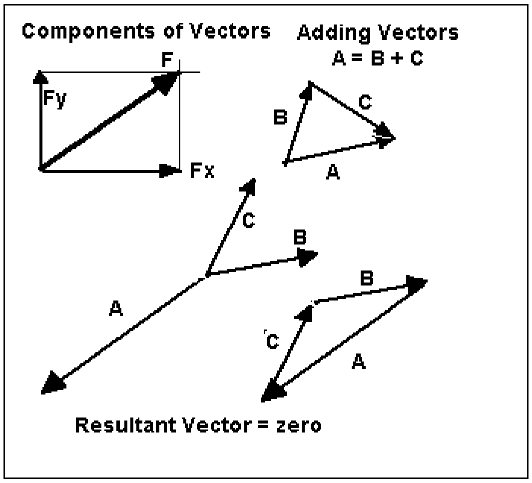
Aerodynamic Basics

Larry Bogan - Jan 2002 version

MECHANICS

Vectors

Force, displacement, acceleration, and velocity



Inertia and Velocity

Inertia is a property of mass. (When there is no force on an object, an object at rest stays at rest - an object moving remains moving)

Distance Units:

mile = 5280 feet
nautical mile = 1' latitude = 6080 feet
= 1.85 km = 1.15 mile
kilometer = 1000 metres

V = *Velocity = distance/time*

Velocity is a vector (has magnitude and direction)
average velocity = total distance/time interval
instantaneous velocity = change in position per time

1 knot = 1 nautical mile per hour
1 knot = 1.15 mph = 1.85 km/h
1 knot = 0.515 m/s
1 knot = 101.3 ft/min

(the last conversion is useful in variometer readings)

Force and Acceleration

a = F/m - Newton's second Law

a = acceleration = (velocity change)/ (time interval)
Acceleration of gravity = **g** = 9.8 m/s^2
= 32 ft/s^2 = 19.0 knots/s
velocity increase in 1/2 second = 9.8 x 0.5
= 4.9 m/s = 9.5 kts

Weight = **Force** of Gravity
= Mass x Acceleration of Gravity

Mass Units: 1 kg = mass of 2.2 lb weight (pound = force)
Units of Force: 1 kg x m/s^2 = Newton (N)
Weight of 1 kg mass:

1kg x 9.8 m/s^2 = 9.8 kg m/s^2 = 9.8 N
1 N = 0.224 lb force

Example - Cable break of Glider on Launch -

(climbing at 45°) cosine(45°) = 0.707
Acceleration of gravity component along the direction of flight = 0.71 (19.0 kts/s) = 13.4 kts/s
For every second you wait to put your nose down, you will lose 13 kts of speed due to the deceleration cause by the pull of gravity. That is why we teach you to get your glider into a flying attitude quickly after a wire break.
If the speed up the wire ~55 kts and the aircraft stall speed (no wire) ~ 30 kts. You have a margin of < 25 kts in speed which is lost < 2 seconds if you maintain a 45° up attitude.

Example: Glider Launch via Winch (initial acceleration)
Mass of Schleicher Ka8b --> 300 kg with pilot
Approximate Acceleration = 0 to 50 knots in 5 seconds
Change to convenient units: 50 kt = 25.7 m/s
a = (25.7 m/s - 0 m/s)/(5 sec - 0 sec) = 5.14 m/s^2 ~ 1/2 g
The Force that the winch cable must pull with is

300 kg * 5.1 m/s^2 = 1540 N = 346 lbs

What would happen if the winch driver yanked you to 50 kts in 2 second?
Acceleration = 25.7 m/s / 2 s = 12.4 m/s^2 = 1.27 g's
Force = 3720 N = 833 lbs --> weak link breaks 1000 lb .

Lift, Weight, Drag and Thrust

Lift, L, is a force that is alway perpendicular to the flow of air past the sailplane (It is not alway normal to the wing).
Drag, D, is a force that is always in the direction of the flow of the air past the sailplane. (perpendicular to the lift)
Weight, W, is the force of gravity always pointing to the center of the Earth.
Equilibrium occurs when all forces are balanced and there is no change in velocity, ie. there is no acceleration.

For a glider at flying at constant flight speed , the sum of all the forces, **L, D**, and **W** add to zero. This is a case of dynamic equilibrium. If there were a resultant (non-zero) force then that would accelerate the glider and change its velocity.
There are two ways to look at the cancelling of the forces on the glider :

1. Coordinate System of the Earth.

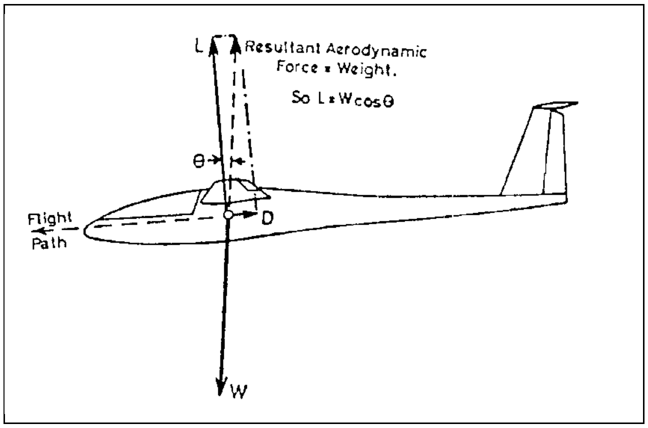
As shown in the diagram below the Drag and Lift add to provide a Force equal and opposite to the weight of the glider

2. Coordinate Systetm of the Glider

The Weight component along the flight path is equal and opposite to the drag force

The Weight component perpendicular to the flight path is equal and opposite to the lift force.

If the glider increases its diving angle, the component of the Weight along the flight path increases and is greater than the drag force. As a result the glider accelerates to a higher speed. This speed will increase until the drag force increases (due to higher air speed) and the glider is in equilibrium again.



Energy and Power

Work = (Force) x (Distance in directon of the Force)
Work done on an object (sailplane) will increase the energy of the object. [Note: Lift can not do work on the glider because since it is perpendicular to the dirction of motion]
Units = N * m = joules

Power = (Energy Change) / (time interval)
Units = j/s = watt (W)
3,600,000 joule = 1 kilowatt-hour

Types of Mechanical Energy:
1. **Kinetic Energy = 1/2 m v^2**
2. **Gravitational Potential Energy = mgh**
= weight * height
where h = height of the glider

Energy is useful in discussing the changes in glider motion. By adding up all the energy of a glider and using the conservation of energy, many difficult problems can be understood more simply. When all energy components are taken into account, energy is conserved. One energy type can only increase at the expense of another form.

There is **Conservation of Energy:** Total Energy = constant
Total Energy = Kinetic + Potential Energy
+ Drag Force x Distance

Example: **Glider flying at constant airspeed**
Equate the energy at two points in its flight
Total Energy#1 = Total Energy #2
$1/2\ mv^2 + mgh_1 + D\ x_1 = 1/2\ mv^2 + mgh_2 + D\ x_2$
so... $mg(h_1 - h_2) = D\ (x_2 - x_1)$
Which says that the loss of gravitational energy equals the loss of energy due to the drag force.The mathematical relationship can be used to obtain the magnitude of a typical drag force from glider performance numbers.

Since we know velocities, not distances - let's look at the rate of loss of energy . If we write the relationship in terms of the rate of change of height and distance, we get:
rate of change of potential energy
= drag force x (distance/time)
(weight) (sink rate) = (drag force) (air speed)
The drag force can be calculated using:
drag force = (weight) [sink rate / air speed]

Let's consider one of the Bluenose's single seaters:
The Ka8b has a mass of 300 kg and when flying at 45 kts has a sink rate of 1.73 kts
Sink Rate = 1.73 kts = 0.89 m/s
Weight (with pilot) = 300 kg * 2.2 lb/kg = 660 lbs
= 300 kg * 9.8 m/s = 2940 N
Rate of change of energy (gravitational) = weight * sink rate
= 2940 N * 0.89 m/s = 2620 Watts
Let's put the drag force in pounds of force.
The Drag force = 660lb (1.73kts/45kts) = 25 lbs
= 113 N
(Interesting that it only requires 25 lbs of force to pull the Ka8b glider through the air at 45 kts BUT by the time the Ka8b is going 72 kts the drag force is 50 lbs and it is sinking at 5.5 kts). The drag for inceases rapidly with speed.

Relative Wind and Relative Motion

Let's briefly look at the effect of wind on flight.We have assumed that the air is not moving. That is usually not the case and we must make the distinction between motion relative ot the air and motion relative to the ground.

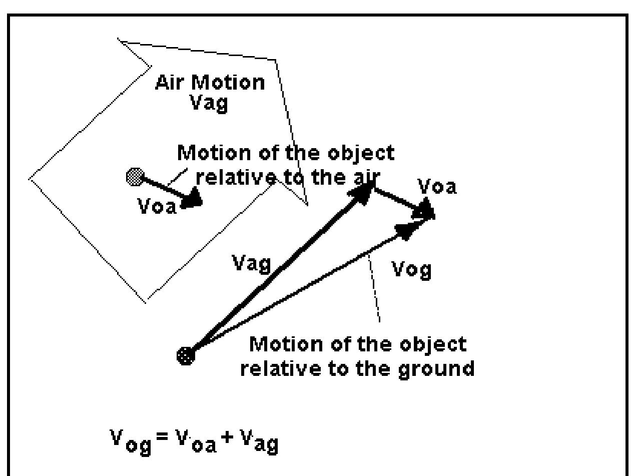
Obviously, wind (the relative motion of air with respect to the ground) must be considered to determine the motion of the glider relative to the ground. In addition, rising or falling air in gusts or thermals affect the relative motion of the air past the wing (and glider). In still air, we have pointed out that the lift force on the wing is perpendicular to the glide path. This glide path is the path through the air and will usually be different from the glide path relative to the ground.

A translation must be made from motion through the air to motion relative to the ground.

WING AND FLIGHT GEOMETRY

Angle of Attack and Lift

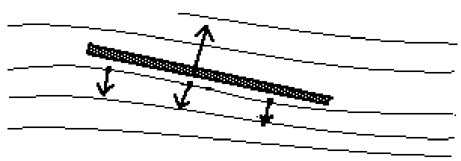
Lift occurs when ever air is deflected downwards by a surface - The surface must apply a force to the air to



force it downward and there is an equal an opposite force on the tilted surface to lift it. A kite is such a flying plate.

Angle of Attack is the angle of the plate with the direction of the wind.far from the plate.

The lift force increases as we increase the angle of attack but at some point will begin to decrease with angle. The extreme case is when the angle of attack is 90^o when the lift is zero.

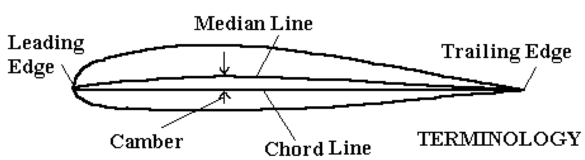


The drag force on the plate increases even more dramatiically as we increase the angle of attack and reaches a maximum with angle of attack = 90^o

Stall Angle is the angle of attack at which the lift device does not have enought lift to hold up the weight. This is at an attack angle slightly larger than the angle that give the maximum lift. (see graph to the right)

An **Airfoil** is a steamlined cross sectional area of the lift device that will provide high lift with low drag.

- The relative wind flows from the left in the above diagram and that defines the **leading** and **trailing edges**. The **chord** is the straight line and distance from the leading to the trailing edge. The **thickness** is the distance between the top



and bottom surfaces at the widest point; usually measured in fraction of the length of the chord. The **mean line** is the line that is half way between the upper and lower surfaces. The **camber** is the maximum distance of the mean line from the chord; measured in fraction of the chord.

- There are a multitude of different airfoil designs and we will not get into the differences. The characteristics of an airfoil shape is determined experimentally in wind tunnels.

To illustrate the effect of the various design parameters on the lift and drag forces, there is an educational Windows software program, **FoilSim,** designed by the Lewis Research Labs of NASA. The program shows the linear aspects of lift but does not show drag force or stall on the airfoil. It is very useful for getting a feel for the effects of shape on the lift of an airfoil. It will print out graphs and data for a large variety of airfoil shapes.You may acquire it by downloading it from the NASA website:

http://www.allstar.fiu.edu/aero/Foilsim.htm

The same site also has an extensive tutorial on flight theory; at **http:// www.allstar.fiu.edu/aero/FlightTheory.htm**

Lift increases with thickness, camber and angle of attack. The magnitude of the lift and drag forces on an airfoil depend on the following parameters:

Shape
Area, S
velocity, V
density of the air, ρ

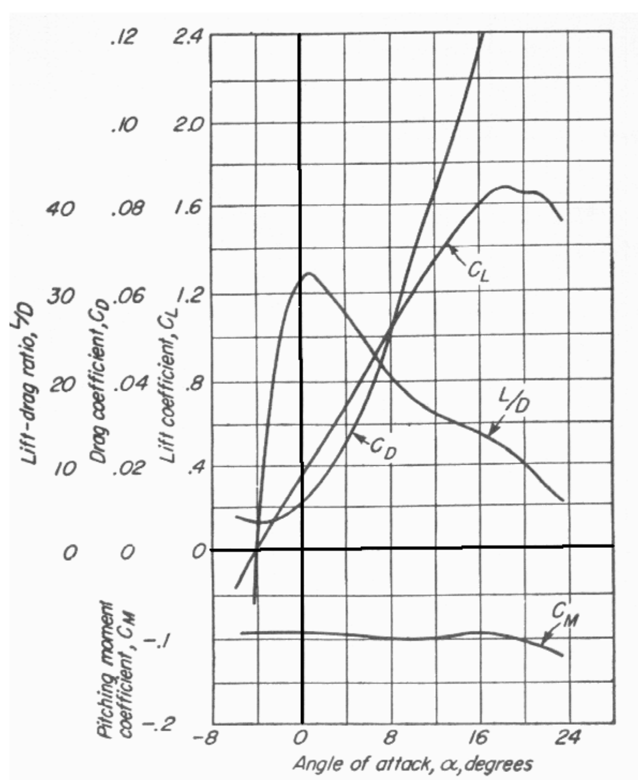
The properties of an airfoil are expressed in terms of the lift and drag coefficients , C_L and C_D . The forces are given by

$$L = 1/2\, C_L \rho\, SV^2$$
$$D = 1/2\, C_D \rho\, SV^2$$

Both forces depend on the square of the air speed and their ratios (lift over drag ratio) is $L/D = C_L/C_D$

The graph below shows the dependence of the coefficients with angle of attack for a typical airfoil.This one has a maximum L/D of 32 at an angle of attack, α, of 1 degree. Note that :

- The lift coefficient increases linearly with α but decreases above 18^o and the wing stalls. At zero α the coefficient has a positive value.
- The drag coefficient increases nearly quadratically with α. Note the different scales on the vertical axis for the two coefficients.
- The lift over drag ratio is maximum near zero α and decreases at larger and smaller angles. This is the most efficient α for the wing.
- The pitching coefficient, C_M, is a measure of the twisting force on the airfoil. This must be countered by other air control surface and weight balance of the airplane.



Wings usually operate near the most efficient angle of attack since the airfoil is aligned along the direction of normal flight. Two conditions will increase or decrease the angle of attack:

(1) A sudden change in attitude will change the α because inertial will keep the plane flying in the original direction until the wing can turn the aircraft.

(2) In slow flight a nose up attitude is required to increase lift but the flight direction is at a smaller attitude. As the attitude increases the wing will stall.

Bernoulli's Effect and Pressure

Bernoulli restated the conservation of energy for incompressible fluids in the form

$$P + 1/2\ \rho\ v^2 + \rho g h = \text{constant}$$

where P = pressure of the air.

The energy is for a small mass of fluid $\Delta m = \rho\ \Delta V$ where ΔV is the volume of that mass.

1st Term --> fluid internal energy = $P\ \Delta V$

2nd Term --> kinetic energy = $1/2\ (\rho\ \Delta V)v^2 = 1/2\ \Delta m\ v^2$

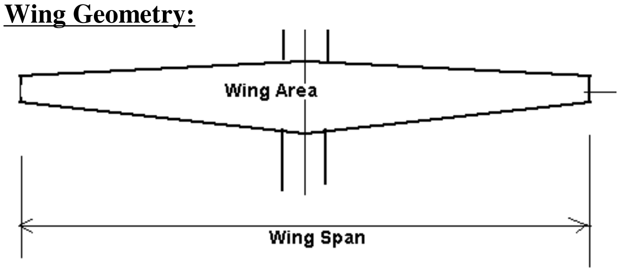
3rd Term --> gravitational potentional energy = $\Delta m\ gh$

As the velocity increases for a fixed height,the pressure must decrease. As it decreases, pressure increases.

(**Demonstation: Blow through a paper arc and see what happens)**

The camber of an airfoil is upward and this causes the air flowing over the upper surface to move a higher velocity than that over the lower surface. This results in a lower pressure above the airfoil than below. (Bernoulli Effect) This effect adds to the lift produced from the deflection of air downward. The difference in velocity is due to circulation around the arifoil. There will also be additional circulation around the wing tips as air flows from higher (below) to lower pressure (above). This is the source of **tip vortices.**

__**Wing Geometry:**__



Wing Span = length of wings tip to tip

Area of Wing = Lifting area of the wing

Aspect Ratio = $(\text{Span})^2/\text{Area}$

= Span/Chord for rectangular wing.

Drag of a wing is proportional to the chord of the wing. By using a long , narrow wing, the lift-drag ratio can be increased. Higher performance gliders have larger aspect ratios.

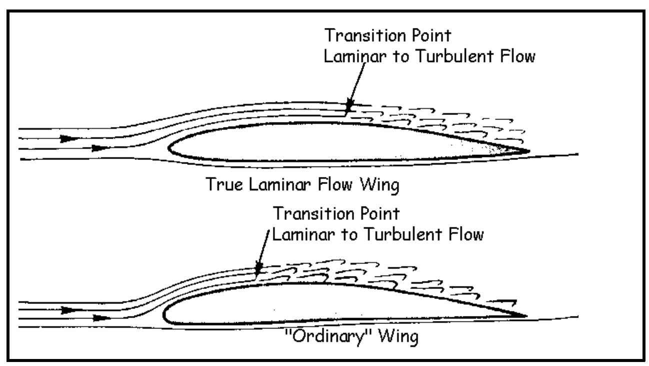
Examples:	**Area**	**Span**	**Aspect**	**L/D**
Schleicher Ka7	17.6 m^2	16 m	14.6	26
Schleicher Ka8b	14.2	15	15.9	27
Schleicher Ka6e	12.4	15	18.1	33
Schempp-Hirth Austria	13.6	15	16.7	34
SH Open Cirrus	12.6	17.7	25	44
SH Nimbus 3	24.5	16.7	35.9	60

Dynamics of Properties of a Wing

Air flows over the wing and adhers to the surface in a thin layer. (boundary layer) The air farther from the surface then only rubs this thin layer of air. If the flow is smooth, there is laminar flow (air flow is layered). Toward the rear of the airfoil the boundary layer gets thicker as the air slows due to frictin. When the speed is slow enough and pressure is lower, the layer will be lifted from the surface and become turbulent. Under these conditions the wing loses lift in the turbulent region.

As the airspeed increases or the angle of attack increases the transition point on the wing moves forward. Laminar flow airfoils are designed to keep the transition point farther back on the wing. Turbulence destroys the pressure differential on the wing and the downwash of the air aft of the wing. This reduces the lift and when reduced enough, the wing will stall.

Vortices or circular motion of air occurs over the wing and behind the wing. These vortices have energy associated with them but do not provide lift. As a result wings are best designed to have as small a vortices as possible - this is the

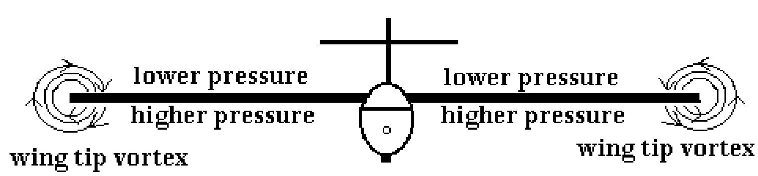


reason that long wings have better efficiency.

__Wings and Control Surfaces__

Flaps and Ailerons

Flaps are moveable parts of the wing that change the airfoil geometry during flight. Flaps generally increase the camber of the wing to increase the lift of the wing and the stall speed is decreased. However, the drag is increased and the wing is less efficient.



Ailerons are like flaps and change the airfoil of the wing. However, unlike flaps, there do not move in the same direction on both wings but in opposite directions. One aileron extends down below the airfoil to increase camber and lift. The aileron on the opposite wing rises and lowers the camber or streamlines that part of the wing to lower the lift. The result is that the first raises and the second lowers the wing .

Rudder and Elevators

There are three axes of motion for a sailplane. The ailerons move the craft in roll. Rudder is on the vertical stabilizer and move the creft in yaw. The elevators are on the horizontal stabilizers and provide movement in pitch.

Bank and Turn

Lift of the wing is used to turn all aircraft. This is done by banking the aircraft so that the lift force points in the

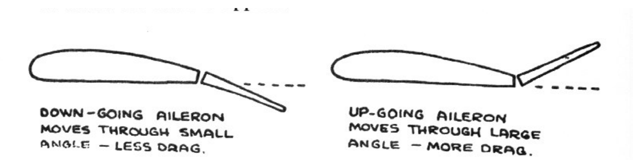
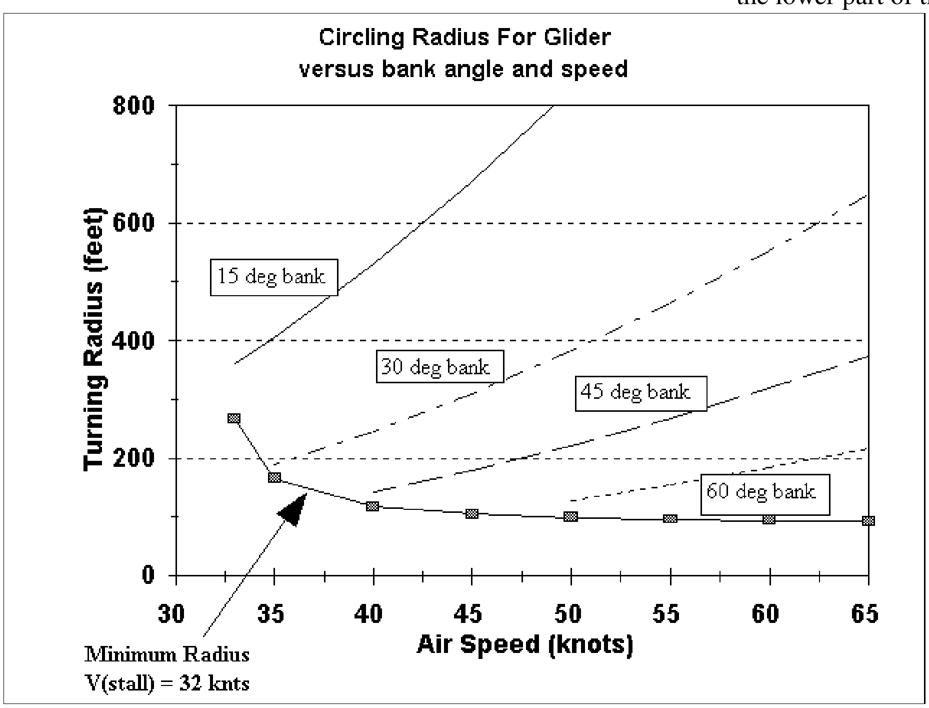


Fig. 12. Differential Ailerons.

direction you want to go. As long as the craft is in a bank it will keep turning. During that time the ailerons are nearly in their neutral postion (more later on this)

In order to maintain horizontal flight, the lift force component in the vertical direction must be equal and opposite to the weight the aircraft. This means that the lift itself must be larger than that in straight and level flight. The necessary lift can be obtained by (1) increasing the angle of attack of the wing, or (2) by increasing the airspeed of the glider. Since the lift and hence wing loading is larger in a bank, the glider stalls speed increases.

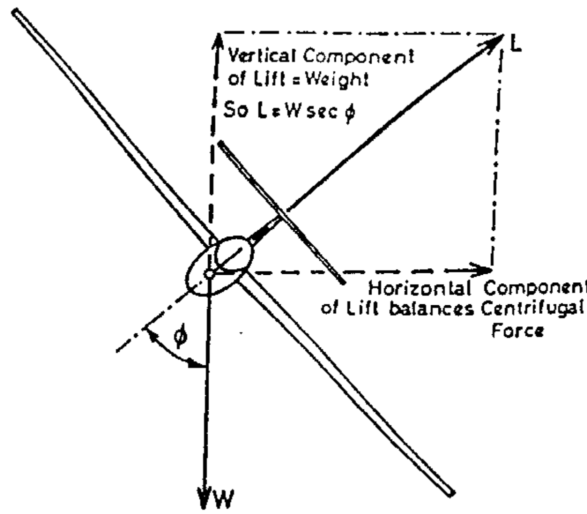


Increasing the angle of attack to gain lift will slow the glider so the pilot must increase speed to gain lift and avoid stalling the glider. The relation between speed, bank and lift is given by the following:

W = L cosine(bank angle)

The following table show how the lift force must be increase with bank angle.

Bank Angle	Cosine	L/W
0	1	1
15	0.966	1.04
30	0.866	1.15
45	0.707	1.41
60	0.500	2.00



The complete relationship between turning radius, bank and speed are summarized in the graph. The stall limit line in the lower part of the graph determines the smallest circle that the glider can make and remain flying.

Note that in a coordinated turn the pilot feels his weight directly equal and opposite the lift force. You can not determine that you are in a turn unless you look at the horizon. The only other indicator is that you will feel heavier. In a bank of 45^o you will feel 40% heavier; while at steep bank of 60^o they are twice as heavy . The aircraft's stall speed increases with increased bank and equals Vs times sqrt(load factor).

Secondary Effects of Ailerons - Adverse Yaw

When the ailerons are deflected to go into a bank and turn the drag of each wing is affected.

Down Aileron raises wing increases drag

Up Aileron lowers wing decreases drag

This not only puts the glider in the banking turn, but because of the differential drag of the wings, pulls the glider in yaw towards the higher drag wing (the upper one). The glider yaw away from the turn. This has to be countered by applying rudder (yaw) in the direction of the turn.

When thermalling there is a great advantage of turning in the smallest radius circle as safely possible. The graph to the on the previous page shows the affects of airspeed and bank angle on the turning radius. Fly as slowly as possible and as steeply as practical. Remember, because of the increased lift required at steeper banks your drag increases and your glide ratio deteriorates.

APPENDIX: Polar and Glide Distance Graphs

The name 'polar' is traditional and comes from the fact that the data used to be plotted versus angle of attack on polar graph paper.

The 'polar' is really a plot of sink rate of the glider versus airspeed. The sink rate is a velocity down and is plotted as negative. The sink rate has a minimum which is 'min sink'. In the 'polar' to the left the min sink of the Ka8 is at the top of the curve at about 35 kts.

The gliders lift over drag or L/D value for any speed equals the ratio of the airspeed to the sink rate. The L/D versus airspeed is derived from the polar and plotted in the second set of curves called 'glide ratio'. Note that the maximum L/D for the Ka8 is at a higher speed (40 kts) than the min sink

The rate of sink of a glider comes from two energy loss mechanisms. (1) The instrinsic friction or drag of the sailplane surface in the air. (2) The 'induced' drag due to the energy loss by giving the push to the air downward. It is the two of these together that produce the shape of the 'polar' curves.

The performance of a glider in all instances of turning, winds, sinking air, etc can be determined the from the glider's polar curve. Only if you understand the polar curve can you get the best performance from the glider you fly.

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