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J. SANS (**13/05/2019**)

Version V5: Analysis of AC75 flight parameters

Suite des documents V1, V2, V3, V4
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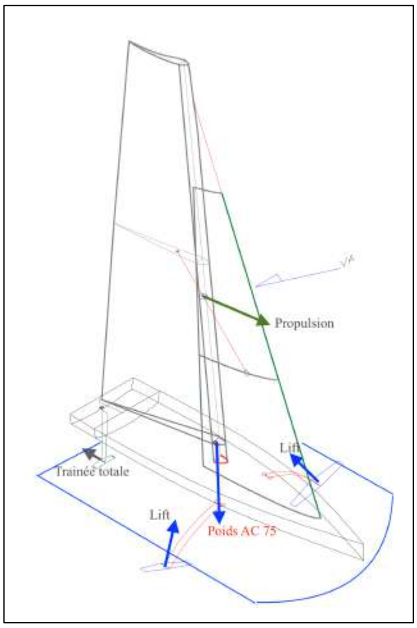
Preamble

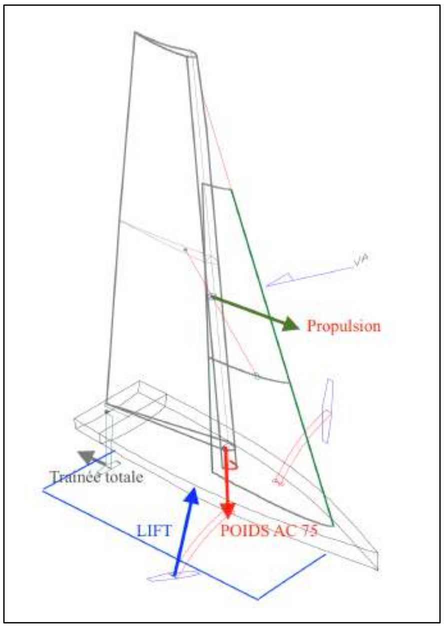
In my previous articles, the studies initially focused on the reality of Foiler navigation and the discovery of the AC75 with mainly the transition from Archimedean to Foiler configuration.
Two analyses were essential:

- Stability in Archimedean mode
- Capsizing situations (AC 75 is then, in fact and against its will, in Archimedean mode) during navigation in Foiler mode.

It appeared that it is not enough to take off, but it is then necessary to evolve on two foils and a rear support plane or a foil and the same rear support plane.

It is during these evolution phases (in regattas) in Foiler mode that flight stability must be perfectly controlled, first in order to maintain speed and then, and this will be essential, to avoid a stall of the foil(s).





If we add that to be efficient, it will be necessary to fly at a relatively constant altitude at all times, we understand the importance of stability and handling in flight.

Flight in Foiler mode

First, imagine the forces involved, whether with two foils or one foil.

In total, as a schematic, there are four forces at work on the CA 75.

- The WEIGHT of the assembly ready to sail (mass 7500 kg or 7430 daN[1])
- The LIFT brought by the foil(s). To fly this LIFT must be equivalent to the WEIGHT.
- The PROPULSIVE FORCE which provides the necessary speed for the production of the LIFT.
- The DRAG, which opposes displacement

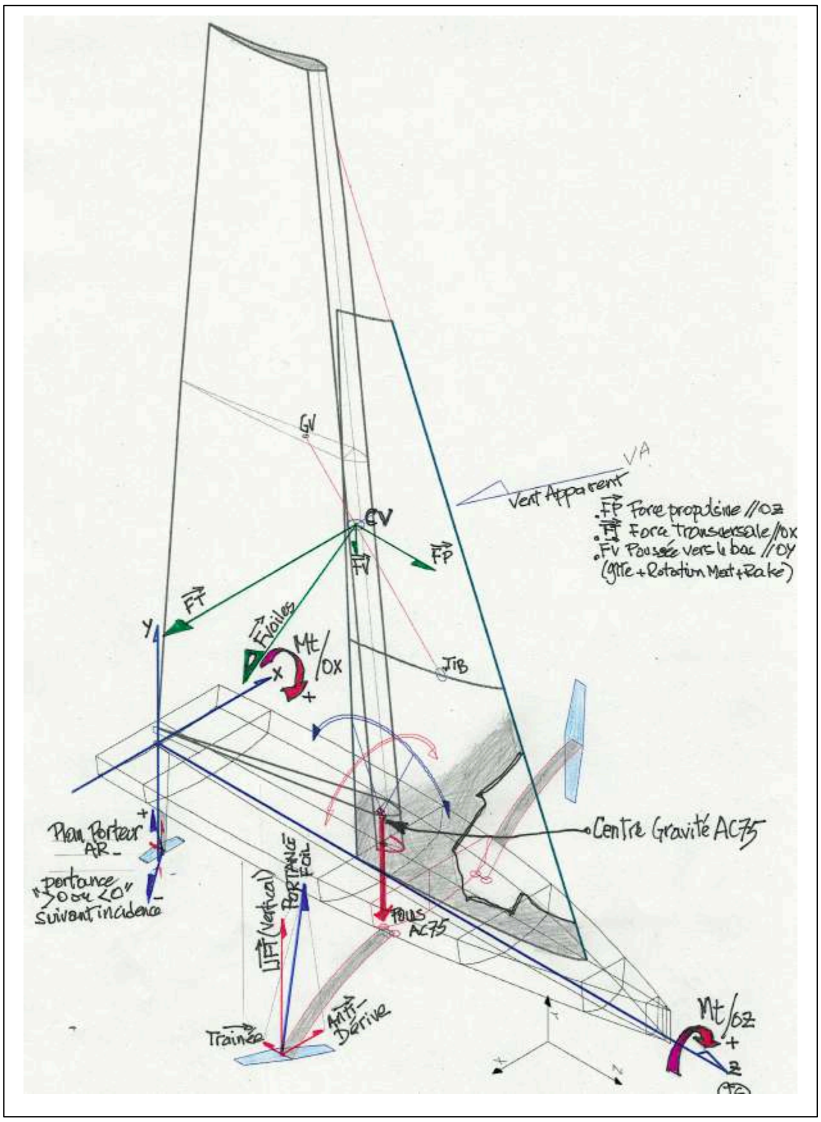
We immediately understand that we will have very little direct influence on the WEIGHT, at most a certain possibility to modify longitudinally the position of the Center of Gravity (the crew is planned for 1100 kg, but its range of evolution in the cockpit is limited).

[1] The force units are expressed in N or daN. Usually in everyday language we speak more of Kg. One daN corresponds to approximately one Kg.

For the FORCE PROPULSIVE, the crew will necessarily make a major contribution, but will be dependent on wind. But the PROPULSIVE FORCE alone is not enough to switch from Archimedean mode to FOILER mode.

The LIFT and its corollary the DRAG then appear as the pivot of flight conditions, since the FOILER mode is based on the boat's necessary support on the foils or foil.

LIFT and DRAG are intrinsically linked, the control of these two forces will contribute to ensuring stable flight and the handling necessary to race.



The drawing on the right shows that in Foiler mode, all the forces that come into play seem more complex.

Only two rotational movements are taken into account:

- The rotation around the XX' axis, or the risk of pitchpole.
- Rotation around the ZZ' axis, or transverse capsizing.
- It should be noted that rotational movement around the YY' axis (vertical axis), known as the "yaw", is not represented.

In reality, the capsizing, if it occurs, is a combination of the two rotations XX' and ZZ'.

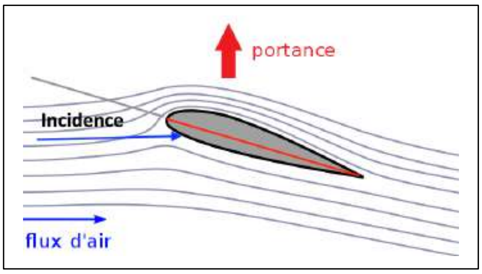
The causes of capsizing in Foiler mode are entirely different from those that exist in Archimedean mode, where everything is located in the relative position between the Gravity Center and the Hull Center as the boat heels.

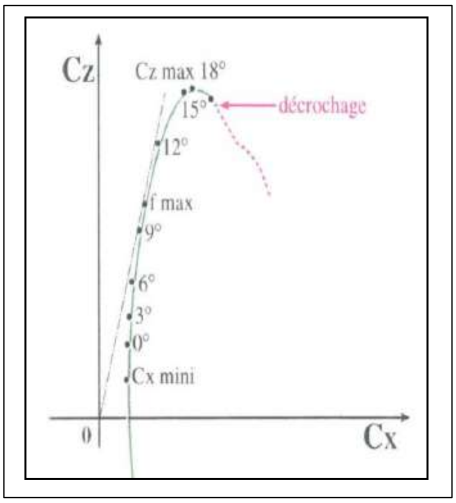
In Foiler mode, the AC 75 is placed on one or two foils. The rear support plane acts as a stabilizer.

In this configuration, only the loss of lift on the foils or a modification of the "centering" of the Foiler will cause an uncontrolled return to Archimedean mode with a risk of capsizing.

To fully understand the field of loss of lift (which produces the LIFT), it is necessary to start from the base, i. e. the wing, which sailors know with the adjustment of the sails but of which they know nothing (or almost nothing) as a means of sustaining.

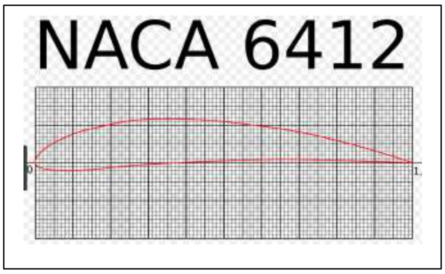
Aerodynamic or hydrodynamic lifting capacity, its application.





Vocabulary specific to the profile of a wing (or foil):

- The extrados: surface where the depression of the air or water flow is exerted
- The intrados: surface where the pressure of the air or water flow is exerted. Depression is more important than pressure.
- The geometric profile: Symmetric or Dissymmetric
- The leading edge: line that runs along the wing and receives the fluid first
- The trailing edge: line that connects the bottom and top surfaces to the "outlet" of the fluid.
- The chord: line that connects the point from the leading edge to the trailing edge.
- Thickness: % that identifies the thickness of the profile. Example NACA 6412 (Thickness 12%)
- The Aerodynamic center: This is the aerodynamic (or hydro) Center of gravity of the profile. To put it simply, the AC is the balance point of the profile. Caution, it is a geometrical calculation which does not take into account the real manufacture (longitudinal member, sheets etc).
- The AC (Aerodynamic Center) is a fixed point specific to each profile shape.
- The center of pressure (CP) is the point where the resultant of the forces resulting from the pressure and depression on the underside and top surface is applied.
  This point moves along the rope depending on the angle of incidence.
- **Cz** represents the lift (lift) **Cx** represents the drag (brake)



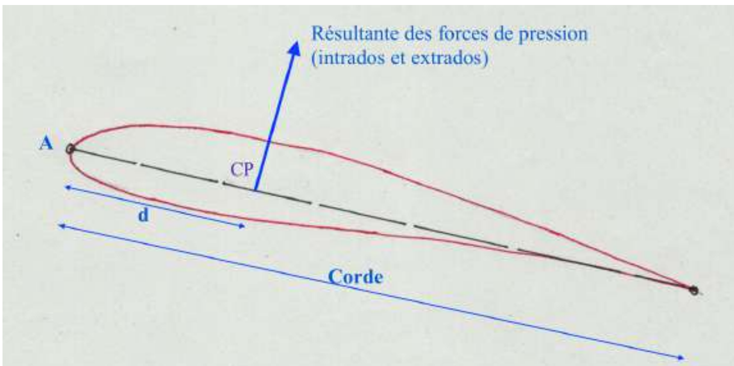
Depending on the incidence of the profile, the **Cz** increases (with a limit), but as the Cz increases, the drag follows.
The two points (AC Aerodynamic Center and Center of Pressure CP) represent the bases of flight stability.

Analysis of the Center of pressure (CP) for an asymmetric profile

The position of the Center of pressure is defined by its distance (d) from the leading edge (point A) of the wing. The distance d is expressed as a fraction of a rope taken equal to 1.

Incidence angle. (In degrees)	Value of (d) in relation to the chord of value 1
0	0.465
2	0.370
4	0.337
6	0.319
8	0.307
10	0.299

Exemple sur un profil du même type



It can be seen that as the angle of incidence increases, the CP moves towards the leading edge and vice versa.

Case of symmetrical profiles.
On a sailboat symmetrical profiles are mandatory on fin keel and rudders, since the incidence is located alternately on one side and on the other, in other words the intrados becomes extrados and vice versa.

Symmetry is reflected by the fact that at any incidence, the Pushing Center is fixed and is approximately 25% of the leading-edge chord.

Calculation of the lift force produced by the foil.

The lift force of a wing is expressed by the relationship:

$P = 1/2 * \rho * S * V^2 * Cz$, où

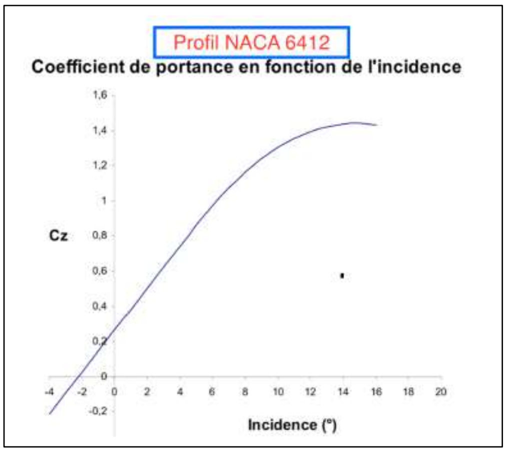
ρ : masse volumique de l'eau
V : vitesse du foil dans l'eau
S : surface du foil
Cz : coefficient de portance. Il dépend de l'incidence **(α)** de l'aile et de son allongement.

The **aspect ratio** (λ) of a foil, not to be confused with its wingspan, has the value:

$\lambda = Env^2 / S$ with :
Env = wingspan and S = wing surface

The Cz curve = f(α) for NACA 6412 profiles. This curve shows that for α =0, the coefficient of lift is zero. We notice that on 60% the progression of the lift is linear.

But this curve corresponds to the Cz of a foil (or wing) whose aspect ratio λ = Env2 / S would be infinite.



This is obviously not the case for a foil, which, like an aircraft wing, must have a finite elongation.

In fact, only the linear part of the Cz curve is interesting (and usable) because the ratio (lift / drag) is constant, which is no longer the case as soon as the Cz curve is rounded.

In this curved area, the drag increases faster than the Cz (Portance), which is much less interesting, it's a bit like braking by accelerating!

From the linear area of the expression of the infinite Cz of the profile (Foil of infinite aspect ratio), we calculate by taking into account the expression of the aspect ratio (λ = Env2 / S), the Cz λ specific to each foil or wing. The aerodynamic engineers were responsible for this calculation.

In the end, the Czλ of a real foil, i.e. of finite elongation (λ) (we know its dimensions), has the value:

$Cz\lambda = Cz/(1+Cz/\pi.\lambda)$
Cz being the infinite aspect ratio coefficient of lift taken from the above curve.

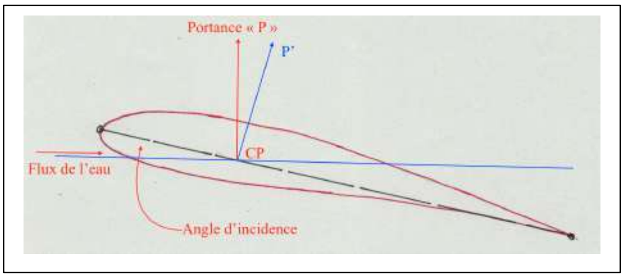
For example, for a foil of 4 m * 0.55 m, or 2.2 m2 (λ = 7.23) and a Cz of 1 (incidence angle of 6°), the Czλ of this foil is 0.958, or 4.4% less.

The difference between the theoretical Cz (infinite foil) and the Cz specific to a real foil design remains small.

If the aspect ratio increases to 8, the Czλ becomes 0.962.
This is normal, since the elongation tends towards infinity... all proportions considered.

Representation on the profile (foil) of the lift force

We have just seen that the Center (CP) is the point of application of the resulting lift force (P).
The vector P is perpendicular to the trajectory (direction of water flow).
The angle of incidence is measured between the profile string (point from the leading edge to the trailing edge) and the direction of the water flow.



The chord of a profile is the well identified basic element of each profile. The Aerodynamic Center (AC) and the Center of Pressure (CP) are located on this chord.

In order to simplify future calculation methods, the projection of the vector P on the perpendicular to the CP chord will be used.
To simplify, instead of calculating P' = P* cos (incidence α) or taking P' =P.
The cosine (6°) having the value 0.9945, this will not disturb the calculations.

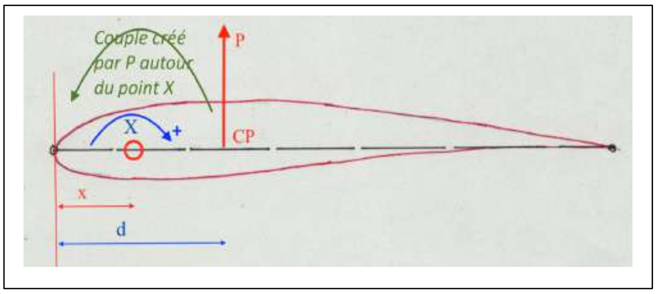
Therefore, in future calculations, the lift applied to the CP point will be taken as equal to:

$$P = 1/2 * \rho * S * V2 * Cz\lambda$$

What about a relationship between the Center (CP), the AC (F), the Lift (P)?

The lift P and its longitudinal position vary according to the angle of incidence of the foil in relation to the water flow.

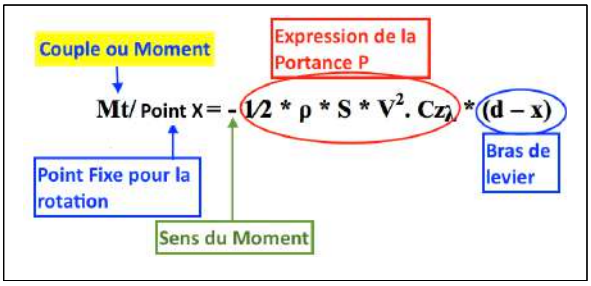
The only intangible elements of a profile, chosen by the architect, are the design of the profile and its chord.



As a general rule, when a point, even any point, and a force identified in intensity, direction and position with respect to this reference point are fixed on a solid body, a torque is created, which will generate a rotation around the reference point.

In static mechanics, to quantify a torque it is first necessary to define (arbitrarily) a reference direction of rotation.
The clockwise direction is used as a reference.

Consequently, the torque created by the lift P applied to the CP Center, around a point X located on the chord at a distance x from the leading edge, is expressed as follows:



Variation of Mt in function of the incidence angle
Knowledge of the stability of a foil requires knowledge of its lift capacity characteristics, i. e. the dimensions of the foil, its elongation, its type of profile, as well as the Cz and positions of the Center of pressure Center as a function of the incidence of water flow, and finally to know how the lift capacity P acts on the balance of the foil (see above).

By experimental analysis of the evolution of the expression **Czλ * (d - x)** as a function of the angle of incidence, the corresponding Czλ and the position of the CP (d), we can see[2] that this expression remains constant when (x) takes substantially the value 0.25.

This means that the Mt/point X (time with respect to point X) remains constant when x = 0.25, regardless of the angle of incidence.

This is true regardless of the type of asymmetric profile.
Point X located at (0.25 * Rope) from the leading edge is called "Pitch foil AC".

Finally, for a drawn foil (as for a wing), there are 3 "fixed" parameters:

- The profile
- The chord
- The position of the AC

Quantify the value of this pitch moment at the AC?

The relationship (1) framed on page 5 above, Mt / X = - 1⁄2 * ρ * S * V2 * Czλ* (d - x), indicates the value of this moment in relation to a point X that is fixed to the fireplace since we are trying to evaluate this moment around the fireplace.

However, it should be noted that when the incidence (α) varies, which occurs almost continuously, two parameters of this equation are modified, namely:

Cz that increases or decreases
CP that moves forward or backward, which implies that the value (d) is permanently variable

Under these conditions quantifying (Mt / X) becomes complex.

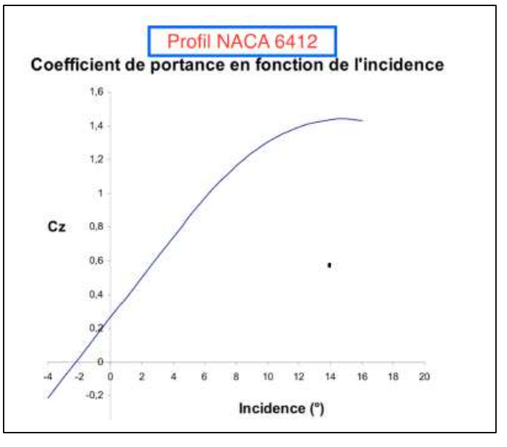
The solution is to introduce a "Coefficient of Moment" (Cmx), this new parameter allows to link the variation of the moment (Mt / X) to that of this parameter alone.

Mt / X = 1⁄2 * ρ * S * V2 * Cmx * c (2) *(c) being the chord of the profile.*

By equalizing the relationships (1) and (2) which are two expressions of the same element (Mt / X), we obtain:

Cmx * c = Czλ* (d - x), i. e. :

$$\mathbf{Cmx = -(Cz_{\lambda} * (d - x)) / c}$$



This expression is only valid in the usual "flight" range (i.e. in the straight area of the Cz curve), i.e. for angles of incidence where the Cz is not zero or very close to zero.

Trials and experience show that there is therefore a point in the profile that is independent of the Cz and the position of the Center (CP).

The moment around this point is written: **Mt / F = 1⁄2 * ρ * S * V^2 * Cmf * c**
Conclusion: On a foil, for each cross section, there is a point called AC (Aerodynamic Center)

[2] This demonstration is based on a chord length of the profile equal to 1.

This point is fixed and located at (0.25*Chord) from the leading edge, it belongs to the section of the profile. C
Unlike the Center CP, the position of AC F is therefore fixed and independent of Cz and incidence.

So any profile, in addition to the lift it can generate and which will be used to lift the Foiler, naturally has a pitch torque around the Foyer that will make the profile dive.
In the end, the foil's pitch moment will have an impact on its lift.

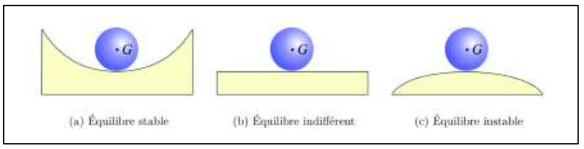
This hydrodynamic property is important because it leads to the study of the notion of stability of flight on foil(s), since it is possible to imagine that the foil's trajectory is straight even when the pilot modifies the angle of incidence to compensate for a loss of lift... up to a certain limit anyway.

Concept of Stability and Balance

It is important to distinguish the notion of stability from the notion of balance.
The stability of a system can only be studied if it is in balance.

First of all, it is necessary to differentiate the use of the name "stability" from the adjective "stable".
The adjective is used to describe the state of equilibrium of a system.
The substantive describes how a system behaves in space (trajectory).

By definition, a balance can have 3 states: stable, unstable or neutral:



A system is said to be in **stable equilibrium** if it tends to return by itself to its initial position when discarded. This is the case, for example, of the Archimedean sailboat between 0° and the angle of capsizing.

A system is said to be in an **unstable equilibrium** if, after being slightly moved away from its initial position, it tends to move further away from it on its own. This is the case of a ball placed at the top of a convex surface, it remains in place as long as its weight (force vector) is strictly confused with the normal at the tangent to the top of the surface.

A system is said to be in **neutral equilibrium** if, when it is moved away from its initial position, it remains motionless in the new position. This is the case for all objects placed on a horizontal plane (friction is neglected). All the positions of the plane are then equilibrium positions.

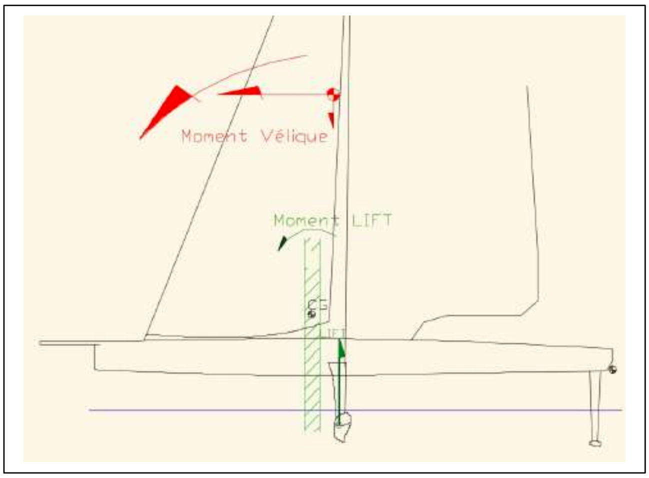
Let's take the hypothesis of an "ideal" Foiler sailing only on two transverse foils without a rear support plane: an IMOCA (foil & angled keel with profile incidence) for example.
In reality, IMOCAs rely on the rear part of the hull, but they can find a stable (temporary) balance only on the front load-bearing surfaces.

Any disturbance will immediately generate a change in incidence and therefore a change in lift P applied to the CP point.

The Foiler obviously has a constant weight during the flight (Weight), therefore a Center of gravity (CG) whose position in space varies very little for the AC75 (depending on the crew's low longitudinal displacement). When limited to the interaction of the Lift created by the Foil(s) and the Propulsive Force, the Foiler is subjected to 3 forces, both listed and the weight of the Foiler.

We can see very clearly that everything is at stake, on the moments of the LIFT and the Propulsive Force in relation to the point of application of the WEIGHT (the CG Gravity Center).

When the platform is designed (the layout of the foils is therefore defined), there is only one variable that can be used by the architect: the longitudinal position of the CG.



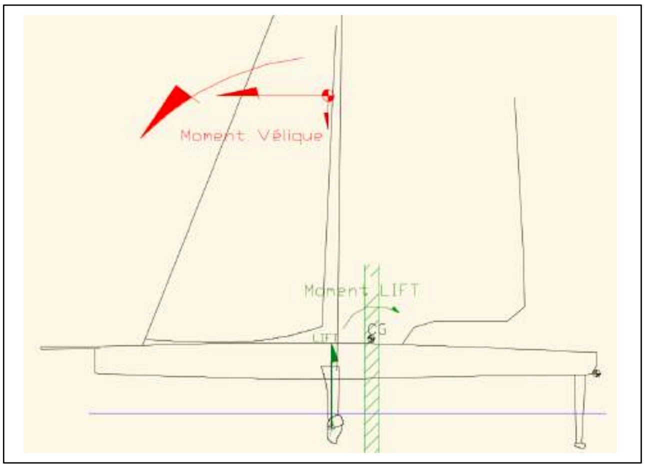
First configuration: The Center of gravity (CG) is located in front of the AC.

The lift exerted at the CP point generates a moment of pitch around the CG which causes the Foiler to rotate around its Center of Gravity (dive motion).

The sail torque increases this instability since it is in the same direction as the torque generated by the foil lift.

The pitch moment of the profile is added to these two torques.

The Foiler is "front centered". He is instable.



Second configuration: The GC is located behind the AC. The lift applied to the CP point always generates a moment of pitch around the CG which causes the Foiler to rotate around its Center of Gravity (upwards movement).

The sail torque increases, it is opposed to the torque generated by the foil lift.

The pitch moment of the profile is always added to the sail torque.

The Foiler is "rear centered". It is possible for a longer or shorter time that the sail torque and the torque from the foils are identical. This results in a "temporary stable position".

Third configuration: The CG and CP are superimposed. If this configuration called "neutral" is possible on a glider, which has no propulsive force, it is totally impossible on a Foiler because of the sail Center which produces a very important sail moment.

The first two configurations can be used on a Foiler provided that there is a regulator torque that:

- Will oppose the nose-down torques (sail + foil + pitch moment) of the first configuration
- Will balance the torque to be sailed (+ pitch moment) and the torque to be reared from the foil for the second configuration.

In the case of the AC75, the initiators of the class rules, impose on the architects a front and a rear limit for the longitudinal position of the Center of Gravity, as well as a maximum vertical position of the CG. In this way they impose a **Rear Centering** (second configuration)

(Simplified extracts from the class rule)
9.7 The longitudinal center of mass (CG) of the entire platform shall be between 9,000 m and 9,600 m forward of the rear reference point (transom).
To validate this position, the following requirements must be met:
(a) both foils in the lowered position;
(b) all trailing edge flaps shall be placed at the center of their range of motion;
(c) the plane of symmetry of the rudder aligned with the plane of symmetry;
(d) the bearing plane of the rudder placed in the center of its range of motion;

9.8 The vertical center of mass (CG) of the entire AC75 shall not exceed 2,900 m above the reference plane of the Archimedean waterline.

It is added that it is prohibited to take on board additional weights (excluding crew) for regattas, and the use of liquid ballasts is also prohibited.

This rule will be applied by adjusting the weight estimate.

The study of equilibrium can be performed from any point identified on a solid subjected to several forces. In this case, we can very well study the equilibrium conditions around the Center of Gravity (CG).

The balance of the Foiler

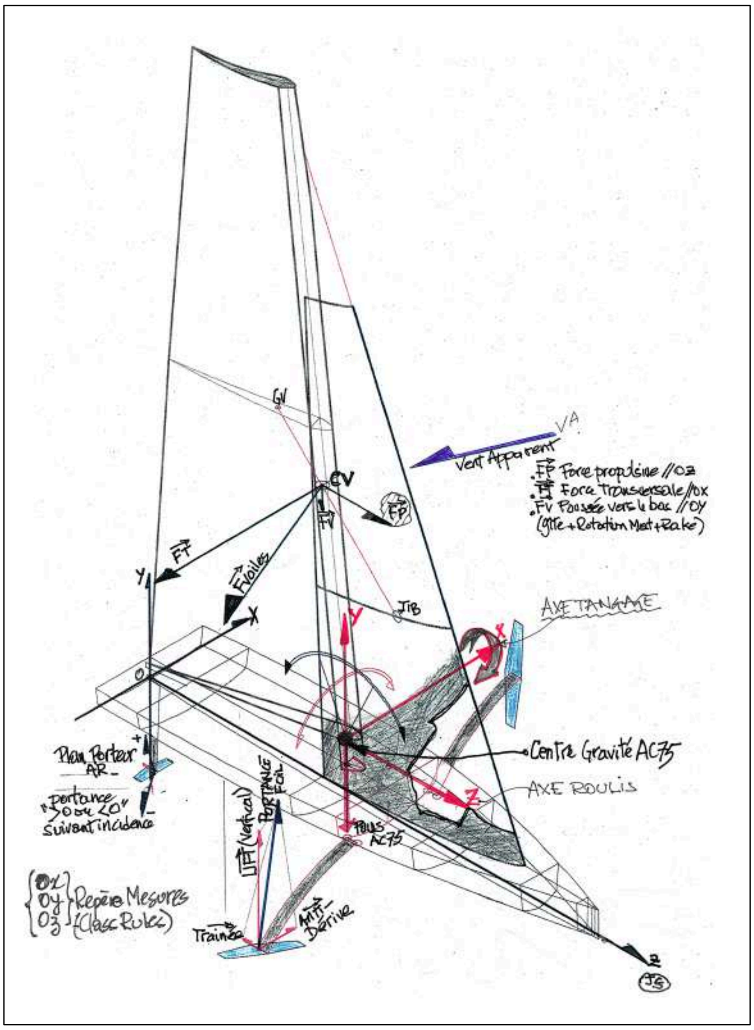
The Foiler is therefore subjected to several forces: its WEIGHT, the LIFT generated by the foil, the PROPULSIVE FORCE and the DRAG.

According to the principle of inertia, in a Galilean reference frame (0x, Oy, Oz), a solid (the AC75 Foiler) is in equilibrium at the time (t) if the Vector Sum of the forces applied to it is zero:

Similarly, for the same solid, the sum of the moments[3] of each of the forces with respect to any point of the solid must be zero: Mt Fext / Pt = 0

This will simplify the problem:

$\sum$ Mt F_{ext} / CG (Center of Gravity) = 0
(the 3 axes in red)



[3] Moment of a force: intensity * lever arm. The moment has a noted direction (+ / -) in relation to a direction of rotation taken as a reference (e. g. "clockwise" or "anti-clockwise").

A/ Inventory of moments around the GX axis (Pitch movement):

i. Moment created by the Foils (LIFT)

ii. Moment created by the lift of the sails: Propelling force (Fp) perpendicular to the transverse plane of the AC75.

iii. Moment created by the lift of the sails: Force // symmetry plane of the AC75 (Fv)

iv. Moment generated by the rear support plane (HPR / tailplane).

This results in the following equality: (looking at the GX axis increasing from the G point, we take the clockwise direction as a positive reference)

(- Mt créé par Lift) + (Mt créé par Fp) – (Mt créé par Fv) +/- (Mt tailplane) = 0

Forces and Lever Arms:

LIFT force: Projection of the lift of the active Foil on a vertical plane parallel to the symmetry plane of the AC75.
Lever arm (LIFT): Horizontal distance between Point G (CG) and the plane perpendicular to the axis of the AC75 passing through the point of application of the lift capacity of the active Foil.

Propulsive Force Fp: Propulsive component of the sail lift capacity (parallel to the AC75 trajectory)
Lever arm (Fp): Vertical distance between point G (CG) and the horizontal perpendicular plane parallel to the waterline plane and passing through the Center of sail center of pressure.

Vertical force Fv: Component resulting from the downwards facing lift of the sails (due to the heel of the AC75, although this heel is small).
Lever arm (Fv): Horizontal distance between Point G (CG) and the vertical plane perpendicular to the waterline plane and passing through the Center of sail center of pressure.

Rear tailplane center of pressure force: Projection on the vertical plane perpendicular to the axis of the AC75 and passing through the Center CP of the rear horizontal tail.
Lever arm (tailplane center of pressure): Horizontal distance between the Point G and the vertical plane perpendicular to the waterline plane and passing through the Center CP of the horizontal tail.

B/ Inventory of moments around the GZ axis (Rolling motion: list of the boat):

Around the GZ axis is the transversal balance of the AC75, of which two moments appear to be predominant.

- Moment created by the transverse component (Ft) of the lift capacity of the sails.
  For the AC75, which operates in Foiler mode at a speed almost always higher than the actual wind speed, the apparent wind (composition of the actual wind vector and the wind speed vector) is "front".
  This means that the AC75, on the whole, sails very close to the (apparent) wind.

  Under these conditions, the angle of the aerodynamic lift with the boat's axis is about 60/70°.
  This results in a propulsive component (// trajectory axis) about 2.5 to 3 times weaker than the transverse component (perpendicular to the boat's axis).
  The action of the Fv component (downwards) of the sail lift amplifies the action of the (Ft) component.
- Moment created by the Foils (LIFT).

In the transverse plane, perpendicular to the symmetry plane of the AC75, the Foil's lift capacity is divided into two perpendicular forces, the LIFT directed upwards and the ANTIDRIFT component directed towards the boat's axis.
These two forces have opposite effects, the LIFT will oppose the capsizing torque (Ft component of sail lift), the ANTIDRIFT component will amplify this heeling phenomenon.
In the case where the Foiler flies on both Foils, the two ANTIDERIVE components are substantially equal and opposite, so the moments they generate cancel each other out.

Note: The moment around the GZ axis created by the rear support plane is negligible.

The equation around the GZ axis is as follows:

(Mt créé par Lift) - (Mt créé par l'Antidérive) - (Mt créé par Ft) - (Mt créé par Fv) = 0
(1) (2) (3) (4)

Only the Moment (1) generated by the LIFT is "favorable", the moments (2), (3), (4) are unfavorable.

The pilot cannot operate on the lever arms which are intrinsically linked to the construction and class rules of the AC75.
It has two parameters on which it can act: the lift of the foil(s) AND the lift produced by the sails....
And again, these two parameters are closely related to the actual wind speed over which the pilot has virtually no control.

The horizontal rear tailplane (PHR) will control the stability of the flight.

As the Foiler is in balance, the stability of the flight must be taken into account.
Flight stability concerns: the way of flying at the most constant altitude possible, but also its ability to react as quickly and effectively as possible when a loss of lift or a loss of propulsive power occurs.

As we have just seen, the Foiler can only sail in configuration 2, i.e. "rear Centered", i.e. when the torque around the boat's AC and that from the weight specifications are as identical as possible.

Except when, at rare (very short) moments, these two torques are equal (see the picture of CHARAL on page 7), it is necessary that the Foiler has a compensating system that will allow the balance of these two antagonistic torques to be adjusted, while producing as little drag as possible (brake !!!!).

This compensating system will be essentially identical to the one used on aircraft (Tailplane or also called PHR, Adjustable Horizontal Plane), i. e. the rear horizontal tailplane.

Technically, it is a "horizontal" plane, with a symmetrical profile, implanted as far back as possible.

The interest of placing this horizontal plane at the rear meets two requirements:

a) Be as far away as possible from the disturbed wake (in "V" shape) from both foils (or even from only one.

(b) Use the largest possible lever arm around the point of rotation to reduce the surface area of this support plane, which implicitly means reducing the drag of this support plane.

The pilot[4] will therefore use the angulation control (+6° / -6° approximately) of the rear horizontal tail (PHR) to control a horizontal flight attitude but also to be able to raise the platform more or less in order to modify the angle of incidence of the foil(s).

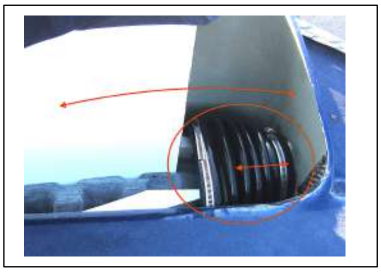
[4] "The pilot" or the autopilot or pilot assistance system.

The AC75 Foils do not have a Rake setting when sailing.

The "Rake" is fixed by each Team during the design phase.

However, the pilot can modulate (decrease or increase) the lift by playing on the flap of the foil.

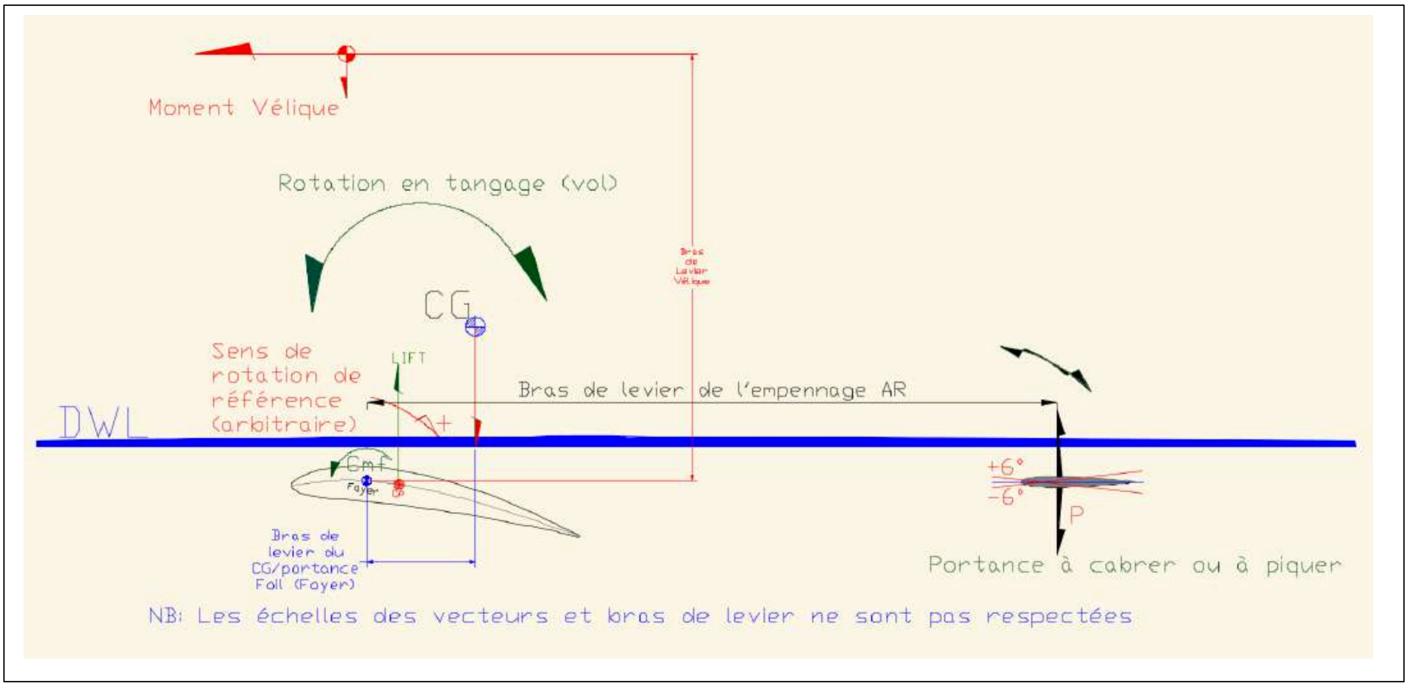
The absence of the rake's navigation setting is due to the fact that when leaving the shell plating, there is already the rotational movement of each arm (Docking position, bell position, clearance from the water).



Adding another rotational movement poses design problems, especially in terms of mass.

The picture above of the hydraulic cylinder that controls the rake of each foil of the GITANA Trimaran gives an idea of the forces involved.

The vertical part of the tail (rudder) controls the trajectory (yaw and direction).



Note: During the take-off phase, the rear tailplane stall (PHR) will be used to raise the Foiler and thus increase the foil's incidence.

Les volets de bord de fuite (flap) de foils centraux

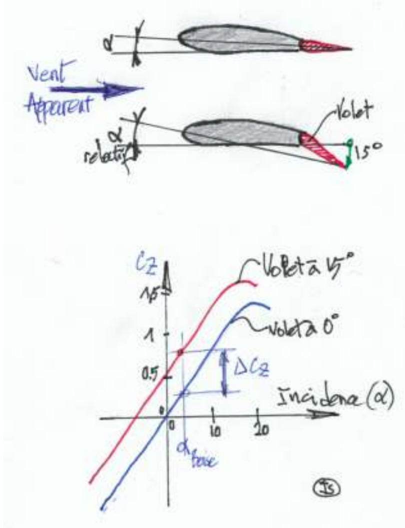
However, if there is one domain, relatively free, it is that of trailing edge flaps. Equipment that should not be marginalized. Indeed, flaps allow to regulate the Cz momentarily, especially since the "rake" of the foils cannot be modified during navigation.

The objective of flaps will be to increase lift, especially in the take-off or manoeuvring phases such as tacking, turning around a buoy.

However, if flaps generate an increase in lift, they also create an increase in drag and drag is a negative element.
It should also be noted that the increase in lift moves the center CP to the rear of the profile and amplifies the pitch moment.

Today, the technology for controlling and deploying trailing edge flaps is mainly based on external kinematics (connecting rods, articulation, mechanical guidance).

These mechanical systems are efficient, but although they are streamlined, they produce a lot of drag, in other words, their aerodynamic efficiency (it is rather the aircraft that use them) is relatively low.



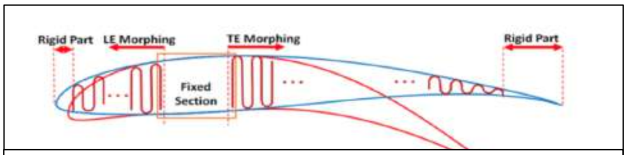
On a Foiler and particularly on the AC 75, the performance required for the trailing edge flaps will be much less important than that required on an aircraft in the landing phase.

Désignation	Forme d'Aile	Angle de braquage	Augmentation portance
Profil de base			
Volet de courbure		45°	51%
Volets intrados sans recul		50°	67%

On Foilers, hydrodynamics engineers will seek a much softer "forced" modification of the water flow using less extreme trailing edge flaps. These flaps will certainly be less effective, but their action will be sufficient to ensure a modulation of lift, for example, during transition manoeuvres where the speed of the AC75 actually decreases (buoy passages, tacking) and also during the take-off phase.

Currently the classic kinematics, based on the use of screw/nut systems, cams, connecting rods generates drag. This technique is also quite complex in terms of design (it should not appear too much when the shutters are not used). It also remains very complex in terms of implementation.

Also, many designers have embarked on the search for techniques to deform the entire wing or just a portion of it, with the exception of the nominal central beam. To do this, they use the property of the elastic deformation of the outer skin, which they can modify by forcing the internal structure.



Publié dans un papier de Jack Haskins et William Jackson (Université de Pittsburg) d'après un article de A. Leite paru dans le "*Journal of Intelligent Material Systems & Structures*".

This type of design uses corrugated skin for morphing (transformation) sections and wire tension as a control mechanism (like a bellows).

Between the morphing sections there is a fixed central section, representing 20% to 35% of the length of the rope.
The morphing section control system allows to operate on each zone independently.

Corrugated skin panels are made of carbon fiber laminates, to ensure complex shapes of variable thickness and also to reduce structural weight.

But I doubt this technique will be used on AC75s. Indeed, it must be possible to integrate an actuator into the foil in an area where space is very limited, and the foil must also be made of steel, since it contributes to Archimedean stability.

The examination of the AMERICAN MAGIC Foils shows a linear hinge over the entire length of the Foil. A single push/pull ball cable system must, a priori, run inside the arm to get a control lever for the flap.

La technologie du Plan Horizontal Réglable /PHR/ (Wing horizontal)

The rear tailplane must be symmetrical, its purpose is to create a nose-in or nose-out torque of the same value for the same positive or negative angle of incidence.
However, its positive or negative angular adjustment range may be different.

On the AC 75, this torque has a large lever arm, between 10 and 12 meters in relation to the foil supports, this torque parameter will compensate for the small tail surface area.
As the profile is symmetrical, the hydrodynamic performance of the PHR will be identical, to the scale factor, to that of a suspended rudder with high elongation.

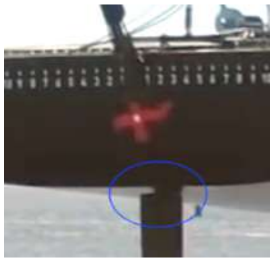
The positive or negative calibration of the incidence obtained by rotating around the PHR's AC is often controlled by a fletner implanted on its trailing edge. This fletner causes its rotation to rotate the PHR.

With this technology, it is enough to control the fletner shutter. As this flap has a very small surface area, little power is required to control it.

But this technology does not seem appropriate for the AC75, still for problems of available volumes, but with an additional constraint which is the passage of the mechanisms from the (fixed) hull to the rudder blade which rotates around a vertical axis.

There are only two possible methods:

- A trailing edge flap installed on the trailing edge of the PHR. By pivoting (horizontal axis) the flap downwards or upwards, the tail, which has a symmetrical profile (zero lift), is transformed into an asymmetrical profile, i. e. with a lift facing upwards (moment to be pricked) or downwards (moment to be pricked). This is the same technology as the one used on Foils.

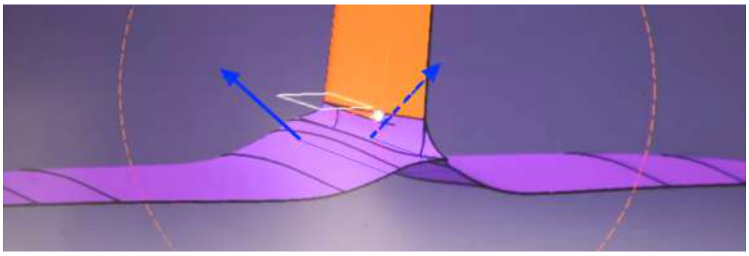


- The rudder blade / PHR assembly is integral. It is the rotation of the rudder blade around a horizontal axis and perpendicular to the symmetry plane of the AC75, which will ensure the change of incidence of the PHR (5 to 6° should be sufficient).
  La technologie est plus simple, elle se résume à une liaison sphérique de la mèche de safran au niveau du palier de coque et d'un vérin qui assure la rotation d'avant en arrière du palier supérieur, lui-même guidé longitudinalement.

I would add that the volume available inside the hull is more than sufficient to install the hydraulic cylinder or a ball screw controlled by an electric motor (finer adjustment).
If we look closely at the AMERICAN MAJIC video, we see that the top of the rudder is not very close to the hull, which suggests that this is the technique they used.

We can also see that their PHR is attached to the rudder blade.

The connection between the rudder blade and the PHR is not only decorative, it generates two inclined lift components that should stabilize the deflection (bending stress) of the rudder blade.



The drag phenomena.

It is probably this parasitic phenomenon (brake) that the designers of each Team will try to minimize.
In addition to the drag resulting from the foil's incidence, there is a drag called "induced drag".

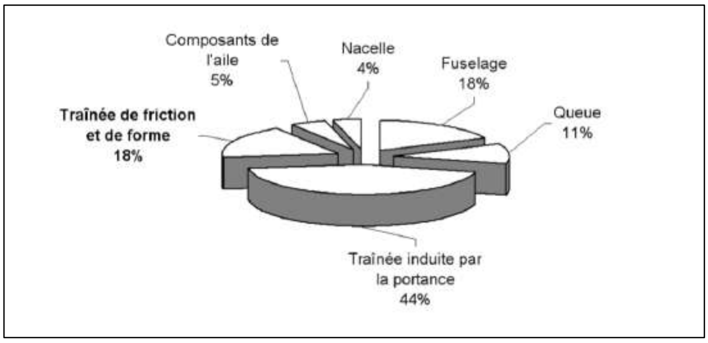
This drag is generated by the interaction of fluid flows flowing on the upper and lower surfaces of the Foil and joining at its end to form a vortex (the flow turns into an intertwined spiral).

On an aircraft, this phenomenon is mitigated with a Winglet at the wing tip or a rounded wing tip.
The induced drag increases as the speed decreases and the angle of incidence increases. However, a significant elongation of the Foil reduces the Vortex.
But the induced drag only concerns the passage of the Foil in water (density 1025 kg/m3), an incompressible fluid.

When the AC75 is in "Flight" configuration, the entire "float" is out of the water, so it is in contact with the air (1.025 kg/m3) which is compressible.

This evolution necessarily generates parasitic drag, such as friction drag, shape drag (friction), interference between the various elements (connection of the arms to the hull, connection of the mast to the deck, rigging, crew, etc.).

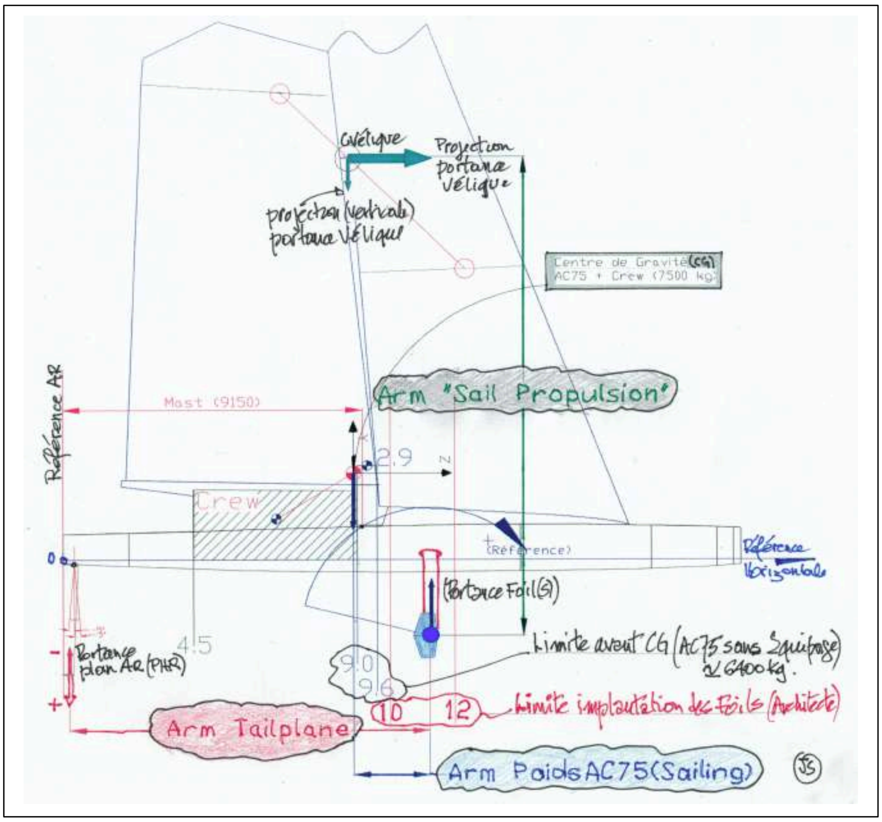
An Aircraft and a Foiler, do not evolve at the same speed, nor in the same fluid. The Foiler on moves in two totally different fluids and even if the physical equations relating to the flow are similar, their behaviors remain very different.



However, it is interesting to look at the inventory of drag on an aircraft, and to note that the drag from wing lift represents only 50% of the total drag.

The centering of the AC75's weights (according to the class rules) total.

The rules of the AC75 class are very prescriptive, in order to limit the architects' inclinations towards "acrobatic" figures when the boats fly.



In addition, the creators of this Class wish to give it a one-design spirit, which is not easy when the boat is as innovative as the AC75.

Certainly, there was the experience of the previous Cup with the AC72, but they were catamarans, so a Foiler configuration easier to control (for writing the rules, do not generalize to piloting) because of the width of the platform and especially because of the 3 points of support on the water.

With the AC75, the Foiler will be supported by a Foil that will carry 95% (or even 100%) of the weight of the boat (including the crew) and whose flight will be controlled with a rear tail located 10 or 12 meters behind the Foil.

In addition, the Foil is off-centered with regard to the axis of the trajectory.

The "Guest racer" is installed between 0 and 2m from the transom.

If the Center of gravity is absolutely limited towards the front, (the forward barrier should be around 9.3m from the transom), it seems free towards the rear of the AC75 for the crew (up to the "Guest racer" area).

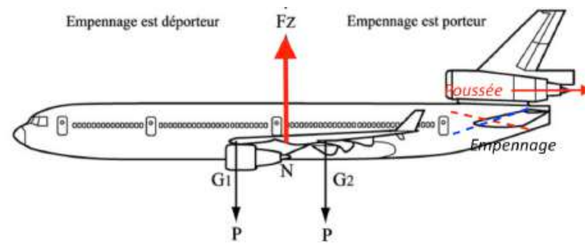
The weight ratio is 6400 kg for the AC75 ready to sail and 900 kg for the crew (the helmsman must remain at his helm).

Since I think the crew will be particularly busy and focused on the flight of the AC75, and longitudinal ballasts are prohibited, there will be no desire to use the crew to make longitudinal weight transfers.

Of the interest of modifying the centering of weights in navigation?
It is not a maritime idea, but an idea exploited by planes.

However, both the Foiler and the aircraft fly.
The aircraft has an advantage, apart from takeoff (and landing) it operates in a single fluid, air (1,025 kg/m3).
For the Foiler, its lift is produced in contact with water (1025 kg/m3), but the "cabin", like its engine (mast, sails) are in contact with the air.
The center of pressure (parallel to the trajectory) of the sails is obtained from their aerodynamic lift, which is far from being parallel to the trajectory of the Foiler.
It is even worse, of the two components of this aerodynamic lift, it is the transverse component that is predominant over the component that provides the displacement. I would add that this point of application of this aerodynamic lift is more than 12 m high (for the AC75).

But let's go back to the flight of the plane.
Aircraft ballast fuel (not passengers), they also consume it.
Ballasting makes it possible to modify the CG position resulting from all the masses.



For an Airbus A320 the take-off weight is 70 tons with 22 tons of kerosene (average values according to the many A320 models). So, by playing on the many different tanks, we can position the CG forward or backward of the AC of the wing reference string (MAC[5] : Mean Aerodynamic Chord), point N on the above drawing.

When G is ahead of N (G1 position), the aircraft is more stable, but less manoeuvrable. This is logical because the more stable the trajectory is, the more difficult it will be to modify with the control surfaces, which makes the aircraft less manoeuvrable. In fact, the aircraft becomes heavier to fly.
But it consumes more, so it needs more power.

When G is behind N (G2 position), the aircraft is less stable, but more manoeuvrable. It is easier to change its trajectory, the aircraft becomes more and more manoeuvrable, but also more "fickle".
The aircraft consumes less fuel, so for identical performance, it uses less power.

5 For a trapezoidal Foil (A=Upper String, B=Lower String, Y=Envergure)
MAC (rope length) = A-(2*(A-B) * (0.5*A + B) / (3 *(A+A+B))
MAC position / upper string = Y *((A - MAC) / (A-B))

For the Foiler, the N point is located on the Foil, as the class rules require an aft Center of gravity, the initiators of the Class Rules prefer handling to flight stability.

This seems normal, unlike the aircraft on which we impose a "rigid trajectory, leaving no freedom to the pilots, except in cases of force majeure", for **the AC75 we want it to race in contact**.
Given the configuration of this machine (the AC75) with "large side legs" it is better that it is very scalable, to the detriment of its flight stability.

Flight configurations

TAKE-OFF

At the beginning I thought that the take-off phase should be done on both Foils.

I am much less convinced of this today, for the following reason: The transition, i. e. the change from a 3750 daN lift on each Foil to 7500 for the single Foil, will be too abrupt and cannot be controlled. This transition assumes that the leeward Foil that is set (incidence) to produce 3750 daN will have to be set in a few seconds to a new incidence (its drag increases) to produce 7500 daN of Lift. The risk of collapse will be too high.

Taking off on a Foil seems more logical.
As the boat accelerates in Archimedean conditions, the pilot quickly climbs up the Foil to the wind.
It should be noted that in my configuration "Foil upwind" and "foil downwind in navigation position (submerged)" the Center of gravity of the Foiler is always almost always in the plane of symmetry of the Foiler, because the transverse distribution of the masses is very little modified.

The capsizing torque is absorbed by the leeward foil.
In fact, in this Archimedean phase, the Foiler behaves like a dinghy where the capsizing torque is absorbed by the crew member on the trapeze, on the Foiler it is the leeward lift that acts as a crew member on the trapeze.

Quickly the windward Foil comes out of the water, the pilot increases the incidence (flap on the trailing edge), the AC75 rests on the leeward foil, which prevents it from capsizing and gradually it is vertically supported on the lift of this Foil, lift that reaches 7500 daN. The increase in Foil incidence is obtained by the trailing edge flap and also by the PHR which is set to the maximum rotation torque, see the diagram below.

Archimedian

Beginning of take-off (pitch up)

Take-off (Horizontal Trim)

(Excerpts from the video "AMERICAN MAGIC")

- ✓ **Archimedian:**

Submerged foil : maximum angled foil flap (maximum lift)
PHR : neutral

- ✓ **Beginning of take-off (rotation):**

Submerged foil : maximum angled foil flap (maximum lift)
PHR : Angled in negative (lift down) to raise the platform.
De facto increase in the angle of incidence of the main foil

- ✓ **Take-off (horizontal trim):**

Submerged Foil : The angle of the foil flap is reduced, the angle of incidence decreases
The speed increases, which compensates for the reduction in the angle of incidence.
PHR : Angled in neutral position
The flap angle alternates between positive and negative (lift up or down)

STABILIZED FLIGHT

In stabilized flight the crew must control:

- ✓ The propulsive force. It depends directly on the marine environment and the boat's course in relation to the wind. The crew can adapt the sail (Replace the Foc by the Gennaker).
  But the speed of the AC75, which is important in Foiler mode, will make the real wind vector less predominant in the apparent wind vector composition.

- ✓ The lift of the leeward foil. It is regulated by the trailing edge flap, which increases the camber of the foil profile and thus adjusts the Cz (see top of page 13).
  It is also possible to increase the foil's angle of incidence (avoiding stall) from about 1.0° to 2.0° by raising the platform by modifying the PHR incidence (which immerses the rear supporting plane by about 10 to 30 centimeters).

- ✓ The piching of the platform (at worst the capsizing). To see the movements of the platform on the video, it is what seems the easiest to manage (Video of AMERICAN MAGIC) because the listing results from an overselling. This momentary oversold period is absorbed by the sail adjustments, without causing the Foiler to lose speed.

Assiette longitudinale (TRIM) « parfaite » *(le trait rouge est calqué sur la ligne d'horizon)*

Le TRIM devient subitement négatif (piquer)…. Correction avec le PHR(?)…. Le Foiler se cabre.

The difficulty of the flight will be to avoid the pitch movement that we can see very well on the AMERICAN MAGIC video.

This rapid rotational action will cause aerodynamic disorders at a height of 26 m in the flow of the air streams that circulate around the mainsail and the top of the jib.

Maintaining the platform's horizontal attitude is very complex, especially since the AC75 Class Rules prohibit the use of gyroscope or flywheel.

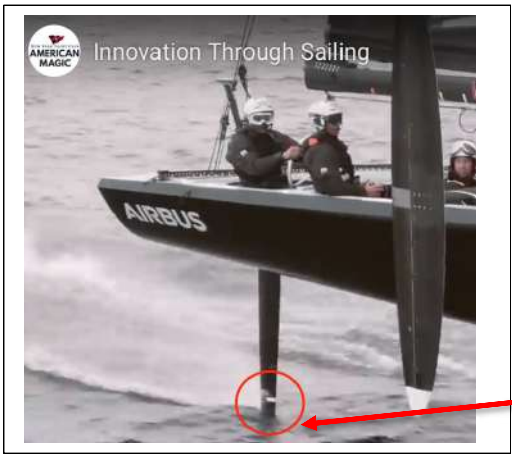
"20.6 The use of flywheels or gyroscopes to store energy or mechanically stabilize the yacht is prohibited. "

Any rotating mass on the yacht shall be no larger than required for its permitted purpose.
In the absence of gyroscopic stabilization, it is the PHR's control that will be responsible for managing this horizontal attitude.

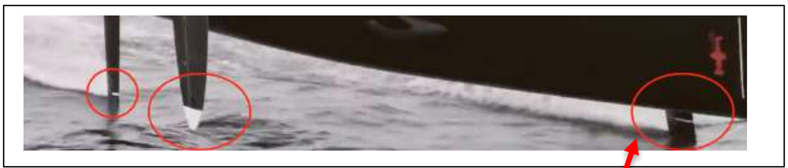
The PHR lever arm (10 to 12m) offers more sensitivity in the torque modulation required to correct a momentary lack of lift in the foil, and this in a more flexible and precise way than a control that would increase the foil's camber, to increase or decrease its lift.

In addition, the immersion of the rudder provides an ideal support for installing two or three sensors. These sensors will be used to evaluate the sinking of the PHR.

The mid-point between these two sensors is on the horizontal plane that passes through the front foil AC.



La marque supérieure est visible



On distingue aussi un des repères sur le bras immergé.

Les bras sont en position « Docking »

A sensor on the end of the "raised foil" will indicate a loss of wind stability.

The principle can be very simple: for example, for the rudder, an orifice a few mm wide on the leading edge, a pipe that rises into the rudder and 50/60 cm from the orifice, a connected pressure switch activates an electrical contact.

If the orifice is submerged, the pressure switch outputs "1", if the orifice is out of water, the information is "0".

This electrical information is collected by a program that controls the rake of the rudder (positive or negative impact of the PHR) and can also control the bending of the submerged Foil.

The flight during the TRANSITION period

This will probably be the most complex part of the flight to control, due to several disruptive parameters:
The risk of proximity of the two boats (it is the AMERICA Cup), which results in a disturbed wind zone in the contact phases.
The change of course related to the passage of buoys.
Crew manoeuvres (adaptation of sailing performance to the new heading)
The inevitable slowdown and then the restart of the boat
The risk of having to respond impromptuly to an opponent's injunction (Race Rule)

We must keep in mind that the AC75 is still a 7.5 ton mass, launched at 25 /30 knots, (13 m/s), i.e. a kinetic energy of:
Ec = 0.5 * 7500 * 132 = 633750 Joules.
The crews will have to learn to master this "flying" boat.

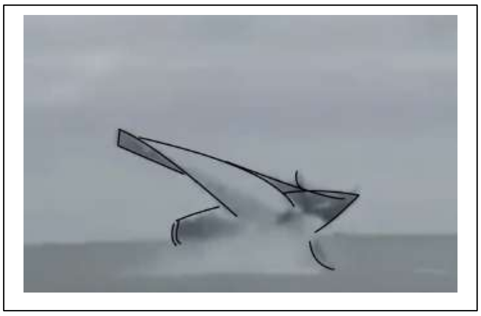
Pictures of the UK Team UK training boat "INEOS" in the SOLENT around 24/04/2019

https://www.youtube.com/watch?v=NVQtQWx3rnM

Chrono : (5 sec) (6 sec)

Tribord amure Le bateau lofe…… Le pilote perd le contrôle, la rotation continue

(7 sec) (9s)



Le bateau passe le lit du vent… Se cabre et vire de bord…. Pour se coucher sur tribord

The "crash" is most spectacular, first by the time elapsed between the beginning of the trajectory anomaly and the final crash: 4 to 5 seconds, then by the trajectory: about 180°.

There is no capsizing, except at the end or it is no longer a boat but a "thing" that seems to fall from the sky (free fall).

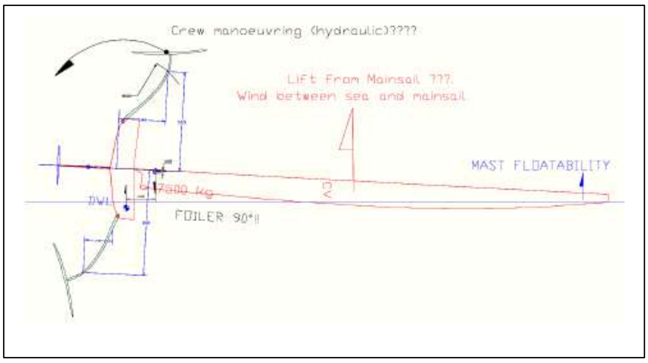
There is no loss of foil lift. The foil carries "very" long (2 seconds!!!).

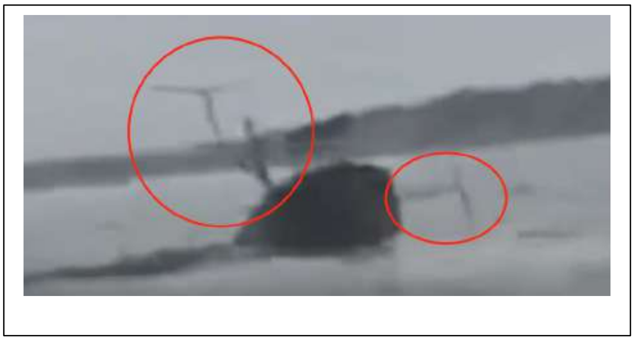
It seems obvious that it is the rudder that stalls, at this moment, the boat starts violently to the luff and rears up very quickly.

From there, with a refusing wind and a very high turning speed (120° in 2 or 3 seconds), the lift of the hull being so high, that it generates a very high lift (surface and speed) which increases the rotation even more.

If we add the energy developed in this rotation, we see that the boat ends up taking off with an incidence of 15 to 20°.

It is no longer a Foiler but a totally uncontrollable machine that is lifted like a plane tree leaf in the autumn.
Just as quickly, the takeoff attempt stops, and it is the free fall.





The starboard foil is still deployed upwards, the rudder is not broken, you can see the PHR very well. The drawing is taken from my article V4 (stability and capsizing)

Let us not be pessimistic, as long as there are no human accidents, it is never more than "breaking wood" as the pioneers of aviation used to say.

This crash shows that transposing these two "mules" (UK and AMERICAN MAGIC) into a 7500 kg AC75 will pose some problems and development periods.

AMERICAN MAGIC, in "capsizes", in a very soft way and stays at 90°.

Unlike INEOS, the loss of control is much less violent, AMERICAN MAGIC this layer at 90° on the water as it happens on a Laser.
Under the same conditions on a dinghy, the crew would instantly cross the sheer line to get on the centerboard and put the boat back upright.

Before capsizing, the boat's speed is in the order of 25 to 30 knots, or 12 to 15 m/s.
The analysis of the video shows that the elapsed time to move the mast into the water is 3 to 4 seconds.
Angularly, the rotation of the boat (longitudinal axis) is 20 to 25°/s.
During the heel to 90°, the boat continues its straight course (it does not luff unlike INEOS), for about 40 meters (in fact the initial speed of 15m/s decreases rapidly).

As soon as it is no longer supported by the leeward foil, the speed drops.

There is certainly a good deceleration, but it is very different from the ENEOS crew, who lose complete control of the boat.

In the case of AM, we have the impression that it "loses" the starboard foil !!!! in fact this is actually the case, not physically, but because of a sudden drop in lift on this foil created by cavitation around the extrados and intrados surfaces of the profile.
Cavitation occurs when the water circulating around the Foil changes from the liquid phase to the vapour phase.

Since the steam has a density 1000 times lower than that of water, the lift capacity will instantly degrade.

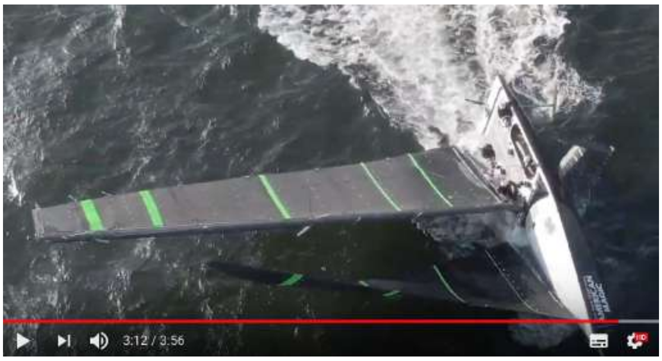
In addition, there is the phenomenon of ventilation, which disrupts the flow around the profile of the Foil.
Ventilation results in an air supply (from outside) on the surface of the upper surface, an air supply that arrives along the connecting element (the arm).

The consequence of these two parasitic phenomena is a collapse of the Foil's lift.
The heel increases.

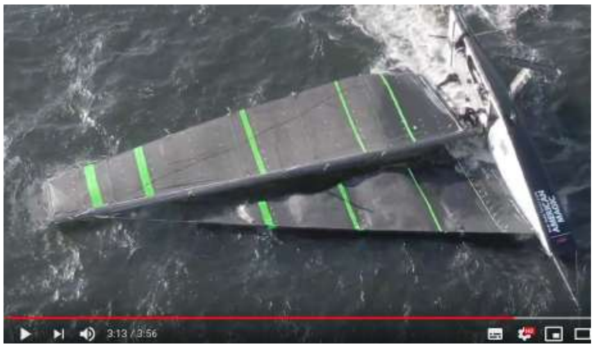
Corollary the angle of incidence moves to the wrong side of the foil, this results in an "inverse lift", even if it is lower because the foil cavities (the force is directed downwards)!!!

3 :11

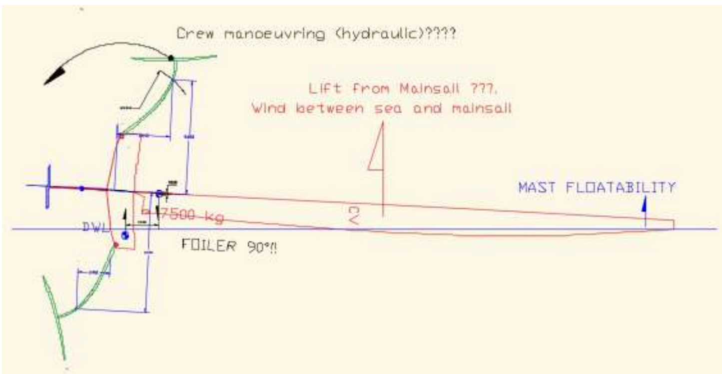
3 :12



3 :12…….



3 :13



This cavitation and ventilation[6] problem limit the speed potential of Foilers equipped with standard Foil profiles (NACA).
There are "super-cavitating" profiles, the problem is that these profiles only "work" when the foil environment produces cavitation.
Not easy to find a solution......

To conclude, I will deliver Robert Lainé's conclusion:
If the boat is counter heeling in a wind hole, the foil will come out of the water or at least get close to the surface, and some airing starts along the arm. If the boat heels again with return of wind ou if the helmsman bares away, the path for air will finally close, but in the meantime the foil will have lost its lift and starts a battle between the speed of radiation while rolling, the angle of incidence on the foil that will increase because of this rotation speed and potentially increase the depression or turn off, and the thrust of sail.
The battel in not won in advenace by the crew, even if it is "MAGIC".....

If we add, to the problems of foil control and flight attitude holding, the very essence of the AMERICA CUP's spirit, i.e. contact navigation (in the meaning of adversary control), the development of this cocktail could be complicated, especially since it is necessary to integrate speed, AC 75 mass and developed energy.

The next step will be to resolve the problem of arbitrage or the Umpire's perception of the mistakes made by competitors may not be able to follow.
Will the drones come into action at the next AC?

Jean SANS (13/05/2019)

[6] **Thanks to my friend Robert Lainé, "spacinover@gmail.com" (former member of the European Space Agency "ESA") for enlightening me on these cavitation and ventilation problems. In association we are preparing a Version 6 "The FOILS of the AC75: ENVIRONMENT, OPERATION, LIMITS".**