Pilot Manual

2- Aerodynamics

Association of Paragliding Pilots and Instructors

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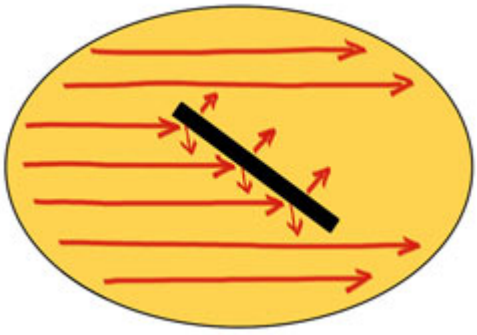
2.1 - The reaction force

Theory of flight - it is still a theory with some unanswered questions but certain facts the experts agree on. You can also read Nasa's website for more details.

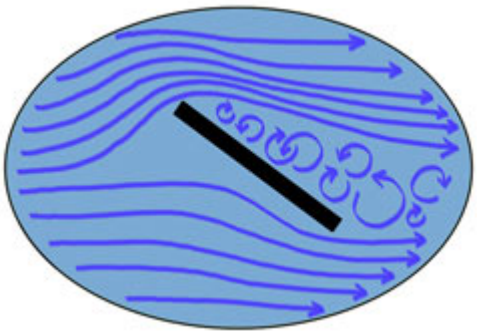
A basic principle of physics.

Newtons third law: For every action there is an equal and opposite reaction
The reaction force.

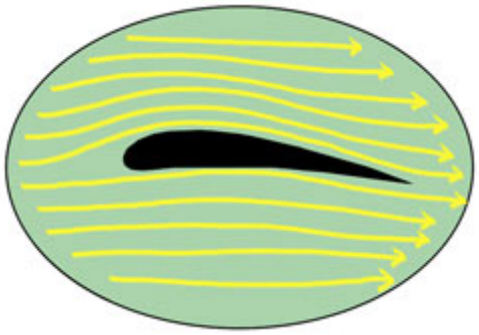
Example - Testing: We place a thin plate in a flow of air particles. If the plate is placed through the flow, the particles hit the plate on one side and bounce being deflected. For every change of impetus of a particle, a corresponding force acts on the plate: the reaction force. This force acts on the plate and generates a component that is not in the flow direction: the dynamic lift.



The other side of the plate ''is lacking'' of deflected particles, which means there is a depression on that side. This creates a vortex volume called: the drag flow.



In contrast to a plate, a wing profile that deflects an air flow does not produce a high vortex volume and so a high lift and a low resistance follow. Both upper and lower surfaces generate lift.



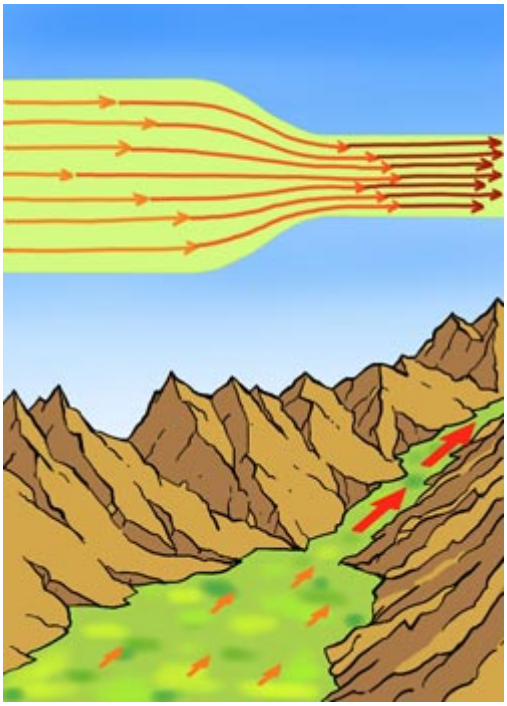
2.2 - Stream lines

A flow process that can be roughly represented by parallel trajectories, is known as laminar flow. On the contrary if whirlwinds occur, the flow is called turbulent.

When the flow parameters, such as speed or pressure, are in a given place and time and are constant, it is called **steady flow** and the particles trajectories are called **streamlines**. All particles move in the direction of streamlines.

A bundle of streamlines is called **stream tube**.

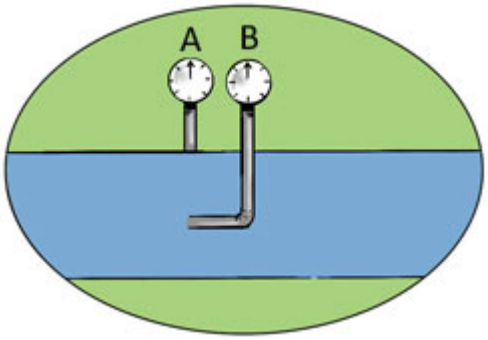
2.2.1 Speed and section



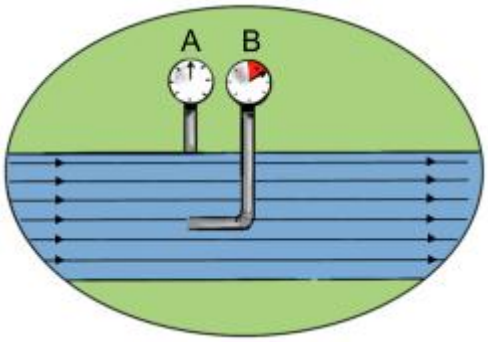
Changing the geometry of a stream tube causes changes in the air flow speed. Indeed, in all places and per unit of time, the same volume of particles must flow. So, when there is a narrowing the speed increases and the pressure lowers (Venturi effect).
Example: When the wind blows consistently in a valley with a regular section, its speed increases at the place where the valley tightens.

2.2.2 Static pressure and dynamic pressure

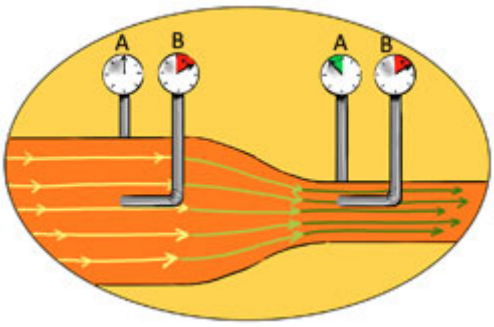
Inside a still tube of air, there is the same pressure in all directions. The barometers A and B indicate the same values.



But when the air moves along the tube with some speed, it forms a stream tube. The B indicator measures a pressure higher than A. A always shows the same pressure as in still air. The difference is obviously caused by the movement of air. The additional pressure is called **dynamic pressure**. A measures the **static pressure**.



2.2.3 The Bernoulli law



The simplified form of Bernoulli's equation can be summarized as:
static pressure + dynamic pressure = total pressure
total pressure is constant along a streamline.

Static pressure (p) + Dynamic pressure (q) = total pressure p0

This constant is called the **total pressure** or ``**impact''** **pressure** (measured by the barometer B).
The flow theory gives a simple equation to the dynamic pressure q:

$$q = \frac{p.v^2}{2}$$

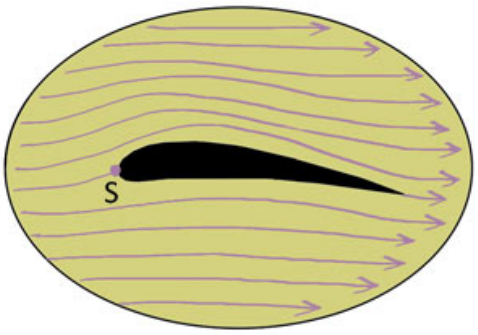
p: air density
v: flow speed

As speed increases, the dynamic pressure also increases and the static pressure decreases.

Testing the Bernoulli law: Take two pieces of paper. Hold both gently in front of your mouth. The stronger you blow between the two pieces of paper the more they come together. The flow speed increases and the static pressure between the paper decreases and becomes lower than the static pressure outside.

2.2.4 Stagnation point

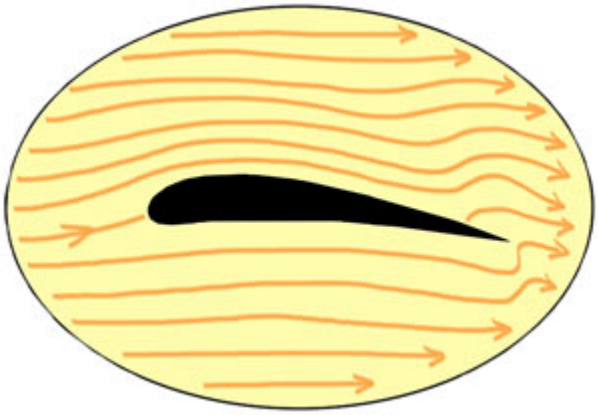
If the fluid flow at some point along a stream line is brought to rest, this point is called a stagnation point (**S**), and at this point the total pressure is equal to the stagnation pressure, from there the flow is divided on both sides of the body.



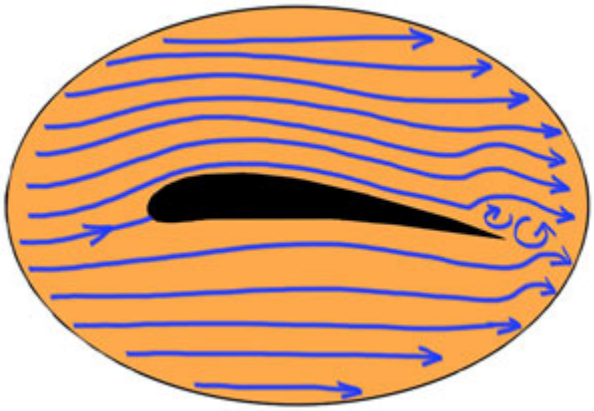
On a paraglider, the leading edge opening is in the area of the stagnation point. Thus the internal pressure corresponds to the total pressure. The higher the flow velocity is the higher the pressure will be inside the glider.

2.3 - The flow around the profile

If the air flow speed is too low, a wing will not produce any lift. The trailing edge may be so quickly surrounded by the flow that no deflection of the stream appears.



At a higher flow speed, the sharp trailing edge is no longer surrounded by the flow and a turbulence is formed, the **attached vortex**. This turbulence detaches from the flow stream that no longer runs in the general flow direction but takes the direction of the profile rear. The air flow is then deflected and according to the reaction force principle, the wing produces a dynamic lift.



2.3.1 Drag

Drag acts in a direction that is opposite to the motion of the aircraft. Drag is generated by the difference in velocity between a solid object and a fluid. If there is no motion, there is no drag.

It is made up of different types of drag.

Parasitic drag: consists of form drag which is the air moving over the object and skin friction which is the boundary layer which forms between the object and the flow.
Parasitic drag increases with speed (example put your hand out of a car window and when the car increases speed the pressure against your hand increases - this is parasitic drag) The more streamlined the shape the less drag is created.

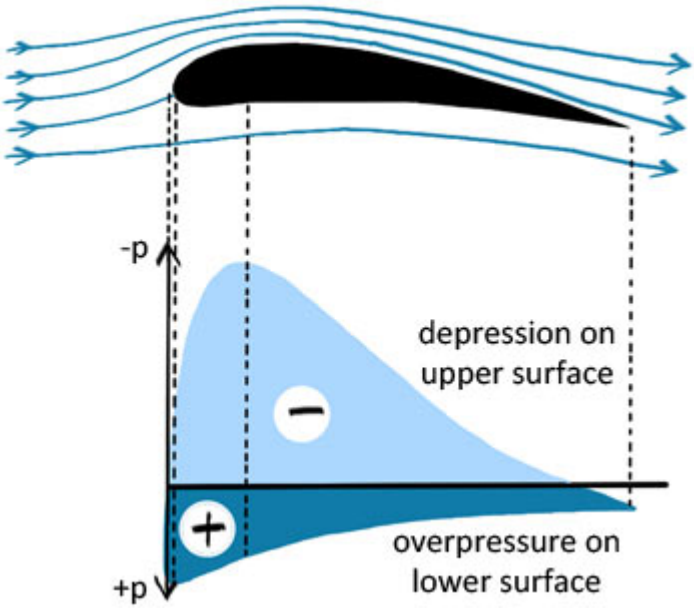
Induced drag
"drag due to lift"
For a lifting wing, there is a pressure difference between the upper and lower surfaces of the wing. Vortices are formed at the wing tips, which produce a swirling flow that is very strong near the wing tips and decreases toward the center of the wing. High aspect wings (long thin wings) create less induced drag than low aspect wings. Induced drag increases in low speeds with a high angle of attack as bigger wing tip cortices are created with a larger pressure difference between the top and bottom surface.

Induced drag decreases with speed.

2.3Total drag

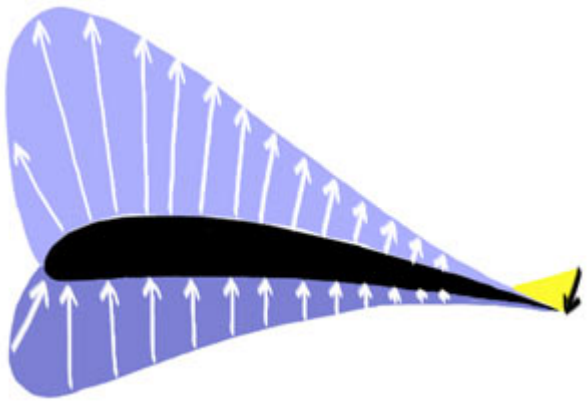
Because parasitic drag increases with speed and induced drag decreases with speed there is an airspeed when total drag is at its minimum and that is airspeed you should fly at in still air to get your best glide angle.

2.3.2 The lift distribution on the wing profile

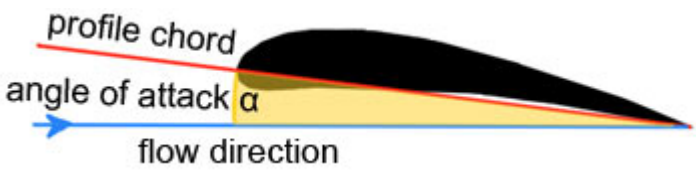


On the wing upper surface, the streamlines are closer to each other than on the lower surface. This presupposes a higher speed, which is indeed the case. According to Bernoulli, there is a **low**on the upper surface of the wing, and an **high** on the lower one.
With an angle of attack of about 10°, 2/3 of the total lift are produced by the upper surface depression and only 1/3 by the lower surface overpressure. The pressure distribution in the profile depth shows that most of the lift is located on the wing front.

The pressures are forces per surface unit. These forces act perpendicularly to the profile surface.

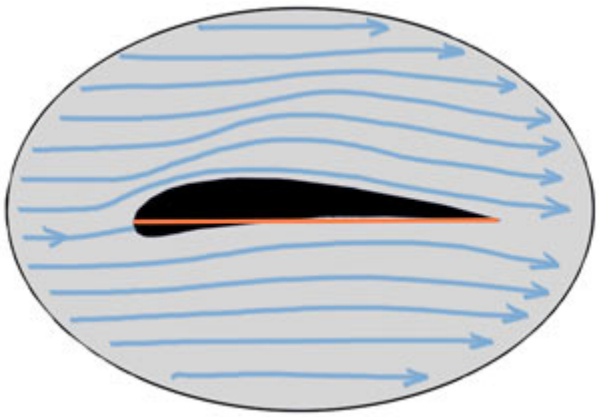


2.3.3 The angle of attack and stall

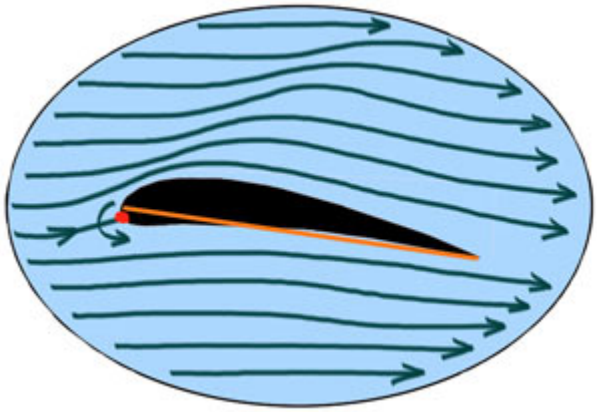


The line that connects the most prominent point of a profile with the one located the furthest back is called the **profile chord**. With the flow direction it forms the **angle of attack** (or angle of incidence).

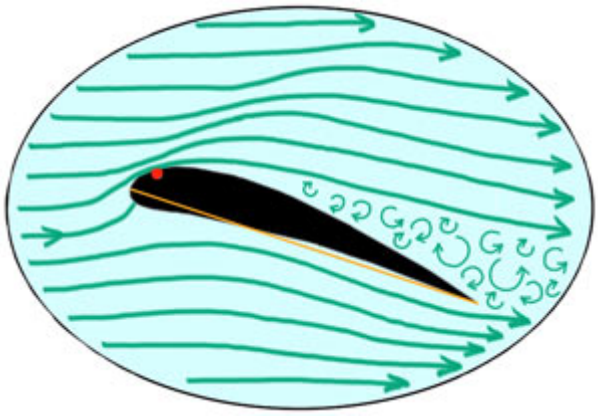
An asymmetric profile with an angle of attack of 0° is still deflecting airflow and producing lift. Only with a negative angle of attack (e.g., -4°) the lift becomes zero.



With the increase of the angle of attack, the stagnation point moves on the wing lower surface towards the trailing edge. The leading edge opening should always match with the stagnation point location (see 2.2.4).



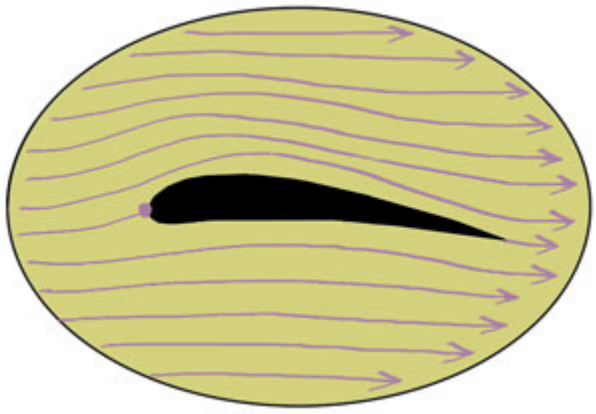
When the angle of attack is increased beyond a critical value (magnitude 15° - 20°), the flow is detached from the upper surface: ***stall*** . Between the detached airflow and the wing, the air is turbulent, the drag increases dramatically and the lift weakens. The point on the profile where the flow of air is detached is called the ***separation point*** .

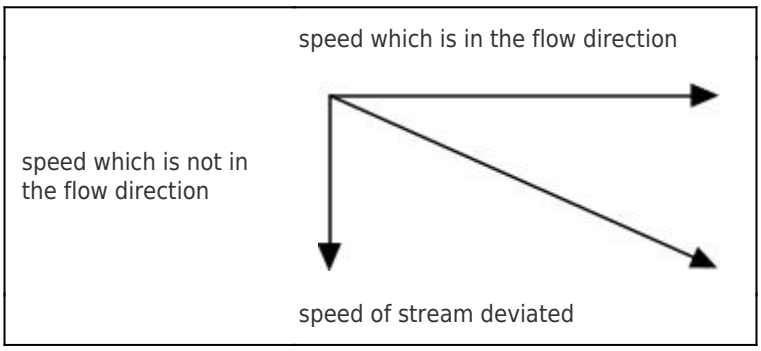


The gliders are manufactured in such a way that the flow drops first to the wing tip. This is achieved by providing a substantially higher angle of attack to the end parts of the wing. When a wing has several sections with different angle of attacks is called the spin of a wing.

2.4 - The flow around the wing

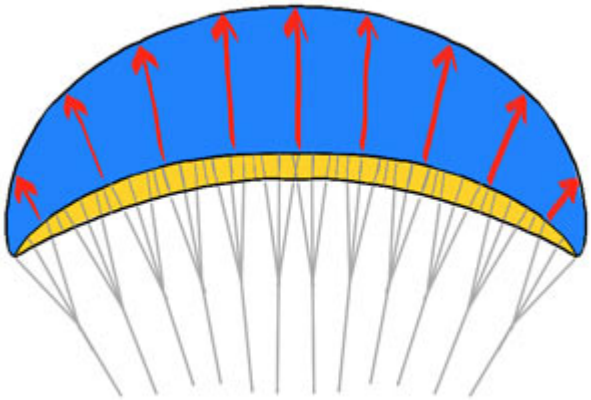
So far, only the air flow at the profile level has been studied as if it was a two-dimensional flow, or in other words, as if the wing had a infinite span.





The air deflection connected with the production of dynamic lift, can be represented by a speed component that has not the same direction as the original flow speed. According to the principle of the reaction force, it’s not just the value of this component that is decisive for the lift intensity but also the amount of air (air mass) per unit of time that undergoes this change of speed, that is to say this also depends on the span.

As the span is not infinite, compensatory flows from the lower to the upper surface appear at the wing tips. This causes a reduction in the lift at the wing tips.



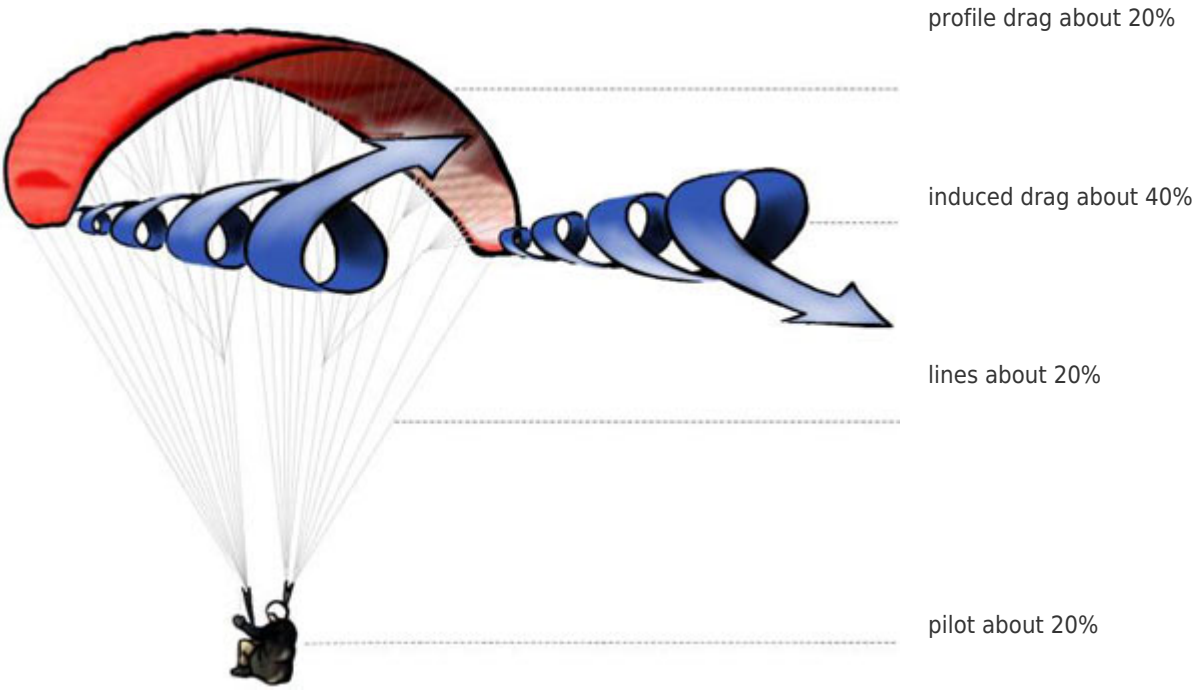
Compensatory flows do not only diminish the lift, but they also produce marginal whirlwinds.

2.4.1 The induced drag

Behind the wing and over the whole span there is a velocity component that has not the same direction as the flow (a ``descent''). The resulting speed of the deflected air is greater than that of the air flow. Thus, the air mass behind the wing has a greater kinetic energy. The continuous physical work needed to keep it (formation of marginal vortices included), is manifested by an additional resistance: the induced drag.
It's not the span that we need to consider for a good ratio of lift and induced drag, but the ratio of span and profile depth (average): the larger the span, the smaller the induced drag.

2.4.2 The total drag

The total drag of a wing consists on the profile drag (shape drag and friction drag) and induced drag. However, beyond the wing, a glider consists on other sources of drag that do not produce lift (pilot, suspension lines).



- A wing that generates lift, also produces drag.
- The larger the aspect ratio, the smaller the induced drag.
- Every wing produces also drag profile.
- The lift produces ``vortex furrows'' behind each wing.

Advice: do not fly too close behind another glider!

2.5 - Lift and drag formulas

A body in a flow undergoes some forces. In the flow theory, a force that acts perpendicular to the flow direction is called lift and the one that acts parallel to the flow direction, is called drag.

The two forces are dependent on following factors:

- **The flow** - Density of air **p**
  - Velocity **v**
- **The body** - Exposed surface **S** (size)
  - Coefficient **c** (shape)

$$\text{lift} : \mathbf{F}l = \mathbf{c}z.\frac{p.v^2}{2}.\mathbf{S}$$

$$\text{drag} : \mathbf{F}d = \mathbf{c}x.\frac{p.v^2}{2}.\mathbf{S}$$

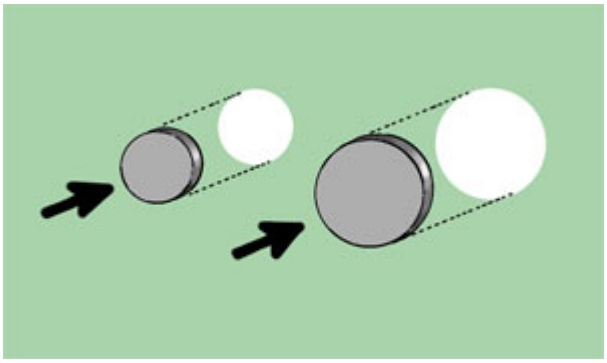
2.5.1 Air density and speed

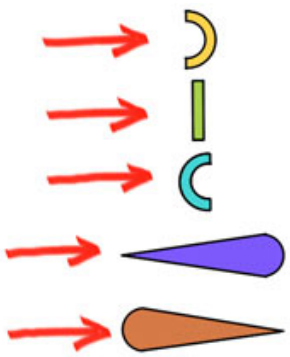
The lift and the drag vary proportionally to the air density and proportionally to the speed square. Air with density reduced by half (e.g., at 6600 m) produces half the drag and lift. Double speed creates a lift and drag four times larger.

Tip - mountain flight (example):
At 4000 m the air density is 2/3 of the one at sea level. As a result of such conditions at this altitude, the lift and drag are also reduced to 2/3. To get the same lift and drag as at sea level a greater speed is needed. So the factor is not 3/2 = 1,5 but only 3/2 = 1,22. A speed of about 20\% larger is required (at take-off as well).

2.5.2 Exposed surface (of frontal area) and shape coefficient

The exposed surface is the surface projected in the flow direction, that is to say, the effective surface perpendicular to the flow direction. For bodies that have the same shape (same coefficient) the resistance varies in the same proportion as the projected surface.
Doubled surface → doubled resistance.



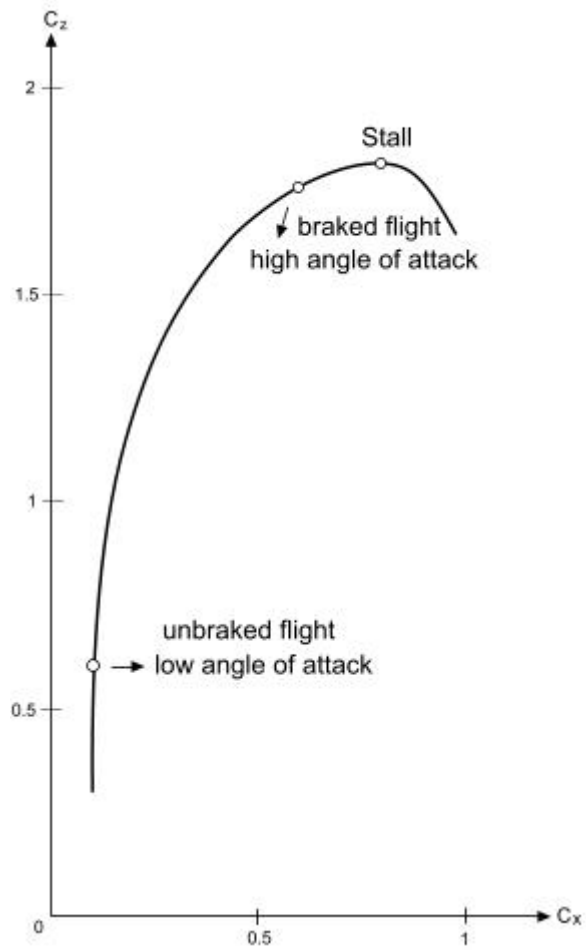


cx = 1.3
cx = 1.1
cx = 0.3
cx = 0.2
cx = 0.1

Depending on the object shape, the air undergoes different disturbances. With an increasing vortex volume, the shape drag also increases. Moreover, because of friction on the object surface, extra drag appears. These influences, including the flow situation, are represented, for every object, by the coefficient Cx.
In the left image: All objects have a circular section.

2.5.3 Exposed surface and wing coefficients

The exposed surface is the wing surface. The projected surface varies indeed with the angle of attack, although this factor is already included in the coefficients.
The Lilienthal Polar Diagram, represents the ratio between the lift and drag coefficient. Each point on the curve corresponds to a specific angle of attack. The curve tends to the right because when there is an increase of the angle of attack, the drag coefficient Cx does not vary in the same proportion as the lift coefficient Cz, but much faster. Although the simultaneous brake traction on a paraglider does not only vary the angle of attack but also the profile, this parameter remains roughly exact.



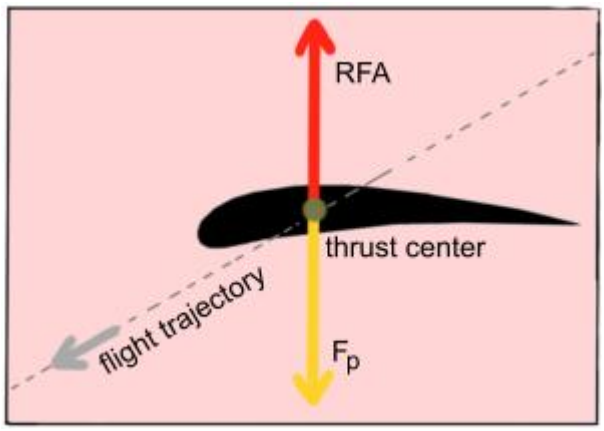
	Lift coefficient	Drag coefficient	Lift/drag ratio
Unbreaked flight	0.6	0.1	6
Breaked flight	1.6	0.5	3.2

2.6 - Gliding flight

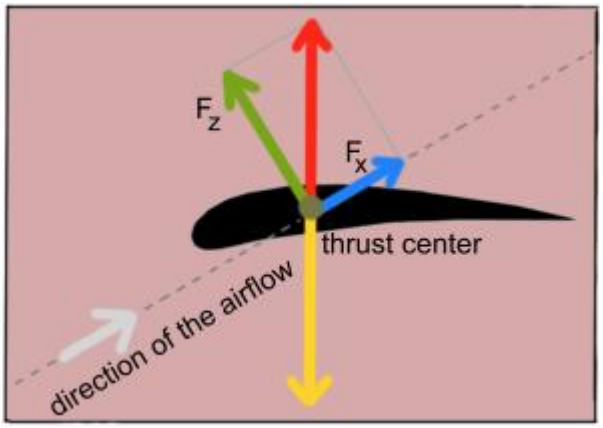
2.6.1 Forces balance in gliding flight

Inertia law: Every body preserves its immobility state or uniform rectilinear motion, as long as some forces do not push it to change.

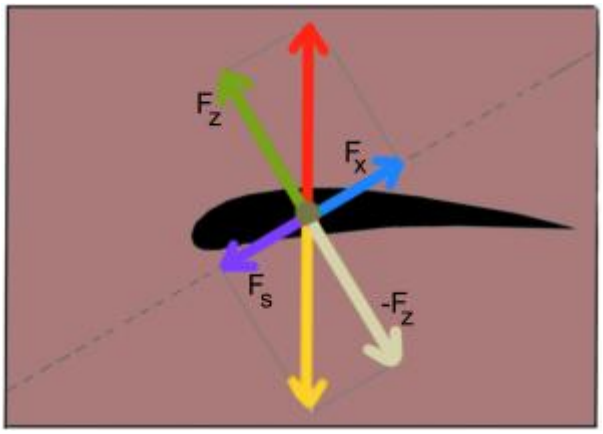
The result of all forces acting on the wing is called **the resultant aerodynamic force**. Its applying point is called the **center of pressure**.
Since a paraglider flies with no motorized force it always reaches, in a straight flight (according to inertia law), a balance between the resultant aerodynamic forces (RAF) and the total weight Fp.
This balance is called: the stationary flight.



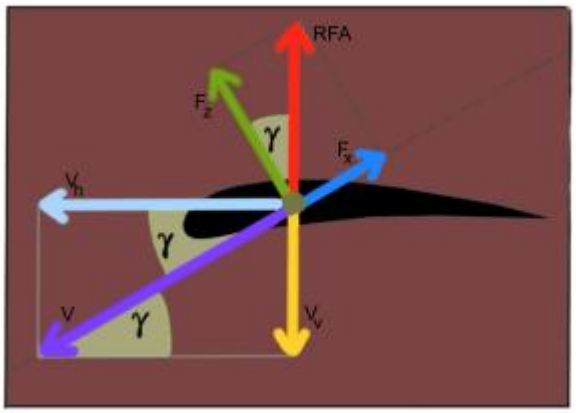
The resultant aerodynamic force has two components, the **lift** (Fz) and the **drag** (Fx).
The drag acts in the air flow direction, and the lift perpendicular to this one.
The flow direction is opposite to the trajectory.



The total weight can be considered the result of two components which are the forces opposed to drag and lift. The component opposed to the drag is called the **thrust** (Fs). The force opposed to the lift has no particular name.



2.6.2 Glide angle and ratio



The angle between the trajectory and the horizontal is called the **glide angle**. It's the same angle as between the flight speed (V) and horizontal velocity (Vh).

The resultant aerodynamic force and the lift form the same angle as the glide angle.

Because of angles equality, the proportions of these angles, respectively their values, must be equal as well:

$$\frac{\text{horizontal speed}}{\text{vertical speed}} = \frac{\text{lift}}{\text{drag}}$$

This proportion is called **ratio**.

The formulas for lift and drag are the same except for their respective coefficient (see 2.5). Therefore the lift-drag proportion is the same of lift coefficients -drag coefficients proportion.

It can be summarized as follows:

$$\text{ratio} = \frac{\text{horizontal speed}}{} = \frac{\text{lift}}{} = \frac{\text{lift coefficient}}{}$$

vertical speed drag drag coefficient

Tip: A paraglider of ratio 6 has a lift coefficient 6 times larger than the drag coefficient (for a corresponding angle of attack) and so the lift is 6 times larger than the drag. Moreover, since the horizontal speed is 6 times the vertical speed, the paraglider can fly (in still air) for a drop of 1000 m 6 km away.

Example of ratio and corresponding glide angle:

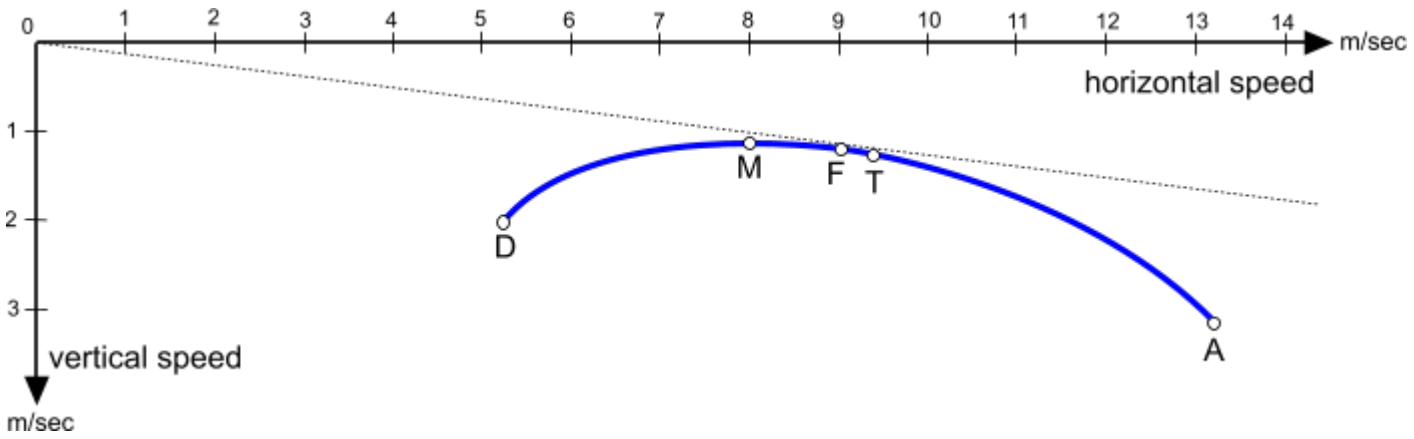
Ratio	2	3	4	5	6	7	8
Glide angle	26.8	18.4	14	11.3	9.5	8.1	7.1

Tip: When changing the total weight during flight, the set of forces and speeds change in the same proportion. A greater total weight causes a higher flight speed. The ratio remains theoretically unchanged. But practice shows that due to aerodynamic elasticity (because the glider does not form a rigid but a flexible airfoil), the profile and, consequently, the ratio, change when there is a change of weight. It is for this reason that pilots of different weights don't fly that far from one another with the same kind of gear and under identical conditions.

When using the brakes, the angle of attack increases and the drag coefficient becomes larger (see 2.5.3) than the lift coefficient. The result is a different ratio and, due to drag increase, a smaller speed. If we strongly pull brake controls, critical angle of attack is exceeded and the air flow drops (stall see 2.3.3.). Indeed, with the critical angle of attack is also given the corresponding speed and we have then what is known as the minimum flight speed that is just before the stall point.

2.6.3 The speeds polar curve

The speeds polar curve represents the proportion between the horizontal speed and the vertical speed. It also informs on the ratios and describes all possible gliding flights, but it is not valid for turning flights. The polar is a function of the paraglider and the load. When the wing load is given, the speeds polar and the Lilienthal polar are reciprocal.



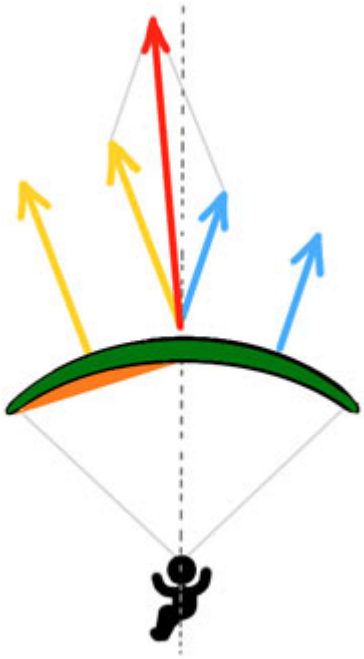
- **Point T**: ``trim speed'' - gliding flight with no brakes applied; displays in normal position
- **Point A**: ``accelerated flight'' - maximum speed
- **Point F**: maximum ratio - can be graphically determined by tracing a tangent to the polar from the origin 0.
- **Point M**: minimum sink rate - M is the polar peak point
- **Point D**: ``minimum speed'' - pulling the brakes causes stall

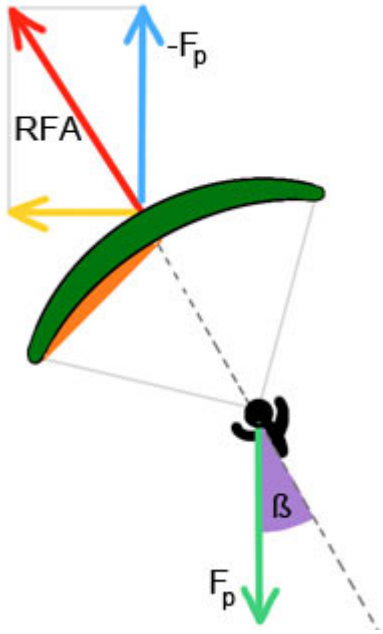
Tip: Using a vario and an anemometer, one can, by flying in an absolutely calm air mass, determine the polar values.

2.7 - The turning wing

2.7.1 Set in turn (described in a reference system at rest)

When pulling a single brake control, the lift and drag coefficients as well as lift and drag, increase in one half of the wing.
The resultant of this half of the wing is larger than the unbraked side.
Therefore the total resultant has a horizontal component directed towards the turning center.
The glider tilts and starts turning.
The pilot mass, according to the inertia law, would tend to go straight down but it is driven in turning by the horizontal component; it follows an inclination of the all system.





Pulling and holding the brake control, the tilt increases until it reaches a uniform turning flight (it's called uniform turning flight when the vertical speed is constant and the movement projects a circular motion with constant rotational speed onto the horizontal plan).
There is no balance of forces.
The weight (Fp) is compensated by the vertical component (-Fp) of the resultant aerodynamic forces (RAF).
The horizontal component provides the circular motion.

Because of the horizontal component, the resultant aerodynamic force is greater than in gliding flight. It is possible, despite the coefficients change, with an automatically increased speed. (An increase of minimum speed).

2.7.2 The turning wing (description in a rotating system)

The pilot receives a **centrifugal force** (Fc) when the wing is turning.
The centrifugal force resultant (Fc) and the weight is called the apparent weight (Fa). The relation between the apparent weight and the weight is called the load factor. (The pseudo unit G is sometimes used as a load factor unit, e.g., 2G.)

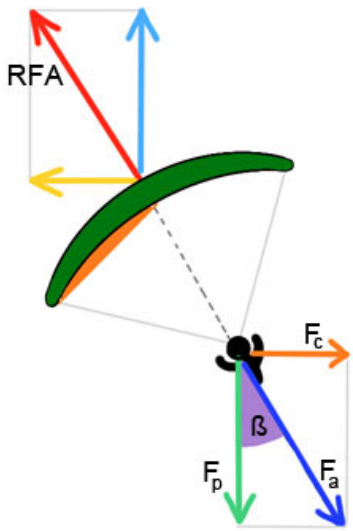
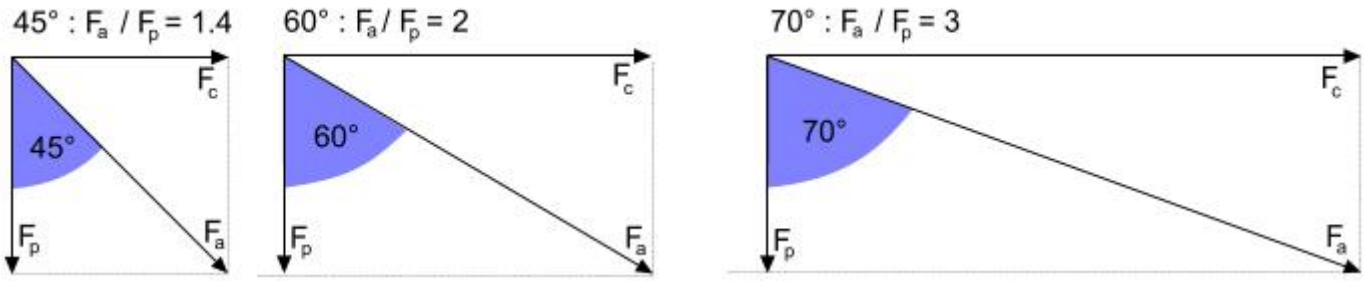


Figure 2-34: Example of load factor: Fa: Weight apparent, Fp: Weight, Fc: Centrifugal Force.



2.8 - Stability and Instability

An aircraft disturbed in its uniform motion can react in different ways:

- **Stable**: After disturbance (e.g., after an extreme maneuver interruption or after tuck), it returns, oscillating, to its original motion.
- **Indifferent**: It remains in its new movement (e.g., a twist that does not stop).
- **Unstable**: The imbalance is increasing. The aircraft rolls away from its original position (e.g., a wing auto-rotating faster and faster).

A safe aircraft is recognized by its high self-stability. The glider gets its stability mainly from the low position of its gravity center. As a result, strong forces act on the horizontal and the cross axis which place the system, after a flight control or imbalance, again in its original situation. Stability is other dependent of the wing load (see 1.2.6).

> **Tip: Attention near the ground**. Despite the high stability, abrupt maneuvers can cause strong pendular movements along with an increasing sink rate and tuck danger.

axis: horizontal
stability : lateral
movement: rolling
axis: transversal
stability : longitudinal
movement: pitching
axis: vertical
stability : the way
movement: yaw