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version of 15 October 2022.   Sylvain FAUTRAT

PREAMBLE

This document is the technical presentation of a device for a different piloting of a paraglider. The text will evolve as the project progresses.
The aim is to explain design principles, not how the equipment is made or how it is flown.
Free flight is a risky activity. The precise choice of materials and dimensions is not discussed.
If readers take inspiration from these pages for their own projects, it is their responsibility to deal with all the questions of strength of the various structural parts, as well as the questions of piloting adapted to their configuration.
At this stage, the scheme acts as a platform for experimentation, without any concern for supplying or selling equipment.

HISTORY

In the version of the paraglider that has become almost universally accepted, the connection between the wing's lines and the pilot is made by a set of risers attached to two fixed points on the harness. Control is achieved primarily by varying the inclination of the two trailing edge flaps (the brakes) and by rolling the harness, and transiently by changing the relative lengths of the risers. Since the early days of paragliding, a number of devices have been explored to improve some aspect of the wing's handling. The approach is generally to implement the risers, or the lines themselves, on pilot-operated components.

Among the systems that have had some visibility are

- risers fixed on the seat plate, which can be tilted, of the harness (*driving harness*, X. Rémond / André Rose)
  Ref : Traité de pilotage et de mécanique du vol, chap11, H. Aupetit
  https://www.pilotage-parapente.com/manuel-de-pilotage/sommaire/pilote-et-pilotage/le-poste-de-pilotage/7-accelerator-and-trims/
- risers attached to two 40 cm bars on the left and right of the pilot, each of which can be rotated around a horizontal axis by the pilot to change the attitude of the corresponding half wing (*steering bars*)
  Ref : Traité de pilotage et de mécanique du vol, chap11, H. Aupetit
- risers fixed on two 12 cm swivel plates that cannot be operated by the pilot, each forming a self-stable swing within certain limits (*piloting plates*, L. de Kalbermatten)
  Ref : Traité de pilotage et de mécanique du vol, chap11, H. Aupetit
- lines fixed and distributed on a rigid rectangular frame located above the pilot (*piloting cage*, Jean-Louis Darlet)
  http://aspicage.fr/.
- lines fixed on two 40 cm bars located on the left and right of the pilot, each of which can be rotated around a horizontal axis, but also around a vertical axis in order to modify the attitude of the corresponding half-wing (*BDBC Bidirectional differential balanced control*, experiments by Nikolay Yotov)
  Ref : http://skynomad.com/articles/bidirectional-differential-balanced-control
  https://www.paraglidingforum.com/viewtopic.php?t=97424

STEERING CAGE

The cage is probably the only device that has been developed over a long period of time and is still used in 2020 by a number of pilots. The gesture is completely different as the main control is achieved by the inclinations of the rectangular frame in roll and pitch, and not by action on the flaps. Via the lines, the inclination is transferred directly to the whole wing; this can be called incidence control.
The lines were initially laid uniformly across the rigid structure. In a second version, the lines further forward on the wing were moved closer to the middle of the structure. The result is a dynamic wing twist effect: during the duration of a roll of the structure, on the side of the wing that is lowered, the rear lines are pulled to a greater length than their front counterparts of the same numbers; on the other side of the wing, the same differences are found but in terms of line slackening. The roll of the wing is then accompanied by a direct yaw, more or less important according to the degree of closeness of the front lines on the structure. This is a dynamic phenomenon, the faster the cage is rolled, the more pronounced the yawing of the wing and its effect on its movement.
Once the wing is installed in a turn, all lines are under constant tension, the cause of the spin no longer exists. As the structure is rigid, the twist is only transient. (The existence of a residual twist in a maintained turn can be discussed by invoking a deformation of the wing, the smaller the better the turn is balanced).

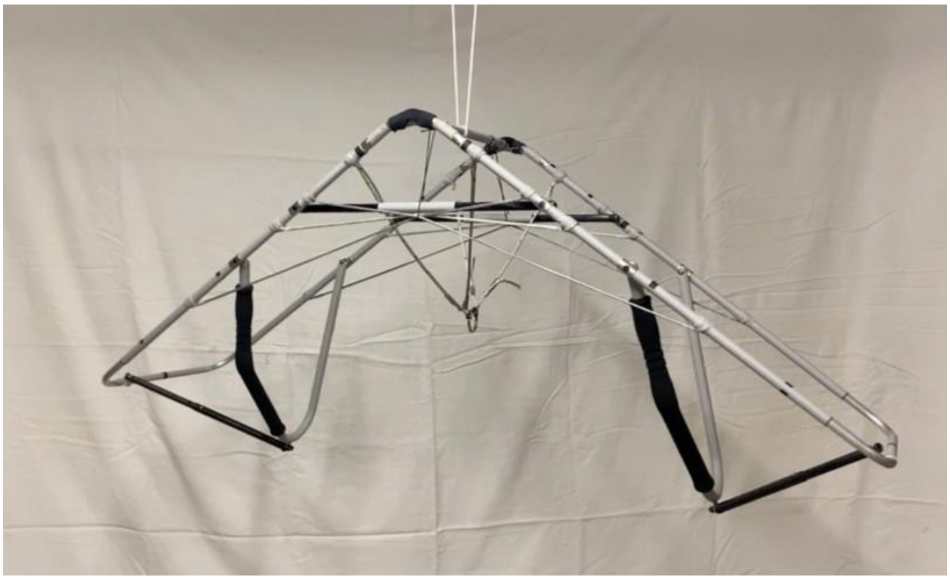
IAP

The word is an acronym for "Pilot Wing Interface", which can be pronounced *iape*.
The development of the iap is based on the flying cage, from which it takes the principle of placing the lines on an extended, rigid or quasi-rigid structure, as well as the principle of main steering by tilting the structure along the roll and pitch axes. The iap is a technical extension of the cage in a certain direction, in the sense that different extensions are probably possible. The iap differs from the cage by choices for the shape of the structure, for the materials, and by the addition of a degree of freedom.

DESCRIPTION

- Form of the structure

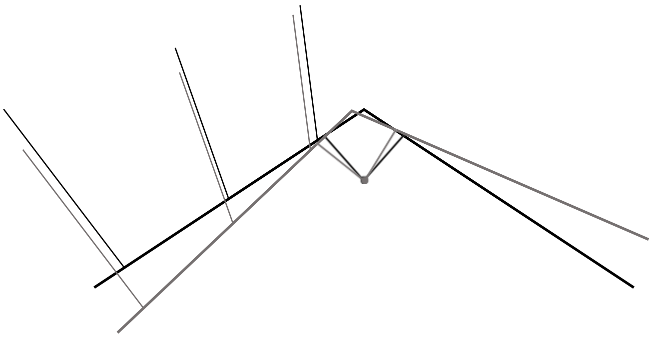
The lines are attached to two rectangular surfaces forming a 110° dihedral. The angle is limited in opening by ropes, and limited in closing by tubular struts, which retract to fold the iap.

- Angles between lines and iap

The line anchors are distributed along four spars, the further away from the middle of the iap the more outboard they are on the wing. In addition, due to the dihedral shape, the angle between a line and the spar increases continuously from the middle outwards, to around 90 degrees for column 3.

[*Here, the lines are marked in a line-column pattern:*
- *line 1 = row A: lines near the leading edge; then lines 2 and 3;*
- *column 1: lines near the middle of the wing; then columns 2 and 3.*]

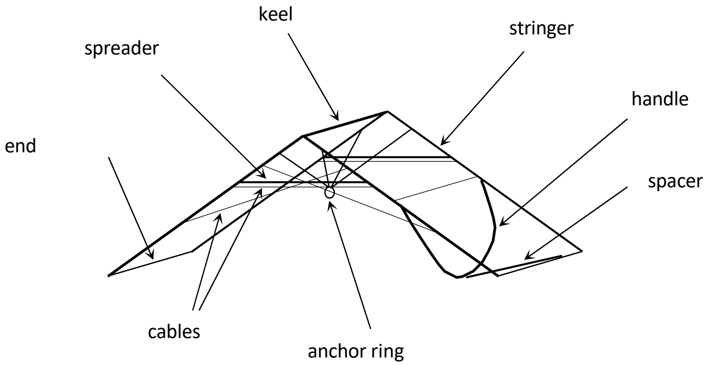


When a roll rotation is imposed on the iap, each line is pulled a certain length on one side and released a certain length on the other side; and for the same line, these lengths increase continuously from column 1 to column 3 (and column 4 of the stabilizer lines, if any).

- Materials used

The straight sections are made of carbon fibre composites.
Sections with a bend are either aluminium alloy or stainless steel. A number of connections are made of rope.

- Nomenclature



DEGREES OF FREEDOM, AND MAIN STEERING ACTIONS

- Rolling and pitching

The pilot operates the handles to tilt the structure in roll or pitch, and the wing is then also loaded for the same tilt. The joint that allows the structure to be tilted relative to the pilot is located at the anchor ring.

- Twisting

For any aircraft in a turn, good coordination in terms of pitch-roll-roll is sought. This is a multi-factor problem that is handled with varying degrees of ease, with the basic shape of the wing being a factor in the equation.
A wing made only of fabric offers the possibility of all kinds of deformation. This possibility is exploited in paragliding when lowering the trailing edge flaps, and in the flight cage when twisting transiently for a turn. With the iap, we have the opportunity to explore the possibilities a little further by allowing the structure to twist to a certain degree. Through the lines, a twist in the iap translates into a twist in the wing.
One condition for a turn that is desired to be roll balanced is symmetry between the forces exerted by the air on the two wing sections. With a flexible wing, one can try to deform the wing in such a way as to adjust the value of the angle of incidence, and consequently the value of the force exerted on each wing section, along the span. From the point of view of the usual parameters, it is rather the attitude angle that can be considered as more directly accessible to the control (in the reasoning, a distribution of attitudes over the span being fixed, that of the incidence follows, then that of the forces).
It is therefore necessary that a piloting action allows the best possible imposition of the attitude of the different wing sections.

[*Vocabulary*: distinction between :
- *warping: evolution of airfoil camber from the middle to the wing tips*
- *twist: the evolution of airfoil attitude from the middle to the wing tips*].

The question arises as to the degree of deformation of the iap into a twist that should be made possible for a typical turn. A theoretical approach, sufficiently simplistic to be dealt with by simple calculations, can provide orders of magnitude. The model used is described in the attached document. For a wing in a balanced turn according to the flight parameters chosen in the attached examples, it can be seen that the difference in inclination to be applied between the middle of the wing and a tip does not exceed 2 degrees. For: a typical steep turn, a mid-wing attitude quite far from its value in a balanced turn without spin (concept introduced in the Appendix), and taking into account the reduced effective span due to the arch shape, etc., one can for example retain 4 degrees as the largest value necessary for the spin to achieve balance.
Mechanically, the tilt of a wing panel is obtained by moving the front bottom line parallel to the rear bottom line (considering them almost parallel). For an end panel (column 3 lines), if the top points of the two lines are for example 1 metre apart, a tilt of 4 degrees corresponds to a translation of 7 cm. This 7 cm can be found practically on the iap, at the points where the two end lines are installed. This is an indication of the degree of deformation that the iap should allow.
In fact, in the layout under test, the front and rear lines of column 3 are not located at the same distance from the keel; for example, with respective distances of 34 cm and 66 cm from the keel, it is understood that a difference in translation between them of 7 cm corresponds at the end of iap to a difference of the order of 18 cm (a 25° angle).
At the time of writing, the efficiency of twisting is being evaluated. Depending on the results, the next step will be to define more precisely one or more modes of use of this function.

- Feeling of inertia due to the structure

With a mass of less than 2 kg, the iap provides very little inertia when handling on the ground or gesturing in flight.

- Secondary controls
  - The central handle on the cage, which allows you to fold the two wingtips (make the ears) in one movement, is found on the iap.

- The two handles, present on paragliders, which allow to lower the trailing edges of the two half-wings (the brakes) are found on the iap. The first use is to create lift when landing.

- A handle at each end of the iap allows the stabilo line to be pulled in the event of a tie.

Different additional systems are to be considered:
- a system to reduce the effort deployed by the pilot to act in pitch (in the first place, to dive the iap)
- if necessary, a system to reduce the effort to act in roll
- a system that would allow the iap to be blocked or limited in roll, and possibly in pitch, to temporarily free the hands. The principle of the cage and iap is, to some degree, to disengage the wing from the pilot in all three axes; in these conditions, without steering, the wing is relatively free and the pilot is never expected to let go of the controls for too long. The system in question would reintroduce a more or less paraglider-like connection on demand.

COMPARISON BETWEEN "WING + RISERS" AND "WING + IAP"?

Using the same wing types, the two configurations obviously share most of their characteristics, and differ in a few others. The question of comparison naturally arises, but it is not a simple and straightforward matter.
A certain characteristic may be an objective advantage in some types of situation, and an objective disadvantage in others.
Moreover, depending on the pilot's level of mastery of his aircraft, or on his type of practice, a characteristic will be perceived as either an appreciable advantage, or an anecdotal advantage, or even a disadvantage.
This is not the subject of this document, which is primarily concerned with information of a physical nature.

VARIOUS EXPERIMENTS CARRIED OUT

- A greater or lesser depth of iap

The longitudinal distance between the front and rear line anchors, or iap chord, or iap depth, can be lengthened or shortened by changing the keel and the two end tubes. The depth is too great if there is difficulty in controlling the wing in pitch, as the lines act on a large lever arm. The depth is too small if the pitch control is insufficient in amplitude, finding its limit when the iap is tilted to 90° when it would be necessary to extend the movement to nose up or nose down. It is also too small if it is difficult or impossible to lift the wing from the ground, as the rear lines are not slack enough compared to the front lines.
The 50 cm depth of the cage had already proved to be too deep for some paragliders, i.e. not specifically designed for the cage. With 28 cm, the problems associated with too small a depth are revealed. The current value is therefore intermediate. It can of course be modified if necessary depending on the wing to be interfaced with an iap.

- Different values of the dihedral angle

In its first version, the iap had a 120° angle between the two planes where the lines are attached. The ground handling of the wing was satisfactory.
The idea of reducing this angle has two purposes. It is a way of increasing structural strength by making triangulation by the various cables more efficient. It is also an opportunity to explore the possibility of eliminating the large handles, with handling performed with the hands directly on the spars or on short sleeves attached to the spars.
The tests with a 90° angle showed two negative aspects. On the one hand, the ease of performing the different manipulations is not as good as with the dedicated handles. On the other hand, instability was felt when controlling the pitch with an irregular wind. When correcting by pitching up the iap, from a certain angle the wing does not resist anymore, on the contrary it acts on the iap by accentuating the pitching movement. The same phenomenon occurs in the nose-down correction. When analysing the situation, we find that the disturbing moment of force is due to the lines hanging low on the iap, in this case the outer lines since the iap has a negative dihedral. As the iap tilts progressively in pitch, the outer lines exert forces, still quasi-vertical, but with a progressively longer leverage arm relative to the anchor ring. The leverage also depends on the distance the anchor ring is attached under the iap. In summary, some lines exert nose-up moments on the iap, others nose-down moments; during nose-up movement, the different moments change, which leads, from a certain angle onwards, to a resultant moment that is nose-up, hence the instability. The situation is symmetrical for a nose-up movement.
For a ring fixed at a certain distance, it is necessary to be able to recognise the values of dihedral angle that are acceptable. This can be done by multiple trials: a value is set for a distance, and the angle of iap is changed, each time with the same wing suitably interfaced to the iap.
The problem can also be modelled for a quantitative study. This is shown in the appendix. It is assumed that an angle of 110° is acceptable for the anchor distances used.

A dihedral effect can also occur with the ears closed, depending on the type of wing and the size of the ears. In this configuration, the forces exerted by the lines of the two closed parts of the wing have a more backward inclination than in normal flight; as the lines in question are actually attached quite low to the wing, this can result in a certain amount of force to dive. It turns out that, from a piloting point of view, such a moment has a positive effect since, when flying with ears, it is advisable to pitch the wing to limit the growth of the angle of incidence on the open part of the wing.

- Different possibilities of amplitude and stiffness of the twist

After several solutions were considered, the return of the twisting movement is ensured by the end tubes. The choice of the type of tube allows the stiffness of the return to be adjusted. It is easy to feel by hand if one end is too resistant when trying to achieve the twist. Conversely, it is less obvious to decide on a lower limit. Tests with zero stiffness were carried out with four free joints between the ends and the spars. This makes it very difficult to lift the wing properly from the ground and impossible to hold it in an irregular wind. This is even more the case if the amplitude of the twist is reduced, using a half trapezoidal iap with half the tips.
At present, the ends are the same length as the keel, and the optimum degree of stiffness remains to be explored under different types of flight.

- Evaluation of the mechanical strength of the structure under static loads

The individual lines attached to the structure each take on a certain fraction of the forces exerted on the wing by the air. These fractions are roughly equal to the fractions of the wing area to which the lines are connected. For a certain total force exerted on the wing, in balanced flight, one can then assign to each lower line the fraction of force that concerns it.
A simple way to perform a strength test is to turn the iap upside down and hang it from the anchor ring at a fixed point. A total test force is chosen and the corresponding force is applied to each suspension point by hanging a heavy object of the correct mass from a rope. In order to obtain the same orientation of the different ropes in relation to the iap as the lines in a balanced flight situation, light spacers are used between each pair of ropes. (The cage was tested in this way, with the structure turned upside down, with equal forces applied at different points of the spars).
The test was carried out using used wooden beams as heavy objects. The total load available was 220kg (3G for a 70kg pilot). The iap showed very little deformation. The triangulation cables did not slip. As the most curved tubes are far from their breaking curvature, further testing will require significantly heavier loads.
The good load-bearing capacity is not a surprise since, on the one hand, the central lines, which are the most tensioned in flight, and the pilot's suspension cables, are attached to the iap more or less opposite each other. On the other hand, the triangulation cords allow the tubes to be loaded partly in compression rather than in bending.

SUITABLE HARNESSES

The attachment under the harness is of the single point type, in place of the two side links at the bottom of the two risers. The connection of a paragliding harness is therefore made by means of a spreader with a central anchorage, the two ends of which are attached to the harness at the two links.
Such a spacer can be designed to have an elastic vertical travel. In the event of a sudden takeover by the wing (violent reopening, fall of the pilot after a large surge), the shock can then be smoothed out to some extent. A deflection of 10 mm per G unit is for example easily achievable.
A harness-iP connection device weighs between 100 and 200 grams depending on the design options.
It is the semi-reclined position that seems to be the most suitable for flying with the hands on the handles of the iap. This position is possible with many paragliding harnesses.

i A P

ANNEXES

The following studies have been initiated to answer questions that have arisen at different times, and to which, in order to move forward, answers, even approximate ones, had to be found. The constraints are conceptual simplicity and computational simplicity, not the search for the greatest accuracy.
At this stage, two studies have been drafted, the third is pending.

Annex A - STUDY OF A TANGING INSTABILITY RELATED TO THE IPA DIEDRAL

An iap with a small angle could have the advantage of being able to be flown directly with the hands on the spars, thus eliminating the need for handles. However, ground handling tests with a 90° angle iap revealed an unstable effect: from a certain pitch angle onwards, the nose-down or nose-up actions were amplified by the wing itself; in order to stop this induced movement, it was necessary to promptly reverse the action of the hands... The interpretation is not difficult: when a low angle iap is tilted (horizontally, to exaggerate), the lines hooked near both ends act with a very large leverage arm (measured from the axis passing through the pilot's anchor point, constituting here the hinge point). In addition, front and rear lines may tend to rotate the iap in the same direction, whereas the first idea would be that, if the front lines tend to rotate in one direction, the rear lines would tend to rotate in the opposite direction.
In comparison, with a flat structure (180° angle), the lines attached at the same span of the structure all have the same leverage. And the front and rear lines act with opposite pitching moments.
Now that the mechanism of instability is understood, a quantitative study is still needed to provide a more accurate benchmark when it comes to choosing an angle of iap with knowledge. The study is simplified as much as possible, while preserving the specific shape of the iap.

The following calculations are intended for those who wish to enter the subject themselves. The conclusions can be read independently.

Model assumptions

The symbols used refer to the following drawings.

• The lines exert forces on the frame whose projections in the vertical plane of symmetry are vertical (a satisfactory approximation because the wing is high with the lines slightly inclined forward or backward).
• We reason with only two lines, a front line and a rear line. All the forces exerted by the front lines are modelled by a single force, of vertical projection $_{FA}$ applied to point A of the drawing. The same applies to the rear lines with the force $_{FB}$ applied at point B.
• The pitching moments are calculated with respect to point O which is the joint at the connector.
• The pitch angle is not extreme, it remains below about 80°.
(Otherwise, the direction of the $_{FA}$ action reverses, more precisely when $_{QaPa}$ < z. For its part, QbPb always remains > z, so no reversal. For its part, $_{QbPb}$ always remains > z, so there is no inversion).
• When the frame is tilted, the force at A remains the same, and so does the force at B. The study focuses on transient effects, after a rapid tilt of the iap, before the wing has moved forward or backward significantly relative to the iap.
• To balance the pitching moment created by the forces at A and B, the pilot's hands act at the two points B of the drawing seen from the front (the same points B are chosen here to simplify the diagram and the reasoning). This action is summarised by a force $_{FPILOTE}$, perpendicular to the direction $_{OPb}$ and defined as acting in the direction of the pitch considered (nose down or nose up).

Study situations

<u>iap specific parameters </u>iap

angle = 90

iap chord: $_{QaQb}$ = 360 mm

anchorage O located at z = 130 mm under the keel

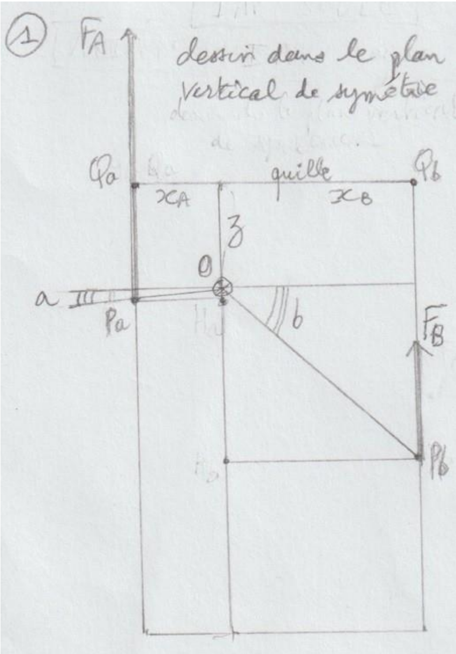
at $_{xA}$ = 110 mm from the front

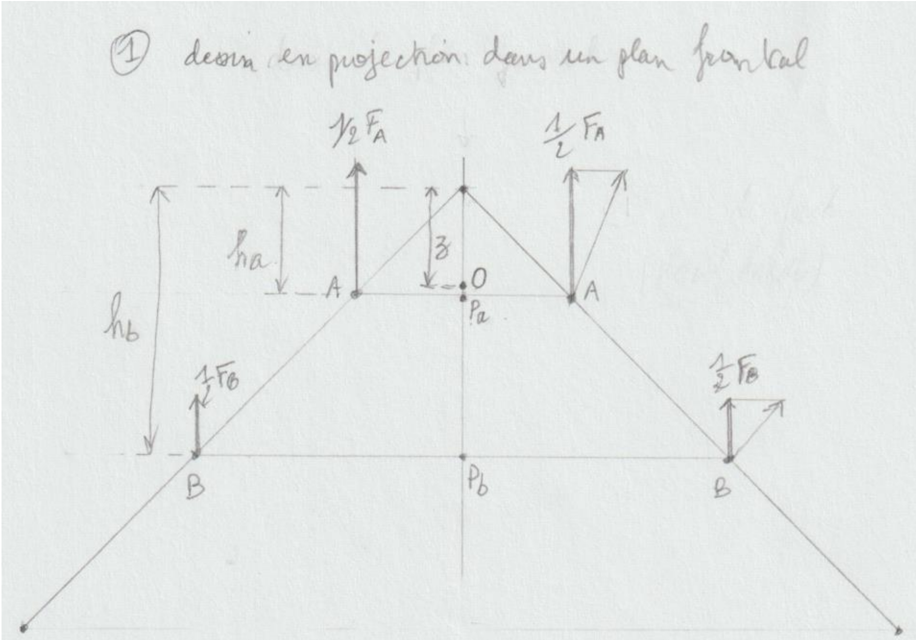
plane at $_{xB}$ = 250 mm from the

rear plane

lines installed along the spars, at QaA = 200 mm from the keel, for the fronts,

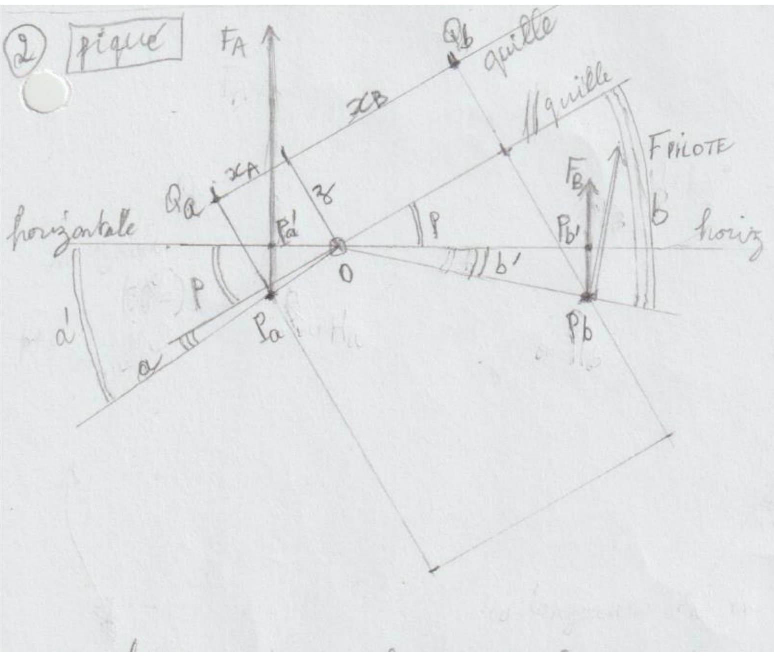
at QbB = 500 mm from the keel, for sterns

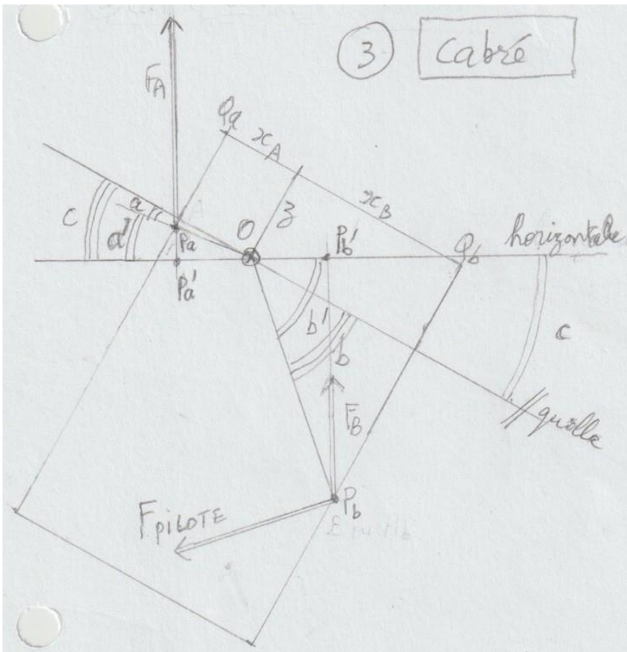




<u>Parameters for pitching situations</u>

pitch angles to nose down: p = 30° to nose up: c = 30° (forcomparison: for a paraglider accelerated to the recommended maximum, the difference in height between the front and rear links is about 150 mm, which is the case here if p = 25°)





Calculation formulas

The different angles a, b, p, c, a', b' are considered algebraically, i.e. including negative values.

1- <u>iap right</u>

The wing exerts a vertical force F which is divided between $_{FA}$ and $_{FB}$. The correct centring of the iap in balanced flight is achieved with values $_{xA}$ and $_{xB}$ such that :

$_{FA} = F\ [\ _{xB} / (\ _{xA} + \ _{xB}\ )\ ]_{FB} = F\ [\ _{xA} / (\ _{xA} + \ _{xB}\ )\ ].$

The heights $_{ha}$ and $_{hb}$ are given by :

$_{ha} =$ QaA . cos(½ . angle of iap $)_{hb} =$ QbB . cos(½ . angle of iap).

The lengths $_{OPa}$ and $_{OPb}$ are given by :

$_{AOPa} = [\ x^2 + (\ _{ha} - z)^2\ ]^{½}\ _{OPb} = [\ ^{xB2} + (\ _{hb} - z)^2\ ]^{½}$.

The angles a and b are given by :

a = arctan [($_{ha}$ - z) / $_{xA}$] b = arctan [($_{hb}$ - z) / $_{xB}$].

Note: the formula for a is valid even if z > $_{ha}$.

2- <u>piqué</u>

3-

The corners are connected by :

a' = a + pb ' = b - p.

Then:$_{OPa}' = \ _{OPa}$. cos(a' $)_{OPb}' = \ _{OPb}$. cos(b').

The balance of force moments in the presence of force F can be written: $_{FPILOTE}$

$\cdot\ _{OPb} + \ _{FB} \cdot\ _{OPb}' = \ _{FA} \cdot\ _{OPa}'$.

Hence the strength:

$_{FPILOTE} = (\ _{FA} \cdot\ _{OPa}' - \ _{FB} \cdot\ _{OPb}'\ ) / \ _{OPb}$.

4- <u>raiser</u>

5-

The corners are connected by :

a' = c - ab' = b + c.

Then:$_{OPa}' = \ _{OPa}$. cos(a' $)_{OPb}' = \ _{OPb}$. cos(b').

The balance of force moments in the presence of force F can be written: $_{FPILOTE}$

$\cdot\ _{OPb} + \ _{FA} \cdot\ _{OPa}' = \ _{FB} \cdot\ _{OPb}'$.

Hence the strength:

$_{FPILOTE} = (\ _{FB} \cdot\ _{OPb}' - \ _{FA} \cdot\ _{OPa}'\ ) / \ _{OPb}$.

Note. If, in the formulae for the nose-up, we take for c the value - p, we recognise for a' and c' the same expressions as for the nose-down angle p, therefore also the same values for $_{OPa}'$ and $_{OPb}'$, and finally the same absolute value for $_{FPILOT}$, with nevertheless a change of sign, which must be rectified to take into account the opposite direction of definition of $_{FPILOTE}$ in the nose-up case. Thus, for a pitch angle value, whether nose up or nose down, the value of $_{FPILOTE}$ is the same and it is sufficient to make the calculation only once.

(Note that this can be anticipated, for example, in the following way. Since the two forces $_{FA}$ and $_{FB}$ are postulated to be always vertical, by turning the diagram 180°, we find the classical case of a compound solid rotating around a fixed axis, with mass concentrated at two points (A and B), subject to gravity and an external moment (that of the $_{FPILOTE}$). The symmetry in this context is obvious).

Calculation results

Selected values for the parameters

Total vertical force, exerted by the wing on the iap, the value: F = 50 kg.

Parameters to be varied and values chosen

iap angle 90° 110° 130°180° (flat iap)

pitch anglep or c : 15° 30° 60° 80°

distance from anchor under keel: 130 mm 170mm210 mm

Parameter of interest

It is the FPILOTE force that is the parameter to be monitored. When its value is positive, it means that, in order to maintain itself, the system effectively requires pilot action in the direction of the current pitch. A negative value means, on the contrary, that the system is unstable, and all the more unstable as the absolute value is greater. What is desired is stability, i.e. positive values for FPILOTE.

Results

DPI angle (°)	90	90	90	90	110	110	110	110	130	130	130	130	180	180	180	180
iap pitch angle (°)	15	30	60	80	15	30	60	80	15	30	60	80	15	30	60	80
Results for a dive or a nose-up																
For z = 130 mm: different values of the iap angle and different values of the pitch angle																
force Fpilot needed to balance the wing moment (kg)	*-2,9*	*-5,7*	*-9,8*	*-11,2*	*-1,6*	*-3,2*	*-5,5*	*-6,2*	*0,3*	*0,6*	*1,1*	*1,3*	*6,0*	*11,5*	*20,0*	*22,7*
For z = 170 mm: different values of the iap angle and different values of the pitch angle																
force Fpilot needed to balance the wing moment (kg)	*-1,5*	*-2,9*	*-5,1*	*-5,8*	*0,1*	*0,2*	*0,4*	*0,5*	*2,4*	*4,6*	*8,0*	*9,1*	*7,3*	*14,1*	*24,3*	*27,7*
For z = 210 mm: different values of the iap angle and different values of the pitch angle																
force Fpilot needed to balance the wing moment (kg)	*0,2*	*0,3*	*0,56*	*0,64*	*2,1*	*4,1*	*5,8*	*8,0*	*4,5*	*8,7*	*12,3*	*17,1*	*8,3*	*16,1*	*22,7*	*27,9*

Conclusions

- For an iap of given angle and z, the stable or unstable effect increases progressively as the pitch angle increases.
- For the 90° iap, with z = 130 or 170 mm, the results (negative values) are consistent with the instability found in the field.
- Increasing z changes an unstable iap to stable.
- Increasing the iap angle changes an unstable iap to stable (at 180°, stability would be strong in all cases).

Appendix B - STUDY OF THE EFFECT OF WING TURNING ON ROLLING BALANCE DURING A MAINTENANCE TURN

Issues addressed

- in a steady, maintained turn, how does the angle of incidence evolve along the span?
- how to define the notion of a roll-balanced turn?
- can the balance be improved by changing the wing's attitude? by twisting the wing?
- for a typical turn with a paraglider, what is the order of magnitude of the useful degree of twist?

Procedure followed

- selection of a roll-balanced flight criterion
- modelling of the wing, wing movement in turns, lift force
- calculation of the kinematic parameters, then calculation of the forces from the kinematic data, using the most basic standard formulas
- examination of the parameter values obtained in some significant turning configurations, and the lessons to be learned from them.

Balanced flight criterion

The aim is to identify trends and not to develop an exact study. In order to simplify the approach, we limit ourselves to the case of an elongated wing, in a slightly inclined turn. In these conditions, for the study of the balanced flight, we retain as predominant on each profile, the force of lift, to the detriment of the drag components.
The following criterion is used: a turn is well balanced when the lift distribution along the span is symmetrical with respect to the centre M of the wing.

Modelling

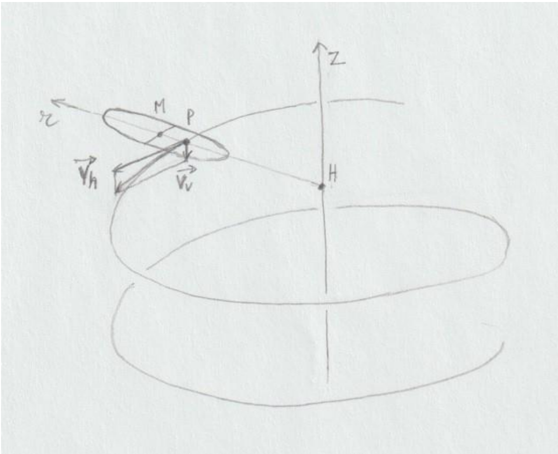
Wing model

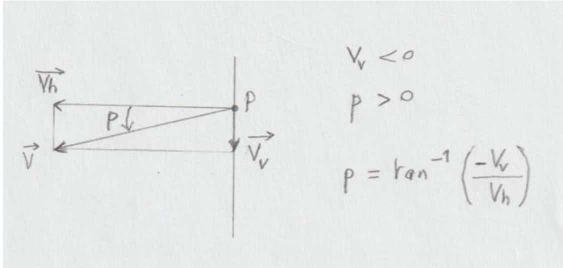
First, the wing is described as flat (no arching, no twisting) and horizontal along the span (no roll). The distribution of chord values along the span is assumed to be symmetrical with respect to the centre M of the wing, but the values of the individual chords themselves are not used in the intended calculation.
For the airfoil located at the r-coordinate along the span, its attitude is defined by the angle a(r) measuring its pitch above the horizontal. In the absence of a spin, the attitude of the different airfoils have everywhere the same value as that a_M at the middle of the wing: $a(r) = a(r_M) = a_M$.
From the above description, a progressive twist can be introduced from one end of the wing to the other, in the form of a certain distribution of an increase in attitude noted Aa(r). From then on, the airfoil attitude at coordinate r is no longer $a(r_M)$ but: $a(r) = a_M + Aa(r)$.
The case of a linear twist, the only one that will be considered here, is of the form: $Aa(r) = k (r_M - r)$, with k the twist coefficient. The additional trim is zero in the middle, and the distribution is antisymmetric between the two sides.
With such a spin, the attitude is written: $a(r) = a_M + k (r_M - r)$.
Note that if d is the half-wing span, the wing extends from $(r_M - d)$ to $(r_M + d)$.

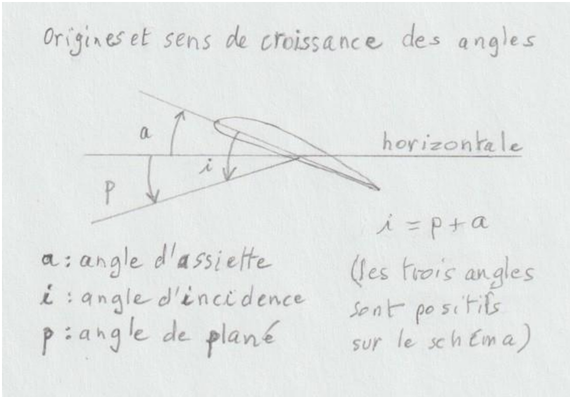
Model of the wing's motion in the air mass

The ambient medium is homogeneous air fixed with respect to an inertial reference frame. The wing is in helical motion: it descends at constant vertical speed $-V_v$, and is in revolution at constant angular velocity about some fixed vertical axis Oz in the air. The usual cylindrical coordinates (r, φ, z) are used, with the z-axis upwards, and the radial coordinate r identifying with the variable introduced earlier for a wing with

the span is well aligned with the radial direction. The horizontal velocity of each point on the wing is then of the form: V_h = r.
The notion of "wing turn radius" corresponds to the value of r_M.







Lift force model
The lift (over a unit area) is written as: F_L = C_L.(½)V^2 .
For the usual airfoils, the lift coefficient is considered to vary proportionally to the quantity (i - i_0), called "absolute incidence", where i_0 is the incidence at zero lift: C_L = C_{Li}. (i - i_0).
In our case, for a profile of coordinate r, since V^2 V_h + V_v) = r + V_v), we obtain: F_L(r) = C_{Li} (½)^2 r^2 + V_v^2).(i(r) - i_0).
2 22 2 2

Parameter calculations
Glide angles
The glide angle p(r) for a profile of coordinate r is expressed from the components V_h and V_v as: p(r) = $\tan^{-1}$ ($-V_v/V_h$) = $\tan^{-1}$ (–ςϖ/ρ).
Geometric" impacts
For each profile, the incidence is related to the glide angles p and attitude angles a by: i(r) = a(r) + p(r).
With a linear twist of coefficient k, this gives: i(r) = a_M + k (r_M - r) + $\tan^{-1}$ (–ςϖ/ρ).
For absolute incidence this gives: (i(r) - i_0) = (a_M - i_0) + k (r_M - r) + $\tan^{-1}$ (–ςϖ/ρ). By analogy, we can call (a(r) - i_0) the "absolute attitude". In M it is: (a_M - i_0).
Lift forces
We now have: F_L(r) = C_{Li} (½)^2 r^2 + V_v^2).[(a_M - i_0) + k (r_M - r) + $\tan^{-1}$ (–ςϖ/ρ)]. F_L(r) can be written as K . f_L(r), posing :
K = C_{Li} (½)
f_L(r) =^{2} r^2 + V_v^2).[(a_M - i_0) + k (r_M - r) + $\tan^{-1}$ (–ςϖ/ρ)].
In the following, it is only the parameters a_M and r that will be varied; it is therefore sufficient to consider the "lift factor" f_L(r) for the study of the equilibrium of the turn.

Parameter values used:
half span: d = 5 m
vertical speed, two values: V_v = - 1.5 m/s V_v = - 2.0 m/s

radius of turn of the wing, two values: $_{rM}$= 15 m $_{rM}$ = 20 m
period of turn and angular velocity :

T = 14 s - = 2/T = 0.45 rad/s T= 14 s - = 2/T = 0.45 rad/s

Acceptable range of incidence angles: 2° - 20

[Ref. for paraglider profiles: (1) Traité de pilotage et de mécanique du vol, section 15, H. Aupetit: range 5° - 20°; (2) Brevet du sharknose: range 1° - 20° https://worldwide.espacenet.com/publicationDetails/biblio?FT=D&date=20120914&DB=worldwide.espacenet.com&locale=en_EP&CC=FR&NR=2972422A1&KC=A1&ND=4].

Digital study

It is conventional to use the formulas of flight mechanics to show, for example, the relationship between flight speed and incidence, the latter depending on attitude control, etc.

Here, the study is at a fixed constant speed, and what is of interest is the relationship between the lift distribution along the span and the attitude distribution (without and with spin).

First page: for information, some graphs of the incidence as a function of the radius r,

- first without twisting for two trim values $_{aM}$ set at -5° and -8°,
- then with three different twists for the -5° plate.

Second page: plots of various graphs (in red) of the lift distribution along the span, i.e. the lift factor $_{fL}$ as a function of the radius r.

On the left hand side of the page there are three cases of absolute trim ($_{aM}$ - $_{i0}$); the second value has been set by adjusting it to obtain a curve of $_{fL}$ that has good symmetry about the middle of the wing.

On the right, it can be seen that by adding a suitable twist, good lift symmetry can also be achieved with the first and second absolute plates on the left, by adjusting the twist coefficient k each time.

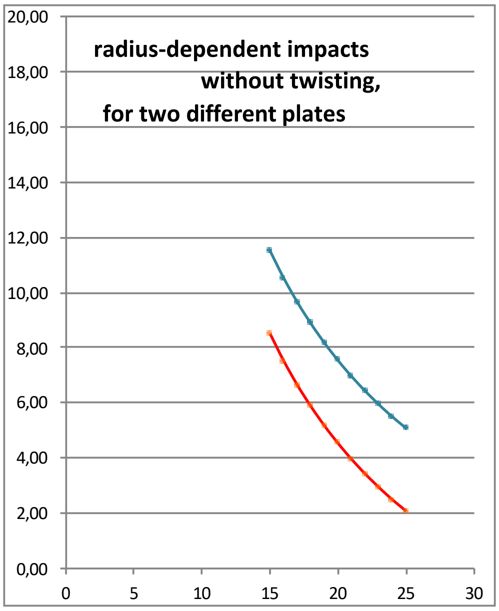
The incidence curves (in blue) are useful to ensure that the values chosen for the parameters are compatible with incidence values within the permitted range.

Third page. The same study as on the second page, for a tighter turn.

Impact as a function of radius r, for some values of the pitch, without and with twist

rM (m)	Vv (m/s)	
20	-2	0,45

plate	aM (°) =	-5	-8
		radiusincidence	incidence
	r (m)	i (°)	i (°)
	15	11,50	8,50
	16	10,52	7,52
	17	9,65	6,65
	18	8,87	5,87
	19	8,17	5,17
middle M	20	7,53	4,53
	21	6,95	3,95
	22	6,42	3,42
	23	5,94	2,94
	24	5,49	2,49
	25	5,08	2,08

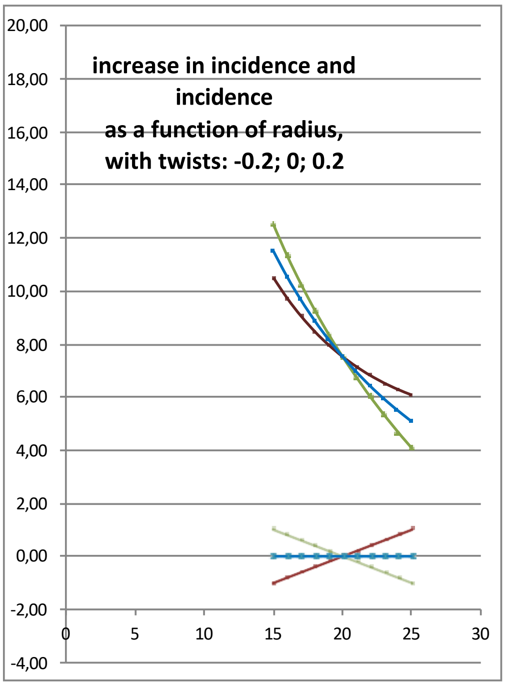


Comment

Increasing the pitch has the effect of increasing the different impacts along the span by the same amount (shifting the curve upwards).

plate: aM (°) =-5

	k =-0,2		k = 0		k = 0,2	
kink coefficient	increase in base	impact	increase in base	impact	increase in base	impact
	Aa (°)	i' (°)	Aa (°)	i' (°)	Aa (°)	i' (°)
	-1	10,50	0	11,50	1	12,50
	-0,8	9,72	0	10,52	0,8	11,32
	-0,6	9,05	0	9,65	0,6	10,25
	-0,4	8,47	0	8,87	0,4	9,27
	-0,2	7,97	0	8,17	0,2	8,37
middle M	0	7,53	0	7,53	0	7,53
	0,2	7,15	0	6,95	-0,2	6,75
	0,4	6,82	0	6,42	-0,4	6,02
	0,6	6,54	0	5,94	-0,6	5,34
	0,8	6,29	0	5,49	-0,8	4,69
	1	6,08	0	5,08	-1	4,08



Comment

The lower graphs show the increase in attitude along the span (the trailing edge is also shown, with the leading edge horizontal).

A negative twist coefficient corresponds to an incidence that decreases inwards at the turn and increases outwards; the opposite is true with a positive coefficient.

lift as a function of radius r, for some values of pitch, without and with twist (1/2)

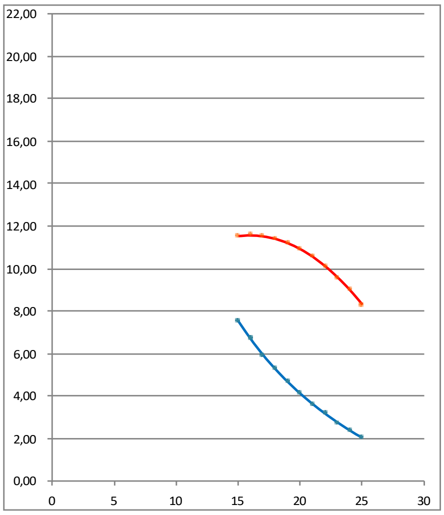
rM (m)	Vv (m/s)	(rad/s)
20	-1,5	0,4

VhM(m/s)	duration(s)
[illegible]	[illegible]

in yellow: arbitrarily set value (for testing) in orange: value adjusted to obtain a symmetrical lift distribution fL is divided by 25 to have values that can be displayed on the same scale as the other quantities

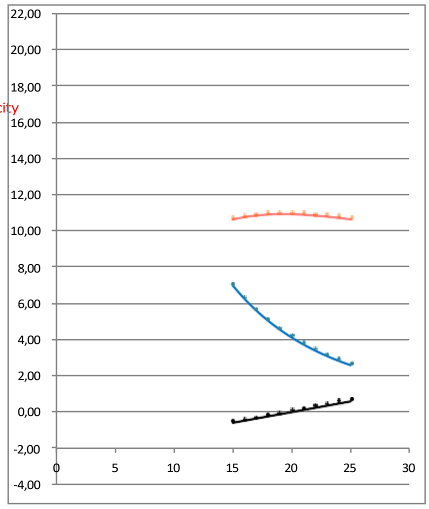
left side: lift without twist (k = 0)

absolute base	(°) aM-i0 =	-6,5
department	incid. absolute	fact. lift
r (m)	i-i0 (°)	fL/25
15	7,54	11,5
16	6,69	11,6
17	5,94	11,5
18	5,27	11,4
19	4,66	11,2
M 20	4,12	10,9
21	3,62	10,6
22	3,17	10,1
23	2,76	9,6
24	2,38	9,0
25	2,03	8,3

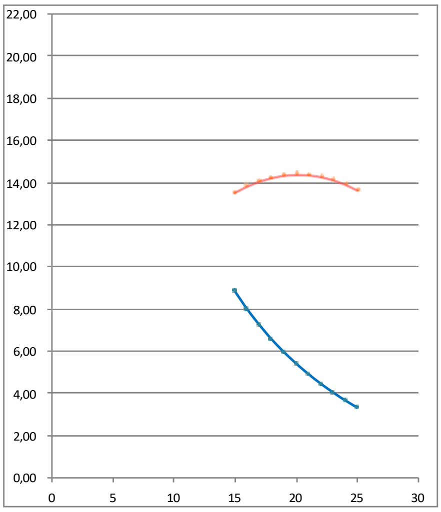


right side: lift with adjusted twist

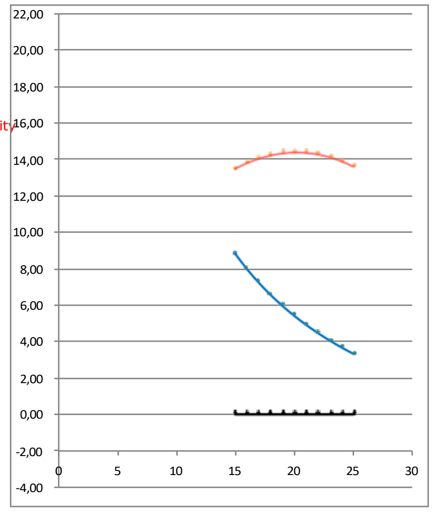
kink coefficient	k =	-0,115
aug. absolute	incid. base	fact. bearing capacity
Aa (°)	i-i0 (°)	fL/25
-0,575	6,96	10,7
-0,46	6,23	10,8
-0,345	5,59	10,9
-0,23	5,04	10,9
-0,115	4,55	10,9
0	4,12	10,9
0,115	3,74	10,9
0,23	3,40	10,8
0,345	3,11	10,8
0,46	2,84	10,7
0,575	2,61	10,7



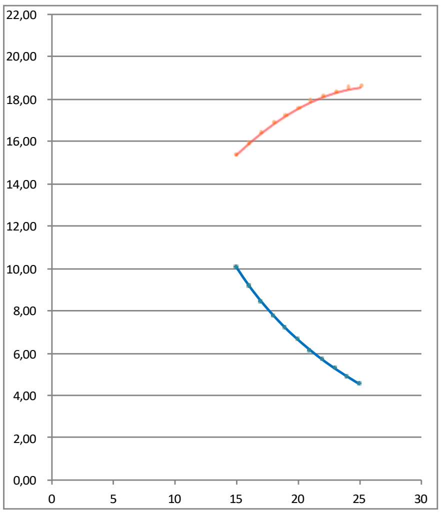
absolute base	(°) aM-i0 =	-5,2
department	incid. absolute	fact. lift
r (m)	i-i0 (°)	fL/25
15	8,84	13,5
16	7,99	13,8
17	7,24	14,0
18	6,57	14,2
19	5,96	14,3
M 20	5,42	14,4
21	4,92	14,3
22	4,47	14,3
23	4,06	14,1
24	3,68	13,9
25	3,33	13,6



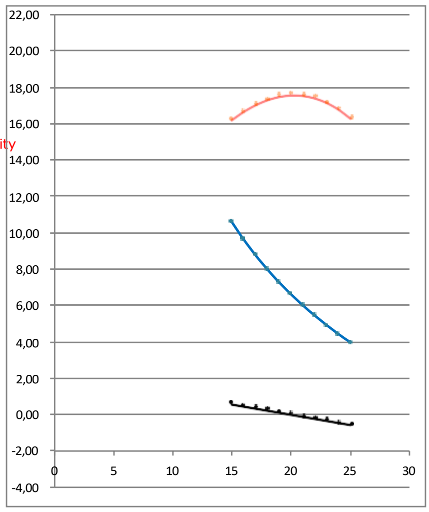
kink coefficient	k =	0
aug. absolute	incid. base	fact. bearing capacity
Aa (°)	i-i0 (°)	fL/25
0	8,84	13,5
0	7,99	13,8
0	7,24	14,0
0	6,57	14,2
0	5,96	14,3
0	5,42	14,4
0	4,92	14,3
0	4,47	14,3
0	4,06	14,1
0	3,68	13,9
0	3,33	13,6



absolute base	(°) aM-i0 =	-4
department	incid. absolute	fact. lift
r (m)	i-i0 (°)	fL/25
15	10,04	15,4
16	9,19	15,9
17	8,44	16,4
18	7,77	16,8
19	7,16	17,2
M 20	6,62	17,5
21	6,12	17,8
22	5,67	18,1
23	5,26	18,3
24	4,88	18,4
25	4,53	18,5



kink coefficient	k =	0,11
aug. absolute	incid. base	fact. bearing capacity
Aa (°)	i-i0 (°)	fL/25
0,55	10,59	16,2
0,44	9,63	16,6
0,33	8,77	17,0
0,22	7,99	17,3
0,11	7,27	17,5
0	6,62	17,5
-0,11	6,01	17,5
-0,22	5,45	17,4
-0,33	4,93	17,1
-0,44	4,44	16,8
-0,55	3,98	16,3



lift as a function of radius r, for some values of attitude, without and with twist (2/2)

rM (m)	Vv (m/s)	(rad/s)
15	-2	0,45

VhM(m/s)	duration (s)

in yellow: arbitrarily fixed value (for test) in orange: value adjusted to obtain a symmetrical lift distribution fL is divided by 33 to have values that can be displayed on the same scale as the other quantities

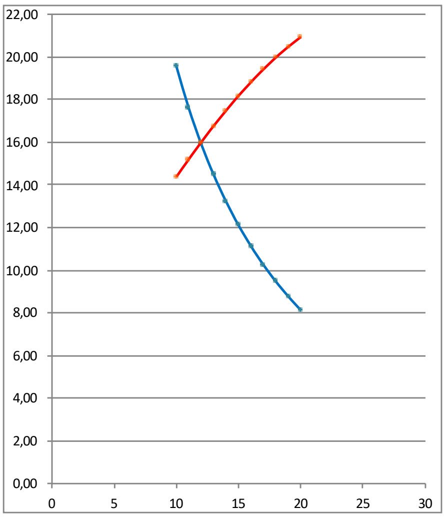
left side: lift without twist (k = 0)

right side: lift with adjusted twist

absolute base (°) aM-i0 = -4,4

depar tment / incid. absolute / fact. lift

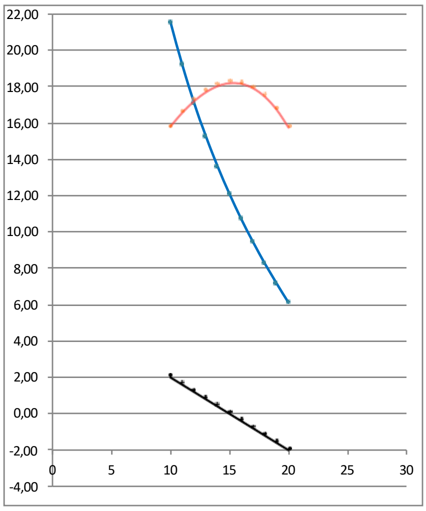
	r (m)	i-i0 (°)	fL/33
	10	19,56	14,4
	11	17,60	15,2
	12	15,92	16,0
	13	14,47	16,8
	14	13,21	17,5
M	15	12,10	18,2
	16	11,12	18,8
	17	10,25	19,4
	18	9,47	20,0
	19	8,77	20,5
	20	8,13	20,9



kink coefficient k = 0,4

aug. / incid. absolute / fact. bearing capacity

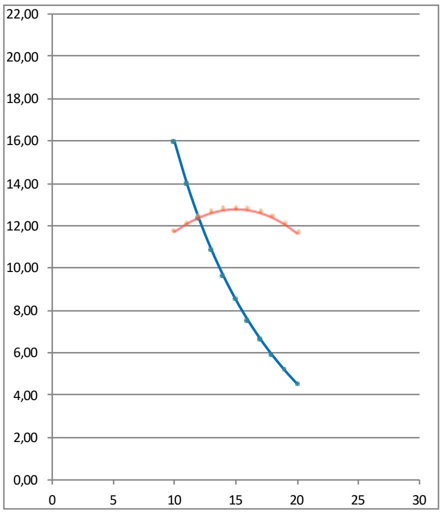
Aa (°)	i-i0 (°)	fL/33
2	21,56	15,8
1,6	19,20	16,6
1,2	17,12	17,2
0,8	15,27	17,7
0,4	13,61	18,0
0	12,10	18,2
-0,4	10,72	18,1
-0,8	9,45	17,9
-1,2	8,27	17,4
-1,6	7,17	16,7
-2	6,13	15,8



absolute base (°) aM-i0 = -8

depar tment / incid. absolute / fact. lift

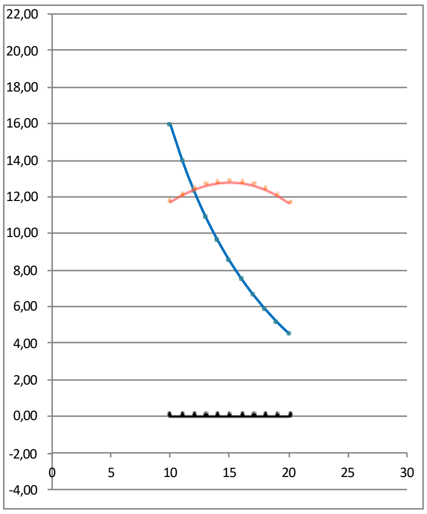
	r (m)	i-i0 (°)	fL/33
	10	15,96	11,7
	11	14,00	12,1
	12	12,32	12,4
	13	10,87	12,6
	14	9,61	12,7
M	15	8,50	12,8
	16	7,52	12,7
	17	6,65	12,6
	18	5,87	12,4
	19	5,17	12,1
	20	4,53	11,7



kink coefficient k = 0

aug. / incid. absolute / fact. bearing capacity

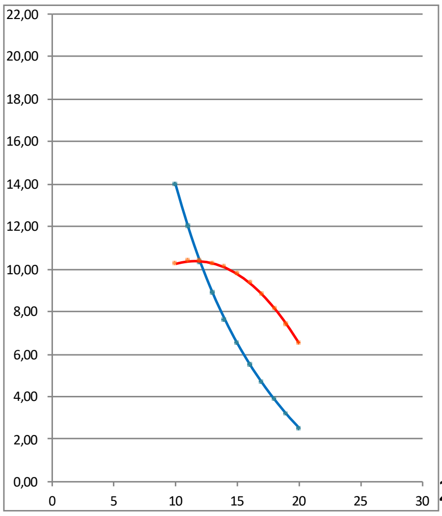
Aa (°)	i-i0 (°)	fL/33
0	15,96	11,7
0	14,00	12,1
0	12,32	12,4
0	10,87	12,6
0	9,61	12,7
0	8,50	12,8
0	7,52	12,7
0	6,65	12,6
0	5,87	12,4
0	5,17	12,1
0	4,53	11,7



absolute base (°) aM-i0 = -10

depar tment / incid. absolute / fact. lift

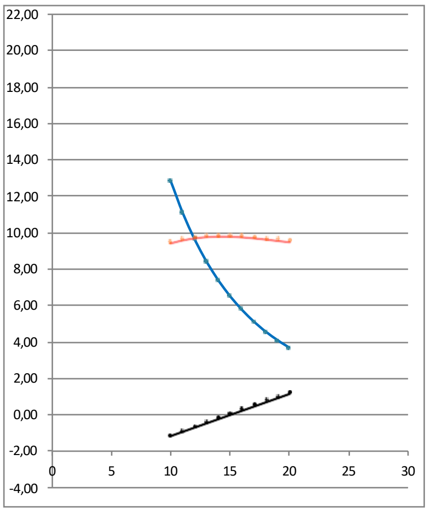
	r (m)	i-i0 (°)	fL/33
	10	13,96	10,3
	11	12,00	10,4
	12	10,32	10,4
	13	8,87	10,3
	14	7,61	10,1
M	15	6,50	9,8
	16	5,52	9,3
	17	4,65	8,8
	18	3,87	8,2
	19	3,17	7,4
	20	2,53	6,5



kink coefficient k = -0,23

aug. / incid. absolute / fact. bearing capacity

Aa (°)	i-i0 (°)	fL/33
-1,15	12,81	9,4
-0,92	11,08	9,6
-0,69	9,63	9,7
-0,46	8,41	9,7
-0,23	7,38	9,8
0	6,50	9,8
0,23	5,75	9,7
0,46	5,11	9,7
0,69	4,56	9,6
0,92	4,09	9,5
1,15	3,68	9,5



Comments on the results

• In summary, for a given turn kinematics :

- It is thus possible to balance the turn by adjusting only the attitude (within certain limits imposed by the allowed values of incidence),
- if the attitude is not adjusted, it is possible to balance the turn by adjusting the twist.

• In the context of this model, the mechanics of trim adjustment are well understood: when the trim is increased, the full span impacts are increased by the same amount, but the resulting increase in lift is greater on the outside of the wing because the velocity factor (squared) is greater there than on the inside of the turn. Symmetrically, the opposite is true for a decrease in attitude.

In conclusion, if the outside of the wing digs in, you have to pitch up the wing. And dive if it is the inside that is sinking.

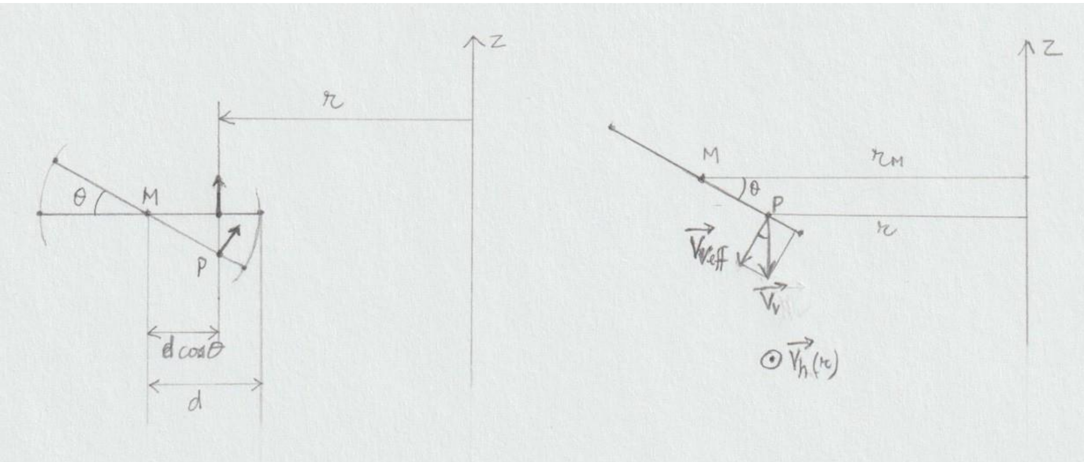
• The mechanics of balancing by adjusting the twist is more intuitive: if the outside is sinking, you have to twist in the direction of an increase in attitude on the outside, and on the inside if it is the inside that is sinking.

Value of results

In general, the modelling does not incorporate all the characteristics of a real wing, the detailed kinematics of a turn, or the air in most cases (see below).

The numerical values obtained are to be considered as indicative benchmarks for considering trends, and not as data to be found by precise measurements in real conditions.

Consideration of the aircraft's turning attitude



In the diagrams showing the horizontal wing and the same wing tilted at an angle, we can see that the changes that affect the quantities used in the calculations are as follows:

r_M ± d ---->r_M ± d.χοσ

V_v ---->$V_{v\text{-}eff}$ = V_v.χοσ

Thus, the values of r to be considered are along the projected span, which is smaller by a factor of cos, and similarly for the term replacing the vertical speed.

(For the record, in the 20° example, the cosine differs from 1 by only 6%).

Apart from these substitutions, the calculation formulae themselves are unchanged. It is still a matter of comparing the forces perpendicular to the wing. Finally, the study results in the same types of graphs of the lift factor as a function of r, as when the wing was considered horizontal.

Imaginable complexities of modelling

This is not the purpose here, but we can list some aspects that have not been taken into account.

a) The velocity vectors are not the same, in norm and direction, in (r_M - x) and (r_M + x). The difference in norm has been taken into account in the calculation of the geometric incidence i(r), and consequently in the calculation of the norm of the lift. But the difference in direction implies a difference between the directions of the two lifts, which is not taken into account when assessing the lift distribution along the span. This could be done at a reasonable cost in complexity.
The difference in direction also results in a yawing moment: the inner lift is inclined further back than the outer lift. Qualitatively, this corresponds to a direct yawing moment (in the direction required for turning).

b) If we consider that a profile has a certain length (its chord), it follows that its various points are not exactly the same distance r from the axis of revolution, and therefore do not have exactly the same geometric incidence.

c) A real wing is not flat but arched.

d) In practice, the airfoils chosen by the designers are not exactly the same from the middle of the wing to the tips (C_{Li} and i_0 depending on r)

e) The air is most often non-homogeneous; in particular, when thinking about thermals, one can envisage introducing an ascendancy of the air, strong near the axis of revolution and decreasing when moving away from it.

f) Better than lift, RFA is more relevant to calculate to discuss the balance of flight. Adding the parasitic drags at the level of the different airfoils could be considered as the introduction of approximate analytical formulas in the calculations. On the other hand, the so-called induced component requires on the one hand to consider the wing globally in 3D flow, but also to distribute it here in a certain way on the different profiles. In the register of complex treatments, one can prefer the modelling by digitisation of the equations of fluid mechanics around a wing in turn, without and with twist.

Appendix C - PROCEDURE FOR INTERFACING A PARAPENTE WING

Here, "interfacing" represents the transfer to an iap of a paraglider wing initially connected to risers.

The operation consists of :

- obtain the necessary information regarding the geometry of the wing's line bundle
- choose the pitch, i.e. in this case an attitude of the iap in straight flight "in neutral" (without effort to pitch up or down)
- choose a distance between the wing and the iap (between the middle of the lower surface and the keel)
- choose the fixing point of each hanger on the iap
- calculate the new length of each bottom hanger
- attach each hanger to the iap.

Next, the position of the pilot anchor under the iap must be determined:

- in terms of abscissa along the keel (the centring)
- in terms of vertical distance under the keel (depending on the degree of pitch stability required).

Finally, the connection between the anchor point and the iap may need to be made more complex, with a view to :

- adjusting the degree of effort in roll
- modulate the effort to pitch up or down.

This section is not drafted.