AERODYNAMICS AND FLIGHT MECHANICS

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Vectors

A vector is a representation of certain physical phenomena characterized by a magnitude, direction and point of origin. Two examples useful for the paragliding are (1) force and (2) speed. To characterize these two phenomena requires knowledge of the magnitude, for example a force of 10 kg or 16 kg and a speed of 35 km/h, their origin (center of the object that is acted upon) and direction (in 2 or 3 dimensions).

To graphically represent the two phenomena we use vectors depicted as arrows (or lines).

Length of vector = magnitude of physical phenomenon. If the scale is 1 cm = 10 kg represented graphically, a vector of 3 cm will then correspond to a force of 30 kg.

Origin of a vector = end without the arrow. For example, this is the point of application of force.

Direction of a vector = shown by the orientation arrow.

Example (Figure A1): In depicting on paper a speed of 30 km/h by a vector V, applied on the object X (center of the object = X ') heading is north west.

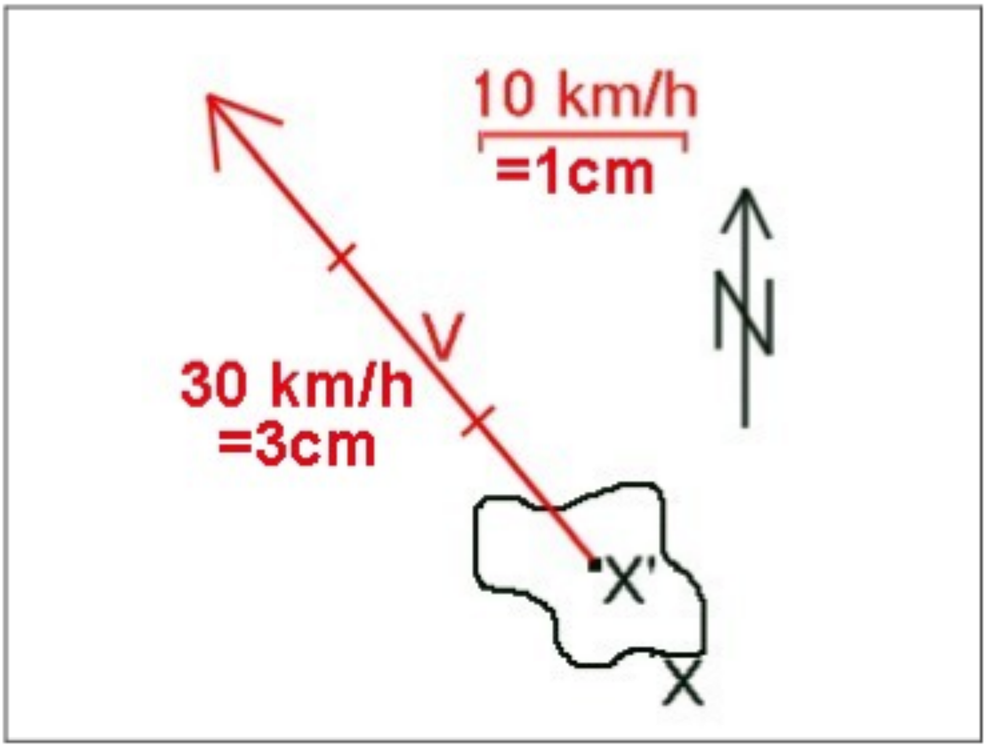


Figure A1: Example of a vector V representing a speed. If 1 cm represents an arbitrary 10 km/h then 3 cm = 30 km/h . V goes to the NW and applies to the object X to point X '.

When two vectors V1 and V2 act on an object, it effect is the same as if it were only acted on by the resultant vector R. This is called adding the two vectors. We cannot simply add up their length because it ignores the directions. Figure A2 shows the technique to add these 2 vectors.

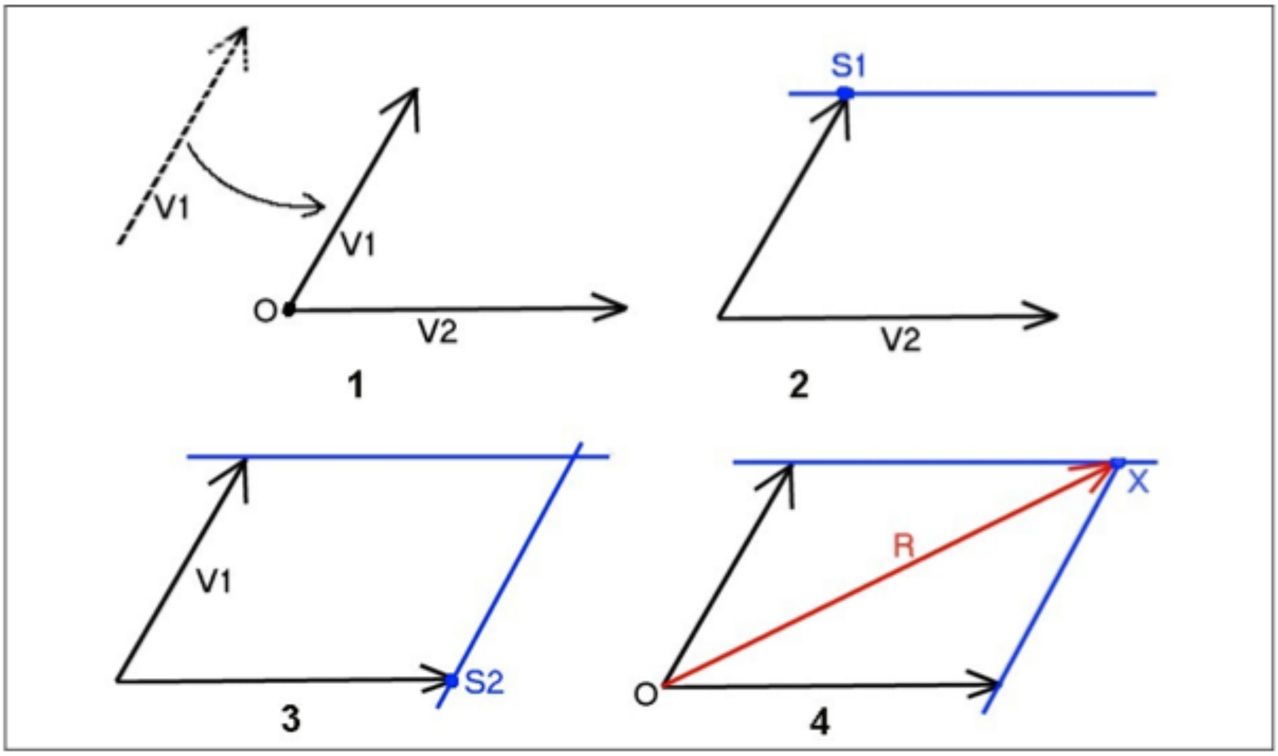


Figure A2: (1) Re-position V1 without changing orientation, so that the two origins of V1 and V2 coincide. (2) Draw a line parallel line to V2 (shown as S1). (3) Draw a line parallel to V1 (shown as S2). (3) The resultant vector R has its origin O and ends at the intersection X of the two parallels S1 & S2.

Special cases: (1) Two vectors have the same orientation and the same direction, in this case simply add up their magnitudes. (2) Two vectors have the same orientation but opposite directions, then the resultant is the difference of the two vectors.

For the **5 questions 001 to 005**, the same basic chart is used: See Figure A3. On the left there are 5 examples of vectors F1 to F5. On the right there are 4 examples of resultant vectors R1 to R4.

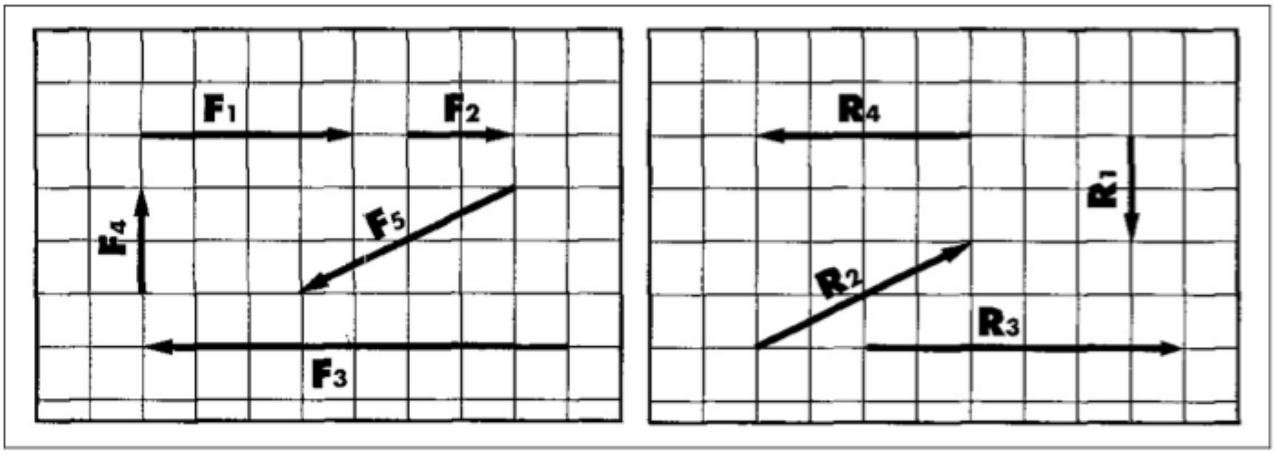


Figure A3: the basic graphic used for questions 1 to 5 (aerodynamics) of the SHV/FSVL paraglider pilot theory examination.

Question 001. Addition of F1 and F2. This is the special case where two vectors are parallel in the same orientation. See Figure A4. R corresponds to R3 Figure A3

Figure A4: addition of F1 and F2

Question 002. Addition of F1 and F3. This is the other special case where two vectors are parallel and in opposite. See Figure A5. R corresponds to R4 of Figure A3.

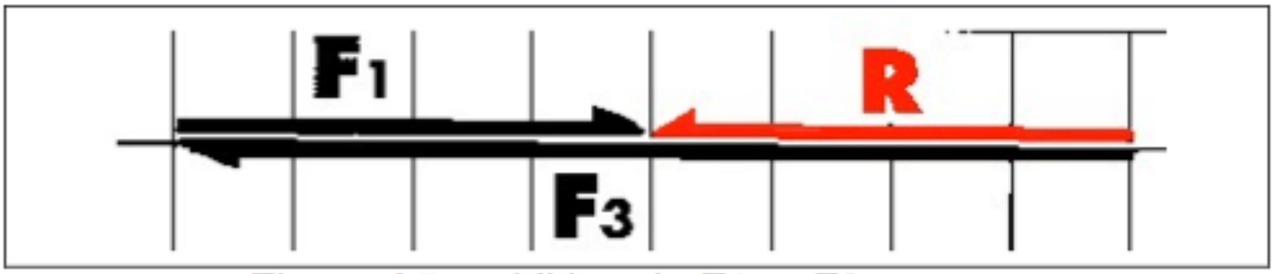


Figure A5: addition of F1 and F3

Question 003. Addition of F1 and F4. See Figure A6. R corresponds to R2.

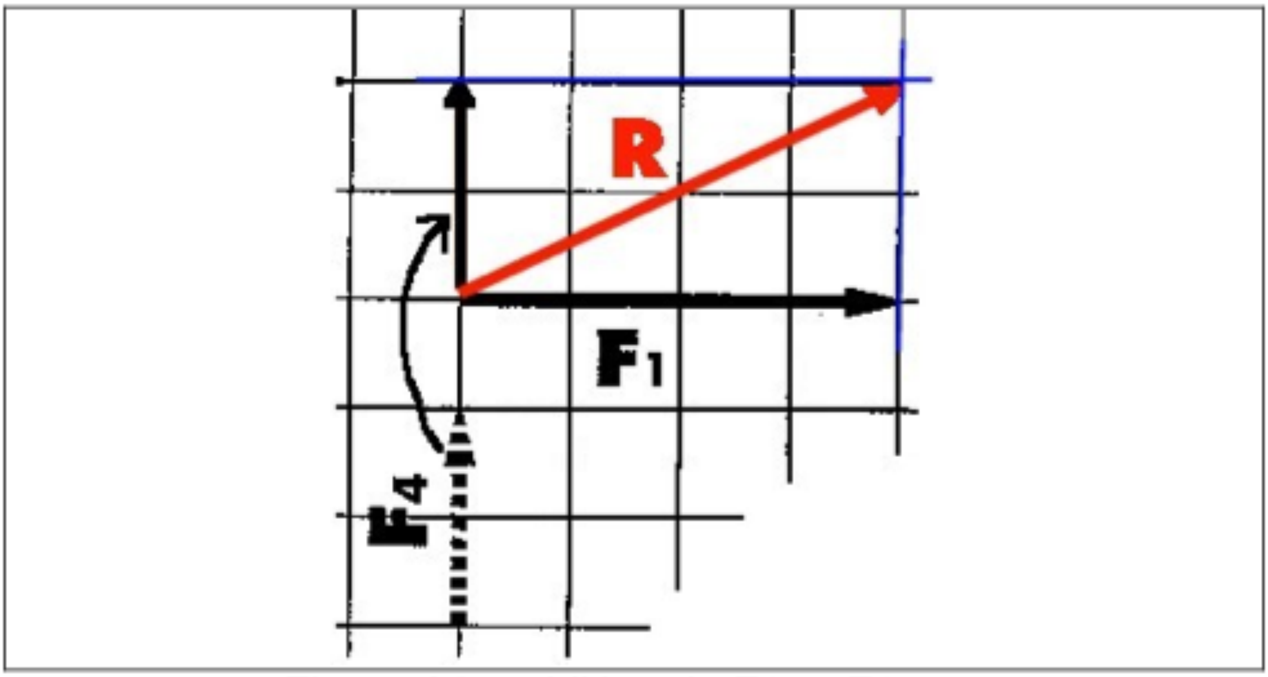


Figure A6: Addition of F1 and F4

Question 004. Addition of F1 to F5. See Figure A7. R corresponds to R1.

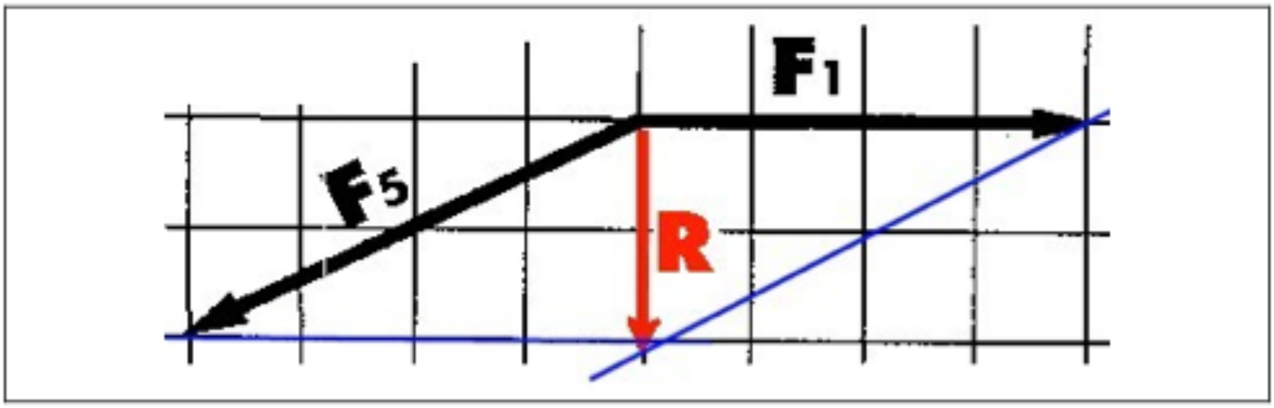


Figure A7: addition of F1 and F5

Question 005. Addition of F4 and F5. See Figure A8. R corresponds to R4.

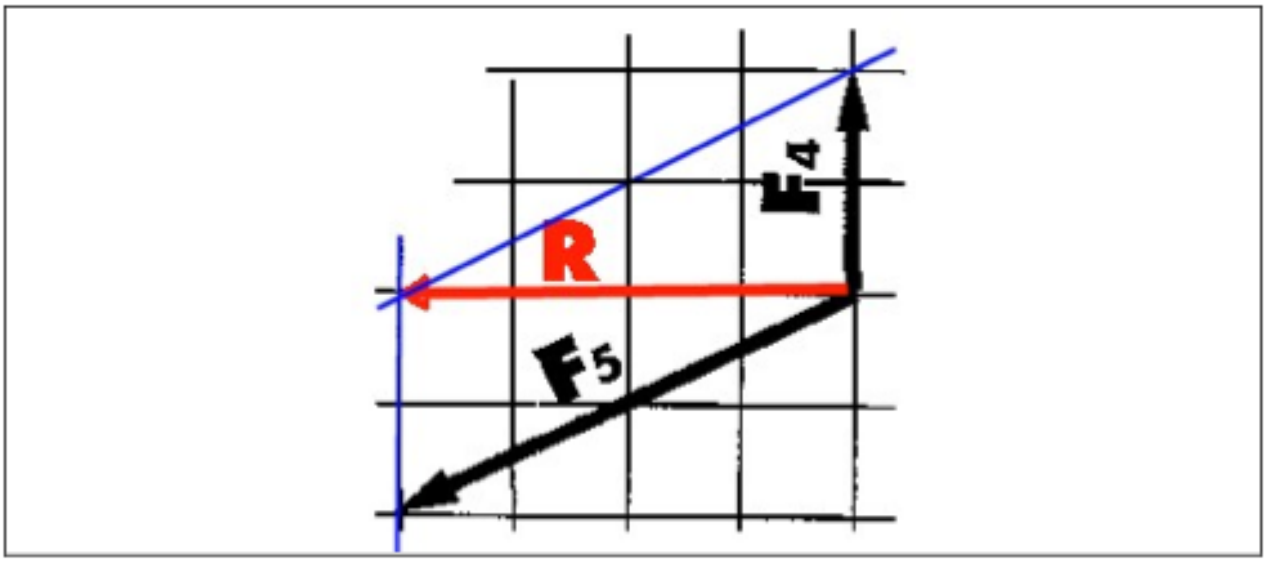


Figure A8: Addition of F4 and F5

Note: You can add as vectors of the same type: eg two vectors of "force" but not different types, eg. a vector of "speed" and vector of "force".

Drag

Wind: Moving air mass relative to fixed objects (houses, trees ... etc..). In the exam multiple choice questions, this is also referred to as "airflow" or "flow".

Relative wind: When travelling at a speed V in an air mass moving at the same speed, the sensation is the same if we remained motionless. When an object moves through air, it experiences a relative wind.

Drag: All objects in a wind (normal or relative) are also subject to a force called drag. For any object this force has the same orientation as the wind. For example if you put a hand outside the window of a moving car, you feel a force pushing your hand backwards, in the same direction as the relative wind created by the speed of the car. Drag is expressed in kg or Newtons (N). 10N = approximately 1kg.

4 factors influence the drag of an object: (1) The surface area of the object exposed to the wind (2) wind speed, (3) the air density and (4) the shape of the object . There are no other significant factors. Note however that the exposed surface depends on the size of the object. See Figure A9 and **question 006**. None of the following influence the drag: the weight, density (or spefic gravity), mass, molecular construction ff the material of the object, humidity, dew point, air temperature or pressure gradient (**questions 006, 014, 023, 032, 041**). For **question 041**, the proper response; "surface characteristics" includes both the object's surface exposed to the wind and the shape of the object.

(1) Exposed Surface: The exposed surface perpendicular to the direction of the wind thus depends on the volume and size of the object. The greater the exposed surface, the greater the. See Figure A9. (**Question 006).**

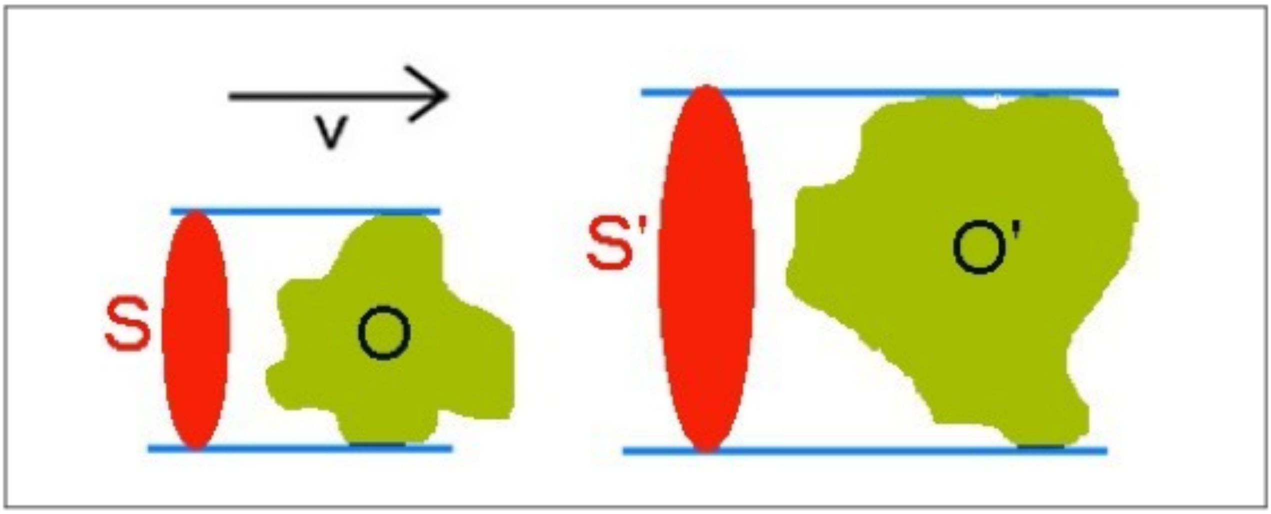


Figure A9: The surface S of the object O in wind V is smaller than the surface S 'of the object O' itself greater than O.

The relationship between drag and the exposed surface is linear: When the exposed surface doubles, (or quadruples or halves), the drag doubles, (or quadruples or halves. **Questions 007 to 009**. See Figure A10.

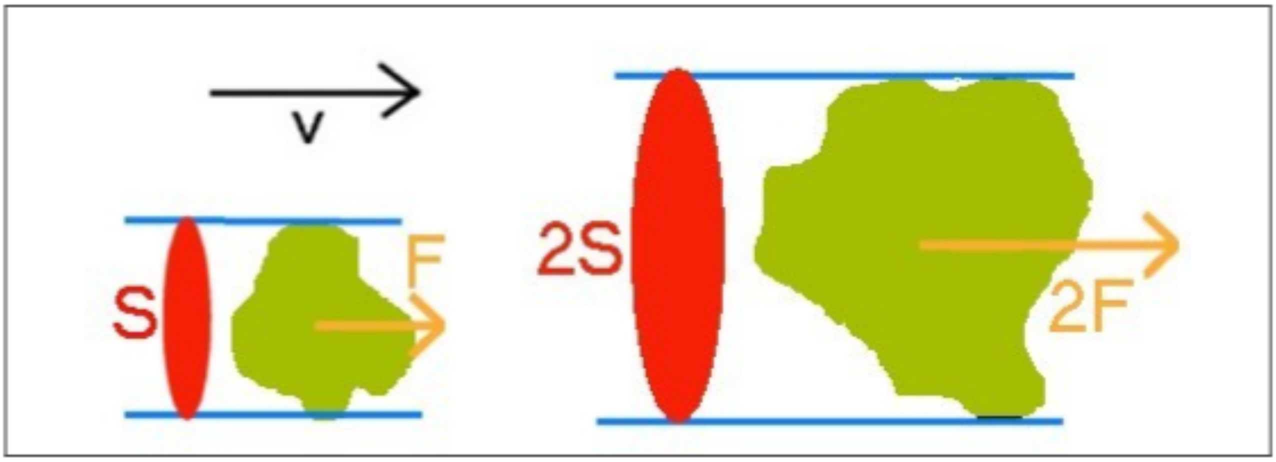


Figure A10: For the same wind V, if the surface of an object exposed to the wind while doubles, the drag (F) will double also.

Further example: If the exposed surface of an object in a wind (V) increases from 2m^2 to 4m^2, this doubles the exposed surface and therefore the drag also doubles. If the drag was 300N (Newtons), it will now be 600N. The fact that the wind is 30 km/h and that everything occurs at sea level is irrelevant to the problem and is included in the question to test the strength of your knowledge. (**Question 010**). Similar examples: if the surface is changed (i) from 2m^2 to 1m^2 (halves), (ii) from 8m^2 to 2m^2 (decreases of a factor 4) or (iii) 0.5m^2 to 3m^2 (6-fold increases), the drag changes respectively from (i) 300N to 150N (halves), (ii) 1200N to 300N (reduced by a factor 4) or (iii) 150N to 900N (increases by a factor of 6). **Questions 011 to 013**.

(2) Wind Speed: For the variations in wind speed, the effect is a less simple. The relationship between wind speed and drag is not linear. In other words, if the speed increases, drag increases much more. More specifically, the drag increases in proportion to the *square* of the speed. See Figure A11. More concretely, if the wind speed (air flow) exerted on the object increases by a factor of 2, the drag is multiplied by 2^2 (2 squared) = 4. **Question 015**.

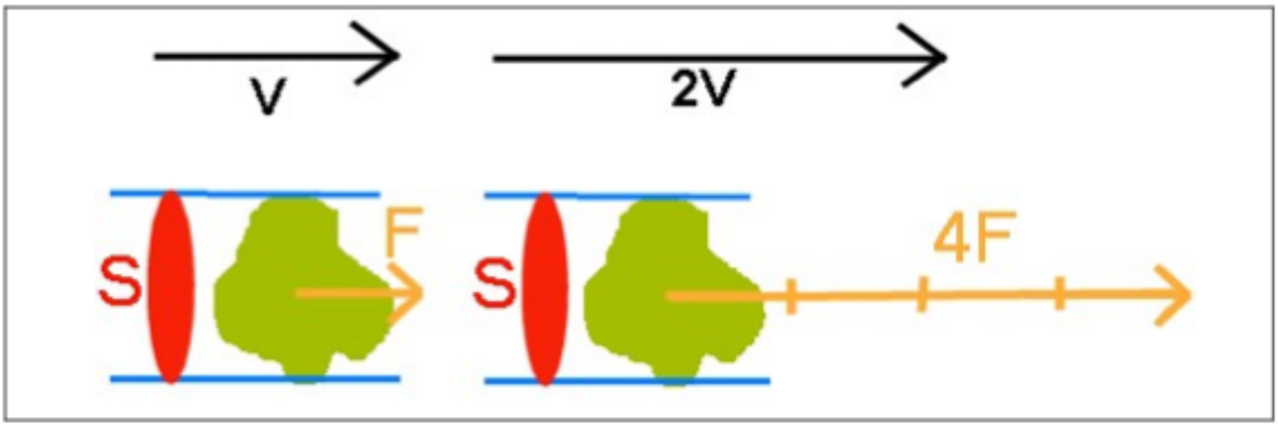


Figure A11: For an identical surface, if the wind speed (V) doubles, the drag (F) experienced by the object then quadruples (4F) in the higher wind.

Examples: If the wind speed (i) triples, (ii) quadruples or (iii) halves, the drag is multiplied by (i) 9. (ii) 16 or (iii) divided by 4, respectively. **Questions 016 to 018**. Another more concrete example: If the wind speed increases from 30 to 60km/h (doubles its speed), the drag quadruples: If it was 300N (Newtons), it will be 1200N. The fact that the exposed surface is $2m^2$ and that everything happens at sea level does not change the problem. **Question 019**. Similar Examples: If the wind speed increases from (i) 30 to 90km/h (triples), (ii) 80 to 40km/h (halves) or (iii) 20 to 60km/h (triples), whatever the surface exposed to the wind, the drag will change from (i) 100 to 900N (x 3^2), (ii) 1200 to 300N (x 0.5^2) or (iii) 100 to 900N (x 3^2). **Questions 020 to 022**.

(3) Air Density: As for the exposed surface, the relationship between air density and the drag is linear. See Figure A12.

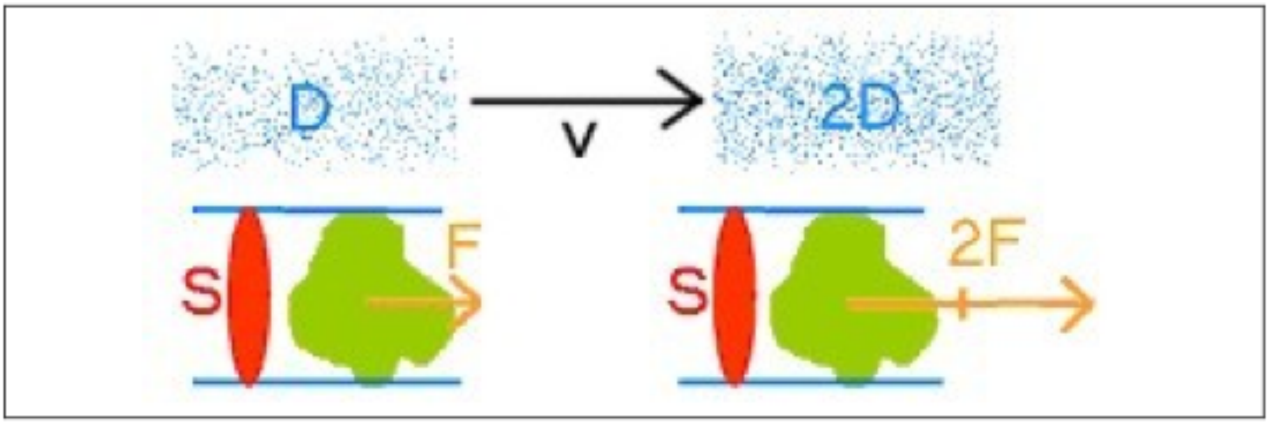


Figure A12: If the surface (S) and wind (V) are identical, and if the density (D) of the air doubles, then drag (F) the object experiences in the wind will double also (2F).

If the air density (i) doubles or (ii) halves, then the drag (i) doubles or (ii) halves respectively. **Questions 024 and 025**.

In what circumstances does the air density vary in practice? The density of air (and air pressure) decreases with increasing altitude. In other words, the air is thinner with altitude. Example: if all other conditions identical, and if an object moves away from the Earth's surface (ie the object gains altitude), the density of air decreases as does the drag. **Question 026**. The relationship between altitude and air density is not quite linear. The more higher the initial altitude the more slowly the air density decreases with increased altitude. In other words, if a body subjected to wind moves away from the Earth's surface (i.e. climbs), the drag decreases faster in the lower layers than at higher altitudes. **Question 027**. The factors should be remembered by heart for the examination: at 1100, 2200, 3300 and 4400m. altitude, the air density (and therefore the drag) of an object subjected to varying wind speed changed by respectively 90, 81, 72, 64% versus the value at sea level. **Questions 028 to 031**. **Memory aid tip:** *the sum of height & density equals 100* → approximate altitudes (in hundreds of m) 10, 20, 30, 40 + the approximate densities corresponding (in% of air density at sea level) are 90, 80, 70, 60%.

(4) Object Shape: For an exposed area of the same object, an "aerodynamic" aspect offers less resistance (less drag) than a less aerodynamic. See Figure A13. The impact of shape on the drag of an object is determined by the “drag coefficient” (Cx). **Question 033**. For example, the object (a) with a flat surface perpendicular to the airflow (wind) has a drag coefficient of 1, the convex object (b) offers greater wind resistance is therefore a higher drag coefficient (Cx) of 1.3. The “aerodynamic” object (c) has a very small drag coefficient (Cx) of 0.08 while the object (d) good aerodynamic shape but not optimally aligned has drag coefficient (Cx) of 0.17. **Questions 037 to 040.** Other applications: Under the same conditions of wind and exposed surface, object with a drag coefficient of 1.3 will be 1.3x larger than that of an object with a drag coefficient of 1. The drag of the first object will be 30% higher. **Question 034**. A body with a drag coefficient (Cx) of (i) 0.33 or (ii) 0.05, will have approximately (i) 3x or (ii) 20x less drag compared to a body with a drag coefficient (Cx) of 1. **Questions 035 and 036**.

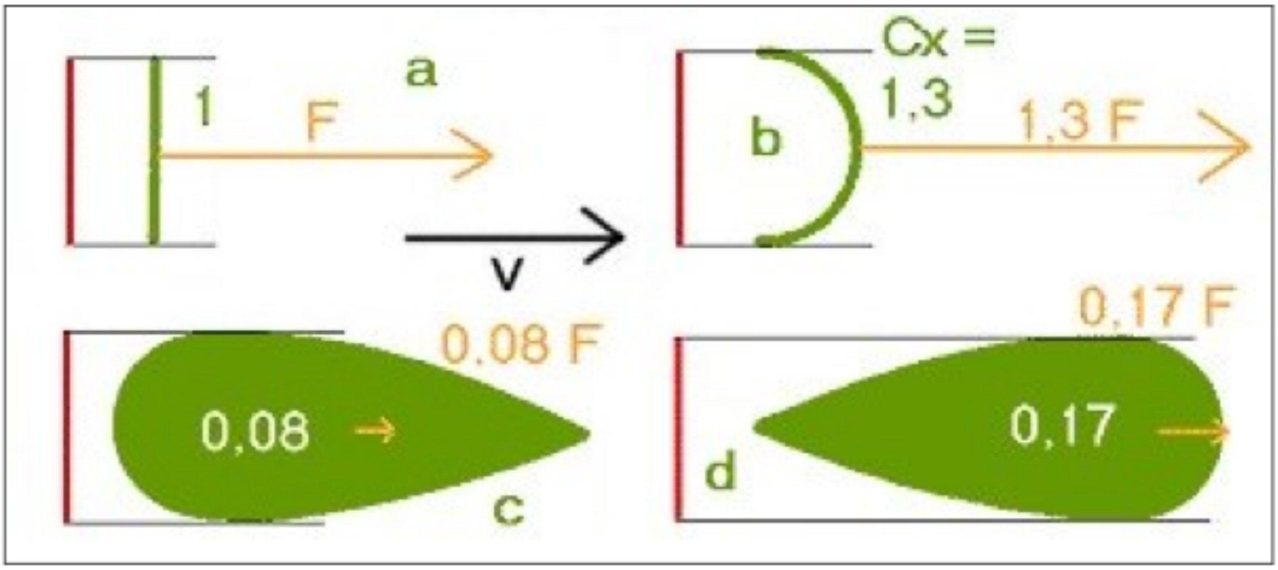


Figure A13: For identical surfaces and wind (V), the drag (F) varies depending on the shape of the object subjected to the wind. For example, the object (b) has drag 1.3x larger than the object of (a) and (c) has a drag of 0.08x vs. that of (a).

Lift and Drag: Profile of a Flat Object Subjected to Wind.

When an object is elongated and flat (eg a wing) and subjected to an oblique wind, two perpendicular forces act on the object: The **drag**, parallel to the wind in the same direction, (like any object), and **lift**, perpendicular to the wind, toward the top surface. See Figure A14.

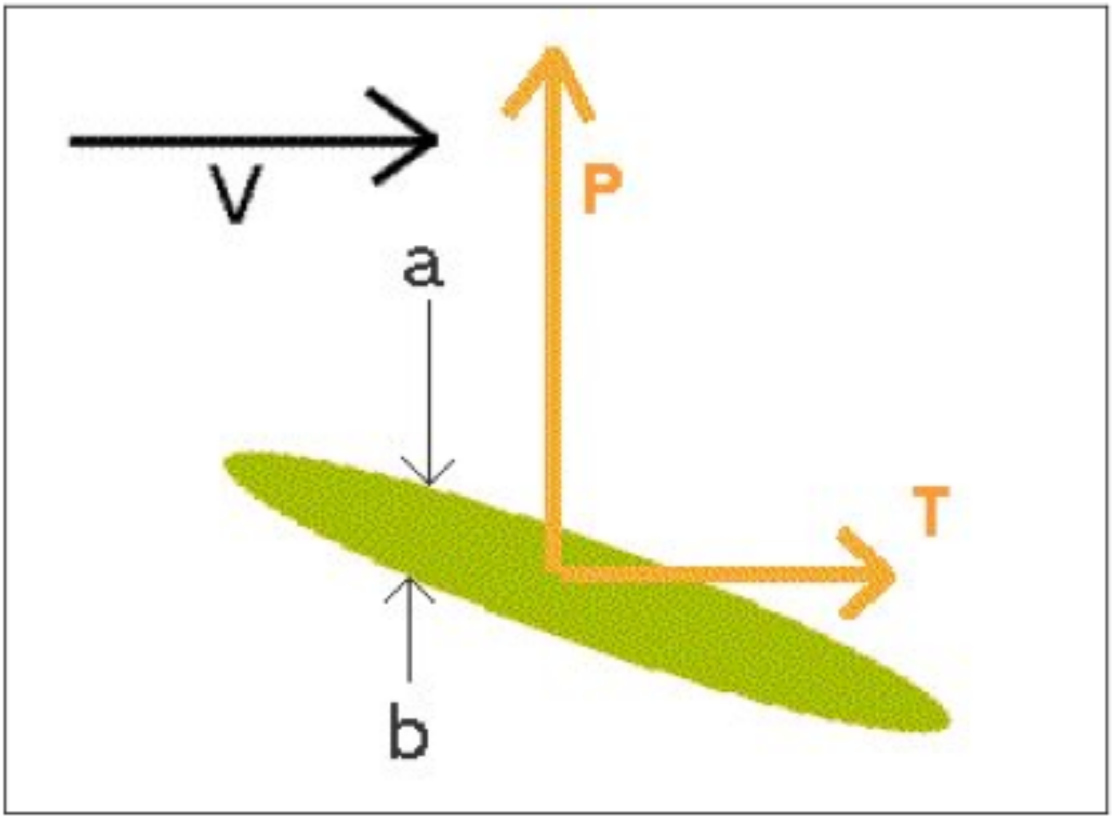


Figure A14: Drag (T) and Lift (P) of a flat object under an oblique wind (V).
a = upper surface, b = bottom surface.

As the with only drag, for any object we find the same 4 factors that influence lift and drag of a flat object: (1) The exposed surface of the object (2) wind speed (3) the density of air and (4) the shape and angle to the wind (angle of attack) of the object.

If the surface or the air density doubles or halved, drag and lift double or are halved. If the wind speed doubles, the lift and drag are multiplied by four (the lift and drag increase with the square of wind speed).

For item 4, the coefficients of drag and lift, (respectively Cx and Cz) depend not only on the shape of the object (Figure A15) but also the inclination of the flat object relative to the direction wind (Figure A16). This is called the angle of attack.

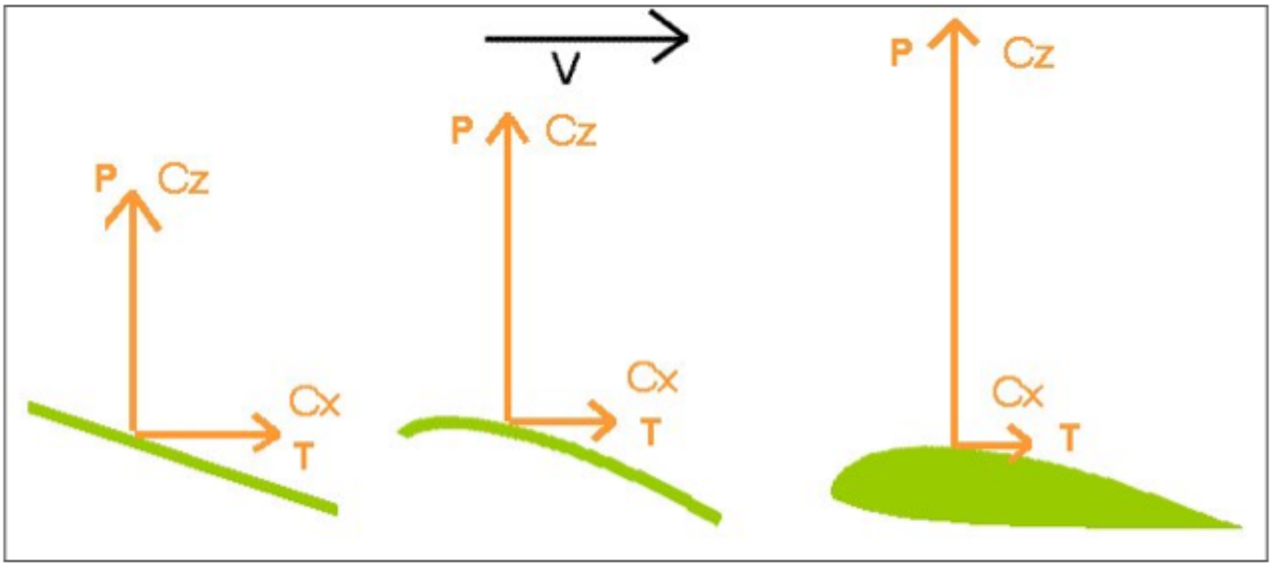


Figure A15: Drag (T) and Lift (P) or Cx and Cz, respectively, of a flat object under oblique wind (V): The more the profile of the object resembles an aerodynamic wing, the more P (or Cz) becomes large relative to T (or Cx).

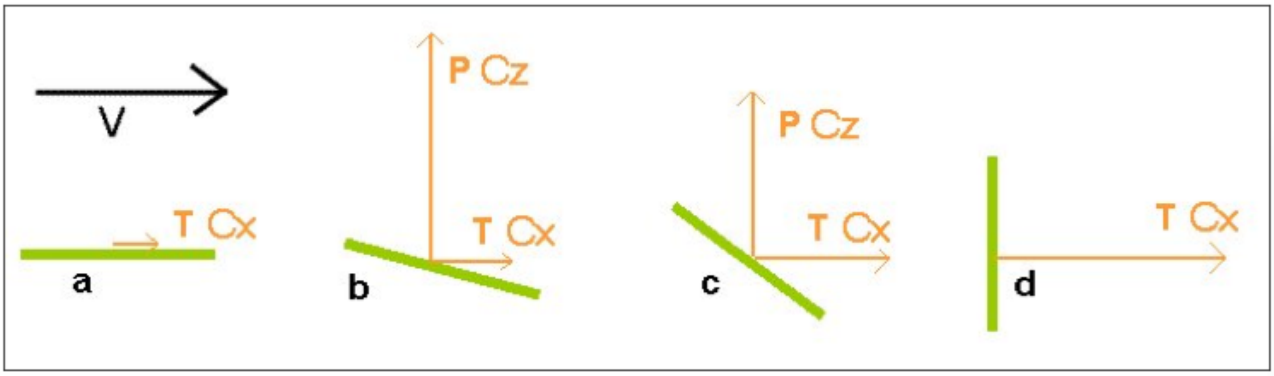


Figure A16: Drag (T) and Lift (P), respectively, or Cx and Cz, a flat object under oblique wind V, depending on the impact. a = nil effect: P and T zero very low. b = low impact: P maximum and T low. c = average incidence: P and T by means. d = maximum effect (perpendicular to the wind): P & T no maximum.

We can now answer questions 050 and 056:

Question 050. The lift depends on the angle of attack. There is a “trap” in the selection of answers: namely that the surface profile is not relevant and it should not be confused with the exposed surface of the object in the wind.

Question 056. The lift depends on 4 factors: size of the wing, lift coefficient, air density, and wind speed.

Distribution of lift: lift can be broken into many vectors distributed around the profile of a wing with a low angle of attack to the wind. See Figure A17. Three comments:

(1) On the top surface, it's a phenomenon of suction (negative pressure) as if the wing was being sucked by a vacuum cleaner so that the underside experiences positive pressure, as a fan blowing on the face. This difference in pressure between the upper and lower surfaces results in spiral air movements at the wing tips (called a vortex or vortices). The

vortices are formed as the upper-surface and lower-surface air pressures attempt to compensate at the wind tips. **Question 097**. The vortecies cause increased drag, resulting in a lower performance of the wing as well as turbulence in its wake. So behind the trailing edge is the greatest turbulence generated by a glider. **Question 098**.

(2) The negative pressure (suction) is about twice that of positive pressure experienced by the underside. With an angle of attack of 10°, the distribution of lift is $^2/_3$ on the upper surface and $^1/_3$ on the lower surface. **Question 054**.

(3) There is also an asymmetric distribution of lift from front to back. The $^2/_3$ of the lift is on the front $^1/_3$ of the wing. **Question 055.**

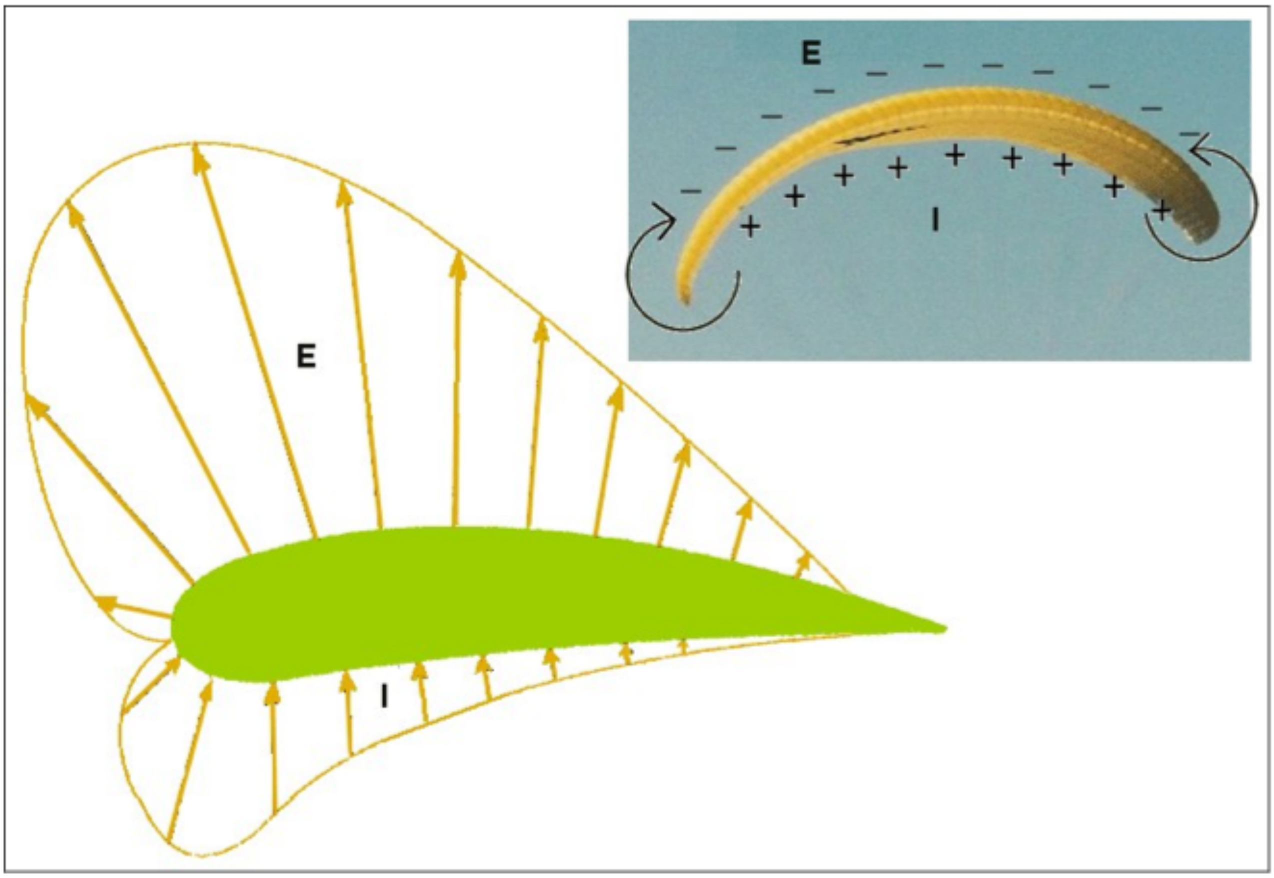


Figure A17: Breakdown of aerodynamic forces around a wing profile.
E negative pressure = upper surface, I = positive pressure = lower surface.

Profile of a wing

The profile of a wing is the shape of the longitudinal section (front to back) of the wing. Figure A18. The profile of the wings of gliders currently is quite thick and very asymmetric with a curved top surface especially on the anterior third of the wing and a lower surface slightly convex. Question 048. The profile is one of the important elements that define the characteristics, including flying and kiting performace. **Question 047**.

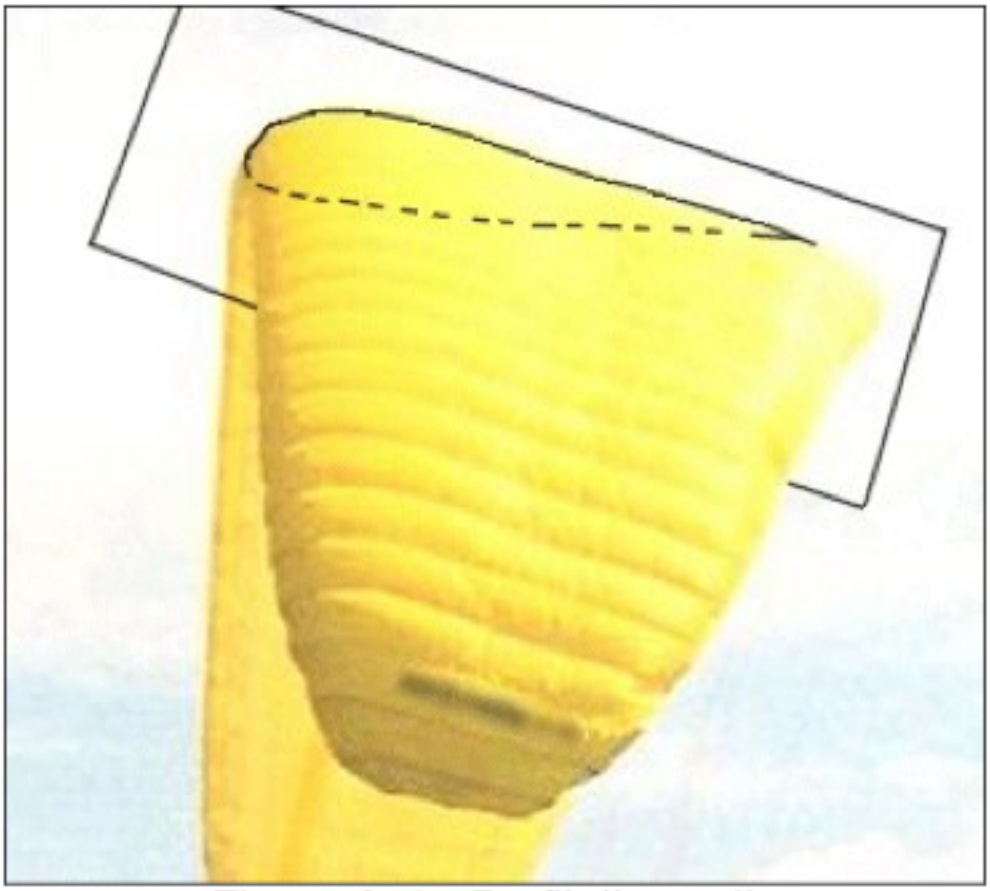


Figure A18: Profile of a wing.

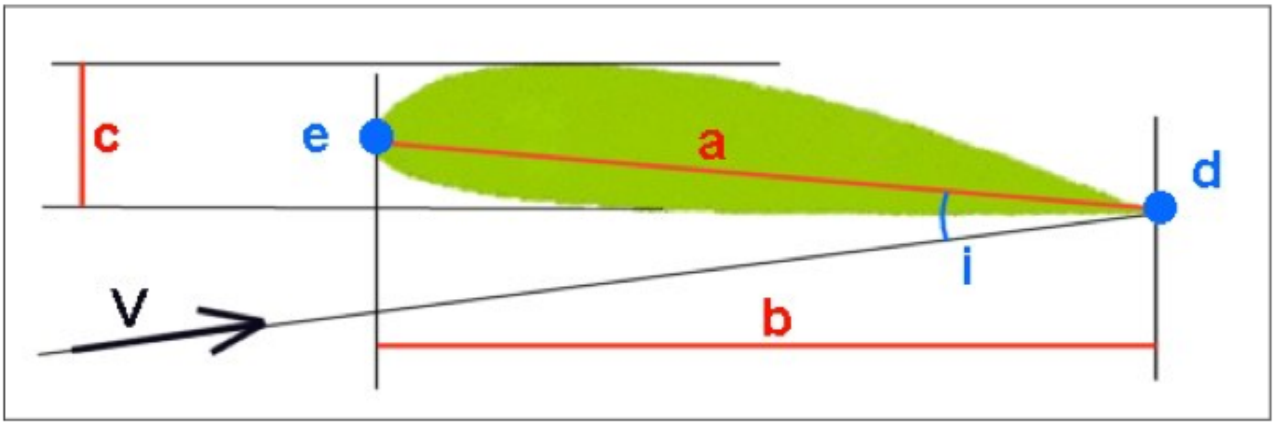


Figure A19: Segments and significant geometric points of a profile.

Significant geometric points of a profile:

See Figure A20. **Questions 042-046 and 049**.

- Measurement (a): median chord of the profile, between (d) and (e)
- Measurement (b): length of the profile, close to, but less than (a).
- Measurement (c): thickness of the profile.
- Point (d): the trailing (rear) edge.
- Point (e): the leading (front) edge.
- Angle of attack (i): Angle between the direction of airflow (relative wind) and the median chord of the profile (a).

Significant aerodynamic points of a profile:

See Figure A20. Questions 062-065, 068 and 071.

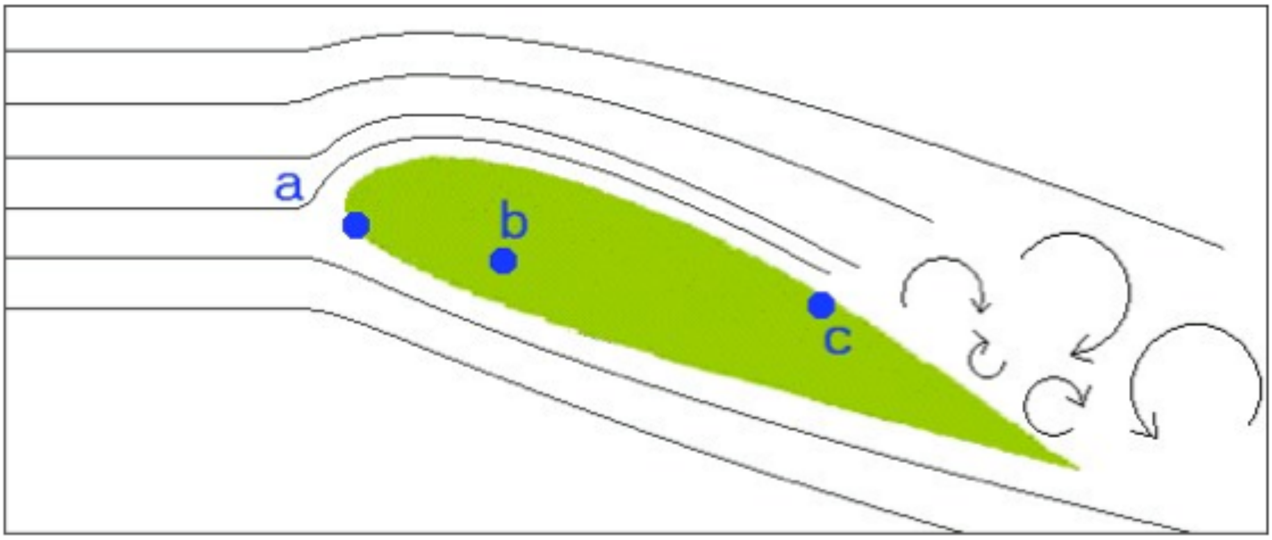


Figure A20: Significant aerodynamic points of a profile.

- Point of stagnation or breakpoint (a): the point on the leading edge where the air streams divide between the upper and lower surfaces.
- Center of thrust (b): the point where all the aerodynamic forces (lift and drag) effectively act.
- Stall point (c): the point on the upper surface where the airflow detaches from the surface of the wing and after which turbulence occurs and leads to a negative component of lift. This occurs mainly at large angles of attack.

These points are aerodynamic not fixed geometrically. Rather they move as the angle of attack varies. For example, the point of stagnation. **Questions 069 and 070**. See Figure A21. When the (already positive) angle of attack of a wing increases, the point of stagnation on the lower surface moves toward the leading edge: figure A21 (right). Conversely, when the (already positive) angle of attack of a wing decreases, point of stagnation moves toward the trailing edge: figure A21 (left).

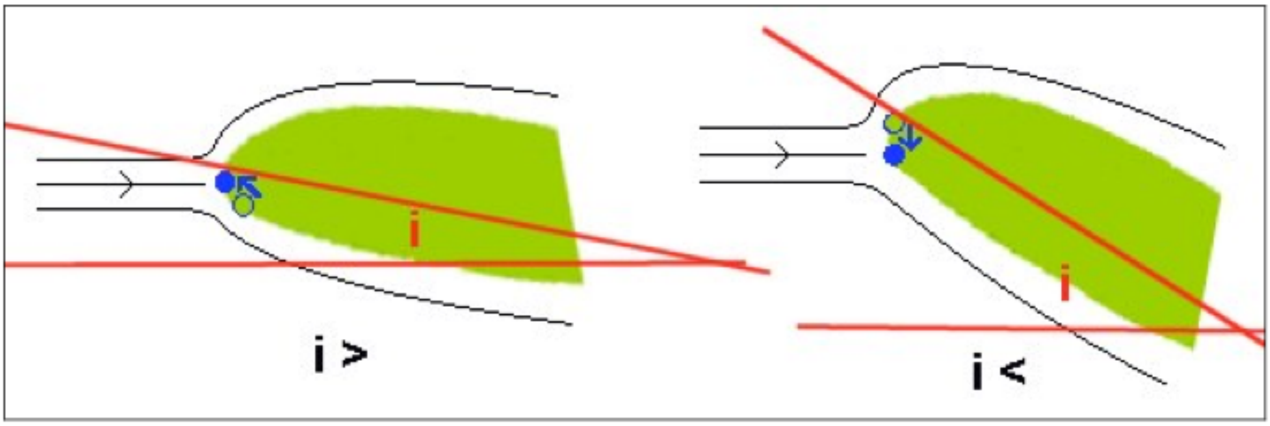


Figure A21: Moving the point of stagnation with changes in the angle of attack. Right, angle of attack (i) increases and left decreases.

Polar Forces & Angle of Attack

The distribution of forces (lift and drag) depends on the angle of attack. Figure A22. **Questions 051-053**.

- In (a), we find the optimum effect (10-15°), with a significant lift and reduced drag through low pressure on the upper and the lower surface pressure consistent and effective.
- In (b), the impact is significant: The lift is reduced and the drag increased. A stall point (X) (see also Figure A20) appears on the upper surface. Behind this point, turbulence results in a component of downward pressure downwards which replaces the negative pressure.
- In (c), the impact is detrimental. Airflow causes the lower surface to have negative pressure, and a positive pressure on the upper surface. With both effects acting downwards, the profile now has a *negative* lift.
- In (d) the angle of attack is zero. While a drag continues, the negative pressure persists on the upper surface, and to a lesser extent, the lower surface. These forces oppose each other and result in a very small lift.

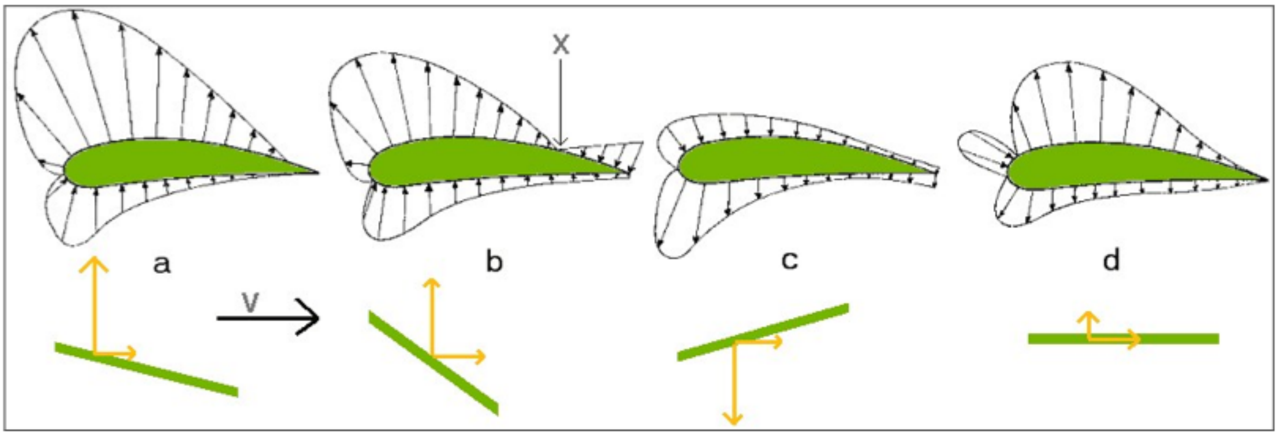


Figure A22: Breakdown of aerodynamic forces around a profile based on angle of attack.

Multiple examples of could be provided to illustrate this effect, but it is more helpful and concise to represent the relationship between lift-drag and angle of incidence (angle of attack) by a graph called a “polar curve”. See Figure A23. The values on the graph are only orders of magnitude for illustrative purposes and should not be assumed to be accurate.

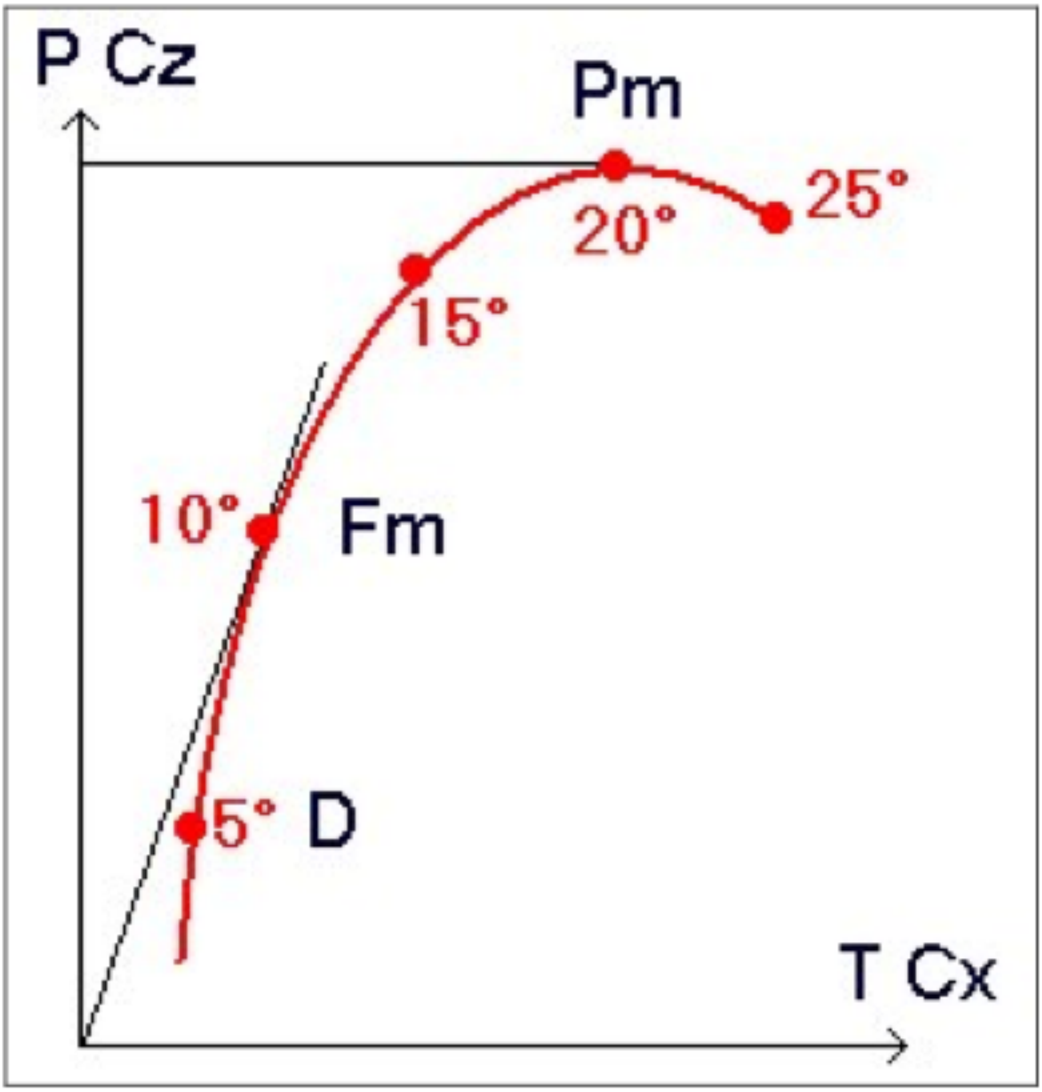


Figure A23: Polar aerodynamic forces. The values 5 °, 10 °, 15 °, 20 ° and 25 ° represent the various implications degree (magnitude).

The relationship between lift and drag of a wing (profile) depends primarily on the angle of attack. **Question 061**. At about 10° the ratio between lift and drag is at its maximum which corresponds to the maximum efficiency and the best glide angle. By increasing the angle of attack, the lift increases, but drag increases to a greater extent. At 20°, the lift is at its maximum, but with the accompanying effect of a relatively high drag. This corresponds to the minimum sink rate. At 25°, the lift disappears and the wing stalls (i.e. it is no longer flying). On the graph, we see that beyong the point of maximum efficiency, if the angle of attack is reduced or increased, then Cz (or lift) decreases or increases respectively. **Questions 058 and 060.**

Geometry of a Wing & Wing Loading

Wingspan: spread (length) between the two ends left and right wing. Question 072. It is generally expressed in m. We distinguish the wingspan "flat" (actual), measured on a wing spread the floor and a wingspan measured on the projected ground projection (shadow) of the wing inflated. See Figure A24. The "flat" span is obviously always greater than the projected wingspan.

Area: total area of the wing. It is generally expressed in m^2. We can see the surface area "flat" (actual), measured on a wing spread the floor and the projected area, measured on the vertical projection (shadow) of the inflated wing. See Figure A24. **Question 101**. The "flat" surface area is greater than the projected or possibly identical for a very flat wing.

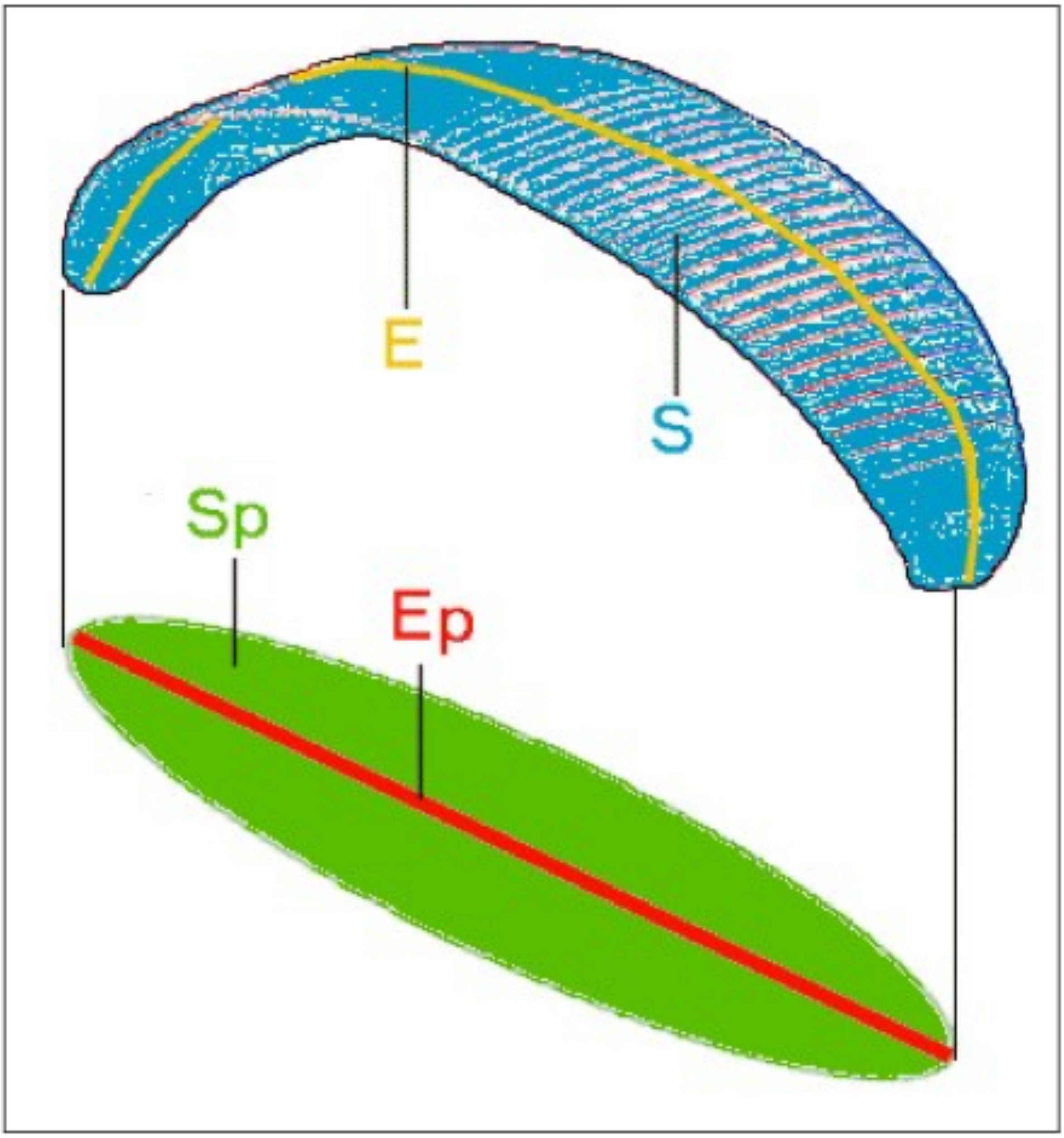


Figure A24: Area and wingspan of a “flat” and projected wing.
E = “flat” span, Ep = projected span, S = “flat” Area, Sp = projected area

Take-off weight: the sum of all the weight carried by the wing, i.e. pilot, glider, harness and everything in it. It is generally expressed in kg.
Wing load = Take-off weight - weight of the wing; that is to say the total weight carried by the wing. Partial answers to **questions 085, 086, 089 and 090**: Maximum Take-off weight of a wing of 5 kg with a maximum load of 95 kg = 5 kg + 95 kg = 100 kg. Minimum take-off weight of a wing of 5kg with a minimum load of 70kg = 5kg + 70kg = 75kg. (This is a typical example for paragliding). Maximum Take-off weight of a wing of 35kg with a maximum load of 90kg = 35kg + 90kg = 125kg. Minimum take-off weight of a wing of 35kg with a minimum load of 65kg = 35kg + 65kg = 100kg. (This is a typical example for delta wing).

Wing loading: Average load (weight) per unit area. **Questions 075 and 076**. It is expressed in general kg/m^2. Wing loading is obtained by dividing the take-off weight by the wing area (usually the projected area). For gliders, the wing loading is usually between 2.5 and 4kg/m^2. Examples of the calculation (**questions 085, 086, 089 and 090**): Calculate the wing loading of a wing of 25m^2. Max. 95kg, min. 70kg load. 5kg weight of the wing. (This is typically a paraglider). With a maximum load, the wing loading = max. take-off weight / 25m^2 = (95kg + 5kg) / 25m^2 = 4 kg/m^2. With a minimum load, the wing loading = min. take-off weight. / 25 m^2 = (70kg + 5kg) / 25m^2 = 3kg/m^2. Calculate the wing loading of a wing of 12.5m^2. Max. 90kg, min. 65kg load. 35kg weight of the wing. (This is typical of a delta wing). With a maximum load, the wing loading = max. take-off weight / 25 m^2 = (90kg + 35kg) / 12.5 m^2 = 10kg/m^2. With a minimum load, the wing loading = min. take-off weight / 25 m^2 = (70kg+ 35kg) / 12.5 m^2 = 8kg/m^2.

Average depth: average difference between the leading edge and trailing edge of the wing. **Question 073**. It is expressed in general meters. See Figure A25. The relationship between the surface area (S) and the average depth (p) and wingspan (e): S = p x e or p = S / e .

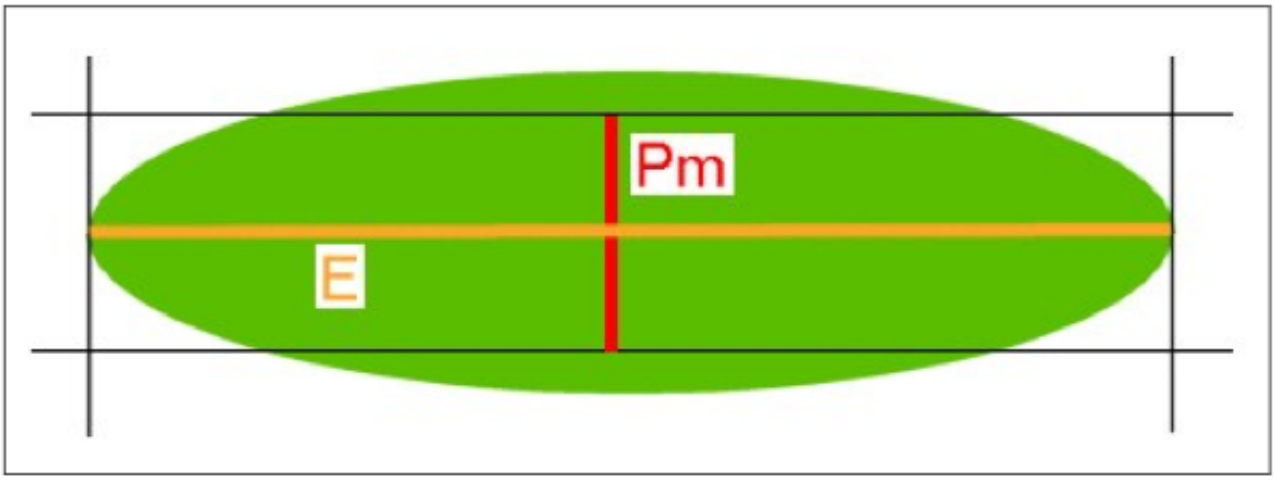


Figure A25: wingspan (E) and average depth (Pm) of a wing.

For example, if a wing has a wingspan of 10m and an area of 25m^2, the average depth is 25m^2 / 10m = 2.5m. **Question 084**. The values of weight and load data in the statement of this question are of course irrelevant. Another example: if a wing has a wingspan of 10m and an area of 12.5m^2, the average depth is equal to 12.5m^2 / 10m = 1.25m. (**Question**

088).

Wing torsion: Changes in angle of attack between different sections of the wing. See Figure A26. **Question 074**. In general twisting of the wing gives better stability of the wing and/or less need for pilot intervention in flight, particularly stalls are less likely and less abrupt.

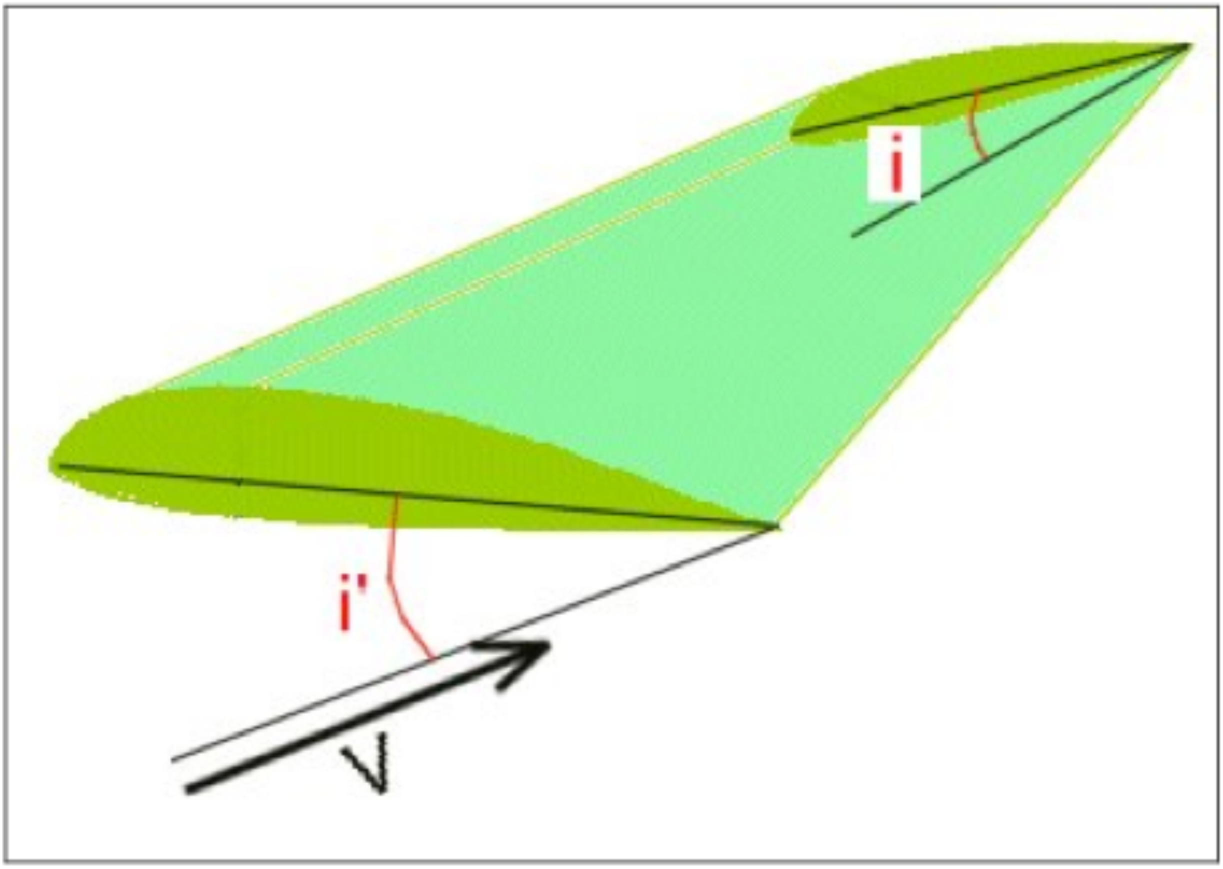


Figure A26: twisting of a wing. I' > i

Aspect ratio: Ratio of average area and depth, ie area/mean depth = e / p. **Question 077.**

Calculation:
$e / p = (e^2) / (p \times e)$ = wingspan squared / area

In fact, the product p x e (wingspan x average depth) is just the area of the wing. See Figure A25. **Question 078**. The latter formula wingspan^2/area is more practical. For the "effective" aspect ratio (flat wing), we take the actual ("flat") values of the wingspan and the area. For the "projected" aspect ratio, we longer we take the projected values of the wingspan and area. With experience and practice, it is easy to recognize, at first glance, a high aspect ratio wing as having a modest elongation. The high aspect ratio wings therefore have a large wingspan and a small average depth. The wings are therefore a little longer with much smaller average depth. Figure A27. **Questions 079 and 080.**

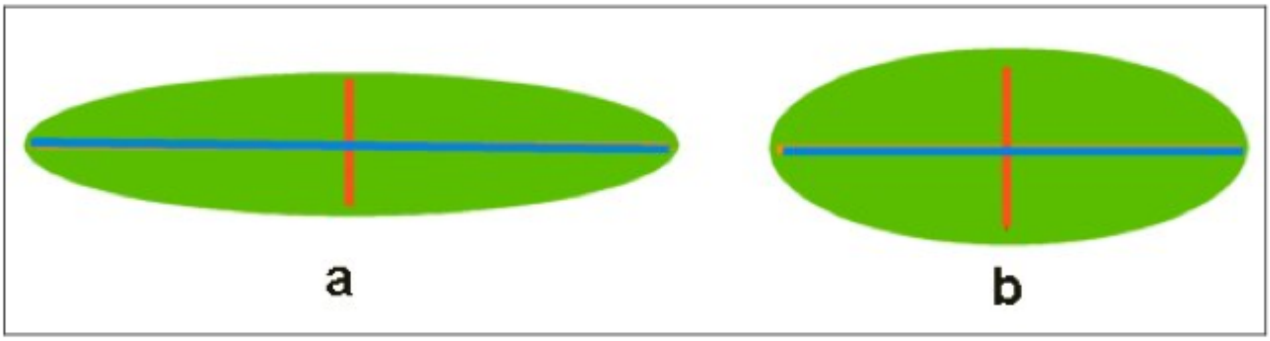


Figure A27: a = b = large and small aspect ratios

When the aspect ratio is large, the wing tip vortices are important and induced drag is large, which improves the performance of the wing in flight.

The aspect ratio of current paragliders is around 5, that of a delta wing is typically 8. **Questions 091 and 092.**

A wing whose aspect ratio = 5 will have a major axis 5 times larger than its average depth or average depth of 5 times smaller than its area. **Questions 081 and 082**.

Examples of calculations: **Questions 083 and 087**. Calculate the aspect ratio of a wing of 10m wingspan and 25m^2 area. Weights and load data are used in the statement only to mislead you and to test the strength of your knowledge. Aspect ratio = 10m x 10m / 25 m^2 = 100 / 25 = 4. Calculate the aspect ratio of a wing of 10m wingspan and 12.5m^2 area. Aspect ratio = 10m x 10m / 12.5m^2 = 100 / 12.5 = 8.

Another example: given the following characteristics of 4 wings (paragliders):

a) Area 32 m^2, 8 meter wingspan
b) Area 25 m^2, 10 meter wingspan
c) Area 20 m^2, 10 meter wingspan
d) Area 24 m^2, 12 meter wingspan

Find the wing with highest aspect ratio and the wing with the lowest aspect ratio. **Questions 093 and 094**. The smallest aspect ratio is easy to find, because the surface is larger (32m^2) and the smallest wingspan (8m.). For largest aspect ratio, is evidently (c) or (d) because the areas are smaller and wingspan longer.
For (c): aspect ratio = 10m x 10m / 20 m^2 = 5
For (d): aspect ratio = 12m x 12m / 24 m^2 = 144 / 24 = 6
So the largest aspect ratio is (d) = 6.

Another example: is given the characteristics of 4 wings (delta):

a) Area 16 m^2, 12 meter wingspan
b) Area 20 m^2, 10 meter wingspan
c) Area 12 m^2, 12 meter wingspan
d) Area 12.5 m^2, 10 meter wingspan

Find the wing with highest aspect ratio and the wing with the lowest aspect ratio. **Questions 095 and 096**. The smallest aspect ratio is easy to find, it is (b) because the surface is larger (20m^2) and the smallest wingspan (10m.). For the largest aspect ratio, it is either (c) or (d) because the areas are smaller and wingspans larger.
For (c): aspect ratio = 12m x 12m / 12m^2 = 12

For (d): aspect ratio = 10m x 10m /12.5 m^2 = 8
wing (c) therefore has the largest aspect ratio = 12.

Equilibrium of Forces for a Glider in Normal Flight

A paraglider, not subject to varying forces (= no acceleration) flies in a uniform linear motion. The resultant of all forces acting on the wing is zero. The total weight in flight (take-off weight, PTV in the diagram), acting vertically downward, must be opposed by a counter force vertically, (i.e. the same magnitude but directed upwards). This force is called the resultant aerodynamic force (FRA in the diagram). See Figure A28. **Questions 102 to 111**. The resultant aerodynamic force can be separated into lift (P) perpendicular to the trajectory and facing upwards, and drag (T), parallel to, and in the opposite direction of, the trajectory (direction of airflow). The component (force) of the take-off weight, parallel to the trajectory (towards the leading edge and opposing the drag) has the same value as the drag and is called the thrust (O).

The trajectory is clearly identical to the direction of airflow. The glide angle (α) is the angle between the trajectory and horizon. Using geometry, we can easily prove that the glide angle (α) is identical to the angle (α') formed by the lift and resultant aerodynamic force (FRA in the diagram). This latter observation is important to define the glide ratio (see below). It should not be confused with the glide angle (γ) formed by the angle between a chord line of the profile and trajectory.

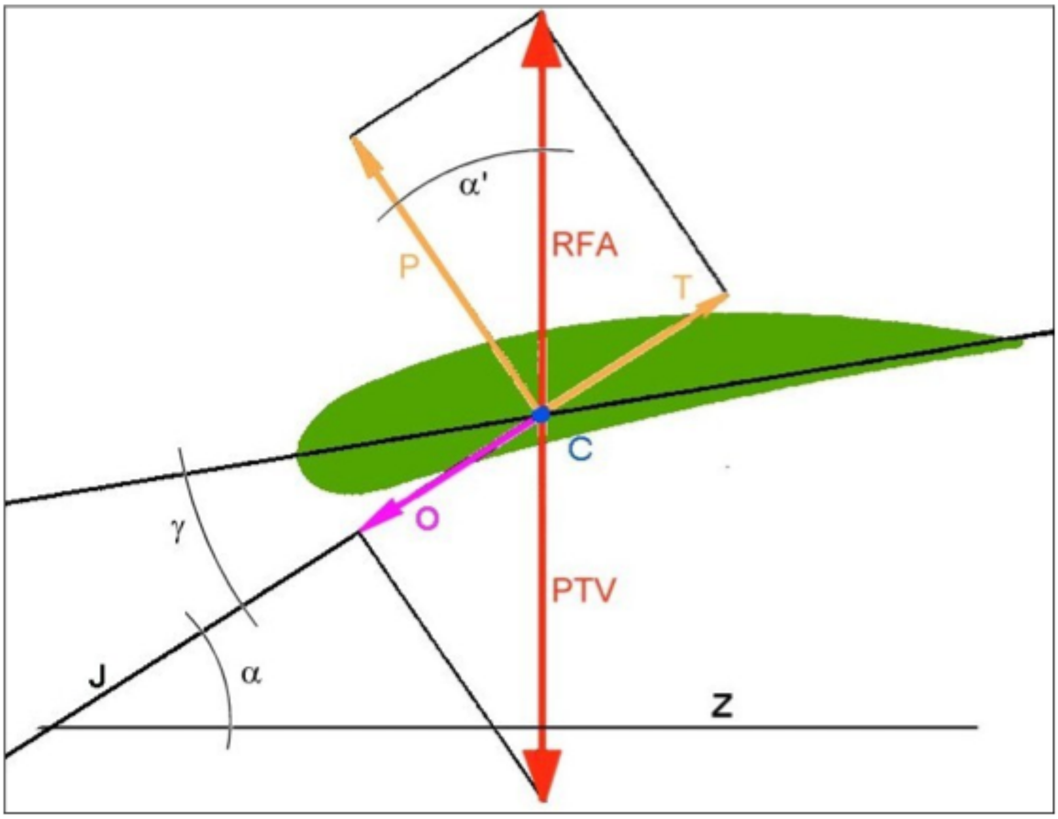


Figure A28: Equilibrium of forces of a glider in straight & uniform flight.
RFA = resultant aerodynamic force, PTV = take-off weight, P = lift, T = drag, O = thrust. J = trajectory (relative wind), C = center of pressure, Z = horizon, α = angle of glide. γ = glide angle.

Glide Ratio of a Wing

The glide ratio of a wing is an important feature to evaluate its performance. The greater it is, the better the glider performs. It is the ratio of the distance traveled vs. the vertical descent. The glide ratio of current (2005) gliders is about 8-9 in still air. The glide angle depends on the angle of attack and varies with the lift and drag. There are 4 ways to calculate the glide ratio. See Figure A29.

1. Glide ratio = horizontal distance traveled (D) / vertical descent (H). **Question 124**.
2. Since the horizontal distance traveled and the lost height is achieved at the same time, glide ratio = horizontal velocity / rate of fall. **Question123**.
3. Since the angles α and α' are identical, the right angle triangles DH and PT' (where T' = T) are proportional. Therefore the glide ratio = D / H = P / T (= lift / drag). **Question 121**.
4. Since the coefficients Cx and Cz are proportional to respectively the drag and lift, when other conditions are identical, the glide ratio = P / T = Cz / Cx. **Question 122**.

In summary:
Finesse = D / H = horizontal speed / rate of fall = P / T = Cz / Cx

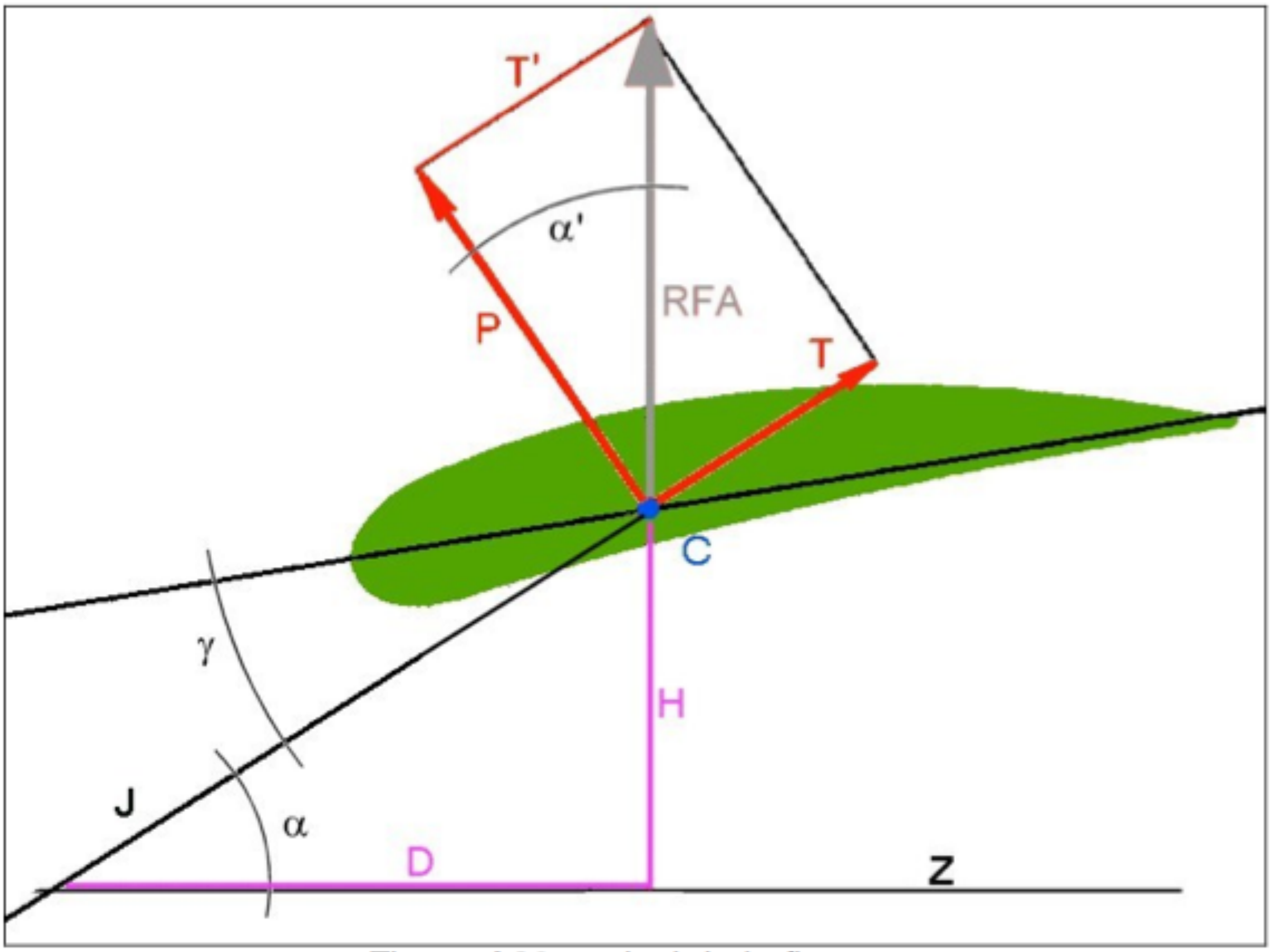


Figure A29: Calculation of glide ratio.

Some calculations and practical examples:

A sailplane with a glide ratio of 8, flying 800m above the ground. What is the greatest distance it can travel in still air? H = 800m and D is unknown. Glide ratio = D / H or D = fglide ratio x H = 8 x 0.8km = 6.4 (**Question125**).

A sailplane with a glide ratio of 12, flying 2400m above the ground. What is the greatest distance it can travel in still air? H = 2400m and D is unknown. Glide ratio = D / H or D = glide ratio x H = 12 x 2.4km = 28.8 (**Question126**).

A glider has descended 900m in altitude in still air while traveling a distance (the largest possible) of 5.4km. What is its glide ratio? H = 900m and D = 5.4km Glide ratio = D / H = 5.4km / 0.9km = 6. (**Question 127**).

A glider has descended 1400m in altitude in still air while traveling a distance (the largest possible) of 7.0km. What is its glide ratio? H = 1400m and D = 7.0km Glide ratio = D / H = 7.0km / 1.4km = 5. (**Question 128**).

If the glide ratio increases (eg H decreases and / or D increases) the glide angle (angle α) decreases. Conversely, if the glide angle (α) increases (eg D decreases and / or H increases), the glide ratio decreases. **Questions 129 and 130**.

If the drag of a glider decreases (see Figure 31 and 29), even if the lift is unchanged, the resultant aerodynamic force (RFA) increases, and the angles α' and α decrease and hence the glide ratio (P / T = D / H) increases. **Question 100**. Conversely, if the drag increases, the glide ratio decreases and glide angle increases. **Question 099**. In this question, a small language error occurs in the French text. The “angle of glide ration” is indeed the glide angle, not to be confused with the glide ratio itself.

If a glider (X) has a glide ratio of 10 and a glider (Y) has a glide ratio of 5 then (X) can travel a horizontal distance double that of (Y) for an identical loss of altitude. **Question 141**.

A glider flies with a glide ratio of 10 in calm air at a horizontal velocity (ground speed) of 43km/h (approx. 12m/s). What is its rate of fall? Glide ratio = horizontal speed / rate od descent = rate drops. Thus; rate of fall = horizontal speed / glide ratio = 12 / 10 = 1.2m/s. **Question 148.**

A glider flies with glide ratio of 8. If it flies in calm air a distance of 1,600m, what is its loss of altitude? Glide ratio = horizontal distance / lost altitude. So; lost altitude = horizontal distance / glide ratio = 1600 / 8 = 200m. **Question 149.**

A glider flies with a glide ratio of 9 in calm conditions and with a sink rate of 1m/s. What is its speed? Glide ratio = horizontal speed / sink rate. So; ground speed = glide ratio x sink rate = 9 x 1 m/s = 9m/s. **Question 150**.

A sailplane is flying in calm air at a speed of 32.4km/h (9m/s) and with a sink rate of 1.5m/s. What is its glide ratio? Glide ratio = horizontal speed / sink rate = 9/1.5 = 6. **Question 151.**

Axes and Flight Stability

A paraglider can have a rotary motion around 3 principal axes (Figure A30):

1. **Vertical axis**: the movement around this axis is called **yaw** (L in figure A30). It is a rotational movement forward/backwards of the wing tips. **Question 114**.
2. **Longitudinal axis:** the movement around this axis is called roll (R in figure A30). It is a lateral movement up/down of the wing tips**. Question 112.**
3. **Transverse axis**: the movement around this axis is called pitch (T in figure A30). It is a movement forward/backwards across the wing. **Question 113.**

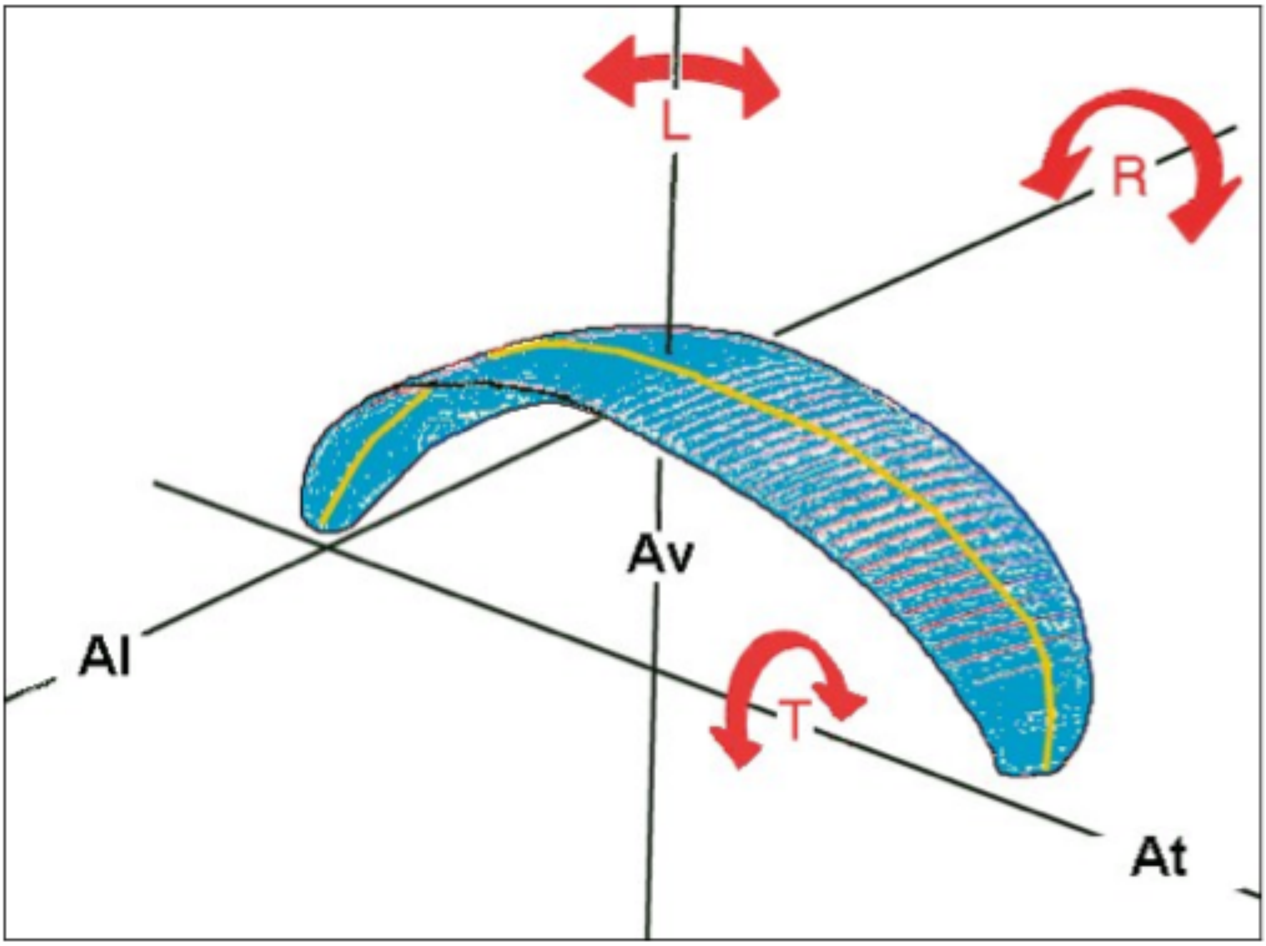


Figure A30: Axes and movements in flight. Yaw (L) around the vertical axis (Av). Roll (R) around the longitudinal axis (Al). Pitch (T) transverse axis (At).

Normally, a glider is constructed so that when it is not subject to any control from the pilot, it naturally flies straight uniform (balanced flight). Moreover, when a force (pilot control) or an external movement (turbulence) temporarily disturbs the glider, it will spontaneously return to its straight and uniform flight, with its normal angle of attack. Such a glider is said to display stable flight characteristics. For example; (**question 117**) a paraglider which passes spontaneously from fast flight (due to the use of the speed system by the pilot) into straight flight at normal speed, without active intervention of the pilot (when the speed system is released) has stable flight characteristics. Other examples: (**questions 115 and 116**) A paraglider which, after flying straight and uniformly, increases its speed spontaneously, without intervention by the pilot, has unstable flight characteristics. A paraglider which retains the flight behavior (flying condition) that is initiated by the pilot, but then released, is said to have indifferent flight characteristics.

The stability of a glider can be defined by its behavior on the 3 principal axes. **Questions 118 to 120**. A paraglider which, in calm air, either (i) rolls (ii) changes its angle of attack or (iii) yaws, without any pilot intervention, is said to be unstable with respect to, (i) the longitudinal axis, (ii) glide path, or (iii) vertical axis, respectively.

Due to some (often fatal) accidents in recent years (2002-2004), there has been much debate on the issue of glider "neutrality in a spiral”. For many paragliders, even docile types (with the most stable ratings), exit from a tight spiral (i.e. continued tight 360° turns) is not necessarily spontaneous and automatic, but requires some active control. These gliders are therefore described to have indifferent characteristics to tight spirals.

Polar Speeds

The subject of polar forces was the basis for the previous section. Associated with this is also the phenomenon of polar speeds: The horizontal (airspeed) and vertical (sink) velocities and their ratio (glide ratio) all vary according to the angle of attack of the glider. Decreasing the angle of attack by "nose diving" the wing, the speed increases. Conversely, when the angle of attack increases by "pitching" the wing, the velocities decrease initially and then only the horizontal velocity continues to decrease while the rate of fall increases again slightly. The combinations of vertical & horizontal velocities that can arise between the minimum flight speed and the maximum flight speed is called the speed range. The **polar curve of velocities** is a graphical representation of horizontal (air speed) and vertical (sink rate) velocities for the entire speed range of a paraglider. **Question 131**. See Figure A31. The 4 angluar values in Figure 4 represent examples of the angle of attack. These are typical orders of magnitude and not precise measures. When the angle of attack is low (about 5°), the glider flies fast. This is at the right of the graph. At 10-12°, the glider is has the best glide ratio (Fmax), i.e. the glider can fly the farthest. When the angle of attack is high (approx. 15-20°) the wing flies slowly. When the angle of attack of a glider flying at its best glide ratio is reduced by 2°, the airspeed is increases. **Question 057**. Conversely, when the impact of a glider flying at maximum glide ratio is increased by 2°, the airspeed decreases. **Question 059**.

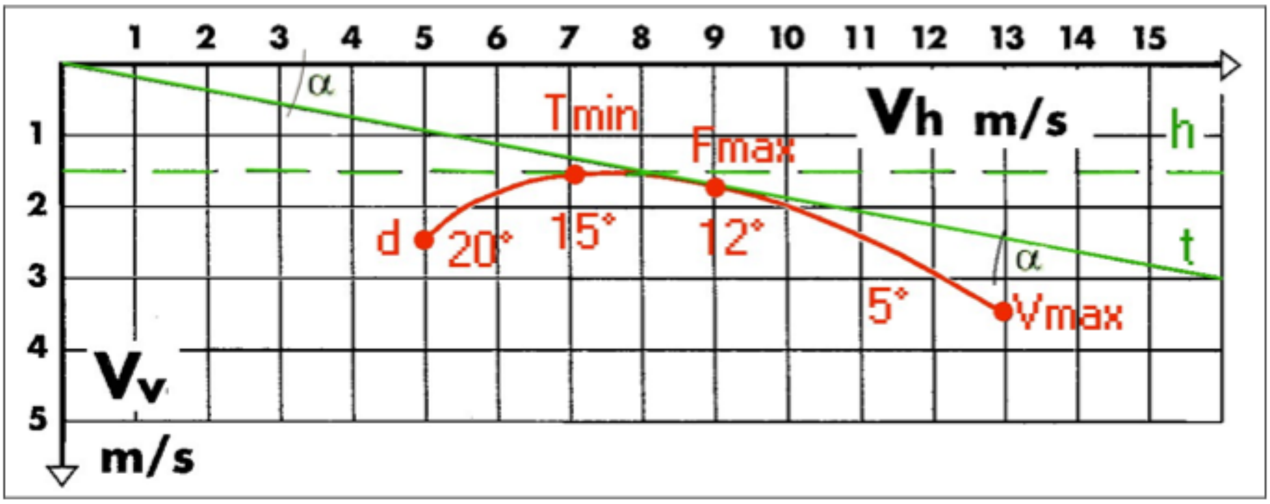
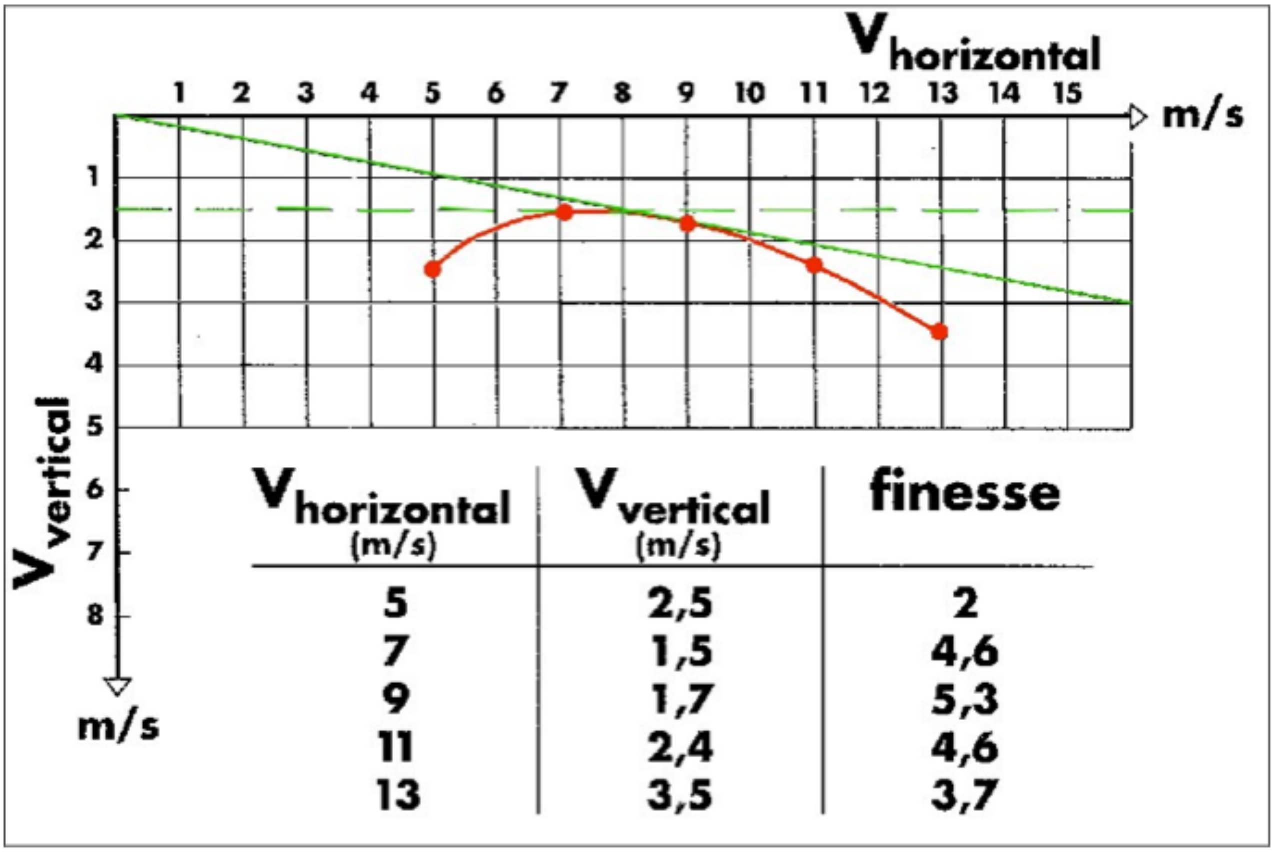


Figure A31: polar speed. Vh = horizontal velocity. Vv = vertical velocity. t = tangent to the curve passing through Fmax = trajectory at max. glide ratio. h = horizontal tangent. α = glide angle.

On the polar curve, we can see 4 main points:

1. **Airspeed at minimum sink rate (Tmin).** This is the horizontal velocity at which the vertical velocity (sink rate) is at its minimum. It is the point of the apex of the curve which passes through the tangent (h). In the example above Tmin = is between 7 to 8m/s with a sink rate = 1.5m/s
2. **Airspeed at maximum glide ratio (Fmax).** This is the horizontal velocity at which the maximum glide ratio is achieved. This is the point on the polar curve whose tangent (t) passes through the origin (of the xy axes). In the example above Fmax = about 9m/s with a sink rate = 1.7m/s More practically the tangent (t) identifies the trajectory with the highest glide ratio. It is clear that no other tangent line for the curve, and intersecting the origin, can achieve a better glide angle (α).
3. **Maximum speed (Vmax).** This is the maximum horizontal velocity the glider can achieve. The glide ratio is not maximized. In the example above Vmax = approximately 13m/s with a sink rate = 3.5m/s The glide ratio is equal to 13/3.5 = 3.7
4. **Stall speed (d).** This is the horizontal velocity when the wing stalls (no longer flies and sinks vertically). The speed just above this is the minimum speed of the wing. In the example above d = approximately 5m/s.

We can now answer **questions 132 to 139**. All these questions are based on the same graph. See Figure A32. The values of speed and glide ratio presented as a table correspond to the polar curve shown. In practice there is no need to look at the curve to answer questions as all the answers are on the table.



Vhorizontal (m/s)	Vvertical (m/s)	finesse
5	2,5	2
7	1,5	4,6
9	1,7	5,3
11	2,4	4,6
13	3,5	3,7

Figure A32: Basic Chart for questions 132 to 139 (aerodynamics) of the SHV/FSVL theory examination for paraglider pilots.

Question 132: What is the airspeed (horizontal speed) corresponding to the maximum glide ratio? In the column "finesse" (English: “glide ratio”) of the table, the maximum glide ratio is clearly 5.3. This corresponds to an air speed of 9m/s (33km/h).

Question 133: What is the best glide ratio? In the column "finesse" (English: “glide ratio”) of the table, the maximum value for the glide ratio is 5.3.

Question 134: What is the airspeed at minimum sink rate? In the column "Vvertical" (i.e sink rate) of the table, the minimum value is 1.5m/s. This corresponds to an air speed of 7m/s (26km/h).

Question 135: What is the glide ratio at the minimum sink rate? In the column "Vvertical" (i.e. sink rate) of the table, the minimum value is 1.5. This corresponds to a glide ratio of 4.6.

Question 136: What is the minimum airspeed? In the column "Vhorizontal (i.e. airspeed) of the table, the minimum value is 5m/s. This is the speed below which the wing stalls. The practical minimum air speed is slightly higher, say 5.6m/s (20km/h).

Question 137: What is the glide ratio at minimum airspeed? In the column "Vhorizontal (i.e. airspeed) of the table, the minimum is 5m/s. In the column "finesse" (English: “glide ratio”) of the table, the corresponding value is 2.

Question 138: What is the maximum airspeed? In the column "Vhorizontal (i.e. airspeed) of the table, the maximum value si 13m/s (48km/h).

Question 139: What is the glide ratio at the maximum airspeed? In the column "Vhorizontal (i.e. airspeed) of the table, the maximum value is 13m/s. In the column "finesse" (English: “glide ratio”) of the table, the corresponding value is 3.7.

Wing loading slightly modifies the polar curve for a wing. The higher the wing loading, the greater the resultant aerodynamic force will need to be to equilibrate the forces to achieve linear, uniform flight. Since the resultant aerodynamic forces increases and decreases with the relative wind speed (proportional to velocity squared), the reverse is also true to maintain equilibrium. In other words, the glider’s airspeed increases or decreases with the increases or decreases in the wing loading. As the airspeed of a glider is composed of horizontal velocity (Vh) and vertical velocity (Vv), these 2 speeds increase or decrease together with the wing loading at each angle of attack. See figure A33.

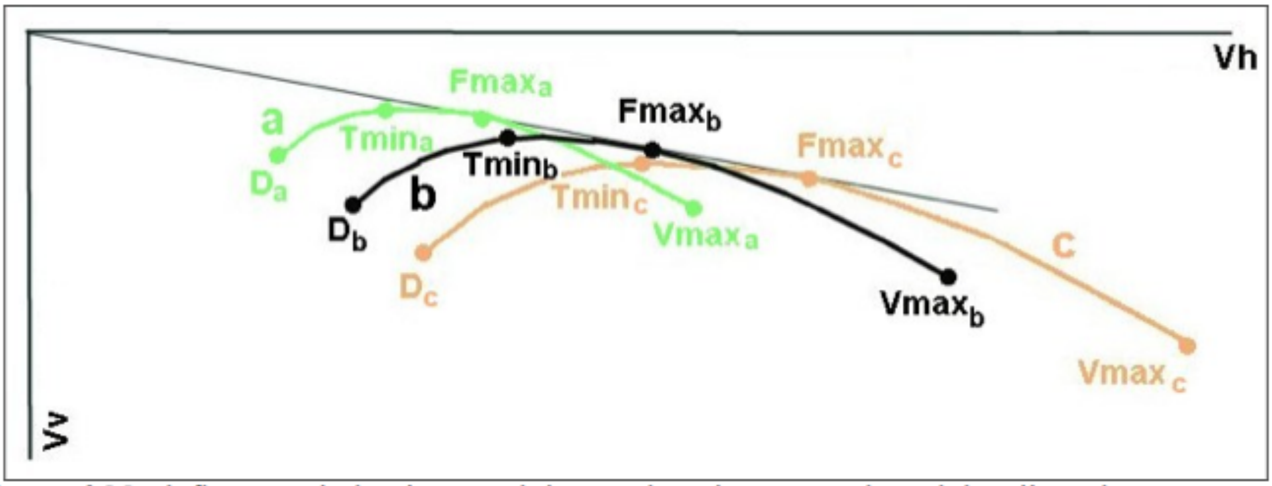


Figure A33: influence of wing loading on the velocities and the polar curve of a glider, a = low wing loading, c = high wing loading and b = average wing loading.

For example, the values, Tmax, Fmax, Vmax of the previous figure increase or decrease with the respective increase or decrease in the wing loading. However the ratio of horizontal and vertical velocities (i.e. glide ratio) does *not* change for a given angle of attack unless the wing loading is either too small or too big (i.e. well outside the range) resulting in a distortion of the profile and therefore a change of the flight characteristics of the wing. The stall speed follows the same rules: it decreases or increases with respective decreasing or increasing wing loading. **Questions 066 and 067**.

Polar Speeds in Moving Air Mass

Until now, we have reviewed the polar speed and glide ratio of a glider that is moving in a very calm atmosphere (no wind). In windy conditions (vertical or horizontal), the polar speeds and the glide ratio of the glider does not change compared to the air mass but does change relative to the ground. For example (Figure A34), imagine a head wind of 6m/s: The entire range of groundspeeds (horizontal) is less than 6m/s while the speed range relative to he air mass does not change. The effect is the same as if the origin of the graph were moved to the right by 6m/s. See Figure A34. With an air speed in the air mass of 7m/s, the ground speed would be 1m/s. With an air speed of 10m/s, the speed would be 4m/s relative to the ground. The minimum air speed (i.e. near stall speed) of 5m/s relative to the mass of air, corresponds to a *rearward* speed of 1m/s relative to the ground (i.e. *minus* 1m/s).

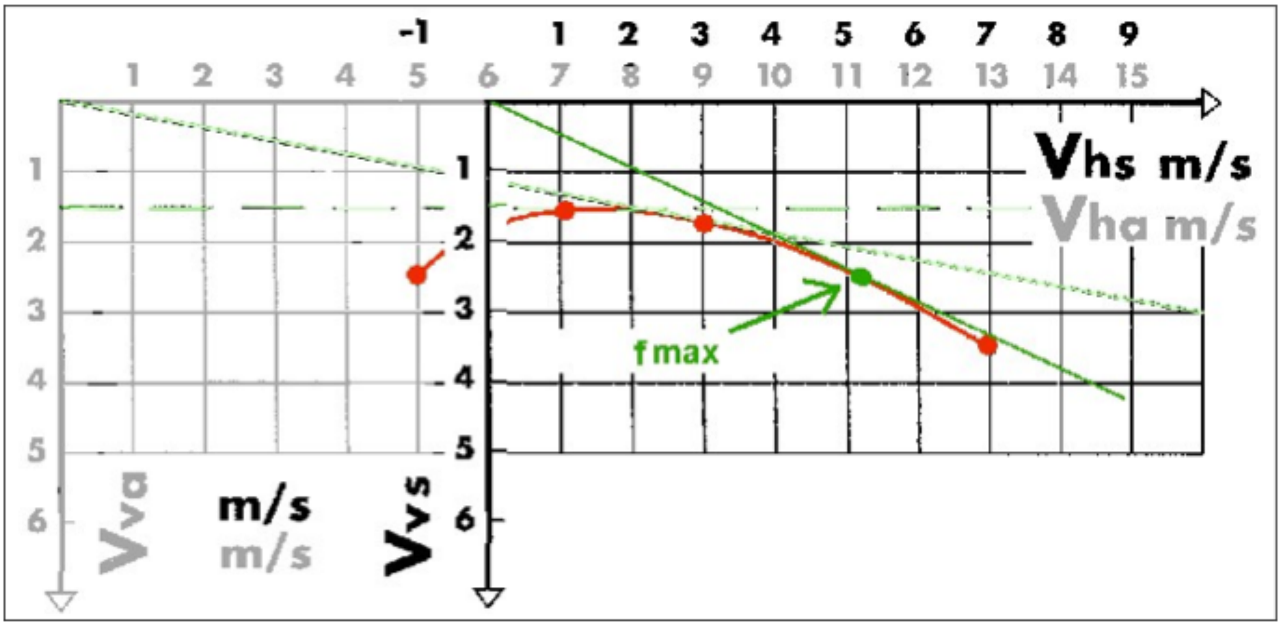


Figure A34: Polar speeds with a head wind of 6m/s. Vhs = horizontal velocity relative to the ground. Vha = horizontal velocity relative to the air. Vvs = Vva = vertical velocity (sink rate) from the ground and from the air. Fmax = maximum glide ratio.

To fly at maximum glide ratio against the wind, a pilot must accelerate the wing. In figure A34, the tangent to the polar curve which intersects the origin of the new axis corresponds to an air speed of 11m/s, or ground speed of 5m/s. This is the speed required to achieve the maximum glide ratio for this glider in a head wind of 6m/s. The glide ratio is only about 5/2.5 = 2. As the head wind increases the glider must fly faster to achieve the maximum glide ratio. **Question 143**. When flying with a tail wind, the same logic shows that the glider must fly at a speed closer to the horizontal speed at minimum sink rate to achieve the maximum glide ratio.

Now consider the experience of a glider in a mass of air moving downward at 2m/s. See Figure A35. The effect is the same as moving the entire polar curve down by 2m/s or adjusting the origin of the axes by 2m/s To obtain the maximum glide ratio (the tangent to the polar curve, intersecting the new origin of the axes), the glider must again fly faster than best glide ratio in calm air. **Question 142**. On the other hand, if a glider flies at a given angle of attack (e.g. for minimum sink rate), then the air speed (presumably horizontal) does not change whether in still, ascending or descending air. **Question 152**.

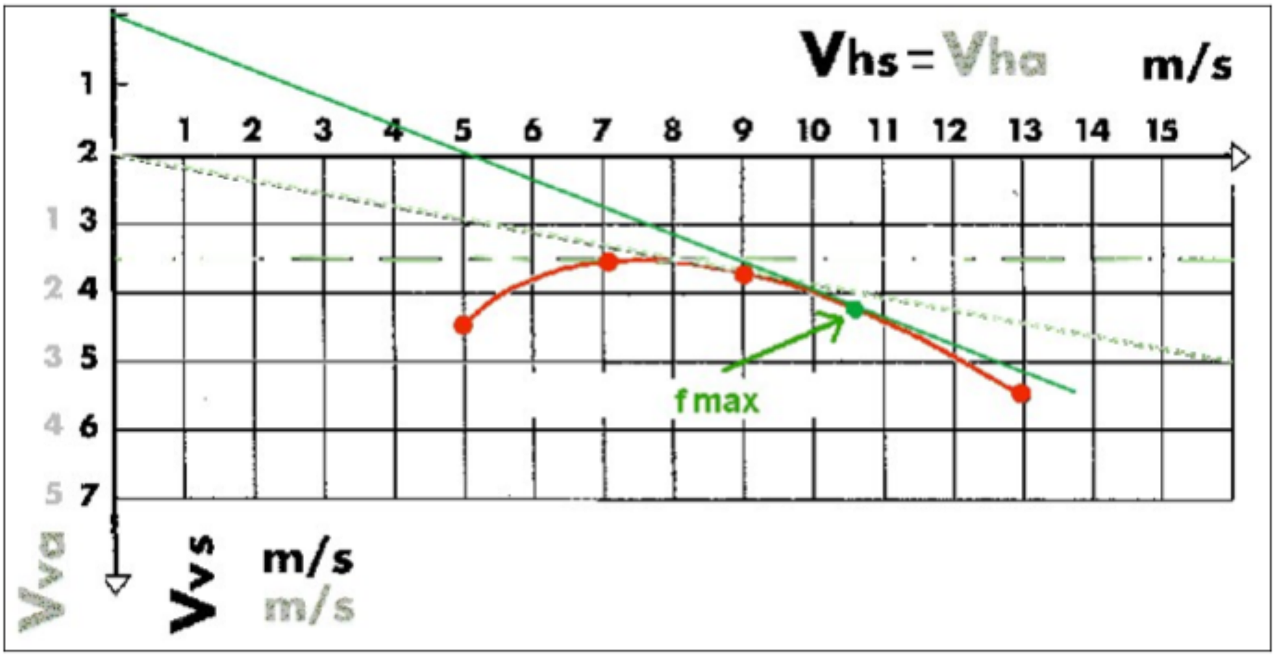


Figure A35: fleece with wind speeds down to 2m/s. Vvs = vertical velocity relative to the ground. VVA = vertical velocity relative to the air. VHS = HAV = horizontal velocity relative to the ground and from the air. Fmax = maximum fine.

Question 140. At what air speed should a praglider, with the polar curve shown in figure A32, fly in order to navigate the greatest distance when flying with a head wind of 8m/s (29km/h) (i.e. with the greatest glide ratio when facing the wind)? From the graph, we see that the tangent (to the polar curve) which passes through the new origin formed by shifting the horizontal axis by 8m/s touches the curve at a horizontal speed of corresponding to 13m/s (or 13-8 = 5m/s relative to ground). The answer can also be verified by calculation: if the wing flies at 11m/s (or ground speed of 3m/s) the glide ratio will be 3 / 2.4 = 1.25. If the wing is flying at 13m/s (or ground speed of 5m/s) the glide ratio will be 5 / 3.5 = 1.43. The values of 2.4 and 3.5 are the respective fall rates corresponding to 11 and 13m/s horizontal velocity relative to the air (the relative wind) or 3 and 5m/s horizontal velocity relative to the ground.

Questions 144 and 145. A pilot is flying at a speed of 36km/h (10m/s) and a sink rate of 1m/s. He reaches an area of downdraft of 1m/s. What are the speed and rate of fall within the downdraft? What is the glide ratio if the air speed is maintained? The horizontal velocity does not change (10m/s) but the rate of fall becomes 1 + 1 = 2m/s. The glide ratio is now 10 / 2 = 5 versus the glide ratio in the absence of a downdraft of 10 / 1 = 10. The glide ratiowas therefore reduced from 10 to 5.

Questions 146 and 147. A glider is flying at a speed of 54km/h (15m/s) and with a sink rate of 2m/s. On its flight path it encounters a headwind of 18 km/h (5m/s). What are its sink rate and ground speed (horizontal), and what is its glide ratio? The rate of fall does not change (2m/s). The air speed is reduced by 5m/s, it becomes 15 - 5 = 10m/s (36km/h). The glide ratio = 10 / 2 = 5.

Equilibrium of Forces for a Glider while Turning & Load Factor

In stabilized turns (i.e. that have already been initialized and follo a smooth curve) an additional horizontal force is added to the total take-off weight (P). This is the centrifugal force (Fc) directed towards the outer circumference of the turn. See Figure A36. **Question 155.**

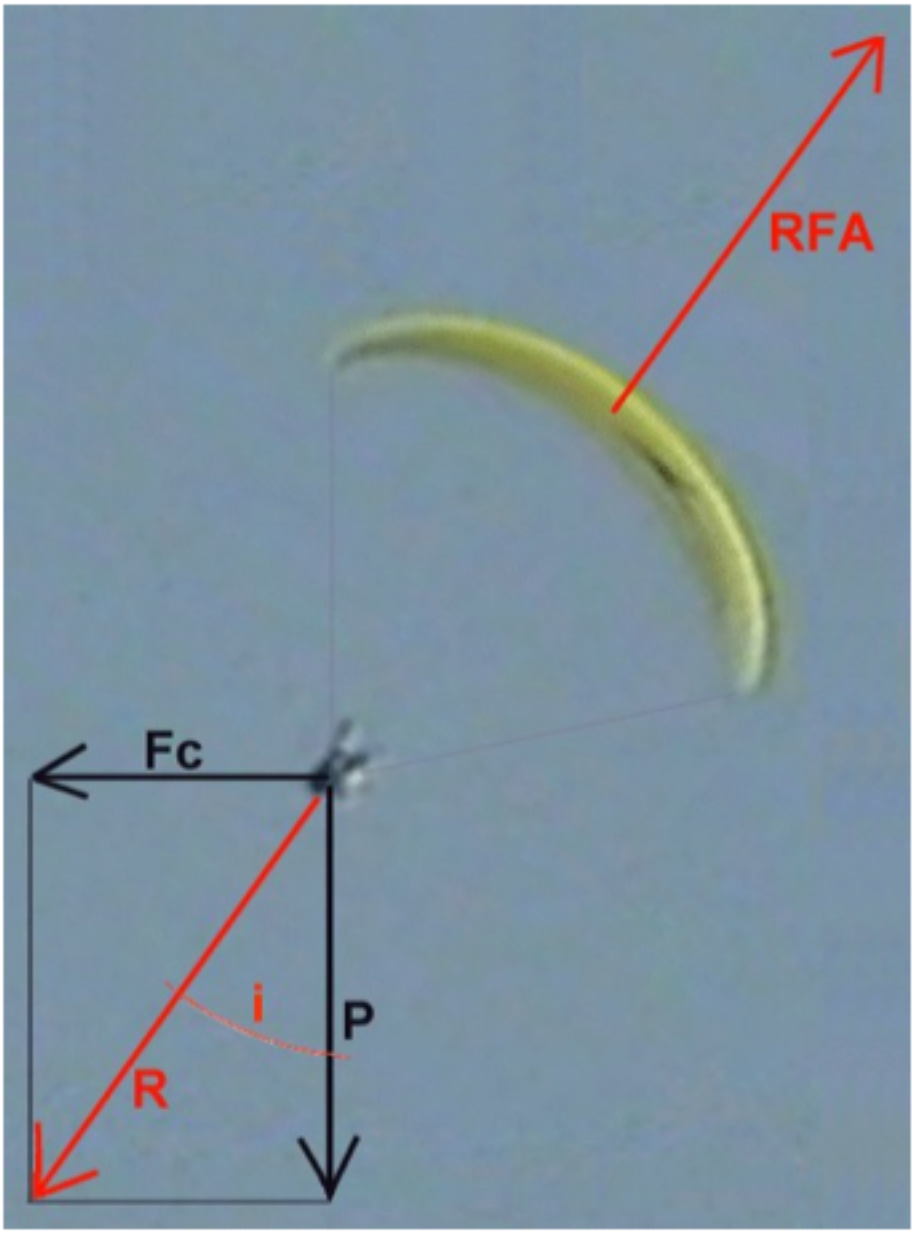


Figure A36: Balance of forces of a glider in a turn. RFA = resultant aerodynamic forces. i = angle of the wing. Fc = centrifugal force. P = take-off weight in straight flight. R = take-off weight in the turn.

Since P (vertical and directed downwards) and Fc (horizontal and directed outwards) are two forces with the same point of origin, the rules of vector addition can be applied. The resultant R (also called effective weight) is directed at an angle downward and outward. It is greater than P. If the turn is sharp (angle (i) of turn is high) Fc is larger and R is large and steeply inclined. R is quantified in terms of P by the number of times that R is greater than P. This number is called the "load factor". Alternatively, the load factor / R = P. **Question 153.**

The load factor is measured in G (i.e. the multiple of a normal gravitational force). If P = 100 kg and R = 250 kg, the load factor = 250 / 100 = 2.5G. **Question 154**.

In a stabilized turn, the resultant aerodynamic force (FRA) will be opposed exactly to R (which is also equal to P in uniform straight flight). Figure A35. The sharper the turn, the greater Fc will be, and hence greater R will be, and the closer to the horizontal it will act. Also, to maintain the equilibrium of forces, the resultant aerodynamic force will also be great and angled close to the horizontal. Since; the wing loading = resultant aerodynamic force (FRA) / wing surface; and the surface of the wing remains the same; the wing loading also increases in proportion to the resultant aerodynamic force.

Remember also that, as the relative wind speed (true airspeed of the wing through the air) increases, the resultant aerodynamic force increases with the square of wind velocity. If the speed doubles, the resultant aerodynamic force is multiplied by 4. The reverse is also true. In a stabilized turn, the resultant aerodynamic force should increase to balance (or "offset") R. To achieve this increase in the resultant aerodynamic force the glider itself will have increase speed, but to a lesser extent. In other words, in a turn the whole speed range is increased, elivating the minimum speed. We can now answer **question 156**. During a transition from a steady straight flight into a turn (also stabilized), the wing loading and minimum flight speed increases.

Figure A37 below shows the relationship (curve c) between the angle of turn and the load factor and the relationship (curve v) between the angle of turn and the factor increasing the speed range. For example, at 30° tilt, the increase in load and speed is insignificant. At 45°, the load factor = 1.4G and the increase in speed is factor of 1.2. Beyond 45°, changes occur much more quickly: At 60°, the load factor is 2G and velocities increase by 1.4. If the normal (straight) speed is 20km/h, the glider will corner at 60° at 28km/h. At 70° it (theoretically) experiences 3G and at 80° the load factor is G6!

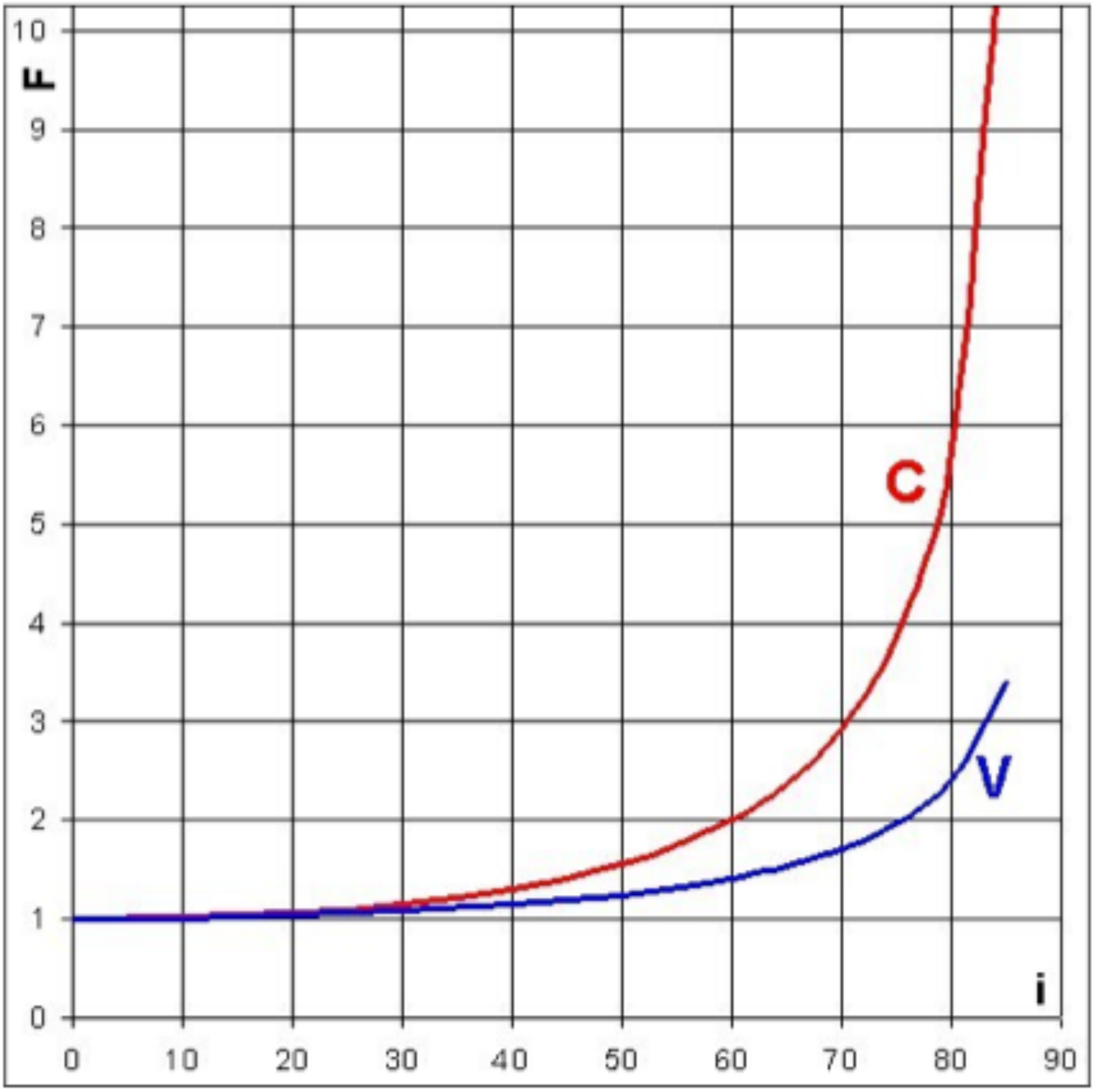


Figure A37: F = load factor (C) and increased speeds (V) relative to the angle of inclination i (°) of a turn.

Answers & commentary for SHV/FSVL theory exam for paragliders
Part 1: Aerodynamics and Flight Mechanics.

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Jean Oberson, March 2005 & Andy Piers, April 2010