l'HYDROPTERE: A story of a dream

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SUMMARY

In 2009, l'Hydroptère broke the symbolic barrier of 50 knots and became the world fastest sailing boat over both 500 meters and 1 nautical mile. This major achievement relied on the high skills of the sailing team but also on technical advances of the boat, resulting from long years of studies and development. This achievement is also an open window to a new goal: flying around the world.
In the present article, we present this long and incredible story, highlighting the different steps, the technology involved, and the background of that project..

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NOMENCLATURE

d	Level of immersion (m)
G_{Ic}	Griffith's critical strain energy release rate (J)
q	Angle of refraction (°)
P,Q	Pixel distributions
p	Static pressure (Pa)
p_v	Vapour pressure of water (2300 Pa)
ρ	Density of water (997 kg m^{-3})
s	Cavitation number ($= \dfrac{p - p_v}{\frac{1}{2}\rho V^2}$)
V	Flow velocity (m s^{-1})
2D	Two-dimensional
3D	Three-dimensional
CVLab	Computer Vision Laboratory
DMA	Dynamic Mechanical Analysis
DSC	Differential Scanning Calorimetry
EPFL	Ecole Polytechnique Fédérale de Lausanne
FE	Finite Element
LIN	Computational Engineering Laboratory
LMAF	Laboratory of Applied Mechanics and Reliability Analysis
LMH	Hydraulic Machines Laboratory
LTC	Laboratory of Polymer and Composite Technology
UD	Unidirectional tape
UFO	Unidentified Floating Object
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1. PRINCIPLE

l'Hydroptère is a sailing trimaran using the lift of hydrofoils in a whole sense, i.e. using them to balance completely the weight of the boat and to pull the hulls out of the water from a minimum boat speed, thus reducing drastically hydrodynamic drag and raising performance to high levels.

2. HISTORY

2.1 BEGINNING

In 1987, with the help of Eric Tabarly, Alain Thébault met engineers from Dassault Aviation in order to imagine a new sailboat, now able to fully flight thanks to new composite materials.
Thebault had to wait until 1992 before starting the building of his boat, the time to experiment on several reduced scale models and to convince partners to follow him in that crazy project.
l'Hydroptere was launched in 1994 and the first fly was a full success, with a nice stability and high speeds reached for that time.

2.2 10 years of reliability

During the ten years following the first flight, l'Hydroptère knew three major crashes.
Indeed, because of this totally new way of sailing, the strengths viewed by the different pieces of the boat were unknown.

1995: Breakage of the leeward crossbeam. After that first crash, in the same way than in aeronautic world, engineers understood they had to set up a full measurement system, in order to record data and better understand the loads viewed by the boat.

1998: Lose of the leeward foil, after the breakage of a link bolt.

2002: Breakage of the windward crossbeam during an offshore sailing at high speed in rough see. Then the team understood it would never be possible to prevent the boat from every peak loads. The solution was to set up shock absorber between the foil and the crossbeam in order to protect the boat structure in every sailing condition.

2.3 10 years of performance quest

In 2004, the team launched a fully reliable boat, with a well-calculated structure, inboard systems to run a full time survey of the loads, and shock absorber to prevent the boat from damages.

Then the team may concentrate on one goal: be the fastest sailboat for offshore sailing.
We made the choice to validate different steps in our quest:

- Costal sailings
- Speed
- Offshore sailings

2005: First costal record. l'Hydroptère crossed the Channel faster than aviator Louis Blériot in 1909, sailing from Dover to Calais in 34 minutes and 24 seconds, at an average speed of over 33 knots.

2006: l'Hydroptère unfortunately collided with an Unidentified Floating Object (UFO) during a Cadiz to San Salvador crossing record attempt. Afterward, Swiss nationals Thierry and Adrien Lombard saved the project and established a contact between the Hydroptère Team and the Ecole Polytechnique Fédérale de Lausanne (EPFL), giving rise to a scientific partnership.

2007: Launch of new version of l'Hydroptère, with new planning floats and a new rigging.

Two new world speed sailing records:
→ 500m/D class record – 44.81kts
→ 1Nm outright record – 41.69kts

Costal records attempts on SNSM (Saint-Nazaire/Saint-Malo) and Brittany Ferries (Plymouth/Roscoff).

The team discover both high speed and offshore potential of the concept.

2008: Studies for the outright speed record over 50kts. In partnership with EPFL, the team work on several domains, mainly hydrodynamics in order to solve cavitation problem, but also on aerodynamic and structural behaviour issues.

Despite nice numerical and experimentation results, the crew met difficulties to stabilize high speed on 500 meters. Indeed, because of instabilities of wind and see conditions (gust, waves), the foil shape needed to be more versatile.
In high windy conditions, with wind gust over 45kt, and after a peak speed of 56.36kts reached, l'Hydroptère capsize the 21st of December 2008.

2009: The design team find the problem of the instability in the behaviour of the boat. In specific conditions of incidence and immersion of the windward foil, at very high speed, a coupling between the twist of the crossbeam and the load on the foil appear.
With a new shape of the foils, the team solved that problem and the crew manage to reach the speed goal over their deeper objectives with two new world records:
→ 4 September 2009: Outright speed record over 500m – 51.36kts
→ 8 November 2009: An incredible outright speed record over 1Nm – 50.17kts

2010 and after: Back to the offshore. After the speed step, the team concentrate on a new one, sailing offshore at high speed.

To reach that goal, the team can experiment offshore thanks to l'Hydroptère, test improvements and measure phenomenon.

Moreover, the team members designed and launched the 8th of October 2010 a new 35 feet catamaran on Geneva Lake. This new boat is the result of years of studies and learning on the oldest boat. This new flying catamaran is a true laboratory that will permit the engineers to better understand the behaviour and the different solutions available.

3. BACKGROUND

3.1 COMPANY

Hydroptère is two companies: Hydroptère France located in Paris with office and shipyard in Brittany, and Hydroptère Suisse located in Lausanne with office just close to EPFL.

3.2 TEAM

Since the beginning of the project, Alain Thébault has been accompanied by passionate professionals from the marine and aeronautical fields. An extraordinary team composed of sailors, scientists and technicians has been created to design, develop and make the boats fly:
- A Sports Team based in La Trinité sur Mer with 8 engineers, technicians and sailors.
- A Design Team based in Lausanne with 5 engineers.
- An Operational Team based in Paris with 2 persons in charge of the communication and the finance.
- A strategic support from 8 engineers on a voluntary basis – called the "Papés" – from high-tech industrial companies (Dassault, Airbus, Assystem...).

3.3 PARTNERS

Two mains sponsors permit the dream going on:
- The swiss bank LOMBARD ODIER

- The swiss watchmaker AUDEMARS PIGUET

4. THE STUDIES

To achieve such outstanding performance with wind as the only driving force, the Hydroptère Team has required to decrease air resistance of all the boat's aerodynamic elements and to improve both shape and tuning of the sails in order to obtain as much propulsive force as possible. But the main challenge is to obtain sufficient lift force from the hydrofoils despite phenomena encountered at high speed like cavitation and ventilation that can lead to hydrodynamic load instabilities. Moreover, structural design, materials choice and manufacture are the main factors affecting the safety and stability of the yacht and can significantly affect its overall performance. In such a trans-disciplinary project, the global design and optimization process usually requires a significant number of inputs and hypotheses coming from different fields like fluid dynamics for the determination of the wide range of loading conditions, or materials science and solid mechanics for the determination of the failure criteria of the materials that can be used. Knowing these design criteria, an iterative design-simulation-optimization process can then be employed to progressively turn an innovative design concept into a highly sophisticated and high-performance hydrofoil yacht.

4.1 MATERIALS

To minimize the weight of the structure while answering to the needs of the design, it is necessary to carefully evaluate and optimize the properties of materials and of their assembly in conditions that are very close to ship yard practice (humidity, temperature, lay-up and processing time, part shape, etc...). Several studies were thus performed to gain confidence and potentially reduce safety factors in the part design.

4.1.1 MANUFACTURING PROCESSES

Most parts of the boat are made of carbon-epoxy composites, either as monolithic parts or as sandwich structures with honeycomb cores. Several processing methods are used, depending on the part design, from lay-up of wet-impregnated fabrics or prepregs cured under vacuum bag only, to prepregs cured in an autoclave. For all these, several studies were carried out to select the best process, including the cure schedule, and to check the part quality after processing. Additional studies were carried out to analyse the influence of the off-axis plies in the final part properties in bending. Occasionally, analyses were carried out on processed parts, especially if potential defects are suspected: visual inspections by micrographs or curing stage by Differential Scanning Calorimetry (DSC) and Dynamic Mechanical Analysis (DMA) for example. A constant interaction between the boat builders, the Hydroptère Design Team and the lab is crucial to obtain best results.

4.1.2 SANDWICH STRUCTURES

A specific study was carried out to compare the design values with experimental results for honeycomb sandwich structures processed with Nomex Flexcore under vacuum bag only (Figure 1). The final aim was to determine how this anisotropic honeycomb affects the properties of the final sandwich of the hull and provided experimental values for simulation model.

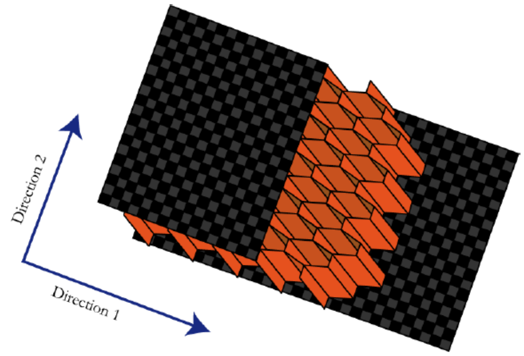


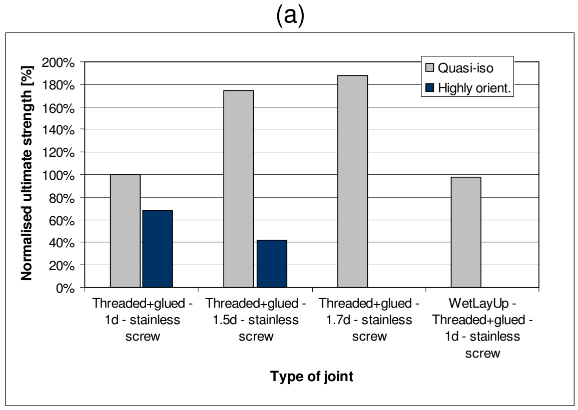
Figure 1: Anisotropy of the Nomex Flexcore and the two main directions

For this, samples consisting of skins only, then full sandwich structures were manufactured and tested in tension, compression and shear for the skins, and in four points bending with several span lengths for the sandwich beams in order to calculate the shear modulus of the core in the two main directions. A careful comparison of the experimental values, with the estimated values from the skins and core properties was carried out and used in the simulated model.

4.1.3 THREADED JOINTS

Several metallic parts are attached to the composite parts through threaded joints, for example the mast railing. A study was conducted to assess the strength of these joints, as a function of the composite type (unidirectional UD vs. quasi-isotropic), the screw material (stainless steel vs. composite), the presence of an insert or not, and how it is assembled (glued screw, screw with release agent and glued). Joints were made, and a testing device was produced that allowed the screws to be tested by extracting them with a force perpendicular to the composite plane. Results show as expected that it is important to reinforce the joint location by quasi-isotropic lay-up (Figure 2). Also, direct threading with a proper tool, with a glue layer, gives the best results. However, a request could be that joints can be removed easily for dismounting and repair. The use of a release agent before gluing the screw does not decrease the ultimate strength, even if the screw is un-screwed and re-screwed. These results do not take into account aging effects. If the screw is to be removed "frequently", a glued insert can be safely used, albeit with a weight penalty.

(a)



(b)

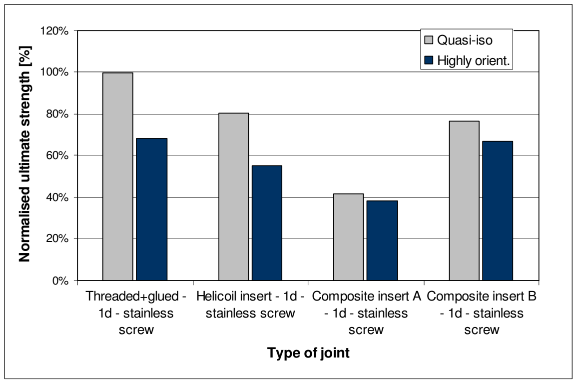


Figure 2: Comparison of the pull-out force for several types of joint
(a) Thread length effects
(b) Thread type effects
(100% reference value correspond to stainless steel screw threaded in quasi-isotropic laminate, with embedment length of the screw diameter)

4.1.4 BONDING

An extensive study was carried out to optimise the surface treatment of titanium for bonding to composite parts. This is crucial to make sure these bonds are designed properly, and the effect of aging is taken into account. For this, comparative measurements of fracture strength and Griffith's critical strain energy release rate G_{Ic} were carried out on adhesive bonded joints with three surface treatments of titanium. Tests were performed un-aged and along thirteen weeks of accelerated aging in salted or de-ionized water at 50°C. Thermo-mechanical measurements were carried out on the epoxy Araldite 420 adhesive alone, with the same aging conditions.
From these results, the best practical solution for the performance and lifespan of the bonded joint was determined. A combined surface treatment of sanding, degreasing and chemical etching shoed the best durability, whereas a treatment using a sulphuric anodic oxidation in addition showed the best adherence before aging. On the whole, bonded joints showed a high variability and a fall of their properties from 30 to 70% at the end of aging according to the surface treatment.

A numerical method for dimensioning was proposed by means of a finite element implementation with a cohesive zone model in Abaqus. This method was validated by simulation of two representative mechanical tests corroborating the experimental results. Experimentally determined failure criteria as well as aging effects and safety factors were thus taken into account in the finite element model.

4.2 STRUCTURE

For precise predictions of the dynamic behavior of the yacht, a detailed and accurate model of the structure is required. However, because of the large number of variables (material properties, geometry and assembly) and their inherent uncertainties, the developed FE model had to be thoroughly validated on the basis of real structural tests. A series of tests have been conducted first on components and then on the whole yacht. The static deformations of key elements were measured under various loading conditions to determine the most important stiffness values and a detailed modal analysis of the foils alone and the whole yacht was carried out.

The measured stiffness's and Eigen frequencies were then used to update the FE model parameters in order to achieve a good agreement between the numerical predictions and the real behaviour of the structure. A FE model optimization method was developed and interfaced with the Abaqus solver to automate the parameter updating procedure and maximize the accuracy of the numerical model (Figure 3).

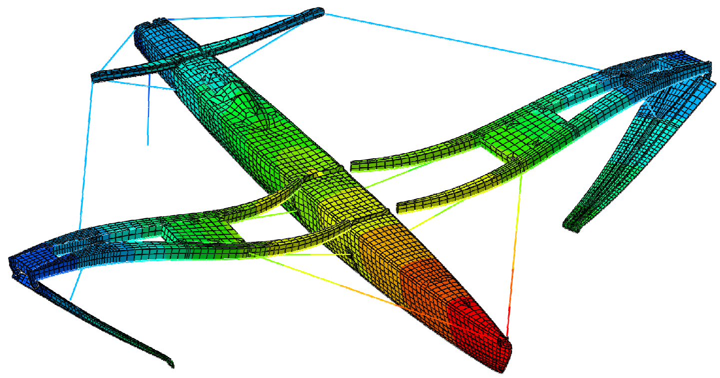


Figure 3: Numerical modal analysis of the whole l'Hydroptère structure using the calibrated model

The calibrated FE model was also used to provide important modal analysis data to the Hydroptère Design Team in order to study the hydrodynamic stability (divergence / flutter) of the rear stabilizator at high speed (Figure 4).

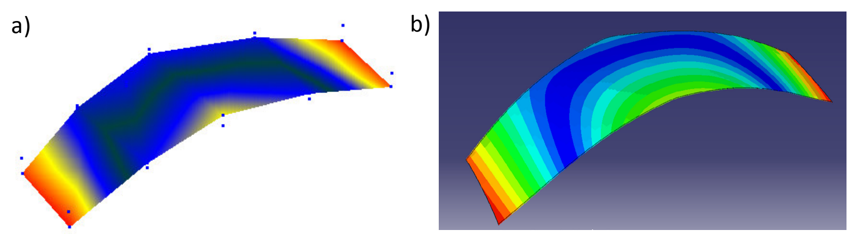


Figure 4: Experimental modal analysis of the rear horizontal stabilizator (a) and predictions using the calibrated model (b)

4.3 ONBOARD MEASUREMENT SYSTEMS

4.3.1 PRESENTATION

A measurement system on board provides the sailors with real time values and is divided into four sub-systems:

- Stress and positioning sensors
- Navigation unit
- Inertial unit
- Video system

The stress measuring and positioning system is composed of 54 sensors, placed on various strategic points on the boat. It includes four types of recordings:

- Strain gauges, measuring local stress, which permit the analysis of the efforts sustained by the structure of the boat
- Accelerometers
- Rotation sensors
- Pressure sensors

All these sensors are connected to HBM digiCLIP digital amplifiers.

The navigation unit indicates the environment in which l'Hydroptère evolves, speed, angle, direction of real and apparent winds, and the GPS positioning of the boat.

The IXSEA Octans inertial unit gives the boat's attitudes, roll, pitch, surge, yaw and dig in, as well as their speeds and accelerations, with great precision.

The video system has been added using Cosworth Pi VIDS2 video recorder, and a few cameras, in order to analyse in real time the submerged depth of immersed appendages, as well as the structure deformation, with video-imaging techniques.

All the values from the four sub-systems are spread in a CAN bus and recorded in a synchronised way into a logger box (Cosworth Pi Sigma LLB data logger), as well as copied to a ruggedized computer (Lemer Pax Posibox) in order to:

- Display with visual and sound effects to inform the test engineer on the applied strain, with an alarm signal if necessary
- Process the data through basic mathematical tools or more powerful tools such as filtering or the Fourier transform.

The real-time data are an essential aid to steer the carbon bird over the irregular air-water interface and after every sail test the collected data is analyzed to make improvement for the next sailing day. Those recordings could also be compared off-line to the estimates of the flight simulator, and serves as a database for improvements or new designs.

4.3.2 COMPUTER VISION EXTENSION

Only the resultant of the hydrodynamic loads on the foil is deduced from the jack load. This resultant is the product of the hydrodynamic pressure distribution over the submerged surface of the foil. Thus, high load over only a tip of the foil could lead to the same jack load than a smaller load spread over the whole foil. The knowledge of the submerged depth of the foil allows refining the true effect of hydrodynamic loads.

The principle of the foil immersion detection was derived at the Computer Vision Laboratory (CVLab). The definition of the level of immersion uses the refraction phenomena. It consists in moving along the edge of the foil, and looking for a change of slope due to the refraction of the submerged part (Figure 5). The method, simple in its principle, could be quite challenging in its application since a lot of perturbations could disturb the detection: changing light condition, reflections or spray drops on lens resulting in blurred images.

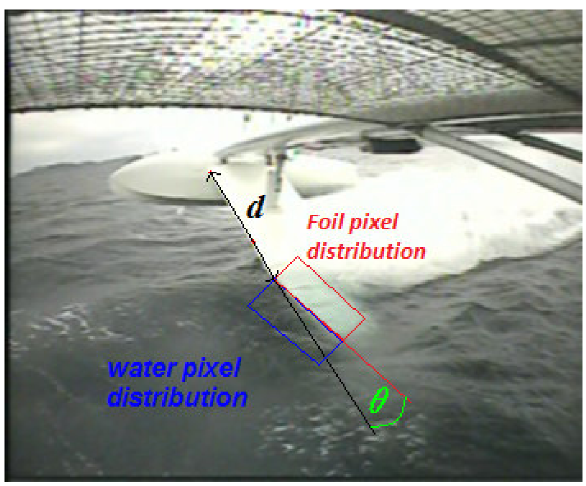


Figure 5: Definition of level of immersion using refraction phenomenon and Kullback-Liebler divergence

The algorithm is based on the maximization of a function of the Kullback-Liebler divergence [3] between pixel distributions *P* and *Q* of the non-submerged or submerged parts of the foil, and water (histogram of pixels), given a level of immersion *d* and an angle of refraction *θ*:

$$F(d,\theta) = \frac{D_{KL}(P,Q) + D_{KL}(Q,P)}{2}$$
$$= \frac{1}{2}\sum_{0}^{255} P(i)\log\frac{P(i)}{Q(i)} + Q(i)\log\frac{Q(i)}{P(i)}$$

The results from this tool can be quite interestingly compared with other synchronised measures

4.4 HYDRODYNAMICS

4.4.1 HYDRODYNAMIC PHENOMENA

4.4.1 (a) Cavitation

The cavitation phenomenon is the formation of vapour cavities within a flowing liquid due to excessive decrease of local pressure [4]. It may occur in a variety of hydraulic systems such as hydraulic turbines and pumps, ship propellers and space rocket inducers. Cavitation may be the source of severe erosion and vibration as well as alteration of hydrodynamic performances.
In the specific case of l'Hydroptère riding at 50 knots, it is almost impossible to avoid cavitation occurrence. As the boat speed increase, cavitation may suddenly appear with a drastic drop of the hydrodynamic lift and a substantial increase of drag and structural vibrations. In this case, the safety may be seriously compromised. Nevertheless, we have worked out the design of the foils to make that phenomenon appearing later and with fewer consequences.

4.4.1 (b) Ventilation

Ventilation is a phenomenon in which air from above the free surface is sucked into a low-pressure zone below the surface. It is of course more important in very low-pressure zones, such as those that can lead to cavitation, and both phenomena are thus strongly interacting. Most often, air from above the surface is guided along the suction side, leading to a drop in lift (as well as in drag, although this is of lesser importance for hydrofoils) [5].

Hydroptère team use numerical simulation and experiments on l'Hydroptère boat in order to define the best solutions to solve ventilation problem.

4.4.2 NUMERICAL SIMULATIONS

Using FLUENT, cavitation was initially investigated by simply “contouring” the low-pressure zones below the vapour pressure; this approach provided interesting but only qualitative results. Another possible approach, using a “mixture” model did not provide adequate results, with a clear tendency to predict very large cavitation zones. More successful was the use of ANSYS CFX with a three-phase flow model. For ventilation, both solvers appeared to perform well, although the convergence properties of CFX were found to be better.

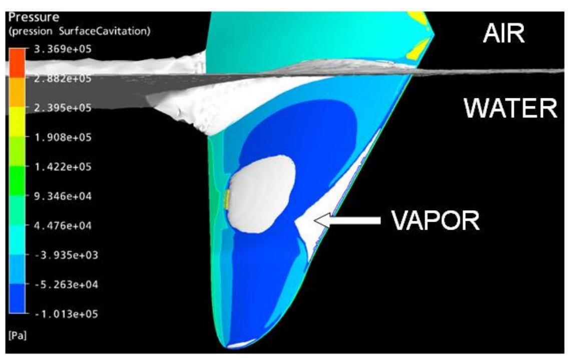


Figure 6: Three-phase simulation using CFX

4.4.3 VALIDATION OF SIMULATIONS

Model scale tests involving three different phases of fluids (air, liquid water and water vapour) are extremely difficult to perform. For validation purposes, phenomena were divided and simulation directed towards two-phase flow cases: cavitation or ventilation alone.

In order to investigate the cavitation phenomenon in the case of l'Hydroptère foils, laboratory tests were carried out at the Hydraulic Machines Laboratory (LMH). 1/10 scaled models of both foils and rudder/stabilizer portions were mounted in the middle of 150 mm x 150 mm square test section of the EPFL high speed cavitation tunnel. A maximum speed of 50 m/s may be reached at the test section inlet and the pressure may be adjusted from 0.02 to 1.6 MPa. Cavitation can then be easily controlled, either enforced or avoided.

To allow for accurate scale up, the flow velocity was set to 15 m/s and the *s* value corresponded to l'Hydroptère speed of 50 knots under atmospheric pressure. For these conditions, a turbulent boundary layer develops on the foil and Reynolds effects may be neglected.
As illustrated on Figure 7, attached cavitation occurs on the foil. The location of the cavity detachment and its length depend strongly on the angle of attack. For low angles (left), cavitation departs downstream to the leading edge and extends rapidly beyond the trailing edge. In this regime, the flow is rather "smooth" with low induced vibration. As the angle is increased (right), the cavitation appears even for higher *s*, and its detachment moves upstream with growing amplitude of the cavity pulsation. The sheet cavitation turns into the so-called cloud cavitation, which is associated with large lift fluctuation and induced vibration.

In the design process, profile sections, distribution and angles of attacks of the foils of l'Hydroptère were optimized to avoid the occurrence of cloud cavitation.

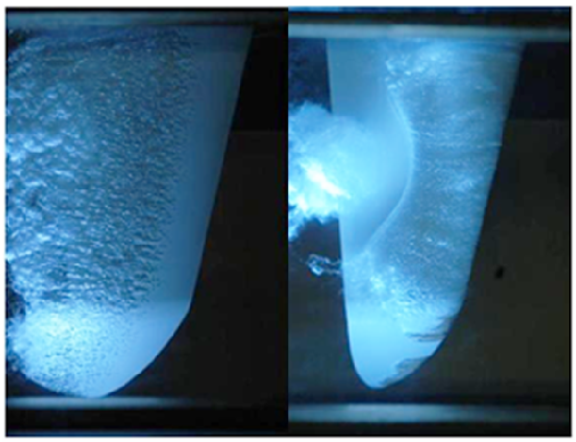


Figure 7: Cavitation trends
(Left: low *a* and *s*=26;
Right: high a and *s*=87)

Initial validation studies were based on direct visual comparison between experimental photos and simulated images for the same flow conditions. Although this is only qualitative, it already gives a good idea of the ability to capture the presence of cavities, their extent and shape, the inception trends, etc.

More quantitative validation was performed through the variation of hydrodynamic loads according to cavitation extent. The experimental loads were determined by mounting the foil on a calibrated 5-axis balance, and compared with the simulated loads.

Ventilation is a more complex phenomenon to validate, since the hydrodynamic tunnel is not suitable for ventilated tests. In fact, really few towing tank can reach the high speed required to reveal interesting effects.

The first step was again directed to visual comparisons to obtain a qualitative assessment, but on the true scale of the prototype. The shape of the wave elevation around the real foils was compared with pictures taken from onboard video recording system.

A second step was the analysing of the loads measured on the foil. Indeed the ventilation will change the arm level of the load, and consequently the measure on the jack. Thanks to that measure combined with video recording, we can analyse the ventilation appearing and effects.

4.5 3D SIMULATOR

To help the design of new solutions, the performance predictions, and the knowledge of the loads for structural design, the team develop since many years a 3D simulator of l'Hydroptère.
At the beginning, this tool was only considering foils working in sea with unidirectional swell.
But more and more developments are added in order to be as close to the reality as possible. It means different way of developments:
- Swell (crossed swell)
- Floats (Archimedean, planning hulls)
- Structure behaviour

And, with the growing of computer power, we can even imagine to take into account hydrodynamics phenomenon like cavitation or ventilation..

5. CONCLUSIONS

In direct association with the Hydroptère Design Team, several laboratories at EPFL have contributed to a number of optimizations of l'Hydroptère that have enabled the sailing team to achieve the world sailing speed records. Several FE models of the structure have been developed and updated. Specific materials have also been developed, produced and tested in various conditions with the aim to optimize the structural behaviour and provide new design solutions. Onboard measurements of structural deformation and foil immersion used to validate and refine the design loads and operation scenarios have proved to be very important in the fine optimization of the yacht. Various foils were tested at reduced scale in a high-speed water tunnel, and the results used to validate numerical simulations.

The collaboration between l'Hydroptère and EPFL continues with further challenging objectives for both sailors and researchers. Several studies have already been directed in order to help the team to achieve larger goals: Offshore records with the absolute dream to fly around the world!

6. ACKNOWLEDGEMENTS

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