ring is a scale which fits round the vario display (assume its an old type vario with analogue display). The ring rotates round the vario display and as you fly at a certain vario reading. The MacReady ring tells you to fly at a certain speed. As you fly at this speed, the vario needle will no doubt move to a new reading and you have to readjust your speed. Do this until the vario needle points to the speed you are flying at and that's it. Modern varios have facilities to link to GPS's to work out your ground speed compared with your air speed and work out headwind/ tailwind components. The vario readings are all fed into the electronics which displays the speed to fly.

11. References and acknowledgements

Performance Flying by Dennis Pagen
Paragliding flight by Dennis Pagen
BHGA Pilot handbook
Touching cloudbase by Ian Currer

12. Revision History

Issue	Date	Comments
1	Feb 97	First Issue
2	24 March 1997	Revised with index