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J. SANS / R. LAINE (**27/05/2019**)

Version V6 : Analysis of cavitation and ventilation phenomena.

Suite des documents V1, V2, V3, V4, V5

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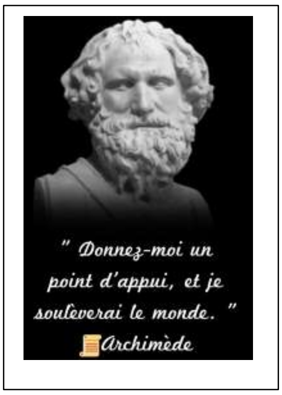
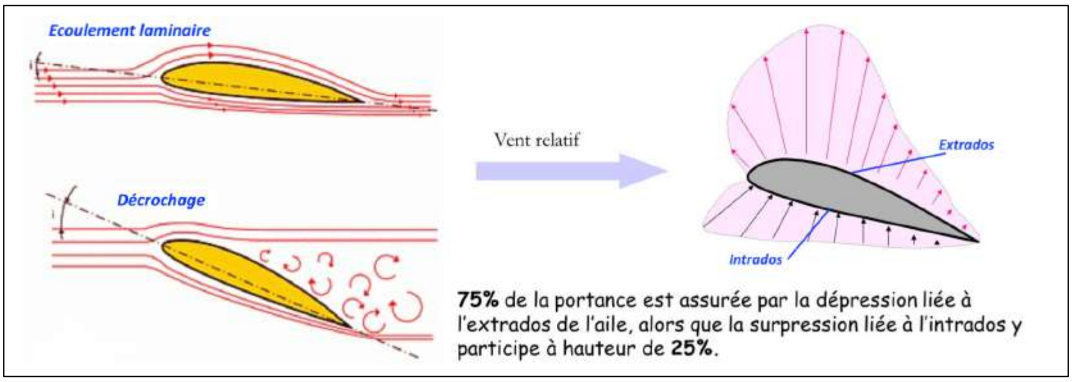


" Donnez-moi un point d'appui, et je soulèverai le monde. "
Archimède

As much as Archimedes' famous principle is the basis for the stability of ships, so much the quote attributed to this illustrious man "give me a point of support and I will lift the world" is not true for a Foiler (In fact Archimedes never said or wrote that.

Simply put, the in-flight stability of a Foiler does not rely on static support on the water. Like an airplane, the Foiler relies dynamically on the fluid surrounding its foils, the only difference being that the airplane is in the air (density 1,225 kg/m³) while the foils are in the water (density 1000 kg/m3).

The basics of the foil environment



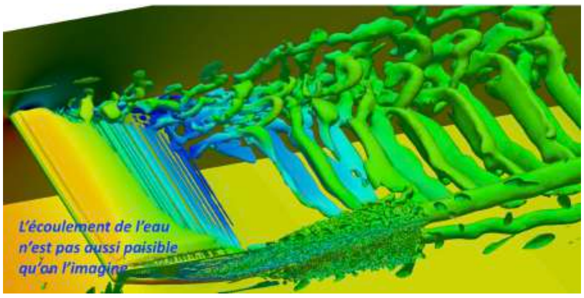
75% de la portance est assurée par la dépression liée à l'extrados de l'aile, alors que la surpression liée à l'intrados y participe à hauteur de **25%**.

When the flow is laminar, i.e. an undisturbed flow or the air or water streams are deflected "gently", the distribution of the depression (extrados) and that of the pressure (intrados) is distributed for 75% by the extrados and for 25% by the intrados.

The "work" produced by the upper surface of the wing or foil is preponderant.
When the angle of incidence, i.e. the angle that the longitudinal axis of the profile makes in relation to the speed vector in the fluid, reaches 10 to 12°, the streams of air or water that used to evolve harmoniously around the profile are transformed into disorderly vortices.
The depression on the extrados collapses instantaneously (it is said that the wing or foil stalls) and the overall lift drops by 75%.

For an AC75 (mass 7500 kg) in flight on one foil, the vertical lift component generated by this single foil must be equal to 7500 kg *9.81 m/s2 = 73575 Newtons.
If this lift falls by 75%, the vertical lift becomes 18393 Newtons and everything collapses.

Things are getting seriously complicated



The foil evolves in water, a much less homogeneous medium than the air around the aircraft wing, simply because it is near the surface (water / air interface).

In the layer of the first 5 meters, the real fluid "water" is "polluted" by air bubbles. These air bubbles can be caused by wave movements, the passage of another boat, but also by elements belonging to the Foiler. For example, the forward Foil will disturb the rudder and its horizontal tail. As long as the speed of the foil in the water remains low, these small air bubbles are of no importance. But when the speed increases, two big problems can appear:

Cavitation and ventilation.

The Cavitation

Cavitation is not specific to foils. It also affects propellers, rudders, turbines, in fact any element that moves at high speed in a fluid.

For foils, cavitation will physically result in a radical loss of lift generated by the surface in depression.

Physically the cavitation phenomenon is triggered when the local pressure reaches the level of the PV saturating vapor pressure.

At this point, the water changes phase abruptly from liquid to vapor.
As the vapor has a density 55 times lower than the liquid, a bubble is formed on the extrados, the water flow is detached from the extrados which causes the foil to lose its lift and erode its surface.

This phenomenon depends mainly on the absolute pressure of the foil and the temperature of the water.

Absolute pressure is the sum of the hydrostatic pressure (height of the water column plus atmospheric pressure) and the pressure/vacuum caused by the flow of water on the foil, for example, or on an unevenness at any point on the foil surface.

When at the temperature of the environment, the **absolute pressure** is lower than the **saturating vapor pressure Pv,** the water then passes into the vapor phase[1].
The value of the saturating vapor pressure is not a universal value, it varies in particular according to the temperature.

Température °C	Pression Vapeur (Pa)
20°	2300
22°	2800
25°	3200
28°	3800
100°	101300

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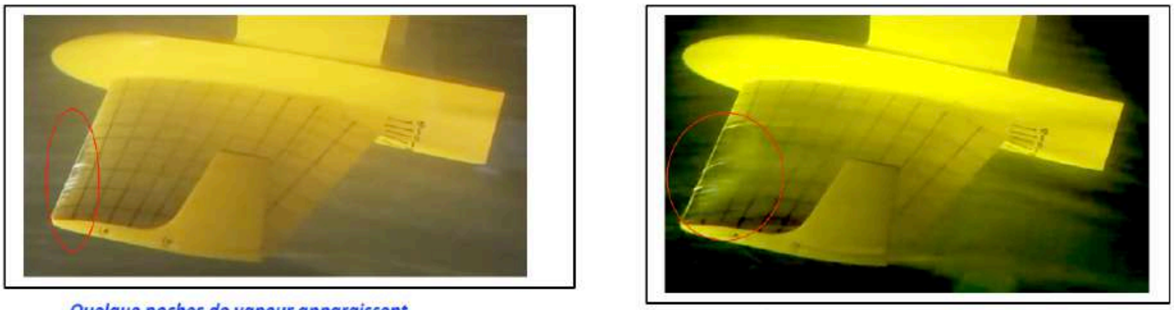
[1] A body remains liquid if sufficient pressure is exerted on it. If a container is half-filled with water (for example) and emptied, some of the liquid will evaporate instantly.
But not all the water will evaporate. Evaporation will stop on its own when the saturation point is reached. At this point, the pressure exerted on the liquid by the evaporated liquid is too high for evaporation to continue.

The cavitation phenomenon is identical to the boiling phenomenon in a pan but at lower temperature, the gaseous phase is made up of water vapor.



Quelque poches de vapeur apparaissent

la surface des poches de vapeur augmente

La surface recouvre près de 40%, la dépression de l'extrados est pratiquement reduite à zéro

Photos extracted from an experiment in a tunnel, on a foil equipped with a Winglet.

For a foil which evolves in a regatta zone where the water is at a practically constant temperature, the cavitation will be limited to the variation of pressure.

A few figures to make the risk of cavitation more tangible:
- Temperature 28°C : Pv = 3800 Pa (Pascal)
- Immersion: h = 1m
- Water density: d = 1020 kg/m^3.
- Atmospheric pressure Patmo = 101300 Pa

The foil is 1m below the surface, the total hydrostatic pressure is :

Phydro = Patmo (101300 Pa) + water column pressure [(height(m)*density (kg / m3) *g] (10006 Pa)

Phydro = 111306 Pa
- Foiler speed: V = 20 m/s (38.87 knots)
- Maximum local (de)pressure coefficient Cp = -1
- Max dynamic pressure: Pdyn = 1/2 * d * V^2 * Cp = -204000 Pa
- Total pressure = Phydro + Pdyn = 111110 - 204000 = -92694 Pa!

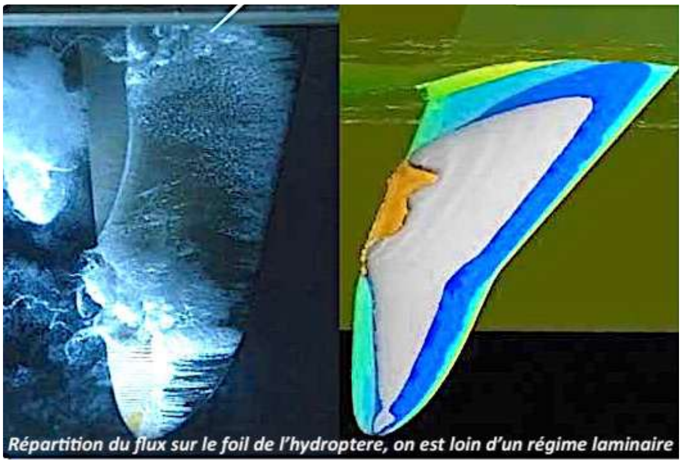
Under these conditions the local pressure is much lower than the saturated steam pressure at 28°C (3800 Pa, see table above).

Consequently, cavitation is certain!

Let's realize the reverse calculation in order to evaluate the tolerable pressure coefficient so as to avoid cavitation phenomena:

Cp = (Phydro - Pv) / (1/2*d*V^2) = 0.4875.

In order to be able to operate a conventional foil at high speed without too much risk of cavitation, it is necessary to be able to reduce the incidence and, above all, to have a suitable foil profile.
If the angle of incidence is too high, even for a short period of time, as a result of a false high-speed steering manoeuvre, cavitation will start and lift will drop sharply, causing a nose-down component to the boat.
Seeing the nose of the boat dive down, the natural reflex of the pilot may be to increase the incidence of the foil in order to regain lift.



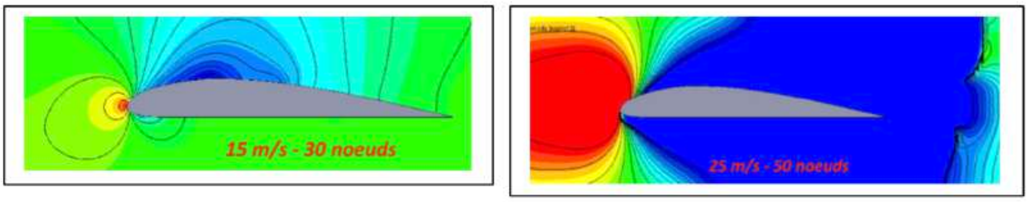
Répartition du flux sur le foil de l'hydroptere, on est loin d'un régime laminaire

Logical reflex since the Cz theoretically grows with the angle of incidence. But this is not the right reaction, because this increase of the angle of incidence actually increases cavitation... and then the boat dives straight down.

Conclusion: At less than 30 knots, the conditions for the creation of the cavitation phenomenon exist little, however it can appear some points of cavitation on the extrados of the foil at the leading edge because at this point the Cp can be locally high.

This phenomenon of cavitation is correlated with the increase of the speed of the fluid flow.

La zone en bleu foncé correspond aux bulles de vapeur qui se forment sur l'extrados et ensuite sur toute la surface du profil (imagerie issue du logiciel « SOLIDWORKS Flow Simulation »)

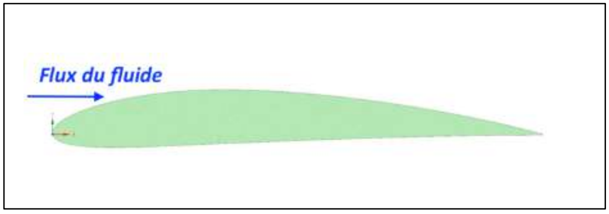


In the end, beyond a certain speed, the entire upper surface of the foil evolves in a bubble of water vapor.

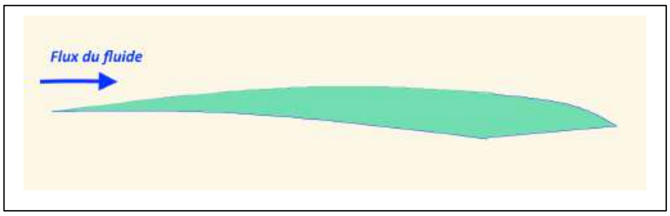
For the usual profiles (NACA or subsonic equivalent), the speed limit is between 40 and 45 knots. Under certain conditions of low load the speed of 50 knots can be reached.

The Foil, (thus the Foiler) then encounters a "WALL" which will result in :
- A loss of lift
- Erosion of the foil surface (loss of material)
- Sound effects up to 110 dB
- A very high vibration regime.

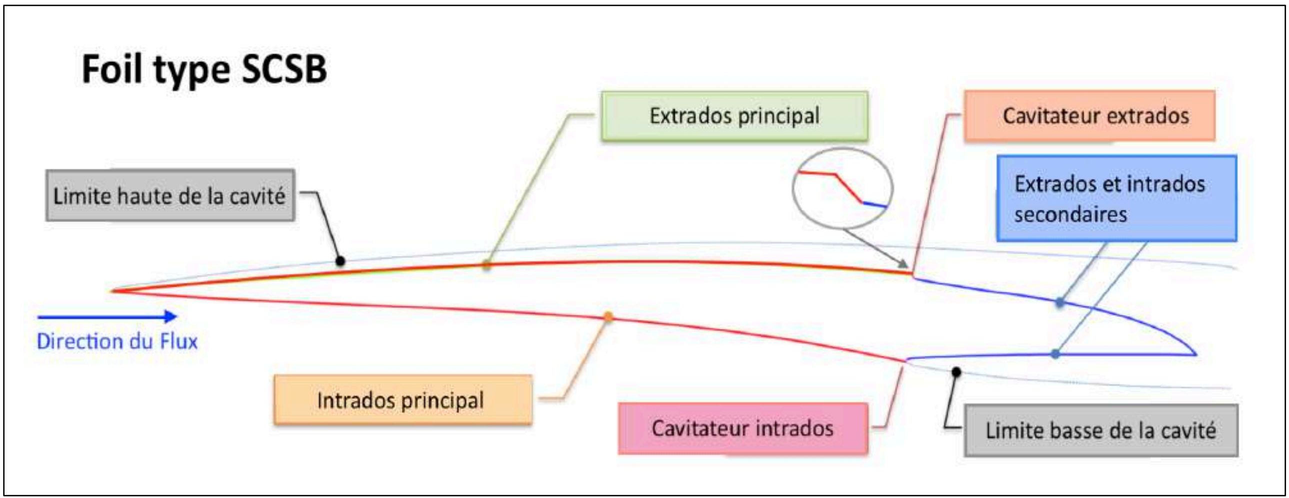
To go beyond this limit speed (i.e. to cross this "WALL"), it is necessary to use super-cavitating profiles or profiles truncated at the point of maximum thickness and having an air inlet at the truncation ("ventilated base" profiles).
The "super-cavitating" profiles are fundamentally different from traditional NACA profiles, by their very unconventional shapes and especially by their hydrodynamic mode of operation.



Profil type « NACA »



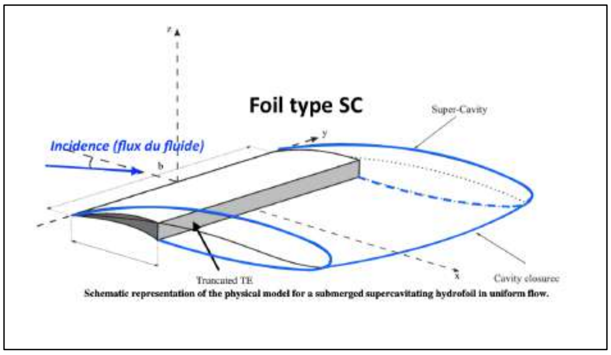
Profil type SCSB



ANATOMY OF THE NEW SC-HYDROFOIL[2]
The sketch, above, shows the main geometric elements of the new "Foil / Hydrofoil SC" family, called SCSB.

The shape of the profile is composed of six topologically different elements:
a) Main extrados ;
b) Main intrados ;
c) Secondary rear extrados ;
d) Rear secondary intrados ;
e) "Cavitator" extrados.
f) "Cavitator" intrados.

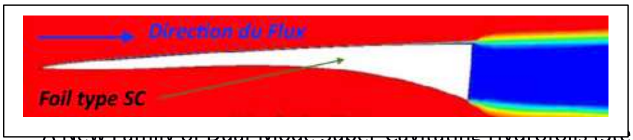
The "Cavitator" is a geometrically shaped discontinuity whose purpose is to fix the starting point of the cavitation phenomenon and to limit its instability and the associated vibrations.

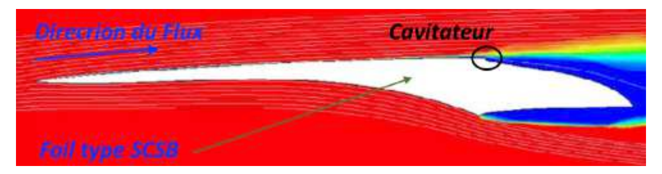


Schematic representation of the physical model for a submerged supercavitating hydrofoil in uniform flow.

From a functional point of view, SCSB Hydrofoils can be considered as being composed of two main elements:

The **main body** defined by a) and b)
Pointed tail, defined by c) and d).





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[2] A New Family of Dual Mode Super-Cavitating Hydrofoils (Stephan
Innovative Ship design lab, i-Ship, Department of Mechanical Engineering Massachusetts Institute of Technology.
(Fourth International Symposium on Marine, Austin, Texas, USA, June 2015)

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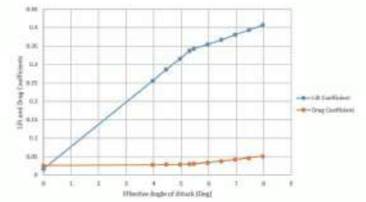
The SC foil is a kind of truncated curvilinear corner.

The SCSB foil adds to the SC foil a short conical part "immersed" in the steam flow.



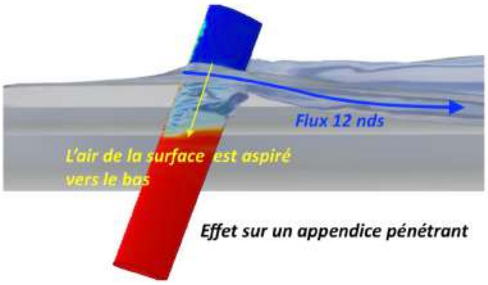
Lift and Drag coefficient distribution of SCSB profile

Extracts from the conclusion of this communication: « *This new family of hydrofoils (foils) is capable of achieving optimum efficiencies (100 knots!!) in both super-cavitation and fully wet or basic cavitation regimes, unlike conventional super-cavitation hydrofoils with profiled trailing edge which pay a high amount of drag in non-cavitation regimes.»*

The difficulty is not to manufacture this type of foil, but to reach the speed at which they are operational, because apparently their main defect would be a lack of lift at low speed.

The ideal would be to start on a conventional profile (NACA) and then move on to a **super cavitating SCSB profile**... easier said than done...

The Ventilation



Ventilation is a very common phenomenon on profiled appendages operating close to the liquid-air interface.

The result of ventilation is physically identical to that of cavitation, i.e., an almost instantaneous loss of efficiency in the function of this appendage.

However, the velocity element is only essential in starting the cavitation phenomenon.

Ventilation will hit appendages penetrating the water such as rudders, Foils support arms, but also Foils (as well as propellers) when they are totally immersed.

The risk of ventilation being more important for the penetrating appendages.

The effect on the penetrating appendages (see drawing above)

The appendix evolves like a profiled volume in an Archimedean regime.

Often this type of appendage is oriented in relation to the flow, which results in an angle of incidence and a bearing effect. This is the case, for example, with a rudder.

From this situation, at the water/air interface, the speed of movement and the incidence generate a wave hollowing on the upper surface of the profile due to the movement. An air suction located at the interface is then created.

The top surface is then locally found in a gaseous environment, which is obviously much less dense than the liquid environment.

The problem is that this down suction will naturally amplify and spread very quickly following the generator of the appendix until it completely covers the extrados and thus completely annihilates its hydrodynamic effect (depression).

On a rudder, this is called "stall", which can occur when the helmsman wants to counteract (angle of incidence) an unintended course.

In the end, the extrados of the appendage, whether straight or curved, behaves like a kind of highway that conducts and diffuses the gas mixture over the entire swept surface, moving towards the end of the appendage.

The effect on fully immersed appendages

A fully immersed appendage may be subject to cavitation, but its immersion normally protects it from ventilation.

In fact there is a poorly defined boundary zone where the risk of ventilation exists.

This is the case when the Foil (like the propeller blades) gets close to the Water / Air interface (the "surface" of the fluid) without even puncturing the surface.

This is even more possible when the Foil is not horizontal, which means that one of its ends is very close to the surface.

This spatial situation can also be caused by the passage in the hollow of a wave.

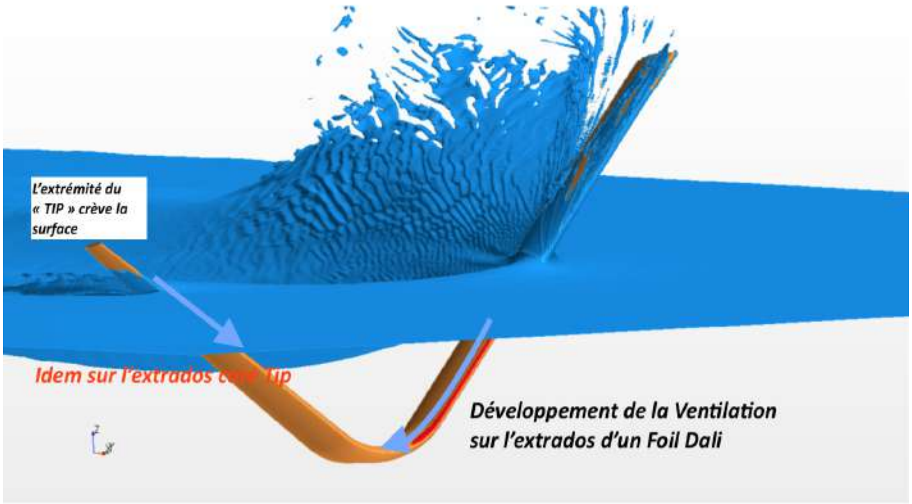
Without the surface being pierced, simply bringing the interface closer (experience shows that the limit is approximately equal to the chord of the appendage) will cause the same effect as that which occurs on a penetrating appendage.

The effect on partially submerged and locally penetrating appendages

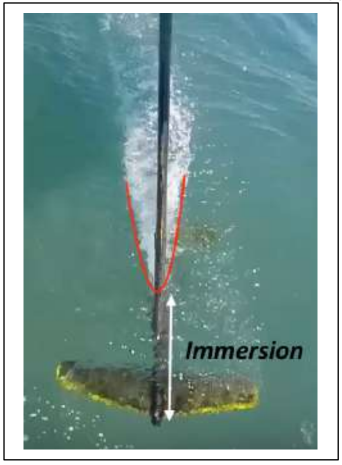
In the case shown here, there are two possible zones where ventilation can be triggered, without any prior cavitation effect:

- The location where the foil, from its exit from the hull, enters the water.

- The location where the end of the "Tip" can in certain conditions break the surface (reduction of the heel of the boat or the hollowing out of a wave).



When the ventilation effect affecting a penetrating appendage expands on the Foil




La ventilation descend au niveau du PHR et se diffuse sur l'extrados du PHR


L'ensemble de la ventilation affecte tout l'appendice (safran + PHR).
Le fluide se compose à pratiquement 100% comme un mélange gazeux.

Ventilation starts on the penetrating appendage, the rudder in this picture, but it is identical for the Foil arm of the AC75. At this stage we can see that the PHR (adjustable horizontal plane) is not affected.

The ventilation expands inexorably downwards and slides on the extrados of the PHR and destroys the initial lift generated by the extrados of the PHR.
In the end, both appendages instantly lose their functions:

- Steering control: vertical appendage (rudder)
- Positive or negative bearing capacity: PHR.

The two events that affected "ENEOS" and "AMERICAN MAJIC" are both related to cavitation and/or ventilation.

ENEOS	: "loss of lift" of the rudder and PHR
AMERICAN MAGIC	: " loss of lift " of the extrados of the leeward Foil.

The physical reality for these assemblies of two appendages (Rudder/PHR and Arms/Foil)
Physically, the ventilation phenomenon is potentially triggered when the local pressure on the extrados of the appendix becomes lower than the pressure of the water column above it.

As we have just seen, when the speed increases, the free surface of the water is "sucked" by the depression of the extrados of the arm, it descends along the extrados and when it reaches the junction of the extrados of the Foil or PHR, it diffuses onto the Foil or PHR.

The lift of the Foil or PHR, which is directly proportional to the density of the fluid in which they are moving, drops instantaneously because air has a density 900 times lower than water.

To regain lift, the Foil or PHR must "dive" deeper to get rid of the air bubble that has attached itself to the extrados, which is not very easy to realize.

A few figures to make the risk of ventilation more tangible:

- Water density: $d = 1020\ \text{kg/m}^3$ Immersion: $h = 1\text{m}$ (arm/foil junction)
- Water column pressure: $Peau = g * d * h = 10006$ Pa (Pascal)
- Speed $V = 20$ m/s (38.87 knots) Coefficient of (de)pressure $Cp = -0.5$
- **Max dynamic pressure : $P_{dyn} = 1/2 * d * V^2 * Cp = -102000$ Pa**

Under the conditions of the above calculation, Pdyn = -102000 Pa, it can be seen that this depression is greater than that of the water column.
This depression is therefore potentially capable of sucking up the water column.

In reality this reaction does not necessarily occur.
Question: Why doesn't it?

To resume, for a Foil with a 0.3m chord, it is assumed that it behaves normally up to 0.3m from the surface, but be careful, if it goes through a wave of more than 15cm of hollow, the immersion condition is broken and the bearing capacity can be seriously affected...

As we have just seen, a foil support arm that crosses the surface and connects directly to the top surface of the Foil, will promote the circulation of the gas cavity from the top surface of the arm to the top surface of the Foil.

On the other hand, if the arm is thin and perfectly aligned with the speed vector (angle of incidence =0°), it will not pose any particular problems.

On the contrary, with:

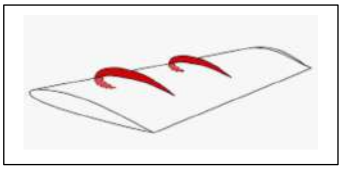
- A profiled arm is designed with a non-negligible thickness (surely necessary to obtain the mechanical resistance).
- An angle of incidence of several degrees (the Foils are off centre in relation to the sail plan and the boat always drifts a little), which results in a high Cp coefficient.

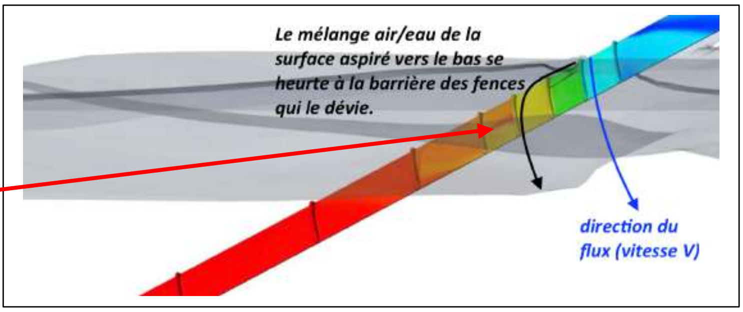
Then its extrados will generate a local hollowing of the free surface of the water and create a path for the suction of air towards the extrados of the Foil which works in a strong depression.
The air replaces the water and as a consequence the lift of the foil drops immediately.

Which solutions?

The most common solution is to prevent the gaseous cavity (air and water) that is created on the surface from being sucked up and reaching the top surface of the Foil or PHR.

The aerodynamic engineers and then the hydrodynamic engineers have solved this difficulty by installing barriers perpendicular to the profile in order to deflect the movement of the cavity. These are the "fences" that are quite often seen on the wings of aircraft.



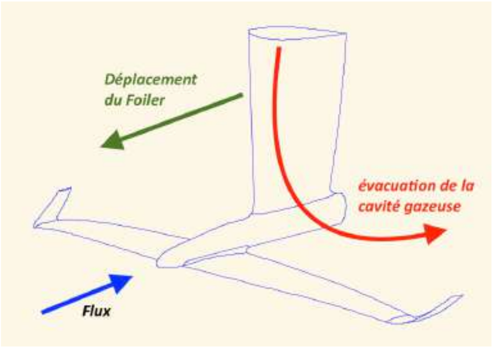


"Fences"
(bulkheads perpendicular to the surface of the profile)

This does not solve all the underwater conditions or the presence of sudden waves, but it is an interesting approach.

For many Foilers, including those that do not have a stern regulator plane (PHR), this would be a real safety feature.

Another solution to reduce this risk is to install the Foil in front of the arm that carries it, so that the trajectory of the gaseous cavity that produces ventilation does not diffuse on the extrados of the Foil or PHR and disperse in the wake of the rudder or arm..



However, this design increases the structural complexity (design and mechanical stress) of the connection part between the arm and the Foil or PHR.

Report

Archimedean design is an art in the hands and pencil of the Naval Architects.

It is true that computer tools have made it possible to improve and optimise hull designs, as well as new materials, but developments and performance gains are progressing slowly.

Racing on an Archimedean support is a Technical Sport, in the sense that architectural creation must adapt to certain constraints imposed by the Box-Rules (there is no such thing as a regatta without rules), which means that the genius of creation must be associated with more or less complex technical solutions.

The Foiler, on the other hand, abandons the Archimedean domain, since the hull becomes almost optional. A Foiler is mainly available because of its flight stability, which is closely linked to the hydrodynamic performance of its Foils and its connecting elements, and also to the pilot assistance functions.

Contrary to the Archimedean sailboat which evolves in 2 dimensions, the crew of a Foiler must manage an evolution in space, that is to say in 3 dimensions and with much shorter reaction times.

The performance of a Foiler depends essentially on the ratio of lift to drag of the Foils. Obtaining lift in a non-homogeneous fluid generates the parasitic phenomena described above, which further complicate the equation.

The mechanical resistance of the Foiler will obviously have to be considered, but this is a more classic problem.

With the Foiler, the Naval Architect leaves his place to the Fluid Mechanics Engineer, the Architect will still intervene on the sail plan although the dimensional and geometrical framework of the AC75 class rule is very constraining.

In the end, the Foiler becomes an engineering research, which transforms the regatta into a mechanical sport.

The next step will be to design with a lot of $ or € a real flight simulator in order to train the crews.

Jean SANS & Robert LAINE (27/05/2017)