SPEED, a symbol of power over the centuries

Jean SANS

Le 14/02/2025

https://experts-yachts.fr/blog-js.html

Acknowledgements

Patrice Carpentier, for his eye as a sailor and journalist.
Etienne Billiet for his proofreading and comments.
Yannick Abgrall, architect, with whom I've had a lot of discussions
Claude Charbonnier, for his experience in the aeronautical industry.
Robert Lainé, a specialist in space missions (ESA) with whom I often write communications.
Hubert Schaff, yachtsman and metalworker.
Nina Sans, graphic designer, for the design of the front cover

CONTENTS

[1] RRS: Acronym for Racing Rules of Sailing (international rule)

Summary

From Archimedean sailing to mechanical propulsion and hydrofoil sailing.

How did we get from the idea of moving around using a floating device, without knowing the laws that allowed it to float, to the idea of floating on water based on the laws of aerodynamics?

Why has maritime mobility technology been a passion for over 3,000 years?

The quest for performance, identified in particular by the concept of speed, became the objective throughout these centuries. Sailors, and soon governments too, realised that the speed of their ships was the key to their commercial success, to victory in the many naval battles and to demonstrating their imperial power. Even the discovery of new continents and maritime routes became a race in which the first to plant the flag was the winner.

These gains in speed involved scientific discoveries and gradually fuelled the excessiveness of the ships designed.

Today, speed remains the prerogative of the art of sailboat racing.

Of course, regattas in the form of competitions between wealthy amateurs and crews of professional sailors only appeared at the end of the 19th century, but the desire to go faster and catch up with a vague silhouette on the horizon haunts all sailors.

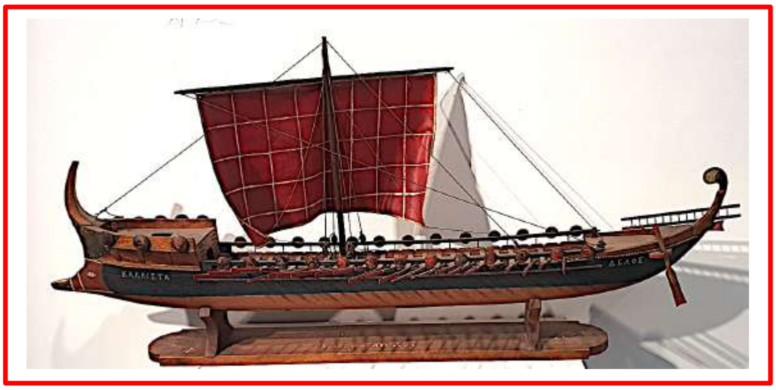
This particularly vast field stretches from 2000/1500 BC to the present day, with an unexpected intruder appearing at the end of the 19th century, although already present in Greek mythology: aviation.

1- At the origin

Originally, walking, running and dancing came naturally. Managing the length and frequency of steps, the spacing of feet, balance due to the body's relatively high centre of gravity, the reaction time when faced with an obstacle, etc... means that the number of data acquisitions and implicit orders must be matched in the space of a millisecond to enable fluid movement. All this seems natural and normal to us. However, as soon as you use a mobile to move around, managing the interface between the mobile in its environment and the helmsman becomes complicated and, above all, shows that there are limits.

Over the course of thousands of years, navigation by sea or river was established in a very specific and gradual way. The period of antiquity in the eastern Mediterranean is relatively well documented in terms of the desire to sail, as far back as 1500 BC.

To do this, you need to master navigation, firstly technically, by building suitable boats, and then you need to be able to get from one point to another.



The Phoenicians, the Greeks and later the Romans developed and acquired a high level of expertise in the construction of triers (also known as galleys), one- or two-masted ships of up to 35 metres in length, (sail and oars) and crewed by 170 rowers (3 per oar).

These peoples criss-crossed and colonised the entire eastern and then western Mediterranean, and even made forays beyond the Mediterranean, as did the Greek Pytheas, who reached Thule (Greenland) around 320 BC. Other daring Greek navigators also bypassed Africa.

Although there are no written traces of any attempt to theorise navigation or design and construction methods, architectural developments can still be seen in the bas-reliefs carved over more than a thousand years.

Archimedes theorised static mechanics for the first time, and in particular the notion of the centre of gravity (of equilibrium) of any heavy body.

This makes it possible to concentrate all the body's weight at this point, which is also known as the barycentre or centre of gravity.

He also laid down the fundamental laws of hydrostatics and Archimedes declaimed, while in his bath, the famous "EUREKA", which is attributed to him, "*anybody immersed in a liquid... etc... etc...*".

However, the design and construction of boats over almost two millennia has been based solely on the generational transmission of practical experience acquired by builders. No practical calculations were conceptualised or formalised.

This is possible because the equilibrium of a boat at sea is implicitly guaranteed by the physical laws of hydrostatics. As soon as you move a boat away from its initial point of equilibrium (0° list), you can see that it always (well, normally) returns to the 0° list.

Of course, this law only applies as long as the heel does not reach the angle of capsize. This scientific concept of capsizing had not yet been formulated and, above all, did not seem to concern the architecture of the boats, which were heavy, long, shallow and designed with an elliptical waterline that gave them relative stability of shape and sufficient stiffness at low angles of heel. The sail plans did not allow for close-hauled sailing, with the gunwale in the water...

But in addition to the commercial use of these ships, which was economically necessary for the states, the design of warships gradually became necessary, which led architects to focus on ever greater speed, power (sails and oars) and manoeuvrability.

2- Mathematics opens up a new approach

From antiquity to the 1500s, only technological developments spread very gradually.

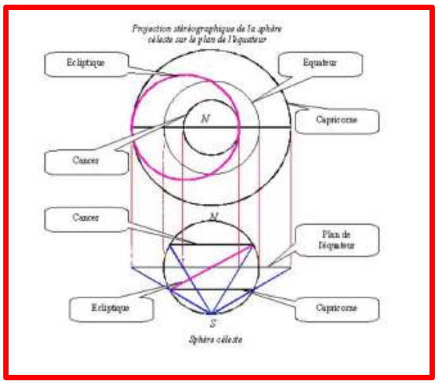
The stern rudder originated in Northern Europe. It is known as a rudder on our racing boats.

Then the astrolabe.

Before becoming a navigational instrument, the astrolabe was the result of a study by two Greek astronomers, Hipparchus (150 BC) and Ptolemy (150 AD).

The original aim of their work was to propose a geometric transformation of the half-spherical celestial vault onto a flat circular disc in order to improve understanding. To do this, they laid the foundations of spherical trigonometry, which enabled them to situate the successive positions of certain stars, the sun, the moon, etc. during each 24-hour period.

Later, the Arab astronomers extended and materialised this work by creating a navigation device. The astrolabe became indispensable and improved with each passing year of navigation.



Around the 12th century, a second navigational instrument revolutionised over-the-horizon navigation: the compass. This instrument, a simple needle with a magnetised end that points automatically and permanently northwards, seems to have travelled a very long way from China before reaching the Mediterranean and Western Europe.

However, all these developments relate to navigation techniques. The most important thing is to improve the way ships are steered and, above all, to identify their route and the accuracy of the cartography.

Paradoxically, until the 1500s, there were no traces of scientific work on ship architecture and, above all, no exchanges between the different civilisations that mainly lined the Mediterranean arc. Throughout this long period, people looked at, modified, copied and adapted different types of ship architecture.

One of the reasons for this is that numbering systems do not encourage the transmission of mathematical knowledge. But they do exist. Numeration was far from standardised or easy to use in calculations throughout antiquity and the first millennium of our era.

For example, the Babylonian system is based on[2] 60 and the Egyptian system is based on a decimal system using 7 hieroglyphs but without the "0" digit. Roman numeration is based on letter symbols combined together (the famous Roman numbers). In fact, there is a plethora of numbering systems, mainly linked to commercial activities. In particular, all these civilisations used fractional notation in parallel, which was practical for trade. The Romans moved towards the duodecimal system (base 12). It is interesting to note that this fractional methodology survives to the present day, with measurements in feet, inches, coins, etc.

This was the beginning of what is known as positional numbering, which originated in the Indo-Arabic world. This method of writing numbers is based on each position of a digit from right to left and links it to a multiplier. So, when we write 249, it breaks down into the addition of 9 units, then 4 tens and 2 hundred. The system uses 10 digits (base 10) marked 0 to 9.

The spread of the positional decimal notation system represents one of the greatest advances, because it is implicitly normative, in the entire history of mathematics

This concept was not the work of a single person, or a single civilisation, but of exchanges throughout antiquity and the first millennium.

This method of writing numbers appeared fairly late in Europe, around the beginning of the 1200s, thanks to Leonardo Fibonacci (an Italian mathematician living in Pisa).

[2] The decimal system is base 10 (0 to 9), while a computer works in base 2 (0 or 1).

Fibonacci travelled to all the major cities in the Mediterranean region, collecting mathematical knowledge and recording it in two works, the "Liber abaci" and the "Practica Geometriae". Fibonacci paved the way for decisive developments in his discipline. In particular, he explained the new method of writing numbers, based on the positional notation system

Fibonacci also introduced the Arabic numerals we know today and the "zero", which enables us to work with decimal numbers.

Fibonacci's work was not confined to conceptualising and disseminating a system for writing numbers that improved the practice of arithmetic, but also produced a number of studies on algebra, geometric arithmetic, etc.

Then, gradually, in Europe, men with a passion for science and mathematics, such as Simon Stevin (1548-1620), Pierre Bouguer (1698-1758) and Leonhard Euler (1707-1783) took up the work of Greek and Arab mathematicians and set about theorising the physical object represented by the boat.

In 1746, P. Bouguer studied the relationship between the relative positions of the CG (centre of gravity) and the CB (hull centre, which corresponds to the hull's centre of gravity) with the Archimedean laws (hydrostatics) by associating weights and moments.

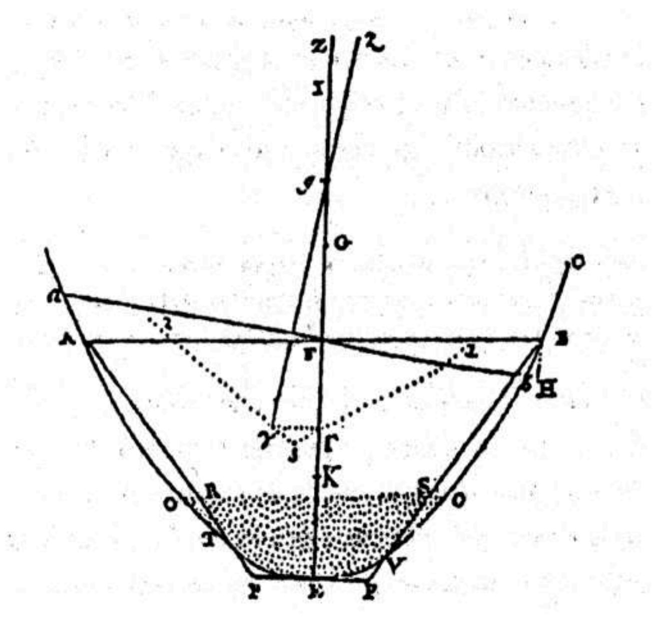


Figure 3-6 : Diagramme du métacentre (Bouguer, Traité du navire (1746), plate 6)

To do this, he used new mathematical concepts such as the foundations of differential and integral calculus conceptualised (around 1687) by Newton (1643-1727) and then Leibnitz (1646-1716).

To do this, he used new mathematical concepts such as the foundations of differential and integral calculus conceptualised (around 1687) by Newton (1643-1727) and then Leibnitz (1646-1716).

From his calculations, he deduced that for small angles of heel (a few degrees of heel), the centre of the hull describes an arc of a circle whose centre is a fixed point in relation to the ship, and lies in its plane of symmetry. Bouguer called this point the metacentre (a reference still used today).

The engineers quickly deduced that when the ship is turning during a list, the centre of gravity must always be below its metacentre, otherwise the ship will roll over.

This deduction represented a major discovery, which opened up the imagination of designers to new types of ships. However, it should be remembered that this period was marked by the sinking of the Swedish warship[3] , the VASA, built between 1626 and 1628, a disaster that validated the need to study stability in navigation.

The "Vasa" is a three-masted ship 62 metres long, with an air draught of 52 metres and a beam of 11.7 metres. She displaced 1200 tonnes and carried 64 cannons. On 10 August 1628, when the ship left port for the first time, it suddenly capsized and sank in the space of a few minutes. This capsize, the first of its kind, was to precipitate scientific progress.

Le naufrage du Vasa – Peinture de Nils Stödberg

From these pivotal years onwards, naval architecture entered a truly scientific era, in the sense that it became possible to study the hydrostatic behaviour of a boat when it heels.

[3] https://experts-yachts.fr/images/STABILITE/PRESENTATION_de_la_STABILITE.pdf

A proliferation of "Treaties on the Design and Construction of Ships", mainly for war purposes, spread rapidly throughout Europe.

In France, P. Bouguer brought together in a 350-page work all the knowledge required at the time to design and build a high-performance ship.

The aim is to optimise manoeuvrability, speed and shipbuilding times... while retaining the Archimedian design


TRAITÉ DU NAVIRE, DE SA CONSTRUCTION, ET DE SES MOUVEMENS.

Par M. BOUGUER, de l'Académie Royale des Sciences, ci-devant Hydrographe du Roy au Port du Croisic & au Havre de Grace.

A PARIS, QUAY DES AUGUSTINS.

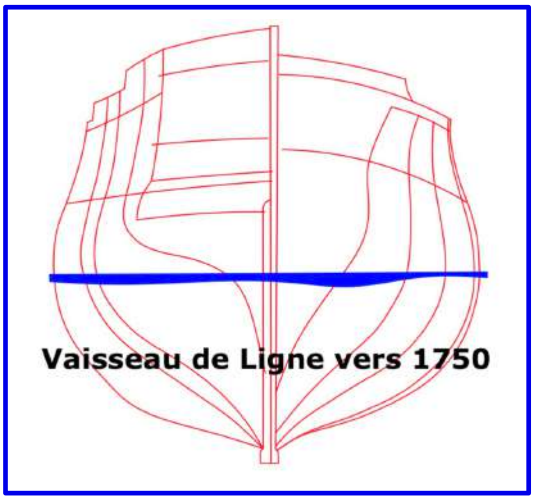
Chez JOMBERT, Libraire du Roy pour l'Artillerie & le Génie, au coin de la rue Gille-Cœur, à l'Image Notre-Dame.

M. DCC. XLVI. 1746

AVEC APPROBATION ET PRIVILEGE DU ROY.

3- We are now interested in the flow of water around the hull.

Technology (materials, propulsion and construction) and armament evolved over time, but the geometric architectural trends became standardised in the shape of a Roman amphora. A second shock occurred when scientists became interested in the flow of fluids around a moving hull.



First, the Swiss physicist Daniel Bernoulli (1700-1782) demonstrated (Bernoulli's Theorem) the principle of conservation of stored energy under certain assumptions about fluid flow.

Then the British engineer William Froude (1810/1879) proposed reliable laws concerning the resistance to forward motion that water opposes to the hulls of ships. He also presented work on predicting the stability of ships.

Then the Irish physicist and engineer Osborne Reynolds (1842/1912) theorised hydrodynamics and fluid dynamics. Although this work has expanded since the end of the 19th century, the basic principles set out at the time remain valid today.

The work of Froude and Reynolds, after that of 1600/1700, represents a second development in naval architecture research. The previous advance concerned only the scientific approach to the behaviour of the object (the boat) subjected to the external forces created by the inclining moment (sails, for example, but also the load) and its static reactions in the presence of these forces, which varied in direction and intensity. The introduction of new mathematical calculation tools enabled the designer to quantify the reactions and prevent random situations. However, the influence of the fluid and the shape of the hull were not taken into account when quantifying performance. Admittedly, designers looked at analogies with fish, but this whole area remains highly pragmatic and empirical.

Froude showed that the drag on the boat depends on the viscous resistance of the fluid and also on the resistance of the waves that the hull encounters. He first calculated the friction of the water on the hull using the following formula:

$$\mathbf{R_f = 0.5 * C_{(x)}\, \rho\, S\, V^2.}$$

(Cx: drag coefficient, ρ: water density, S: wetted surface, V: ship speed)

He then looked at wave resistance and demonstrated that this force, which runs counter to forward motion, depends on the water/air interface that develops from the bow wave to the wake at the transom.

He notes that the hull, as it moves over this horizontal body of water, hollows out this surface.

He deduced that the resistance to forward motion results from the energy required to produce this deformation of the free surface (a horizontal plane) of the water. Froude quantifies this force with the expression:

$$\mathbf{R_W = 0.5 * C_{(w)}\, \rho\, S\, V^2.}$$

(Cw: wave resistance coefficient)

The sum of these 2 opposing forces is called induced drag. There are two important parameters in both formulae: the surface area of the hull (wetted surface area) and, above all, the speed of the boat, which is expressed as the square of the hull surface area.

Froude's work shows engineers that any increase in the general geometric characteristics of a vessel, the aim of which is to gain speed and/or volume, physically generates an increase in induced drag that increases with the square of the speed, and which will be opposed to the performance we want to achieve.

This was an interesting analysis, but Froude was then faced with the problem of how to assess the speed in order to quantify the induced drag. To do this, he invented the hull basin, working on hull models built on a reduced scale. He gradually developed a technique for assessing drag using models towed in a tank. In 1871, a test centre for model ships became operational at Chelston Cross (near Dartmouth).

This first hull tank was replaced a few years later by a new 150 m long, 6 m wide and 2.75 m deep facility at Haslar (Portsmouth).

From these experiments Froude and his team deduce:

- When the boat's speed is low, the displacement of the hull generates few waves. As a result, the resistance due to the effects of waves R_w is reduced. It is the viscous resistance R_f that becomes predominant, hence the importance of having a small wetted surface and a clean, low-roughness hull.

  The Froude number (Fn) is then less than 0.4.

  The Froude number has no unit, 0.4 representing a reference.
- As speed increases, wave resistance R_w increases faster than viscous resistance R_f. The maximum wavelength of the wave is the dynamic waterline length (LFLOT). LFLOT corresponds to LWP + a percentage of the boat's slenderness. On a sailboat, LFLOT increases as soon as the boat heels due to the effect of grazing arches and slender bows. The boat then reaches its Archimedean speed limit, known as the "critical hull speed".

  The Froude number (Fn) is 0.4.

Finally, Froude shows that the dynamic waterline length represents the basis of the maximum speed achievable in the pure Archimedean regime.

Froude estimates the Archimedean critical speed by the formula:

Vc = Fn * (g*LFLOT) ^0.5 where g = 9.81 m/s^2, LFLOT in m, Fn=0.4, Vc in m/s.
Vc (m/s) = 1.25* (LFLOT)^0.5 or **Vc = 2.44* (LFLOT^0.5)** to obtain Vc in knots.

This velocity potential calculation is based on theoretical calculations of R_f and R_w, cross-checked as the model moves linearly through the hull tank. A 'balance' evaluates the forces generated by the shape of the hull during this displacement at different speeds in the tank, up to the moment when the wave formation deepens between the bow and the transom, meaning that at that moment the hull has reached its Archimedean critical speed.

Experimentation in hull tanks also enabled the heeled model to be moved. The designers of these tanks very quickly incorporated wave or swell generators. It was not until around 130 years later that CFD (Computational Fluid Dynamics) replaced (not completely) the hull tanks.

A ship of the line, a military designation from the time Louis XIV or Nelson, has a waterline length (LWL) of 55 to 65m, a displacement of 1,500 tonnes, a beam of 10 to 12m and a draught of 6 to 7m. For this type of vessel, Froude's formula gives:

Vc = 2.44 * (60) ^0.5= 18.50 knots.

This mathematical approach was not possible, because at the time, boats did not have the engine power to reach this speed.

	HERMIONE (1779)	STAR of INDIA (1863)	LE BELEM (1896)	HORST WESSEL (1936)	CLASS 40	WILD OATS XI	CLASS J (1935)
LHT Hors Tout	66.00	84.50	58.50	90.00	14.23	34.02	42.64
L Coque	44.20	65.70	51	83.50	12.19	30.48	42.64
LWL (LFLOT)	44.20	60.00	48	71.00	12.40	30.48	30.10
BAU	11.24	11.80	8.80	11.90	4.50	5.10	6.76
Tirant d'air	46.90	45.00	34.00	44.90	18.50	43.50	50.00
Tirant d'eau	5.78	6.70	3.50	5.20	3.00	5.89	4.64
DSPL	1250	1197	800	1784	4.580	28.12	174.5
S Voilure	2200	2050	1200	2065	252	1185	920
Vitesse effective	**13 Nœuds**	**14.5**	**12**	**19**	**18**	**27**	**14.5**
Vitesse critique archimédienne Vc	**16.22 Nœuds**	**18.90**	**16.90**	**21.48**	**8.60**	**13.47**	**13.40**
DSPL^(1/3)/S^0.5	**0.230**	**0.235**	**0.268**	**0.268**	0.105	0.088	0.184

The ratio DSPL^(1/3)/S^0.5 expressed in homogeneous units gives an image of the displacement (weight) per unit of wing area.

For several centuries, technologies (and above all materials) have limited the air draught of rigs and the length of yards, as well as the constraints associated with the handling of spars by sailors. Then increasing the sail area amplifies the mechanical stresses in the structure and raises the boat's centre of gravity, thus reducing its initial stability and diminishing manoeuvrability, which is a major handicap in a naval battle.

It's interesting to see that the CLASS J ratio (1935s) is quite high. These CLASS Js were designed to be very stable in weight. This configuration gave them gigantic sail surfaces thanks to a steel mast.

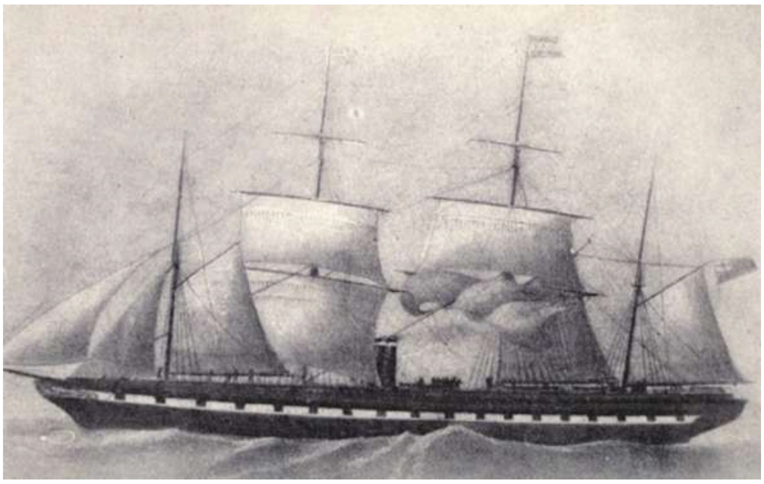
This means they can exceed their critical speed, something that was technologically out of reach for 3- or 4-masted boats.

The ratio DSPL^(1/3)/S^0.5 (in homogeneous units) expresses the load in tonnes per m2 specific to each boat.

4- The race for maritime gigantism is on

Towards the middle of the 19th century, the steam engine, followed by the adoption of the propeller, transformed the maritime landscape.

In 1845, the Great Britain had an iron hull and was propelled not by sails or paddlewheels but by a propeller. She was 98 metres long with a beam of 15.5 metres and could displace 3,500 tonnes, carrying 360 passengers and 130 crew and loading 1,100 tonnes of coal. Her engine has 4 V-cylinders and develops 1,600 hp



In July of the year it was launched, it arrived in New York (Lizard Point / New York 2900 miles) after less than fifteen days at sea (averaging around 9 knots).

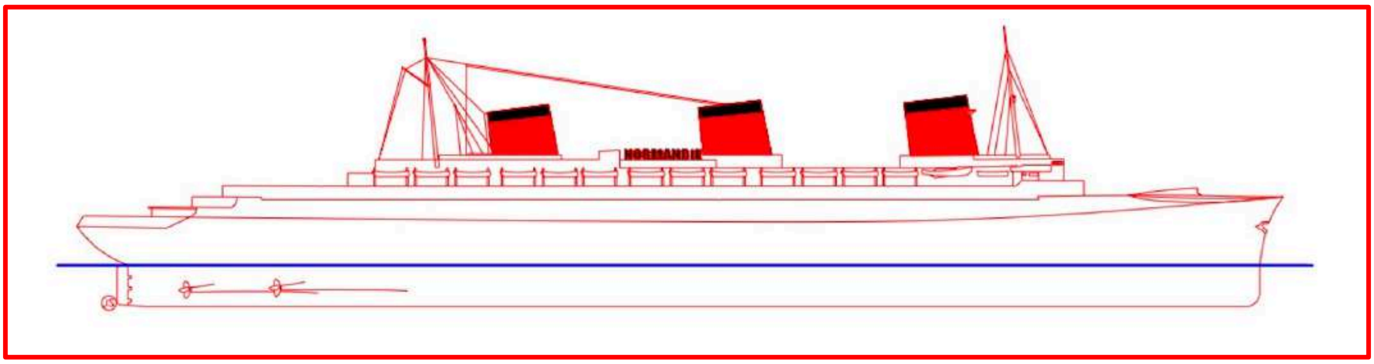
Applying the work of W. Froude, it has a hull speed of almost 24 knots. We can therefore see that the architects favoured regularity over performance in terms of speed, but they were restricted by the amount of coal they could carry (excessive consumption when speed increased), which was limited if they wanted to maintain a net tonnage that was economically favourable (maximum cargo and passengers).

Until the 1960s, research focused solely on improving the performance (speed and armament) of warships and merchant ships (tonnage on board).

The large ocean-going commercial sailing ships (4-masted or 3-masted barque) disappeared within 40 years, not because of the arrival of steam ships, but because of the introduction of diesel engines, which were more compact and, above all, more fuel-efficient.

This race for gigantism and speed is illustrated in particular by ocean liners (the famous Blue Ribbon). It began in 1836, and was codified at the beginning of the 20th century on the Europe/USA route. The principals became, more or less directly, the States, including Germany, France, Great Britain, the USA and Italy, which thus displayed their political, technological and economic power

France won the trophy twice with the Normandie.
Length 313.75 m Beam 36.40m LFLOT 300m Draught 11.20m DSPL 70100 T
Power 160000 CV
Maximum speed 32 knots



The crossing (2900 miles) of the "Great Britain" in 14.5 days in 1836 was reduced to 4 D 3H at an average speed of 29.32 knots for the "Normandie" in 1935.

The average speed has increased from 8.4 knots to 29.32, a gain of 350%! Displacement has increased by 2000% and power by 10,000%, for a vessel that is 3 times longer (98 to 313 m).

It should be noted that the application of W. Froude's formula predicts an Archimedian critical speed of 42.2 knots for the "Normandie".

This technological aside is intended to show that the history of techniques linked to mobility always converges towards an asymptote and is materialised by a stabilisation, particularly of speed, which only a change of paradigm can alter. Crossing the Atlantic in ocean liners will come to an end with the arrival of four-engined subsonic jet aircraft. The transition to supersonic commercial flight would suggest that a new development, supported by the States, was underway. However, the economic and, above all, ecological impact of supersonic flight destroyed this idea.

5- The idea of a sailing regatta is born

The first regattas between sailing boats took place in 1835, first in the South of England and then in 1838 with the creation of the "Sté des Régates du Havre". The first America Cup Challenge took place in Cowes in 1851.

However, fleets remain small. In terms of architecture, architects in Europe are focusing on weight stability, while in the USA, designs are geared towards shape stability, often with drifts, due to the environment of the East Coast bays.

During the 1835 / Ww2 period, although the length and displacement of pleasure boats (regattas) increased, the general trend was towards heavy, narrow, over-canopied boats. It would take more than 30 years for sail area to be taxed in the measurement formulas. Construction techniques were limited to jointed planking caulked to the frames and keel parts. Only boats like the J-Class used steel and aluminium alloy for certain parts. But whatever the architectural trend, the displacement of boats remains imposing.

In 1928, the British architect Uffa Fox (1898-1972) disrupted this intellectual atmosphere by designing small dinghies that glided and sailed at a speed greater than the Archimedean critical speed (Vc) laid down by W. Froude.

The general idea is to design a hull that is wide at the waterline and shallow, without overloading it with sail area.

6- How does the transition from Archimedian mode to planning mode come about?

We need to start again from hydrostatic logic. When the boat is stationary, buoyancy is the only force that keeps it afloat. It naturally balances the boat's weight.

At low speed, the Archimedes' thrust exerted on the hull decreases because the surface of the hull, as it moves forward, produces a buoyant force that lifts the boat. As a result, its volume under water decreases.

As speed increases, lift increases and, as a corollary, buoyancy continues to decrease. However, the drag generated by the shape of the hull also increases.

Above a certain speed, which varies according to hull shape (the vast majority of hulls never experience this bliss), the boat is in a planning situation.

At this point, the buoyant force (vertical) can represent up to 60 to 70% of the initial Archimedean thrust (weight of the boat). The boat no longer "floats", but moves on the surface of the water: it is level.

During the boat's acceleration phase, wave resistance increases and reaches its maximum just before the hydrostatic phenomenon known as planning is triggered. At this point, the physical resistance to forward motion decreases considerably.

This transition requires a peak of energy so that the boat can ride its bow wave and set off on the plan, i.e. in permanent overspeed as long as the wind conditions remain relatively stable.

But viscous resistance, the result of friction between the water and the surface of the hull, increases with the square of the speed (**R_f** = $0.5 * C_{(x)\,\rho} S V^2$), which explains why, even though the boat is gliding, i.e. above its critical hull speed, it cannot continue to accelerate indefinitely... Unless it is supported vertically by other appendages and its hull rises out of the water. This represents another area of displacement, but not an Archimedean one!

7- Quel est l'ordre de grandeur de la vitesse en mode planning ?

In established planning mode, the Froude number (Fn) is of the order of 0.65**.**

The theoretical critical speed in this mode then becomes:

Vpla = 3.96 (LFLOT^0.5) to obtain Vpla in nodes.

Or Vpla (m/s) = 2.04 * (LFLOT^0.5)

Key figures:

LFLOT= 10 m	Vpla= 12.52 nds	LFLOT= 12 m	Vpla= 13.72 kts
LFLOT= 18 m	Vpla= 16.80 kts	LFLOT= 30m	Vpla= 21.69 kts

Although this approach is scientific, it remains theoretical. The results obtained with this formula only express orders of magnitude, because the transposition into reality depends essentially on the shape of each hull, the evolution of the position of the hull centre, the loading trim (longitudinal and transverse position of the centre of gravity) and the centre of sail. All these parameters influence a boat's ability to glide.

This field was not really conceptualised until several decades after Uffa Fox's initiative. One of the reasons for this, and perhaps the main reason, was the construction technologies used and materials available before the middle of [the] 20th century to build hulls that were relatively light and therefore had little displacement.

8- Speed becomes the target

Whatever the field, military or commercial, since the dawn of time, and more recently in regattas, increasing speed has been the objective of designers. Gaining a few tenths of a knot over the competitor or opponent requires more power and more technology, while taking scientific research into account.

However, the ratios of speed gains to fuel consumption, range and weight increases quickly became unprofitable, both technically and economically. The improvements made by the architects inevitably came up against the drag created by the viscous resistance of the fluid (seawater) and the waves in which the hull was moving.

Then, at the very beginning of the 20th century, we discovered how to fly with a motorised device called an aeroplane, which immediately gave some people ideas.

9- The boom in engines.

From the early 1800s, inventors such as the American Fulton designed innovative steam engines to replace the slow and bulky reciprocating piston system.

They use steam injection onto the blades of a circular wheel (a turbine). The system is compact and efficient, but has a major disadvantage in that its rotation speed is high, difficult to adjust and reversible.

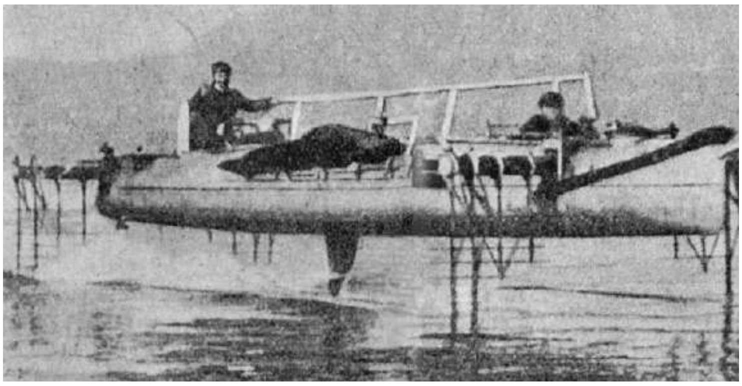
In those days, steam engines could turn in either direction, so it was possible to sail in MAV or MAR.

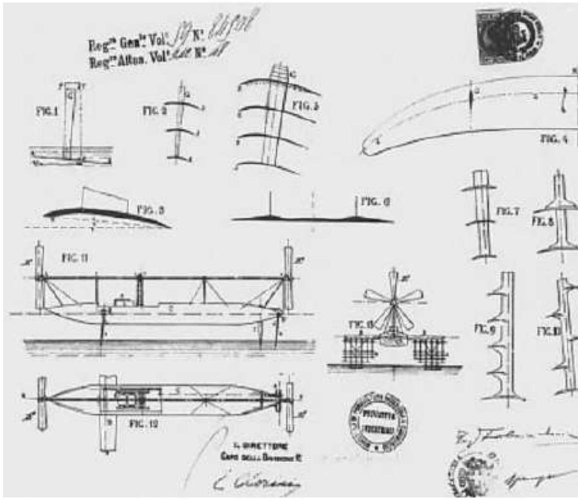
Given the difficulty of manufacturing reliable gearboxes and inverters, it took several decades for the turbine to become established on ships. Solutions came in the form of new materials such as steel, which only became available from 1855, and industrial aluminium from around 1880.

However, some groups of engineers or self-taught people set about the idea of increasing the speed of boats by applying the work and research of other colleagues whose aim was to create an aeroplane and fly, which amounted to "landing" the boat on wings immersed in water. They realised that the density of water was 800 times greater than that of air, making the gamble feasible.

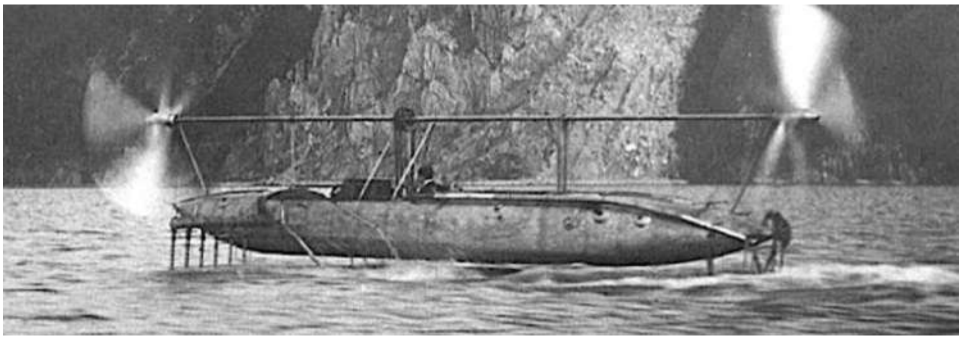
One of the most famous achievements of this period was that of the Italian engineer Forlanini in 1910

The drawing below shows a transformation of the original version of the foiler, which uses a submerged propeller, replacing it with two aerial propellers, one tractive and one propulsive.





Versions hélice immergée et hélices aériennes



10- The birth of the technique of aeroplane flight.

The desire to fly takes us back to Icarus when he escaped from the labyrinth in which he was trapped. But his dreams of grandeur were to prove fatal, as the sun melted the wax that held together the sails made of bird feathers.

Flight began with a few jumps around 1890, by the "bat", christened "Éole", then "Avion" by Clément Ader.

In fact, in the technological environment of the 1st (era) of the industrial revolution, the idea of flying was still on the minds of many scientists and engineers. A great deal of research was being carried out in Europe and the USA on the design of a machine capable of taking off and moving through the air.

Among others, the Englishman George Cayley (1773-1857) described the phases to be explored in order to fly, i.e. propulsion, drag, lift and its corollary, stall. He also understood that the wing plan had to be fixed and should not reproduce the flight mechanics of birds.

Finally, he saw the need to design a tailplane to stabilise flight horizontally. Other researchers took up his work and conceptualised it, but came up against a major difficulty called motorisation (propulsion).

Around 1850/60, the petrol engine, which had just been finalised, was seriously unreliable. Only the widely available steam engine was available, but this mechanical unit, even miniaturised, posed an insurmountable weight problem for installation on an aircraft, especially as these steam engines ran on coal. Frankly, it's not practical on an aircraft.

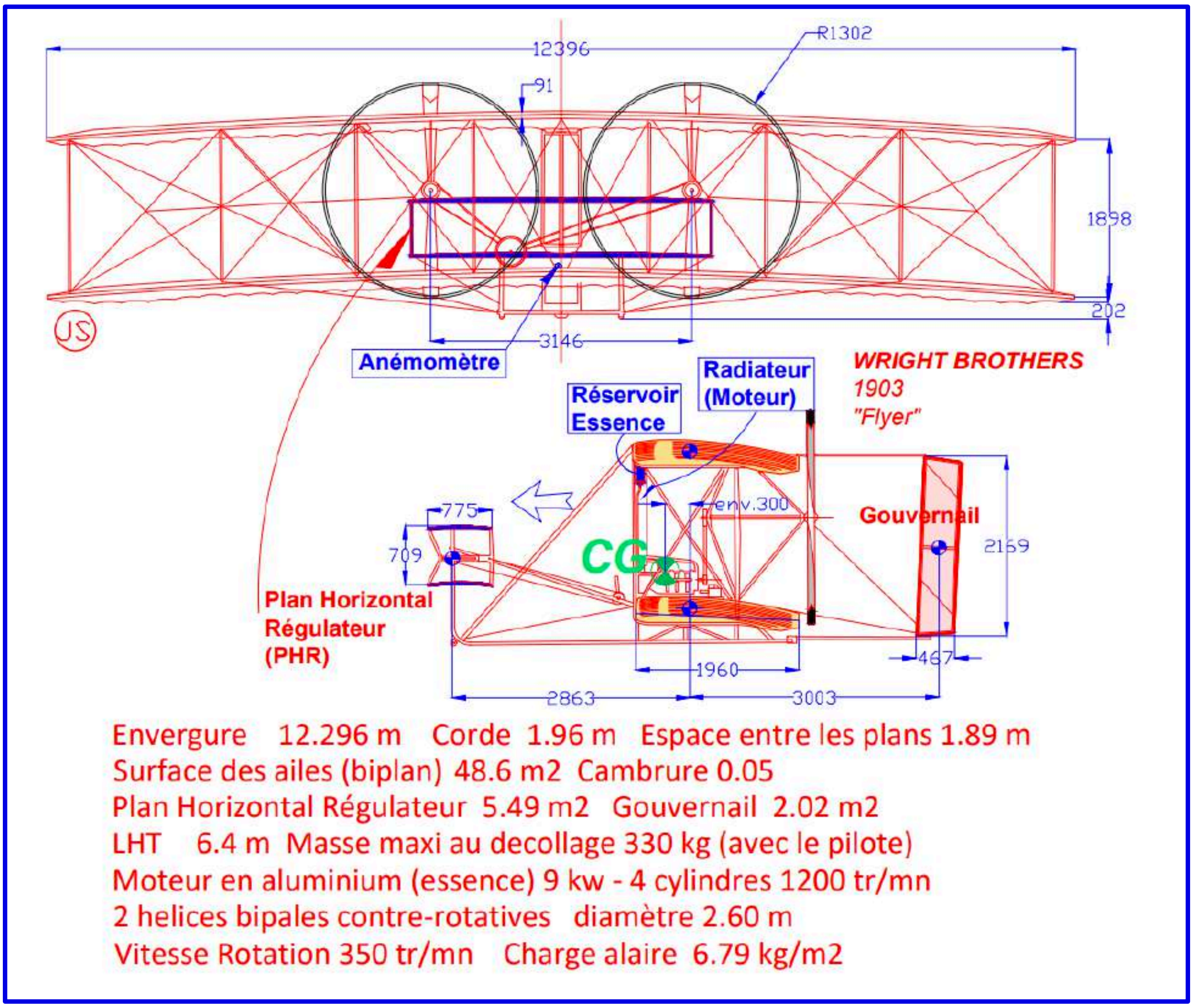
In the USA, after many tests, particularly on model or real gliders, the Wright brothers, great observers of the flight of birds when they glide, understood that flying, i.e. creating vertical lift greater than the weight of the aircraft, was only part of the problem.

The other part concerns flight control, which breaks down into 3 degrees of freedom (rotations): roll, pitch and yaw. This work by the Wright brothers represents their greatest contribution to the mastery of flight and actually makes it possible to fly.

Lift alone does not allow you to choose your route. An aircraft will only exist when it is capable of taking off from point A and returning to the same point after a flight.

The Wright brothers designed a single-engine, twin-propeller petrol plane in which the wings (lift) were fitted with a mechanical system that, by twisting the tips of the wings using a set of cables, made it possible to control the difference in lift of each wing in the airflow. This instability creates the roll. This feature is known as wing warp.

The Wright brothers designed a single-engine, twin-propeller petrol plane in which the wings (lift) were fitted with a mechanical system which, by twisting the tips of the wings using a set of cables, made it possible to control the difference in lift of each wing in the airflow. This instability creates the roll. This feature is known as wing warp.



But the major contribution of the Wright brothers was the addition of two parallel double appendages

1) The vertical rudder, located at the stern, controls yaw and is used to steer the boat on course. This is inspired by the rudder invented by sailors.
2) Above all, they install a lift (Horizontal Control Plane) at the front.

The role of this lift is to control pitching by applying a nose-up or nose-down action.

Some five years after their first flight, the Wright brothers combined the vertical control and the horizontal lift at the rear.

The year was 1903, and this configuration still corresponds to the architecture (PHR + vertical rudder) of today's aircraft, although there are a few V-shaped variants of the tailplane, which do not call into question the principle of yaw and pitch control.

The Wright brothers' plane is interesting to analyse:

Firstly, it has a biplane wing, which, although less aerodynamically efficient than a monoplane model, is above all easier to manage mechanically. In fact, 48.6 m^2 in a biplane is equivalent to around 35 m^2 in a monoplane. To fly, this aircraft must produce a lifting force equal to its weight at take-off, i.e. with the pilot and full tanks of fuel and water (engine cooling), i.e. 330 kg * 9.81 = 3237 Newtons (9.81 represents the acceleration of gravity).

This value represents Fz we need to reach to fly.

$$\mathbf{Fz = ½*\rho *V^2*S*Cz}$$

In this **Fz** formula, only two parameters were unknown to the Wright brothers.

This is the available take-off speed **V, i**.e. effectively produced by the propulsion of the 2 propellers and the lift coefficient of the biplane wing **Cz.**

At the time, knowledge of the efficiency of aerial propellers was still unknown. Fixed-point traction tests had not yet been carried out.

The Wright brothers designed and built two twisted two-bladed propellers made of glued wooden slats. They turned at 350 rpm (36.6 rpm) in opposite directions to avoid the effect of gyrating torque.

Their diameters of almost 2.6 m, combined with a narrow chord width of around 0.146 m, ensure high aerodynamic elongation (AR around 8.5), which improves traction performance.

As far as the lift coefficient of the wing was concerned, once again it was completely unclear, and no studies had been carried out. The very observant Wright brothers drew inspiration from kites and their tests on a few prototype biplane gliders of their own making. They opted for very cambered wing profiles, which in fact had a high low-speed lift of around 0.7.

This corresponds to a take-off speed of around:

V^2 **= Fz /(½*ρ *S*Cz) =** 3237/(0.5*1.292*0.7*48.6) = 147 and V= 12 m/s (43km/h)

43 Km/h is the wind speed required to take off ....

Aware that the power of the engine (9kW), coupled with the 2 propellers, did not produce enough propulsion to achieve the speed of 43km/h, the Wright brothers installed the plane on a wooden inclined surface (well-greased) some twenty metres long, angled at around 8 or 10°.

With the engine at full throttle and the thrust of muscular arms, at the end of the glide the aircraft has enough wind speed to take off.

The first attempts produced chip jumps, 37m at a speed of 11 km/h or 3m/s, then 284 m in 59 seconds or still only 4.89 m/s or 18 km/h. We're still a long way from the 17 m/s needed to obtain 3237 Newtons of lift and thus stabilised flight. "The plane is behaving more like a glider attempting to take off.

In fact, the aircraft proved to be fairly unstable in roll during take-off, although the pilot, lying on a platform in the lower wing, had a system that allowed him to move sideways, but the reaction time was not enough to control the roll.

The Wright brothers, decidedly inventive, installed an asymmetric[4] manual warping mechanism at the ends of the upper wing. This system could be adjusted in flight.

By dint of tests and breakages, they rebuilt a 3rd prototype, with increased surfaces for the control elements (rudder and PHR), better performance in the design of the propellers and a slight lightening of the aircraft. All this work enabled them to complete a 38km flight in 39 minutes, reaching a speed of 58.5 km/h (16.23 m/s).

The accuracy of flight time measurements, like that of the number of kilometres flown, remains open to question, but the fact remains... we take off, we fly and we land. Let's not quibble: in 1905, two years after their first attempt, the Wright brothers laid the technical foundations that would be applied to future generations of subsonic aircraft.

It is interesting to note that with their inclined take-off aid, the Wright brothers inaugurated the catapult[5] ...

11- From air to sea

Immediately after the Wright brothers' success, the enthusiasm for aviation spread instantly across Europe and of course to the USA, where the Wright brothers toured Europe to present their plane. As early as 1860, some people were already thinking of replacing air with water, in order to obtain a motorised boat that could be lifted entirely out of the water, free from the constraints associated with this fluid (drag resulting from viscous resistance and waves).

[4] This system still exists on aircraft.

[5] They improved on this system by creating the weight catapult. A 700kg mass was dropped from a height of around ten metres. It was connected by a cable and propelled the plane...

At the beginning of the 20th century, scientific work on aircraft wings (airfoils, aspect ratios), and therefore on lift, began to develop. We know that the lift of a wing is proportional to its wing area projected horizontally and to the square of its speed of travel[6].

The lift applied to a wing immersed in water (a 'foil') also depends on the density of seawater (1025 kg/m^3), which is 793 times greater than that of air (1,292 kg/m$^{3)}$ at an altitude of around twenty metres.

Fz = ½* *V²*S*Czρ

Fz: lift (in Newton), ρ density of the fluid (in kg/m$^{3)}$, V: speed (in m/s) S: reference surface area (m²) Cz: unit coefficient of lift

Applied, for example, to a 2000 kg boat and assuming a C_Z of 0.3 (average value), we obtain the product **(V²) * S** as follows:

(V²) * S = Fz /½*ρ * Cz

(V²) * S = (2000*9.81) / (0.5*1025*0.3) = 19620 / 153.75 = 127.61

A motorised hydrofoil, designed with an active foil area of 2.08 m^2 (i.e. 2 foils of 2.6m * 0.4m) takes off at a speed of 15.21 knots

V = (127.61 / 2.08)$^{\mathbf{0.5}}$ = 7.83 m/s

If the designer decides to take off at 18 knots, i.e. +20%, (9.26 m/s), the surface area of the foils required for take-off drops to 1.48 m^2 (-30%), i.e. 2 foils of approximately 1.86m * 0.4m.

12- But first take off

The main difficulty for a boat will be to reach a speed that generates enough lift to lift the hull out of the water, without having to resort to excessive active foil surfaces. Unlike an aircraft, a vessel changes its conceptual environment between the moment when it floats (it is then "Archimedean") and the moment when it flies supported by its foils and its hull no longer touches the water (it is then in hydrodynamic lift). For a motorised vessel, it's almost too simple. All you need is a propulsion speed, and therefore power (engine + propeller), so that the active surface, combined with a suitable foil profile, generates an upward force (lift) equal to the boat's mass.

See the calculation above.

Under these conditions, the hull no longer has an "Archimedian" function, it serves only as a "container" (passengers, engine, fuel, etc.).

[6] The shape of the profile, the environment and the incidence also have an influence.

13- Then maintain stabilised flight

In flight, the boat behaves like an aeroplane, "carried by its foils (lifting surfaces)". No longer subject to the constraints of the hull passing through the water, its speed increases. But since hydrostatic laws no longer apply, there is no longer a centre of buoyancy (CB), so there is no longer a restoring torque defined by the product of "Ship's weight X horizontal distance between CG and CB", the torque that ensures a ship's stability.

Balance in flight depends on the action of 3 forces: the weight applied at the centre of gravity (CG), the lift at the aerodynamic centre of the foils (CP), and the thrust from the propeller or the centre of gravity for a sailboat (CV).

The difficulty lies in the interaction between these 3 forces, as the speed at which a sailboat is moving fluctuates at any given moment depending on the strength and direction of the wind. This dependence appears to be the main factor causing imbalance, since the lift generated by the foil is based on the boat's speed and its angle of incidence in relation to the fluid.

This permanent imbalance means that flight parameters have to be continuously adjusted over time.

The horizontal plane (PHR) does not have a lifting function. It can be "load-bearing", with the lift directed upwards, or "weight-bearing", with the lift directed downwards. Its role is to stabilise the platform in pitch and thus adapt the (longitudinal) balance within the limits of variations in lift and vellic force.

14- The state of the art in foiler design

Before going into the state of the art of ocean foil navigation, it should be noted that since the dawn of time, increasing the speed of ships has been the objective of scientists, engineers, naval architects and navigators. Admittedly, the increase in displacement continues, but the laws of physics stabilise this increase, whether in the commercial or military sector. A major reason for this self-limitation is the interaction between linear measurements, cubic volumes and squared surfaces.

To illustrate these relationships, let's take a cube with a side of 1 metre. If we multiply each edge by 3, we get a cube with a side of 3 m, and the volume increases from 1m^3 to (3X3X3), i.e. 27 m^3.

The volume scale factor becomes 27. Filled with water, a 1 m cube has a mass of 1,000 kg. The 3m cube has a mass of 27,000 kg (27 tonnes)! In terms of surface area, the 1 m cube has a developed surface area of 6 m^2, while the 3 m cube has a developed surface area of 54 m^2 (scale factor 9).

Changes in these factors of scale mean, among other things, an increase in the power required and, as a corollary, an increase in the volume of fuel carried.

Of course, motorised foilers have been widely developed, notably by the military in the form of prototypes and in the commercial sector for passenger transport (some are still in operation).

Many of us remember the 'Condor' foilers, in service between 1964 and 1993, sailing from Saint-Malo to Jersey, Guernsey and Weymouth (31m X 12.6mX 3.7m, 2 V12 engines of 1400 kW each, Speed 30 Knots, Consumption 600 L/Hour).

A Brest / Ushant link with a Soviet hydrofoil "Kometa" existed between 1970 and 76, then the ship was stored on the quayside of the commercial port of Brest to end up at the ship cemetery in Landevennec where it was deconstructed in 2010.

Another initiative in 1979, which linked Dieppe to Brighton in 2 hours, with a foiler developed by Boeing, quickly ran out of steam[7] . The main enemies of these types of vessels are the mini wrecks lying around at sea, and even fishing nets and traps that are difficult to identify when sailing at 15m/s or 30 knots.

Even the Southampton Cowes route with the Shearwater foilers, well known to Solent sailors, was discontinued in 1992 due to a lack of profitability, and the shipowner reverted to Archimedean catamarans.

The search for speed turned to air-cushion vessels, such as Hovercraft or Naviplane. The adventure spanned some fifteen years. While the carrying capacity was significant, the speed achieved - 50 to 60 knots, greater than that of foilers - required diabolical power, since the vessel had to be supported (vertical fans) and translated (aerial propeller) at the same time.

7 Two years of operations

The "Jean Bertin", 50m X 23 m, 2300 kW consumes 5 tonnes of paraffin per hour. The end of tax-free paraffin and the end of subsidies will almost certainly doom these types of vessels.

The British still operate a Hovercraft service between Portsmouth and Ryde (Isle of Wight). Having used it several times, the link is certainly fast (15 minutes) but the craft is relatively spartan (70 passengers), very noisy and smelly (paraffin).

In fact, the engineers of these Hovercraft have to reconcile the lightest possible powered and equipped platform, in order to support it using a minimum of energy and floor space, while offering a maximum number of passenger seats to optimise its performance on each trip.

This equation quickly turns into a nightmare.

Gliding...

In offshore regattas, which are of particular interest to us, the evolution and technical management of offshore multihulls is taking place very slowly, although the architects and engineers are quickly up to speed with the theoretical state of the art.

For example, in 1995-2005, Alain Thebault's Hydroptère really flew in a stable horizontal attitude. Admittedly, it accumulated speed records over very short distances, but it lacked reliability.

Its design and development focused on the technologies needed to fly, and this was successful. But at the same time, no thought was given to adapting it to ocean navigation, with all its inherent constraints.

The surprise launch of the AC75 in 2017 (monohull foiler for the America's Cup), revived the idea of a full ocean foiler.

Many predict that this foiling technology will become the alpha and omega of ocean racing in the years to come. The reality is still in its infancy.

Before describing the physical phenomena linked to the lift of a lifting surface circulating in the water (the foil), let's look at how the stabilised flight of a sailing foiler is achieved and also what difference there is between the flight and the Archimedean environment, even when a boat is sailing to plan

15- The balance in stabilised flight of a winged foiler (The Moth)

As soon as you mention foils on a sailboat, you start dreaming of a hull levitating above the waves ...

Down to the smallest scale factor, the study of navigation in a Moth[8] provides a clear picture of all the constraints that need to be managed in order to control the flight.

In Archimedean mode, the stability of a sailboat is expressed by the balance between a positive righting moment which opposes the heel produced by the swaying moment. This torque is expressed by the combined action of the boat's weight multiplied by the horizontal lateral distance between the CG (boat's centre of gravity) and the CB (hull centre).

This process is automatic, in the sense that the crew doesn't have to do anything to ensure that the balance between these two torques is maintained. We can also see that the boat's balance poses no problem when an autopilot is engaged, even though it acts exclusively on the heading.

If the autopilot is unable to control the boat's trajectory, the laws of hydrostatics will always bring[9] the boat back to a 0° (heel).

As we have already stated, the laws of hydrostatics no longer apply to a Moth, as no part of the hull touches the water after take-off.

A foiler in full flight becomes a platform (hull + structure) on which a helmsman sits.

Two symmetrical wings (foils) at the ends of the centreboard support this platform above the water. In order for the lift to remain integral and above all stable, the lift generated by these foils must be permanently equal to the weight of the platform + helmsman + mast + sail. However, this condition (two opposing forces: lift vs weight) is not enough to ensure the Moth's balance above the water. The final equilibrium must necessarily include the buoyancy of the sail.

---

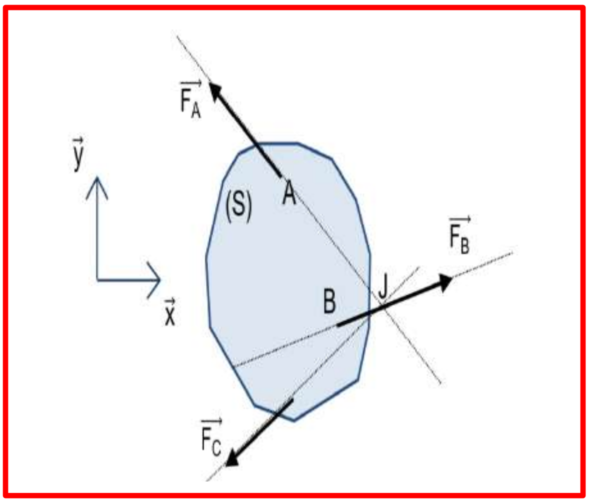
[8] The idea of flying a Moth was born in Brisbane, Australia, in 1972. The Moth is a single-handed dinghy created in 1928 in the USA. Its architecture is based on a restricted measurement formula.

[9] In this demonstration I exclude the hypothesis that the capsize angle is reached (Avs), which would result in negative stability and the obligatory capsize of the boat.

There are 3 forces in space:

- The weight of the platform + helmsman + mast + sail.
- The lift created by lifting surfaces (foils)
- The vein thrust.

The fundamental principle of statics[10] is as follows:
For a solid body to be in equilibrium in space, it must :



- ➢ That the vector sum of the forces is zero.
- ➢ That the sum of the moments of each of the forces with respect to any point in space is equal to zero.

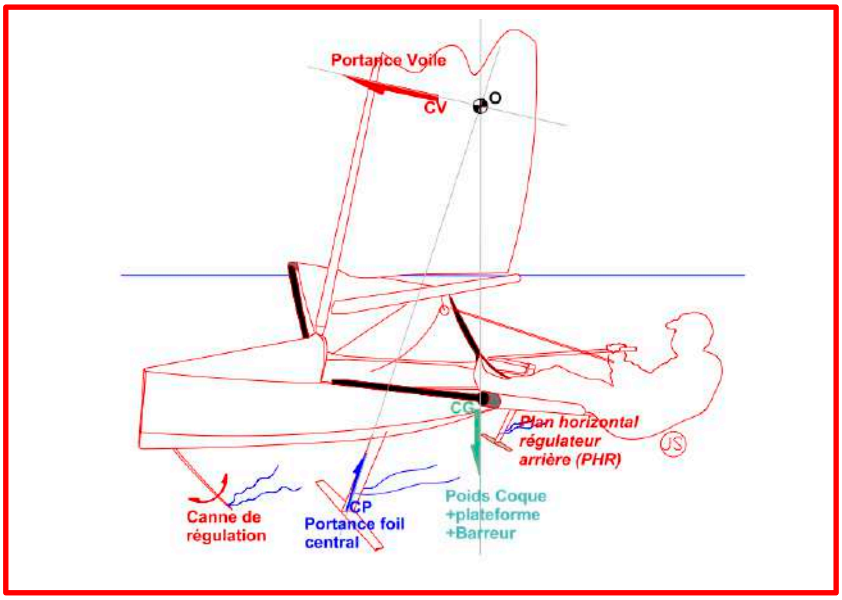
But this situation of perfect equilibrium which combines these 3 forces can only exist very temporarily, because beyond a few tenths of a second (at 30 knots the foiler travels 15 metres per second), at least one of the parameters defining any force changes and destroys this precarious condition of equilibrium.

[10] The field of statics considers that the mechanical elements studied are undeformable and immobile. In addition to statics, there are the fields of dynamics, strength of materials, hydrostatics, etc...

Analysis of each of the three forces:

- <u>The weight (P) of the platform + helmsman + mast + sail.</u>
  The intensity of the weight (expressed in Newtons) of the platform + helmsman + mast + sail is constant.
  The direction of this force is vertical and downwards.
  The CG position corresponds to the barycentre between the CGs of the platform, mast, boom, sail and helmsman.
  The helmsman's position is constantly changing, as are the heel, trim and orientation of the sail. This results in spatial variability in the final position of the CG.

- <u>The lift of the central lifting surface (Foil)</u>
  The amount of lift depends on a number of parameters, including the unit coefficient of lift (C_z), the foil profile, its surface area, its incidence and the speed of the foiler.



  - For example, for a NACA 64-12 profile (common for these types of foils) the C_z varies from 0.4 for 4° incidence to 1.42 for 14° (Cz is a number without unit).

  - <u>Speed</u>
    A Moth foiler sails in flight mode at between 10 and 25/28 knots, but remains sensitive on its trajectory to variations in true wind speed (light or heavy air). This instantly results in the boat slowing down or accelerating. For example, an effective drop in the Moth's instantaneous speed from 14 to 13.5 knots will cause a 7.02% drop in lift (calculated on the square of the speed variations).

    Based on 30 kg for the boat and 80 kg for the helmsman, i.e. 110 kg, a lift of 110*9.81 / COS (10° heel) = 1095 Newtons is required to fly.

    A drop in lift to 1000 Newtons (influence of -7.02%), which corresponds to a 3.57% drop in boat speed, will make the foiler's balance very precarious.

But the decrease or increase in speed has an impact on the unit coefficient of lift C_z**.** A drop from 1.2 to 1.0 in C_z (a 16% fall) causes a fall in lift to 833 Newtons. This shows that speed regulation is becoming essential for flying.

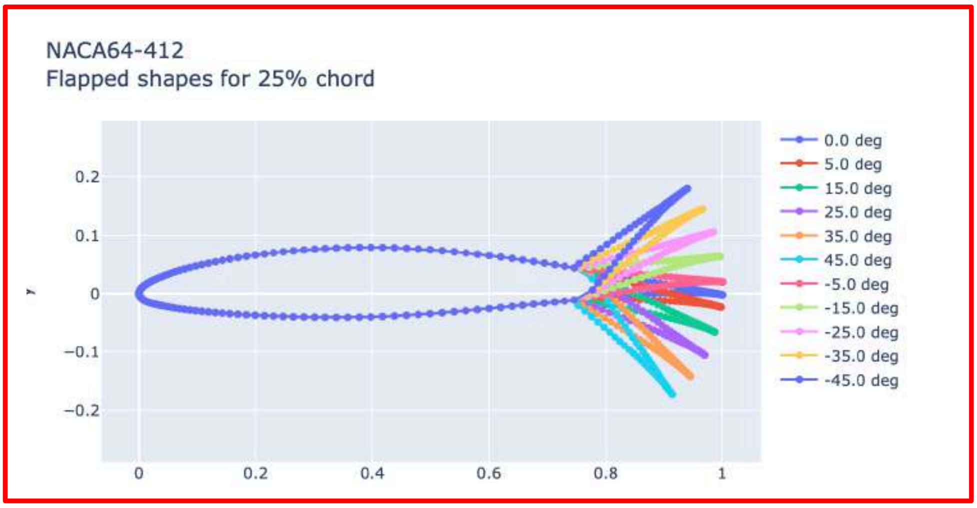
- The foil

  It is located perpendicular to the end of the centreboard. In flight, the helmsman controls the heel by shifting his weight, but the Moth is never perfectly vertical.

  It can even sail against the wind. In all cases, the lift created by the foil follows the angle of heel, which means that the C_z (unit coefficient of lift) has to be increased in order obtain permanent lift equal to P/cos(heel).

  As the trim also plays a role, the thrust of the foil must be

  P/ (cos(heel)*cos(trim)).



A movable trailing edge flap fitted to the foil bends its transverse profile and increases the value of Cz. Lift then increases with the angulation of the trailing edge flap, up to a certain limit set by the onset of profile cavitation. This causes the foil to stall.

However, in flight mode, the platform's range of movement around the foil's 'centre' must remain within a cone with an angle of 25 to 30° at the apex, so that the helmsman retains control of the foiler

- The sail thrust.

  Its intensity depends on the apparent wind speed, the true wind and the heading, and implicitly on the sail trim. The heel and trim (pitch angle) of the boat interfere with the spatial position of the sail force.

So, the flight equation:Σ (of the 3 external forces =0) appears complex to satisfy permanently, given the instability of the parameters relating to each of these forces. Continuous regulation is therefore required to achieve stabilised flight.

16. Control systems for hydrofoil Moths

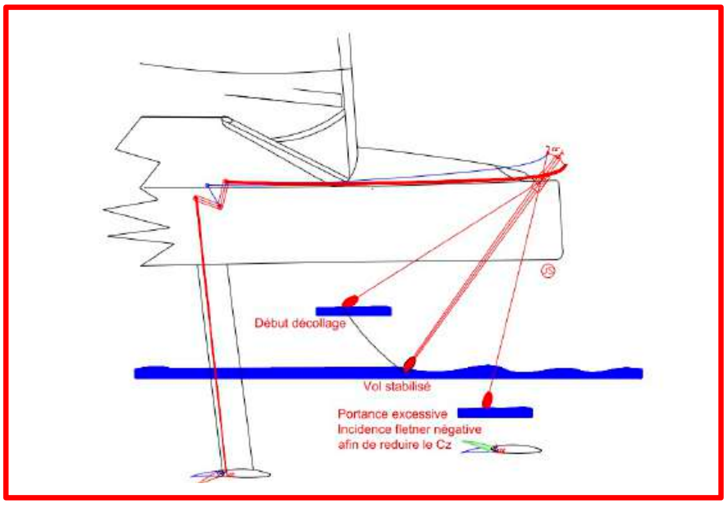
A Moth foiler has 3 control systems:

- A fully autonomous sensor system, connected to the flap on the trailing edge of the foil, which ensures a permanent balance between the lift produced by the central foil and the weight of the foiler.
- An aft lift controlled by the helmsman and fitted to the rudder (also known as PHR for Plan Horizontal Regulator). It is used to control the positive or negative trim of the foiler.
- The helmsman's actions on the yaw (rudder), the power of the sail and the spatial position of the foil's centre of gravity.

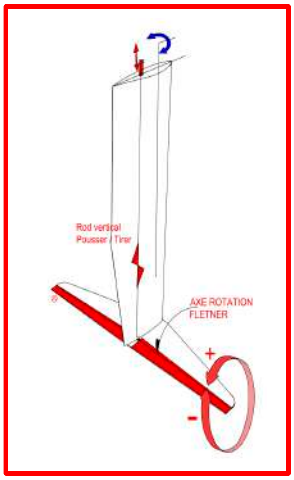
The sensor system that adjusts the lift of the central foil

It consists of a pivoting rod whose centre of rotation is located on the bow at deck level.

At the end of this rod is a spoon or float (as big as an egg) which, when it comes into contact with the water, produces a hydrostatic thrust upwards or falls back under gravity. The torque produced is used to drive the trailing edge flap of the central foil.



The rotation of the rod moves horizontally on a rod which, by means of a 90° angle transmission, pushes or pulls a vertical rod located in the rear part of the daggerboard in order to operate the foil's trailing edge flap.



The angulation of the flap increases or decreases the value of the unit coefficient of lift (Cz) of the foil profile.

Schematically 3 cases occur:

- During take-off, the flap is highly angled, which increases the Cz to its maximum value.
- In stabilised flight, the flap is such that the profile is superimposed on the NACA base profile.
- In the event of overpower, the incidence of the flap becomes negative in order to prevent the foil from breaking the surface of the water. This causes cavitation on the upper surface and a loss of lift, resulting in a reduction in flight altitude.

This regulation system is perfectly continuous and requires no energy input apart from the drag of the spoon or egg in the water generated by the movement of the boat and that of universal gravity.

An aft lift at the end of the rudder blade

The rudder is located on a tubular 'pylon' assembled on the transom.

The PHR is located at the lower end of the rudder. To situate the foil assembly on the daggerboard and the PHR on the rudder, the respective draughts in Archimedean mode are 1.10m and 0.95m. The flight altitude fluctuates around 0.80m / DWL in Archimedean mode.

The PHR must be lower than the central foil so that it does not move in the disturbed wake of the central foil.

The PHR profile is symmetrical. Its function is to control pitch and therefore flight trim. As a result, its angle of incidence can be positive or negative in relation to the horizontal plane. This means that the PHR is either weight-bearing (it raises the stern of the boat and causes it to pitch down) or weight-reducing (it lowers the stern and pitches the boat up).

Under no circumstances does it contribute to the boat's overall lift, which is provided solely by the central foil controlled by the control rod.

Installation on a pylon (offset backwards by around 0.5m) reduces the active surface of the PHR.

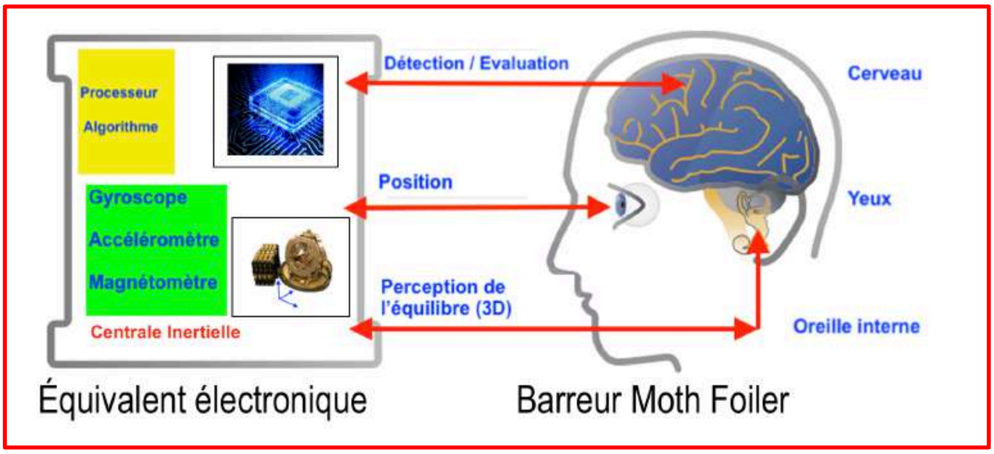
The nose-up or nose-down action resulting from the torque produced by the lift or offset of the PHR is linked to its horizontal distance from the central foil (hinge focus).

The helmsman's actions.

On a Moth foiler, the helmsman has a stick with 2 functions:

- ✓ The stick itself, which steers the rudder and controls the yaw.
- ✓ A rotating handle at the end of the stick that adjusts the angle of the PHR.
- ✓ It also controls the canopy setting, and therefore the power available and required.
- ✓ Finally, it manages the spatial position of the boat's centre of gravity in flight.

The manual piloting of a full foiler calls on cognitive functions (brain, inner ear, eyes, buttocks, muscles) that enable it to be in constant interaction with the environment and the immediate situations that arise.



It perceives, concentrates, acquires and processes dozens of pieces of information per second (heel, pitch, pressure, slack, noise, risk of collision, obstacles, etc.) and interacts to maintain the dynamic balance necessary for stable flight.

On a Moth, the human system does not need electronic aids to manage a flight.

In the end, the helmsman is almost a perfect inertial unit, in the sense that he is capable, up to a certain limit, of managing the complexity of the Moth's dynamic equilibrium in flight.

We'll come back to the types of piloting possible and the contribution of equipment such as an inertial unit to flight stability management in a later chapter.

In short, in addition to the automatic altitude control, the helmsman has 5 control levers:

- ✓ PHR control (handle on stick)
- ✓ Course control (usual rudder rotation).
- ✓ Controlling power with the mainsheet
- ✓ Final attitude control on its movements on the platform in order to adapt to changes in lift generated by the control rod.

The only obstacles are fatigue, which progressively alters cognitive functions, and the disappearance of certain reference functions in very specific environments. For example, a Moth helmsman will find himself unable to perform a stabilised flight on a dark night with 100% cloud cover and no landmarks on the coast.

Admittedly, these conditions will never be encountered in Moth foiler regattas.... But a crew would encounter them in offshore races.

In certain conditions, therefore, it would seem impossible to pilot a vehicle exclusively "by human means" without on-board or external technological aids.

17. Transpose the flight of the Moth onto an offshore sailboat?

The reality visible on the Moth shows that since the very beginning of the 2000s, a monohull yacht has been able to fly and, above all, to race without difficulty.

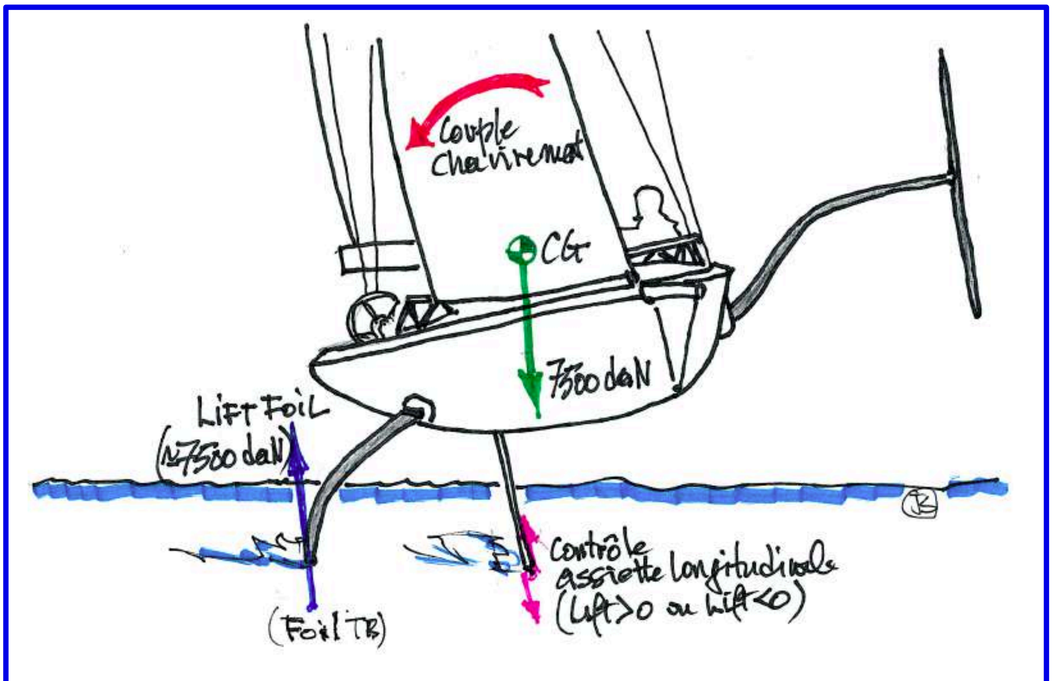
It's true that monohulls have been flying temporarily for over 60 years, with varying degrees of success, but these flights have been for trials and record attempts, and in no case for sailing in the form of regattas, whether coastal, around three buoys or offshore

Summary image extracted from a video published on 30/11/2017 by TEAM NEW ZEALAND, Defendant at the 36th AMERICA CUP.

In November 2017, a little over 15 years after the Moth, the AC 75 monohull project as support for the 36th AMERICA CUP appeared in a computer-generated image presentation without any real boat of this type existing.

The video posted on the Internet by Team New Zealand is very surprising. Of course, we're used to the Moth's performance, but to go from a 3.35 m dinghy weighing 135 kg, including the helmsman, to an unballasted monohull weighing 22 m and displacing 7000 kg is intriguing.

Although only computer-generated images are available, in addition to the characteristics of this new AC75 class, they nevertheless allow us to quickly extract a great deal of information about this one-design with restrictions (Box Rule) chosen for the 2021 AMERCA CUP.



Overall length: 75' (22.86 m)
Hull length: 68' (20.70 m)
Maximum beam: 5.30
Mast height: 26.5 m GV+Foc sail area: 220 m^2
Regatta displacement: 7500 kg (6800 kg version 2024)
Crew (originally) 10 to 12: An average of 850 kg to 1020 kg.

The class rules published four months after the November 2017 presentation will limit the crew to 8.

In addition to this technical data, the video shows a speed of 22 knots when the boat is supported on its leeward foil. The regattas to come will show that this speed estimate was very pessimistic overall.

Reconstructing the plans of this full foiler monohull from video footage has enabled us to refine its characteristics, bearing in mind that certain assumptions had to be made about the various materials used in its construction

For example, are the foils made of carbon or steel, and the same goes for the arms? What type of jacks: hydraulic or screw? What type of power: all-electric, all-hydraulic, mixed?

What are the limits for control-related servo systems?

A whole series of unanswered questions until the one-design rule is published, which will be in March 2018. But there's nothing wrong with thinking and imagining.

This foiler repeats all the analyses presented in the previous pages about the Moth, i.e. in flight the AC 75 is balanced by 3 systems of forces.

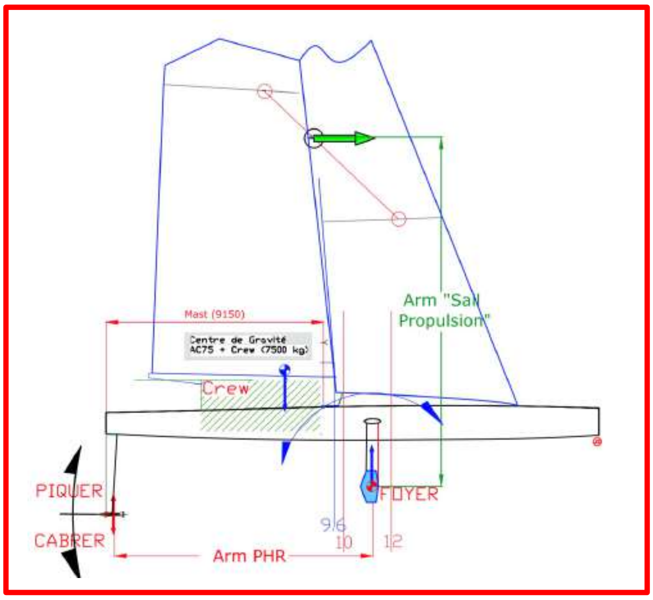
Each force is a 3D vector, which changes during navigation in intensity and direction. Only the vector representing the mass of the boat and its crew is always vertical and constant in intensity, which is not the case for the Moth.

The boat moves in an orthonormal environment, i.e. :

Oz: Longitudinal direction (the boat's heading)
Oy: Vertical direction
Ox: Lateral direction (lateral drift).

Each of the 3 forces has three components on (Ox, Oy, Oz):

Vellic force: This is produced by the lift of the 2 sails. It changes according to the wind, the orientation of the sail, the type of sail and the heel.



- Component on Ox: the daggerboard, the boat generally glides downwind.
- Component on Oy: results in a downward thrust (the boat sinks slightly)
- Component on Oz: this is the force that ensures forward propulsion

Force produced by the foil: This is generated by the lift of the foil.

In theory, it depends on the :

- ✓ Adjustment of transverse angulation from inside to outside (known as "CANT")
- ✓ Back and forth angulation adjustment (known as "RAKE")
- ✓ Orientation adjustment (vertical axis), (Known as "YAW").

This force is directed upwards, and its vertical component (parallel and opposite to the boat's WEIGHT vector) is usually called LIFT.
In fact, this component lifts the foiler, allowing it to leave Archimedean mode and move into FLIGHT mode.

The architecture of the foil system (pivoting arm and 'skate' type foil) limits the possibilities for adjustment when sailing. Only the incidence (RAKE) of the foil can be modified, and not directly, but by adjusting the camber of the profile using a trailing edge flap.
The intensity of this force is the most important factor in a foiler.

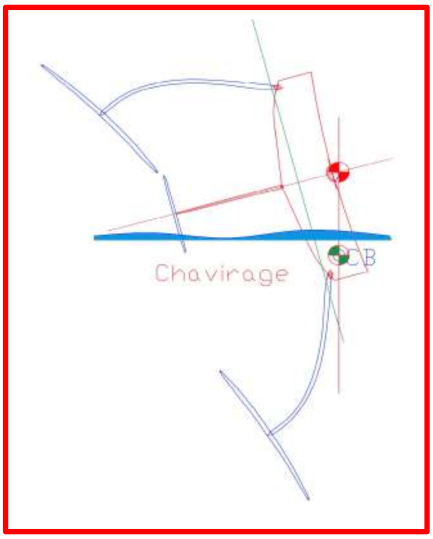
When the foil stalls, the whole edifice collapses.

Vertical force produced by the rear horizontal plane: This horizontal plane is identical in principle to that of the Moth, i.e. it has a symmetrical profile because its lift must be able to be alternated, i.e. directed upwards or downwards. This lift or offset of the PHR regulates the horizontal trim of the foiler.

The measurement rule requires the boat to be '*centred aft*', which means that the centre of gravity of the foiler with the crew on board is located aft of the forward foils (Foyer). A precise dimensional range defines the position of the crew in relation to the transom.

Under these conditions, depending on its angle of incidence, the tailplane produces a torque (+) or a torque (-), either "nose up" or "nose down"

The mass of the boat generates a vertical force applied to its centre of gravity (CG). In a defined configuration, the CG remains practically invariant during navigation.



But for both the Moth (or the Persico 69f and others) and the AC75 (now complemented by the AC40), these foiling monohulls operate in much the same flying environment, i.e. a protected area, at best with some chop, a real wind limited to 25/30 knots and no external ballast (at best a daggerboard) and daytime sailing.

The absence of external ballast gives them a stability that is not in line with coastal or offshore sailing criteria. Some prototypes in the MINI 650 Class are experimenting with full flight on foils, but keeping the keel fin and bulb. During trials, these prototypes showed impressive potential (of the order of 25, 28 knots) as soon as they were sailing on the reach.

But in offshore races, even those that are very downwind, which are the basis of the Mini 650 Class, the results show that the appendages that ensure Archimedian stability (keel sail and bulb) generate a lot of drag and penalise these foilers.

The results do not show any real superiority in terms of racing compared to the Archimedean protos sailing on the schedule.

Attempts to integrate lifting appendages (inclined and then curved daggerboards) into ocean-going multihulls began in the 1980s. These appendages may be retractable, but they cannot be controlled in terms of trim. There is no pitch stabilisation system. The aim is not to fly.

The architects' main aim is to partially lighten the hulls to reduce drag and increase righting torque to gain power.

These changes are particularly noticeable in the fleet of 60-foot ORMA multihulls.

The gradual development of carbon/epoxy composites and their use in place of fibreglass/polyester is contributing to a huge reduction in the number of structural samples and planking, and therefore platform weight.

18. First the multihulls

Since 1998, the ORMA Class has limited the force of this lift by restricting the projected surface area of the daggerboards fitted in the floats.

This decision allows excesses to be contained and above all prevents the pitch of the platform becoming totally uncontrollable when the leeward float is too far out of the water, which increases the inherent risks of capsizing. In fact, no one really addresses the issue of pitch control and maintaining flight altitude.

All these attempts and research into improving the performance of boats, whether monohulls or multihulls, are leading us to rethink the context of the notion of flight, as was the case in aviation in its day.

Flying a foiler means carrying out the usual manoeuvres of an Archimedean sailboat on a set course, but moving in lift above the water, at a relatively constant altitude and a trim close to the horizontal plane. Returns to Archimedean mode should be as rare as possible.

It wasn't until 2017 that a team (Gitana) presented a platform for an ocean-going trimaran that was actually designed for full flight.

Obviously not everything has been fully developed for ocean racing, but the essential support and control bases are well defined and in place.

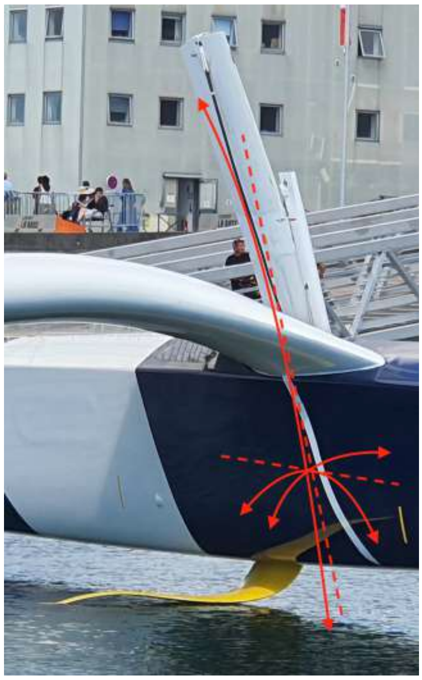
All these platforms, whether for the AC72s launched in 2013 or the ULTIMS, are based on the major ideas finalised for the Moth.

Multihulls (AC 72, CLASS C, ULTIMS[11] for example) benefit from the stability provided by the width of their platforms, which makes them much less sensitive to heeling and above all produces a righting torque that can be used in flight as well as in Archimedean conditions.

[11] Multihull ULTIM 32/23: LOA 32m / beam 23m / air draught 35m / float volume 220% of the boat's weight.

On catamarans, the foil assembly (inner 'L') and active PHR are always located in the leeward float.

For ocean-going trimarans, the platform is supported by the leeward foil (also known as the inner 'L'), which provides 75% of the lift, and the foil at the end of the centreboard (25%), known as the 'ray wing'[12] .



The stingray wing has an asymmetrical profile (type NACA 64-412[13]) and provides part of the lift for the central hull. The line between the centre of lift of the (active) L-shaped foil and that of the stingray wing is roughly transverse (the centreboard is approximately 1.5 m aft of the foils). This line represents the hinge in the balance (nose down/ nose up) when the trimaran is flying.

[12] The distribution of lift between foils and rays is similar.

[13] 64-412 corresponds to a NACA (National Advisory Committee for Aeronautics) identification, the last two digits express the thickness in %. The 64-412 is cambered, while the 64-1é is symmetrical. This type of profile is often used for foils, including IQ boards.

To obtain a longitudinally horizontal platform, a balance must be struck between the wind torque (aerodynamic force X distance between the centre of the sail and the hinge) and the torque produced by the weight of the boat (displacement of the boat X horizontal distance to the hinge).

An identical configuration for ocean-going monohull foilers will be explained below.

However, under certain sailing conditions, the lift of the stingray wing can increase the heel of the platform. This rotation reduces the lift of the L-shaped foil and raises the central hull.

In order to re-establish the optimum attitude, close to 0°, the incidence of the stingray wing is then reversed (offset).

This operation lowers the altitude of the central hull around the leeward foil, straightens the platform and takes the weight off the foil. On a foiler, flying with a platform close to the horizontal plane improves speed.

The active PHR in the leeward foil is retractable. When sailing, it is combined with the one at the end of the central rudder. These two lifting surfaces act as pitch stabilisers.

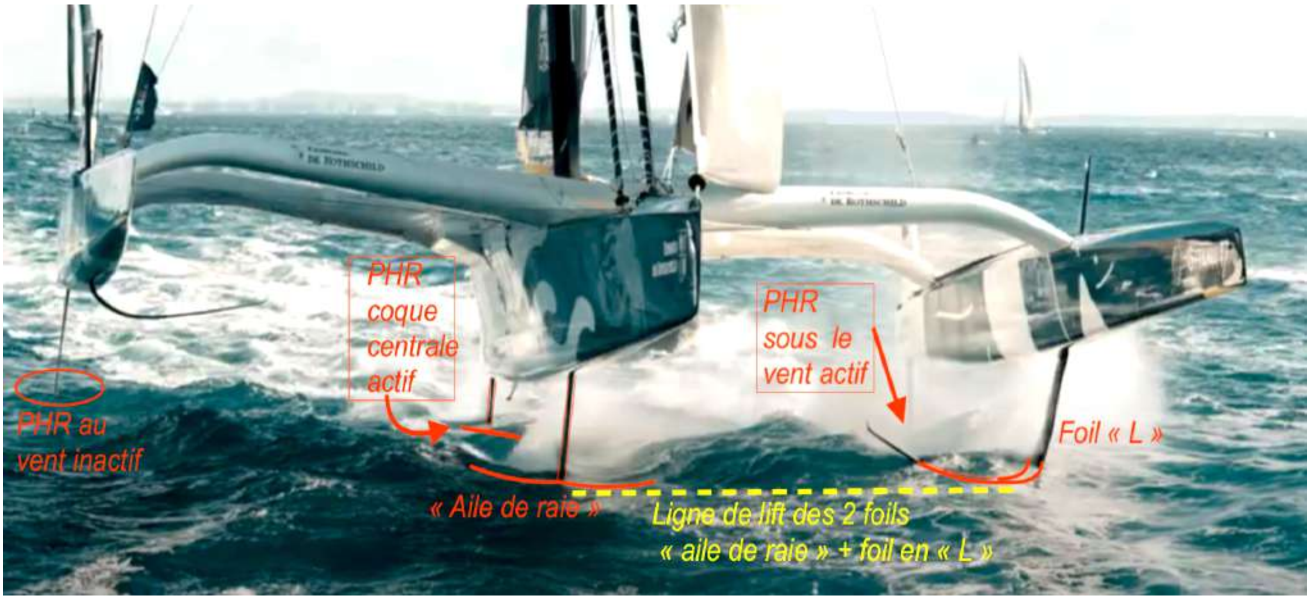
PHR and its rudder, fitted in the float (in the raised position)

PHRs use symmetrical profiles that can be made load-bearing or load-relieving by adjusting the angle of the trailing edge flap (>0 or <0), which creates a nose-down action on the platform, with the stern of the trimaran rising, or a nose-up action, with the stern descending. The performance of the PHR located in the float is better than that of its counterpart in the central hull, as it is more immersed

Overall, multihull platforms allow the lifting surfaces to be geometrically distant from those used to control flight trim. The initial stability of a multihull platform, with a clear advantage for the trimaran, means that in-flight manoeuvrability is far superior to that of monohulls.

It is easy to understand that a monohull in flight will suffer from the particularity of its platform. As the width of the platform is very narrow, there are two architectures for positioning the lifting surfaces. Either a centrally symmetrical double foil, like the Moth, or a foil with the active part offset to leeward.

Balance when sailing an ocean-going trimaran.



However, as an ocean-going or coastal monohull also sails in Archimedean mode and therefore has to meet stability and performance criteria (countering the drift effect), a keel fin and often a bulb become necessary. The drag of the bulb (which always remains submerged) exists in both Archimedean and flight modes.

The 26,000-mile test bed provided by the solo circumnavigation of the globe aboard ULTIMS (the ARKEA ULTIM 2024) enabled the teams to assess the resilience of the appendages and their resistance to the effects of cavitation, and to compare the results of numerical simulations of the profiles, aspect ratios, flap proportions and spatial geometries of the appendages with those recorded (a few million) during sailing.

Analyses of this real-world database are used to calibrate the algorithms that manage the servo-controls that control the appendage settings. This calibration based on real data is essential for flying as soon as the autopilot is engaged.

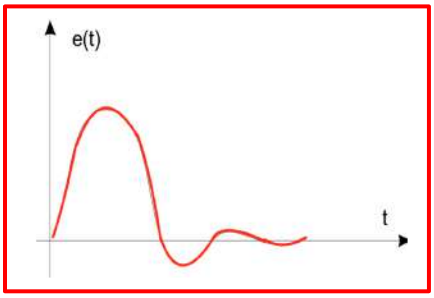
This is of particular interest for complex closed-loop control systems (PID: Proportional / Integral / Derivative, in the mathematical sense of the terms)

This closed-loop control system is based on a real-time comparison between a setpoint to be respected, for example a flight height or angle of incidence of a foil, and the actual measurement taken at time 't'.

The result of the comparison between the actual situation and the flight plan parameters feeds an algorithm which controls the physical components in action to ensure flight stability.

It will be the Horizontal Plane Regulator (PHR), or the foil flaps, or the "stingray wing", or even directly the incidence of the foils... Or even the trajectory?

This type of control, known as "closed loop", uses the following elements:



- Entry instructions
- A process to regulate
- A sensor to detect the instantaneous value of the process
- A control algorithm that manages the control: the "PID".
- An output to an actuator or device in order converge the state of the system towards the process input setpoint.

The other control method uses the principle of "open loop" control. The starting point is the system state objective set by the helmsman. To achieve this objective, the helmsman gives instructions for algorithms to process and control actuators in order to modify the original state.

But instead of having an automatic system that compares reality with the objective to be achieved, we rely on the helmsman to bring about this change. On the other hand, in this type of open-loop servo-control, the instructions given by the helmsman do not have to achieve the desired objective.

An internal technical hazard or one generated by the external environment can escape (or disrupt) the processing algorithm.

In this case, flight stability may elude the pilot, who may not be able to identify the undesirable parameter and thus return to a stable flight situation. This is apparently what happened to the AC75 "American Magic" and "Prada".

In this sequence, which lasts around ten seconds (foiler speed 15 to 18 m/s), the pilot loses complete control of the foiler, which pitches up at more than 20°, with the bow 8 m above the water, and falls back, damaging the hull to the point of almost sinking ("American Magic").

For this edition, the class rules restricted the use of servo-controls to open-loop systems in order to highlight the piloting and therefore the crew.

This particularly spectacular incident was limited to "breaking wood[14] ", but could have been much more serious.

During the 37th Cup, which took place in Barcelona in 2024, the class rules authorised the introduction of closed loops to control certain servo systems. This did not eliminate 'mast in the water' capsizings, but losses of control ending in 'uncontrolled double axels' were virtually eliminated.

[14] Expression used in the early days of aviation to describe landings that were somewhat outside the rules of the art of flying.

19. Foils: the best (speed) but also the worst (loss of control)

Whether it's a sail (laminar aerodynamic flow) or a submerged appendage (hydrodynamic flow), the laws relating to the evolution of these lifting surfaces are identical. However, the fluid circulating around the upper and lower surfaces changes by a ratio of 800, since the density of air is 1,295 kg/m3 and that of seawater 1,025 kg/m3.

Although the flow speeds of the two fluids, air and water, are virtually identical, between 10 and 40 knots, we must be wary of jumping to conclusions because of their different densities and also because air is compressible, unlike water.

There are two physical phenomena: cavitation and appendage ventilation.

Cavitation results in a loss of lift on the upper surface of the lifting surface (foil, for example).

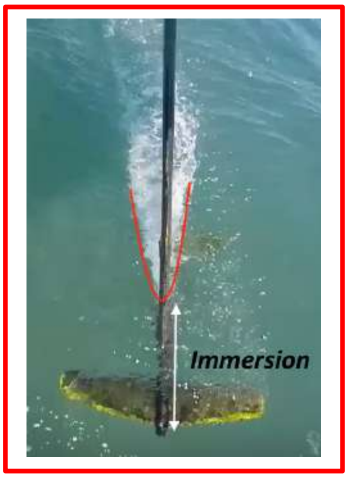
Ventilation results from flow problems on partially submerged appendages.

First of all, ventilation:

All appendages, whether rudder, daggerboard or foil, are subject to the hydrodynamic phenomenon of ventilation when they are in motion.

This phenomenon originates at the interface between the two fluids, air and water.

The movement of the appendage (speed of the Archimedean boat or foiler) generates a hollowing of the water surface at the air/water interface and a suction of the air along the appendage, which immediately annihilates its lift.



Even in the case of an appendage with a symmetrical profile, there is always a top surface and a bottom surface in relation to the direction of the fluid (rudder angle for a rudder or yaw for a foil). The hydrodynamic depression sucks the air towards the surface of the upper surface.

The local deepening of the water surface is clearly visible. The air then spreads along the appendage and almost instantly destroys its lift.

This effect can occur without any cavitation on the upper surface of the appendage. It is commonly said, for example, that the rudder stalls.

Consequence: on a rudder fitted with a PHR at the tip, the air instantaneously propagating along the upper surface of the airfoil destroys the lift of the upper surface of the PHR when it reaches the "T" of the PHR.

In the three photos above, when ventilation begins, the upper surface of the PHR is still in an undisturbed hydrodynamic regime.
When ventilation reaches the junction between the two appendages, they instantly lose their hydrodynamic functions:

- Steering control: vertical appendage (rudder)
- Positive lift or negative offset: PHR.

Paradoxically, in the triggering of the ventilation phenomenon, the speed element is not of primary importance, as is the case for cavitation

<u>What are the solutions?</u>

The most common solution is to prevent the gaseous cavity (air and water) created at the surface from being sucked up.

Aerodynamicists and then hydrodynamicists solved this problem by installing barriers perpendicular to the profile to deflect the movement of the gas cavity.

These are the "**<u>fences</u>**" that are often seen on aircraft wings.

Admittedly, this doesn't solve all submersion conditions or sudden waves, but it is an interesting approach to improving flow.

The current trend among hydrodynamicists is to protect the **PHR,** the **T-shaped foil** or **the stingray wing** by offsetting this lifting surface in relation to the rudder or the arm which carries it, so that the trajectory of the gas cavity which produces the ventilation does not spread over the upper surface of the **PHR,** the **T-shaped foil** or **the stingray wing** but is dispersed in the wake. On the other hand, this arrangement increases the structural complexity (design and mechanical stresses) of the connecting piece between the rudder and the PHR.

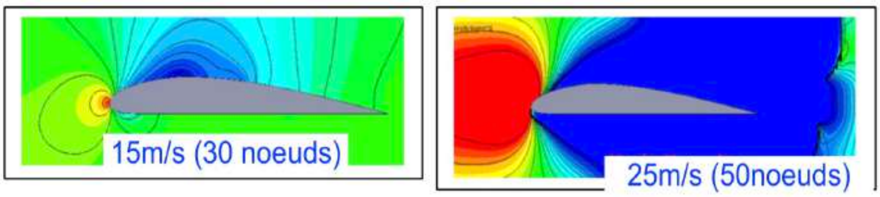
Another solution is to thicken the profile of the penetrating section at the air/water interface. This option increases drag very locally.

Then cavitation:

The flow speed of the fluid around the foil is one of the factors involved in cavitation. Other factors include the surface condition or shape of the profile, or the unsuitable aspect ratio of the appendage.

The maximum speed potential available to all foilers equipped with 'subsonic' foil profiles is virtually identical.

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 »)



By '***classic series profiles***' we mean profiles of around 12% thickness and low camber. These profiles correspond to optimum speed potential of up to 40 knots[15] for a foiler, provided, of course, that the necessary power is available.

It can be seen that at a certain speed the foiler is faced with an impassable wall, as the upper surface begins to cavitate and then stalls (zero lift).

The moment "t" when the upper surface radically stalls (surface in depression) and the lower surface follows, depends not only on the speed, but also on the moment when the local pressure existing on the upper surface reaches the level of the saturation vapour pressure $\mathbf{P_V}$.

[15] These same types of profile allow you to fly at 850/900 km/h on a jetliner.

The cavitation phenomenon is identical to boiling in a saucepan, but at a lower temperature, with the gaseous phase consisting of water vapour

The only difference between boiling and cavitation is in the "motor" that triggers the phenomenon.

Boiling involves varying the temperature at constant pressure and cavitation involves varying the pressure at constant temperature.

At this point, the water suddenly changes phase, from liquid to vapour. As vapour has a density 55 times lower than liquid, a bubble forms on the upper surface and the water flow is detached from the upper surface, causing the foil to lose lift and eroding its surface

Cavitation depends essentially on the absolute pressure at the foil and the temperature of the water.

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

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

When, at the ambient temperature, the **absolute pressure** is lower than **the saturation vapour pressure P_v**, the water passes into the vapour phase[16] . The value of the saturation vapour pressure is not a universal value and varies according to temperature.

For a foil operating in a zone where the water is at a virtually constant temperature, **cavitation will be limited to the variation in pressure.**

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

- Temperature 28°C : P_v = 3800 Pa (Pascal)
- Immersion: h = 1m Water density: d = 1020 kg/m³.
- Atmospheric pressure P_{atmo} = 101300 Pa

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

$$P_{hydro} = P_{(atmo)} (101300 \text{ Pa}) + (10006 \text{ Pa}) = 111306 \text{ Pa}$$

16 This section was written in collaboration with Robert Lainé. A body remains liquid if sufficient pressure is exerted on it. If you half-fill a container with water (for example) and empty it, some of the liquid will evaporate instantly.

But not all the water will evaporate. Evaporation will stop on its own when the saturation vapor point is reached. At this point, the pressure exerted on the liquid by the evaporated liquid is too great for evaporation to continue.

The additional value (10006 Pa) represents the pressure of the water column, i.e. the product of its height (m) X density (kg / m3) X acceleration of gravity g

Application

- Foiler speed: V = 20 m/s (38.87 knots)
- Maximum local (dis)pressure coefficient Cp = -1
- Maximum dynamic pressure: $\mathbf{P_{dyn}}$ = 1/2 * d * V^2 * Cp = -204000 Pa
- Total pressure = $\mathbf{P_{hydro} + P_{dyn}}$ = 111110 - 204000 = **-92694 Pa**!

Under these conditions, the local pressure is well below the saturation vapour pressure at 28°C (3800 Pa, see table above).

As a result, cavitation is certain!

To reduce the risk of cavitation on a classic foil travelling at high speed, you need to reduce the angle of incidence and use an adapted foil profile, i.e. one that is thinner.

If, as a result of a false steering manoeuvre at high speed, the angle of incidence becomes too great, even for a short time, cavitation will start and the lift will fall sharply almost instantaneously, causing the boat to nose dive.

Seeing the boat's nose dip downwards, the helmsman's natural reflex will be to increase the incidence of the foil in order to regain lift.

A logical reaction, since the Cz theoretically increases with the angle of incidence. However, it's not the right reaction, because this increase in angle of incidence actually increases cavitation... and then the boat dives straight down.

This means that it is very difficult to sail permanently around this critical speed (a sort of 'red line'), of which we only know the order of magnitude (38-40-42-45 knots) and which depends closely on the flight height (pressure of the water column). The amplitude of variations in foil immersion (including waves), in relation to flight altitude, means that hydrodynamic pressure ($P_{hydro)}$ cannot be servo-controlled in real time with sufficient precision to control the incidence of the foil and the PHR in particular.

The other related harmful effect of cavitation is the alteration of the roughness of the foil surfaces (surface sanding effect, whether metallic or composite). This increase in roughness causes an irremediable ("aerodynamic") drop in the appendage's performance.

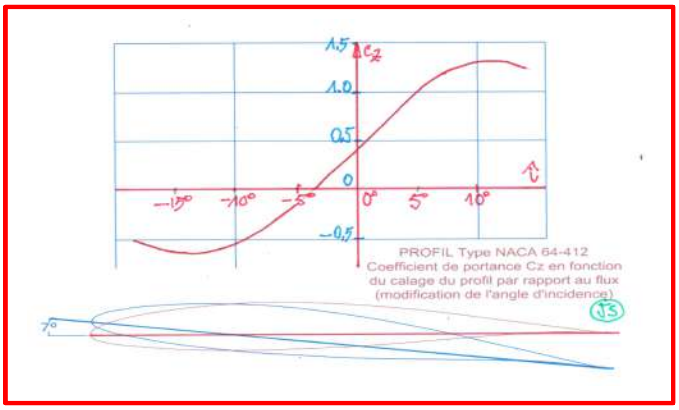
Of course, the ability to fly at high speeds is rapidly accessible. The difficulties arise when you want to achieve stabilised flight at a maximum speed that does not cause cavitation.

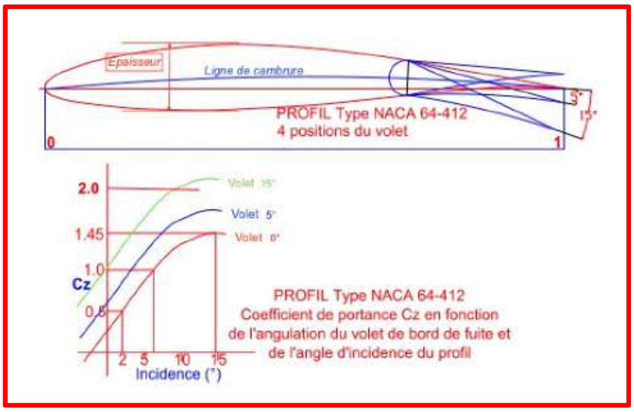
The engineer in charge of the flight then has to make compromises in the choice of foil profile, because before flying, you have to take off at a much lower speed.

Take-off speed and the very rapid transition to maximum possible speed obviously depend on the power available, but above all on the lift coefficient Cz of the foil profile. The Cz depends on the relative thickness and camber of the profile.

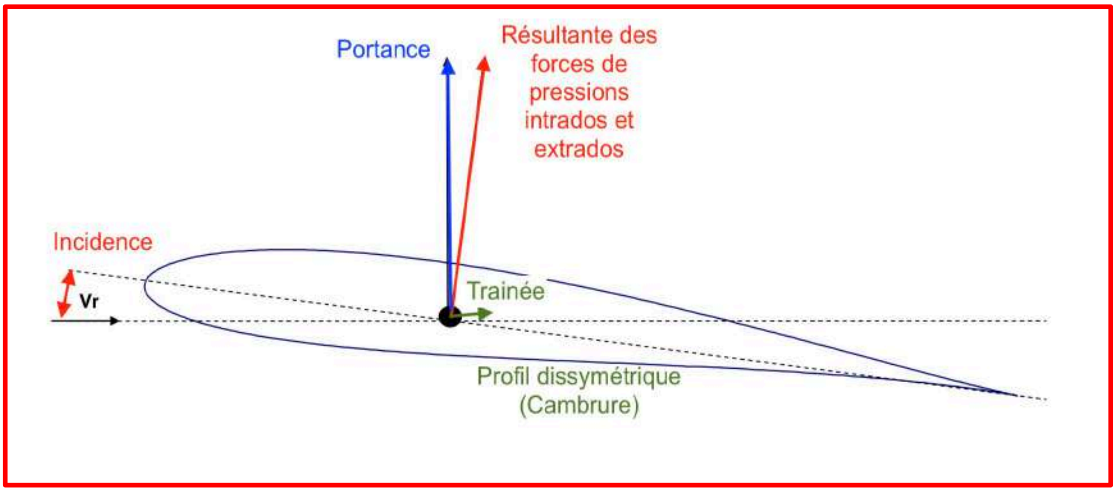
A thick profile and a large camber allow a lower take-off speed, but generate a lot of drag which limits the speed potential, which must be compensated for by increasing the surface area of the foil.

Experience shows that a profile of around 12% thickness combined with a low camber seems to be the best compromise





Increase in Cz as a function of incidence or trailing edge flap



Fz ("red" force) = ½*ρ*V²*S*Cz

Lift is modulated by adjusting the Cz using two techniques (see above).

Either the angle of incidence (the 'rake') is modified directly by pivoting the airfoil (and therefore the foil), or a trailing edge flap is oriented to increase the camber of the airfoil.

The flap system on the trailing edge requires less energy, but more complex kinematics. On the other hand, changing the angle of attack directly requires a great deal of effort, using a high-pressure hydraulic actuator.

The speed potential therefore depends essentially on the shape of the profile and its geometric setting, which is not surprising. On a sailboat, we apply this principle by constantly modifying the 3D shapes of the sails to adapt them to the incidence and speed of the apparent wind.

The difference in the case of a foiler lies in the fact that the foil represents the hydrodynamic part of the 'boat' and it is the performance of this part that is modified (3D trim) and not the engine represented by the sails.

The other important point is the range of speed variations obtained. As soon as the foiler is stabilised in flight at its optimum speed, i.e. when the lift balances the weight of the foiler, this increase in speed reduces the incidence of the foil and therefore its drag. By successively reducing the angle of incidence, a minimum drag is obtained and a target speed set just before the cavitation phenomenon is triggered. The whistling and vibration of the foil are excellent warning signs that cavitation is beginning.

20. The 40-knot "wall

The inevitable phenomena of cavitation and ventilation affecting the lifting surfaces designed from so-called "subsonic" profiles, lead the foilers to come up against a "WALL (40 knots)".

In navigation, this translates into:

- A fall in lift
- Severe erosion of the foil surface (loss of material)
- Sound effects of up to 110 dB
- Very high vibration levels.

The drop in lift[17] resulting from cavitation, i.e. the stalling of the foil, may at the start of the phenomenon only very partially affect the upper surface of the foil, but generally it propagates instantaneously and becomes total.

On a foiler, the situation is irrecoverable. Detecting the onset of cavitation using a sensor remains random because the response time of the

[17] Loss of lift can also be caused by the angle of incidence of the airfoil being too great, and this situation can be detected with an incidence sensor.

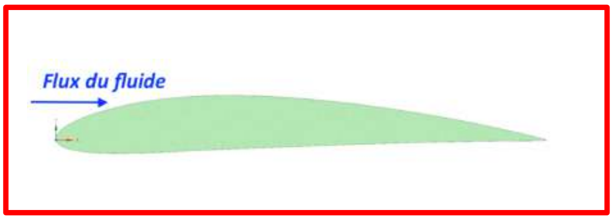
helmsman or the PA is very short due to the speed of propagation of the vapour bubble.

As long as the foiler remains within the speed threshold corresponding to these perceptible external phenomena, there is little risk of cavitation. However, the risk of erosion, particularly of the upper surface, increases if you sail permanently as close as possible to this speed zone. In the final analysis, flying at maximum potential speed is risky in terms of both equipment and flight stability.

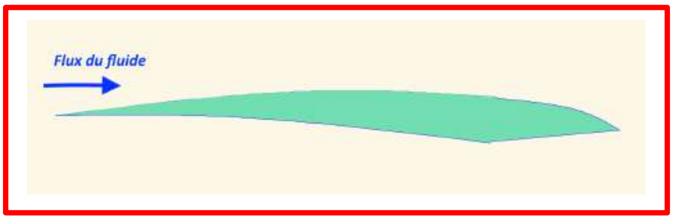
21. Can we get beyond this "wall"?

If you want to go beyond this speed limit (i.e. get over this "WALL"), you need to use super-cavitating profiles or profiles that are truncated at the point of maximum thickness and have an air inlet at the truncation ("ventilated base" profiles). Truncation consists of physically replacing a corner or edge with a facet.

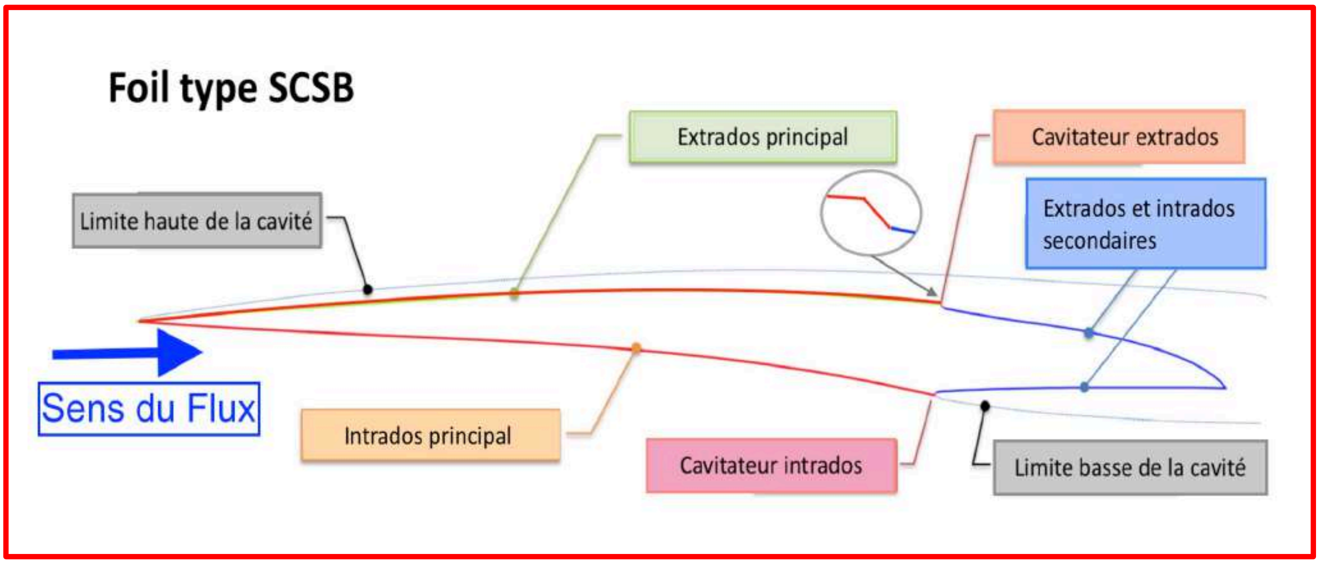
Super-cavitating" airfoils are fundamentally different from traditional NACA airfoils, due to their highly unconventional shapes and, above all, their hydrodynamic mode of operation.



Profil type « NACA »



Profil type SCSB



In a paper given at the "*Fourth International Symposium on Marine, Austin, Texas, USA, June 2015*" on the theme:
"A New Family of Dual-Mode Super-Cavitating Hydrofoils Innovative Ship design lab, i-Ship, Department of Mechanical Engineering Massachusetts Institute of Technology (MIT)".

Speaker Stephano BRIZZOLARA explains:

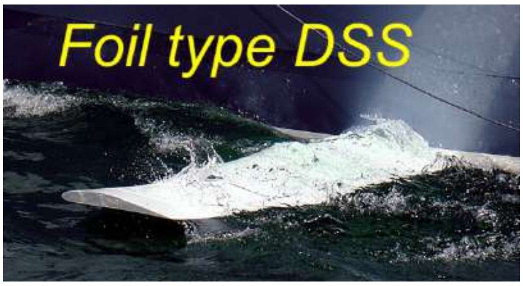
"*This new family of hydrofoils (foils) is capable of reaching optimum speeds (100 knots!!) in both super-cavitation and fully-wet cavitation or basic cavitation regimes, unlike conventional foils which generate significant drag in non-cavitation regimes*."

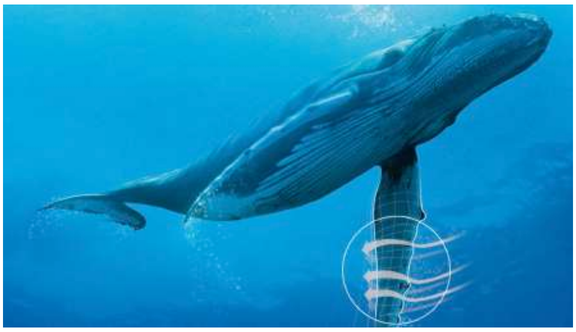
The difficulty is not in making this type of foil, but in reaching the speed at which they become operational, because apparently their main defect is a significant lack of lift at low speed. The ideal seems to be to start with a conventional profile (classic NACA or similar) and then move on to **a super cavitating SCSB profile**... easier said than done...

Taking off with SCSB profiles requires propulsion power (afterburner: 33% more on a Rafale for around ten seconds). However, while afterburning is conceivable with a jet engine, it is still a dream for sailing propulsion.

22. Humpback whales give architects ideas

These marine mammals, 13 to 15 metres long and weighing around 25 tonnes, are equipped with lateral fins reminiscent of the foils on IMOCAs or DSSs, although they are used in part for propulsion.





These fins have several surprising characteristics. Firstly, they have a very high aspect ratio of around 6 (Aspect Ratio = Wingspan^2 / surface area), and secondly, while the trailing edge of these fins (foils?) is a smooth curve, the leading edge is a sort of surprising sinusoidal curve.

The transverse profile, on the other hand, is virtually identical to an asymmetrical NACA profile in the 12% thickness range.

This particularity of the "wavy" leading edge, contrary to the results obtained in hundreds of tank tests, has led[18] several teams of scientists to investigate the effectiveness of these protuberances on the leading edge of these fins.

Do these shapes provide passive flow control in order to reduce cavitation and/or reduce the noise induced by the flow of water around the fin?

The experiments were carried out on four foils from the NACA 0012 series at incidence angles of 7° and flow speeds of up to 10 m/s. One of the four models is a 'normal' profile identified as the reference, while the three models studied have undulating leading edge shapes with different amplitudes of sinusoidal protuberances, which locally modify the profile chords (between 2 and 4%).

The flow results show that cavitation appears first in the troughs of the modified surfaces and is limited to just behind the troughs of the protuberances. This contrasts with the basic model, where cavitation starts at the leading-edge line and extends spanwise.

It appears that under certain conditions of incidence and fluid velocity, the protuberances reduce cavitation by 25 to 60%.

The acoustic analysis also shows that the leading-edge protuberances effectively reduce the noise induced by the flow on the lower and upper surface, particularly at high flow speeds

It's only a short step from there to inspiring naval architects. As early as 1994, Gilles Ollier (founder of Multiplast) modified the keel of the first Figaro (Plan Berret/Finot) in the same style as the rudder fitted to the SWAN 50, which did away with the one-design rating of the Figaro race and caused controversy over the running of the Solitaire from Brest (France).

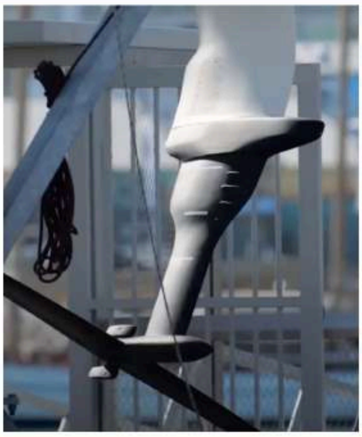
The result will not be convincing, but sailing during the Solitaire does not provide the environment of reflection, rigour and analysis required to carry out scientific work and analyse possible gains in performance.

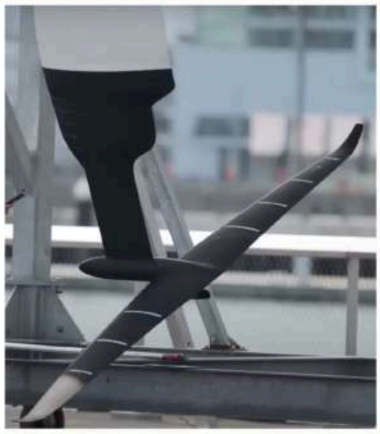
---

[18] Experimental investigation on cavitation and induced noise of two-dimensional hydrofoils with leading-edge protuberances (**November 2022). Physics of Fluids 34(12) DOI : 10.1063/5.0127170**

All designers try to improve air foil performance, but above all they try to counter the risks of hydrodynamic failure of a foil due to ventilation or cavitation phenomena.

Numerical modelling is of little help, as are tests in hydraulic tunnels (identical to wind tunnels), because the dynamic movements of the arm/wing assembly are virtually impossible to recreate in the laboratory.





23. ULTIMS evolve: "Sodebo 2024 »

After the race ARKEA ULTIM 2024 (January/February 2024), the trimarans in the ULTIM class underwent a complete maintenance operation, as well as new developments based on the experience gained during this 26,000-mile voyage.

The geometry of the side foils, only one of which is active under sail, is based on a predominantly linear active wing surface, which optimises the lift provided by the foil. The profile of these two foils is thin, asymmetrical and has a low camber. This choice reflects the general sailing conditions encountered by these ULTIM trimarans in offshore races with downwind conditions.

ULTIM CLASS
LHT 32 m Bau 23m
DSPL 15 tonnes (approx.)
Air draught 37m

Upwind sail area 450 m2
Canopy 650 m2

Ratio ($S^{0.5}/DSPL^{0.33}$) :
Upwind: 0.860
Downwind: 1,034

We therefore look for profiles that generate less drag (thinness and less camber). The lower unit lift of this type of airfoil is offset by the gain in speed (speed is squared in the calculation of lift).

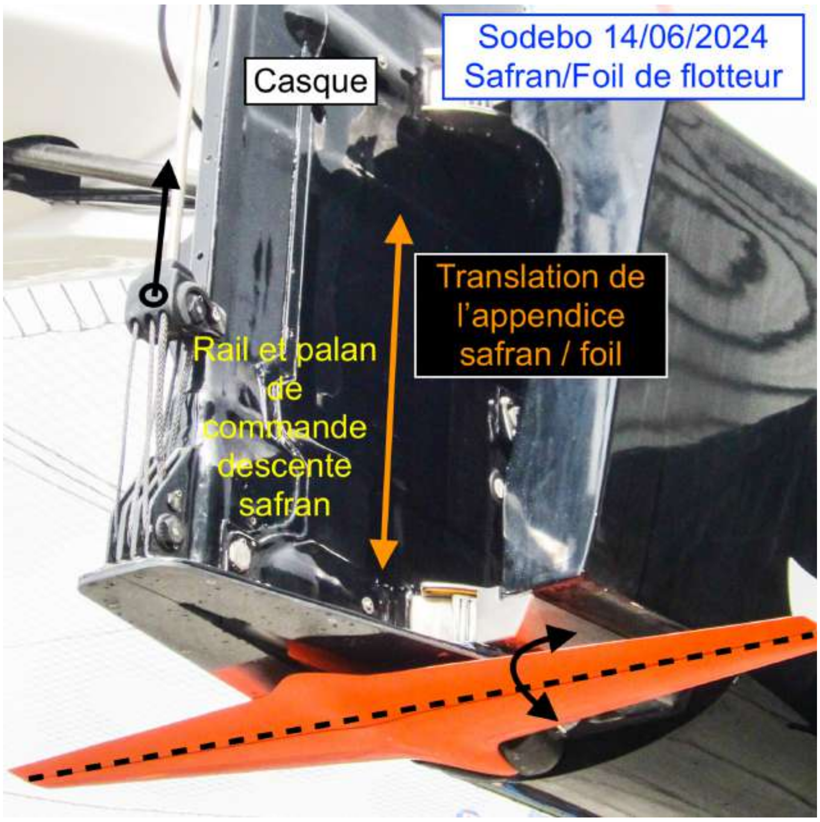
The incidence of the foil is controlled by acting on the complete rotation of the foil and its shaft (axis perpendicular to the plane of symmetry of the platform). It is clear that using a trailing edge flap to continuously adjust the lift, as is done on the AC75, represents the best 'aerodynamic' solution, but this solution generates a mechanical complexity created by the 'L' shape of the foil.

The designers prefer to use a hydraulic cylinder integrated under the deck of each float, admittedly this represents weight and the need to work with high pressure (around 250 to 300 bar), but the system is reliable and also more resilient in the event of minor impacts with floating obstacles.

The stingray wing at the end of the centreboard has a special status. Firstly, it is designed with a symmetrical profile, and secondly, it has a trailing edge flap that gives it two functions:

⇒ When the trailing edge of the flap is pointing downwards, the stingray wing supports the central hull.

However, if the flap is directed upwards, the lift reverses (offset) and the stingray wing move down the central hull.



This stingray wing management may seem anachronistic, but in fact this offset function helps to control the transverse attitude of the platform at around 5 to 10°, particularly in the event of over-steering, and also improves control of altitude and flight angle.

⇒ When sailing (flying), the leeward rudder and the centre rudder control the yaw (trajectory). However, each float rudder is retractable.

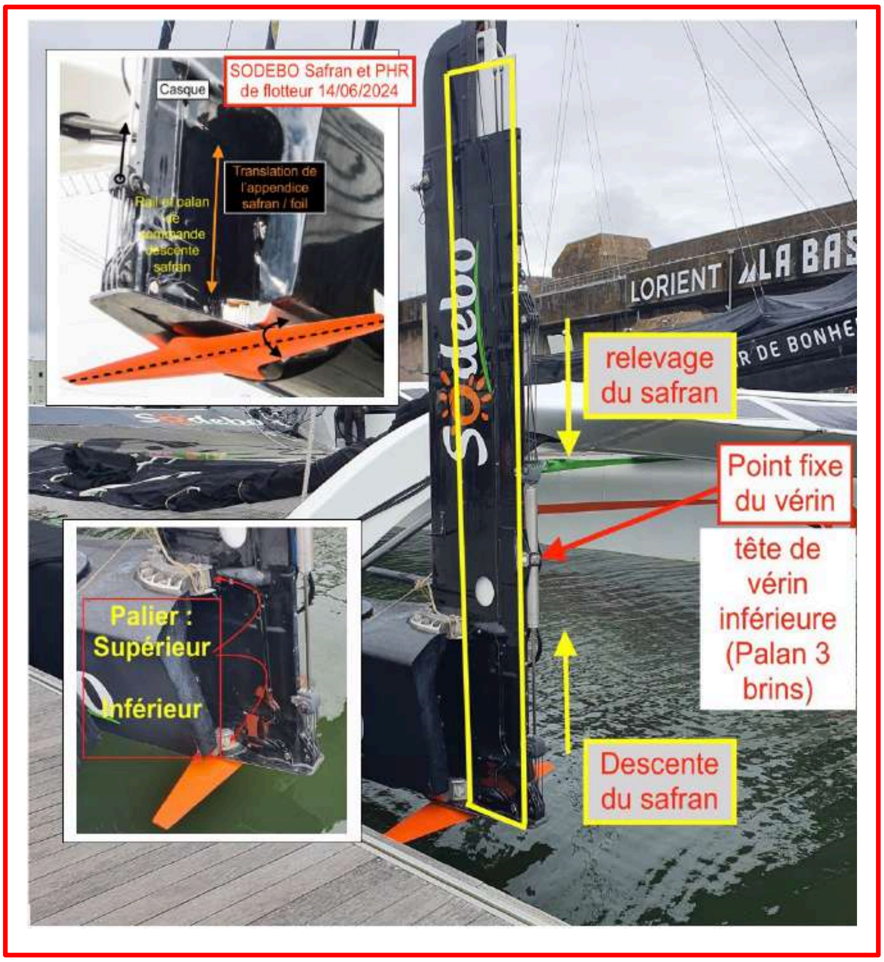
Each rudder and its PHR, located in the float, slides vertically in a helmet which only has a rotational movement (vertical axis).

A hydraulic cylinder (double rod) connected at each end of the rod to a 3-strand hoist moves the rudder blade and its PHR up or down.

An internal rod in the rudder blade acts on a bevel gear which controls the rotation of the trailing edge flap.

At first glance, the design of the central rudder is fairly conventional, with a carbon stock. However, the appendage has an aspect ratio of around 4.5 and its relative draught in Archimedean mode is greater than that of the stingray wing.

This choice is dictated by the desire to avoid the turbulence generated by the skate wing affecting the PHR of the central rudder.



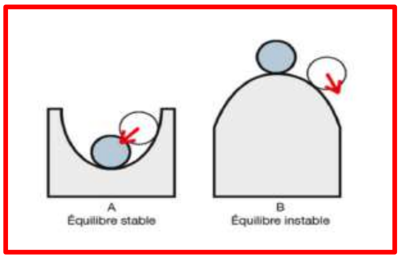
In fact, this is nothing new. If you look at an aircraft in profile, you will see that the horizontal tailplane (PHR) and its control surface (rudder) are higher than the aircraft's wings.

In fact, the same laws of flow govern aerodynamics[19] and hydrodynamics to the nearest density 1.293 g/m^3 vs 1025kg/m^3.

However, the position of the PHR has been shifted slightly forward of the leading edge of the rudder and an ogive appears in the plane of symmetry. Note that this feature also appears on the stingray wing.

[19] Subsonique aerodynamics.

24. Switch from multihull to monohull foiler



Firstly, the transition from a boat reacting to Archimedean laws to those of a foiler implies a complete paradigm shift.

Secondly, the craft, whether multihull or monohull, will alternate between the two worlds (Archimedean or flight), often at random.

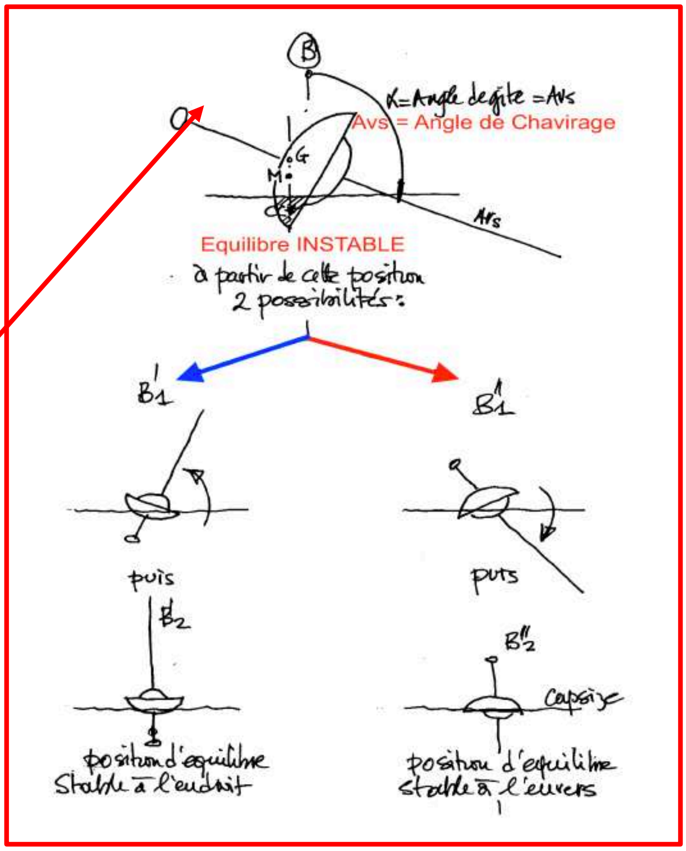
In Archimedean mode, the hydrostatic laws relating to the equilibrium of a monohull and a multihull are in principle fairly simple. Schematically, these two torques oppose each other when the boat heels:

⇒ The aero torque produced by the apparent wind (This torque is the product of the transverse component of the aero force and the vertical distance from the centre of the hull, which corresponds to the angle of heel).

⇒ The hydro torque (based on Archimedes' principle) around the same hull centre (This torque is produced by the boat's displacement multiplied by the horizontal distance between the hull centre and the vertical line passing through the boat's centre of gravity).

Starting from zero heel (vertical mast), under the effect of the aerodynamic torque, the Archimedean righting moment increases, reaches a maximum and then drops to an angle of heel where it becomes zero.

<u>This angle, known as Avs, corresponds to the capsize position of the monohull or multihull</u>. Beyond this angle Avs, capsize is inevitable up to 180° of heel. 180° of heel corresponds to a boat's second state of equilibrium (it is assumed that it remains watertight in this position with 180° of heel).



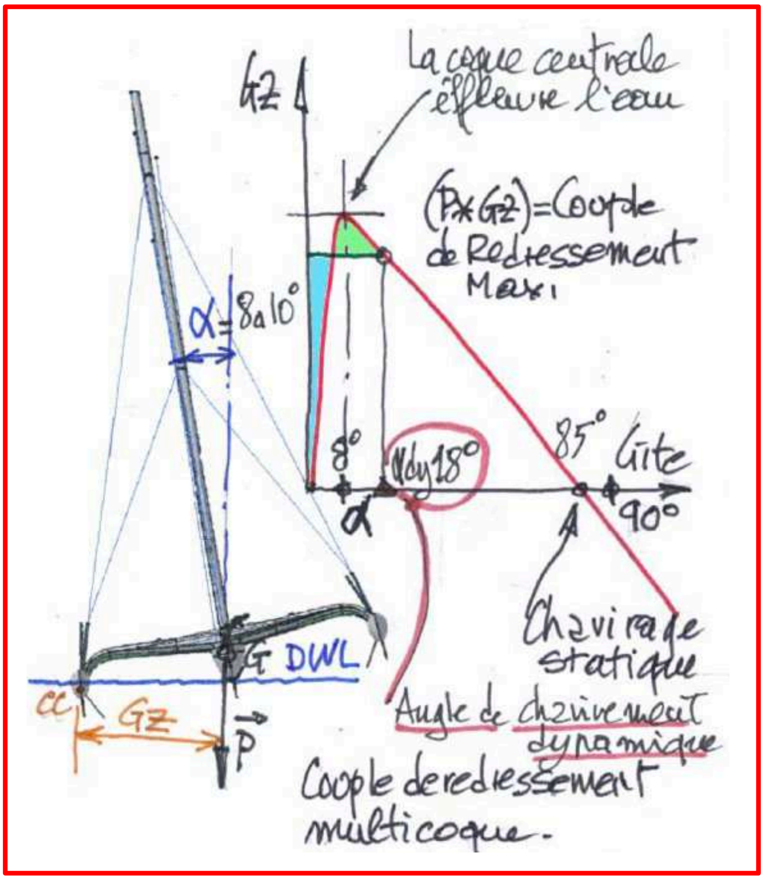
For a monohull, the capsize angle depends on 2 parameters: the vertical position of the CG and the width of the hull, which determines the leeward displacement of the centre of the hull.

The value of the Avs angle, close to 120° for a monohull, is limited to 80°, or around 85° for a multihull.

The laws relating to equilibrium in flight are very different. Firstly, these laws are based on the relative speed of the fluid, which evolves around the profile of the lifting surfaces and their orientation in relation to the fluid.

Then, when the vertical lift, equal and opposite to the boat's weight, collapses, mainly due to aerodynamic failure, in-flight lift disappears and equilibrium is destroyed.

It's easy to see that there's a big difference between a foiler which, when operating in Archimedean mode, benefits from a **permanent stable equilibrium** between 0° and Avs°, whatever the steering conditions (including errors), and the same foiler which, when in flight, is **in a totally unstable equilibrium at all times due to the foil's lift**.



This results in very different constraints between conventional navigation (Archimedean model) and those applied to the flight domain.

For monohulls in Archimedean mode, the range of the stable equilibrium zone is between 0° and Avs°. Without going into the details of the standards in force[20] , let's just say that Avs must be at least equal to :

[20] The data presented below concerns yachts sailing in category A (offshore races).

- 130° - (0.002 * displacement in kg).
- Added to this requirement for Avs is the need to design a hull shape which, when heeled between 0° and Avs, generates a righting energy of 172000 kg.m.deg. This requires an important surface under the curve (part >0 of the righting moment).

On the other hand, when a foiler flies, it rests on the support surfaces. Around **this** "**fulcrum**", there are two antagonistic couples.

- ✓ The torque linked to the thrust of the sail (aerodynamic force).
  And
- ✓ That generated by the weight of the boat applied to the centre of gravity.

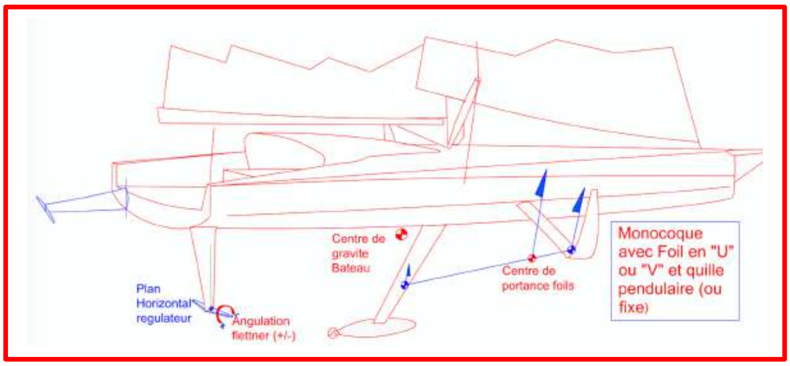
The lift appendages are usually installed in two technical configurations:

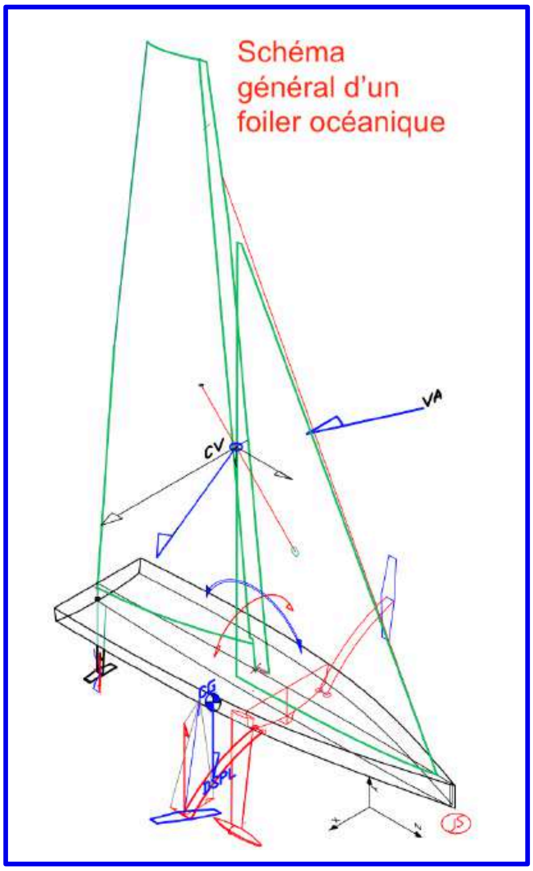
- ✓ A curved leeward foil + a pendulum keel with a bulb angled to windward. A fixed keel would generate virtually no vertical lift.
- ✓ A leeward T-shaped foil + a fixed keel fitted with a bulb.

The drift option with internal ballast doesn't work because it increases displacement and ultimately results in excessive wing loading, which limits the possible flight envelope.

As with multihull foilers, the aft flap (PHR, Plan Horizontal Regulator) fitted to the rudder ensures flight stability (horizontal trim, Trim >0 or <0).

Without this control system, it's impossible to fly... at most you can lift off and pitch the boat up. This is currently the case on IMOCA boats, where PHR is forbidden by the class rules.





Versions « Foil courbe » où « Foil patin »

24. The transition from Archimedian environment to full flight mode

Flight is therefore achieved by using displacement speed to generate a vertical lift force equal to the boat's displacement.

Unlike the aircraft, which loses around 4.5% of its weight during the take-off phase (paraffin consumption), which still represents 26 T for an A380 weighing 578 Tonnes, the monohull foiler navigates at constant displacement in Archimedean mode or in flight

To be more precise, a monohull foiler in full flight, whose bulb is constantly submerged, also benefits from vertical hydrodynamic lift (admittedly weak) equal to the weight of the volume of water in this bulb.

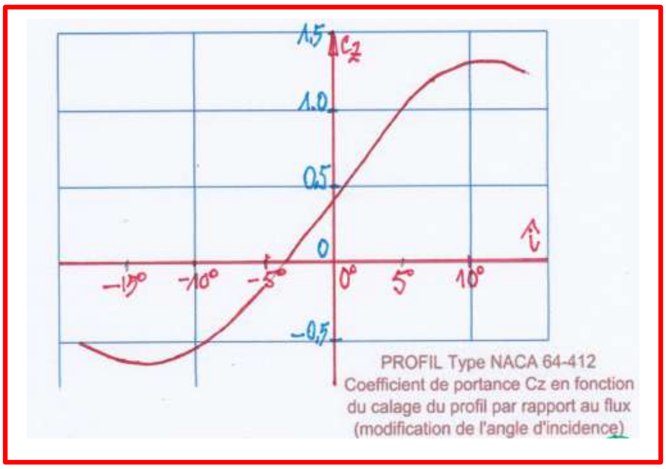
For example, a 7500 kg displacement monocoque foiler fitted with a 1700 kg bulb, i.e. 154 dm^3, receives a hydrostatic vertical thrust of 158 daN when in full flight, which contributes 2.11% to lift.

Take-off consists of "rolling along the runway" in order to gradually reach the speed where the lift force (in Newton) becomes greater than that exerted by the weight of the boat, i.e. roughly its displacement in Kg multiplied by 9.81 m/s^2. When this speed is reached, the pilot pitches the boat up and stabilises it at the desired altitude in horizontal flight.

This take-off speed is a matter for the designer to decide, but requires a compromise between the surface area of the foil, its aerodynamic profile and the angle of attack set by the pilot.

26. Hydrodynamic (aerodynamic) compromises

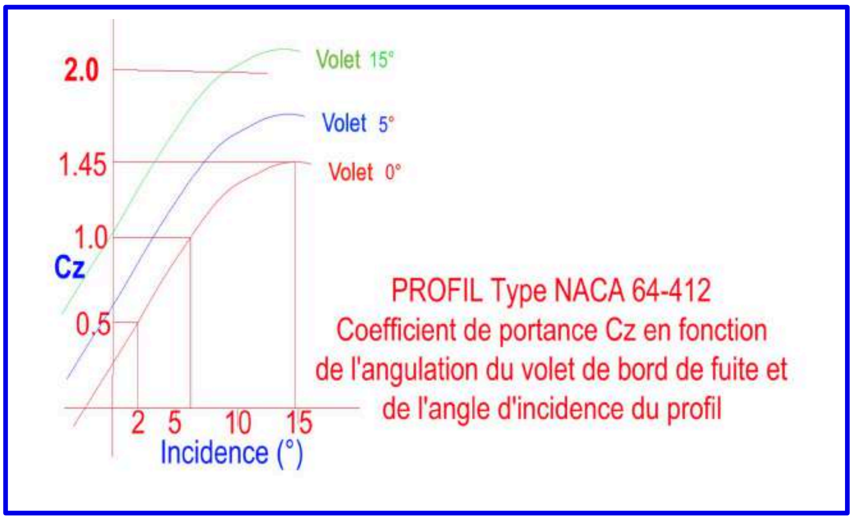
Each of the two types of foil used requires a different design strategy. L-shaped foils that can be retracted in translation (such as on IMOCA boats or ULTIMs) cannot be fitted with trailing edge flaps, unless complex and ultimately fragile and unreliable kinematics are devised, so they must have an asymmetrical profile that is fixed and defined at the design stage.



This results in a change in the Cz linked solely to the angle of incidence with the fluid.

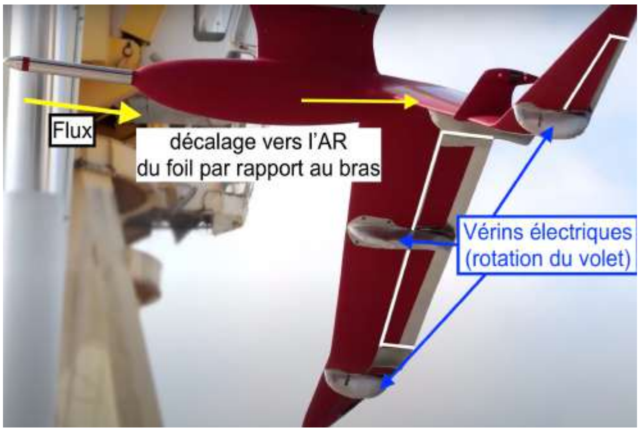
On foils of the 'skate' type assembled on an articulated arm (e.g. Flying Nikka or AC75) the kinematics controlling the rotation of the arm means that the angle of incidence of the foil profile cannot be modified when sailing.

However, this technology allows trailing edge flaps to be fitted, accentuating the camber of the foil profile in order to increase the basic unit lift coefficient (Cz).



The use of a trailing edge flap is to the detriment of drag, but the flap regulates the Cz more finely and consumes less energy.

Some of the latest-generation 'skate' foils have a gull-wing shape with 2 trailing edge flaps per side, controlled independently by small electric cylinders.



Whatever the technology chosen by the designers, at some point the 'aero' profile of the foil has to be determined, i.e. its relative thickness and camber.

As already mentioned, the choice of a thicker, more cambered foil profile produces more lift at low speed, and therefore allows a lower take-off speed. Remember that the aim of a foiler is to sail for as short a time as possible in Archimedean conditions. On the other hand, these families of profiles, which are thicker and more cambered, favouring take-off, imply larger wing surfaces, more drag and, ultimately, lower performance in stabilised flight.

Opting for a later take-off, i.e. at the very start of planing mode, reduces the surface area of the foil and allows the use of a thinner profile, less cambered, and therefore producing less drag. This type of profile allows you to quickly reach a speed in horizontal stabilised flight close to the 40 knots limit.

Even in the 'thin' profile family, the choice of 'aero' profile is not insignificant: a difference of 1 to 1.5% in Cz quickly translates into significant differences in distance covered in 24 hours.

This is what happened in ULTIM, to the advantage of the "Banque Populaire" boat, in the final 2300 mile stretch of the 2023 TJV between Recife and Martinique (a pure speed run) between "Banque Populaire" and "SVR Lazartigue". During this race, the differences between the profiles were small, but sufficient to allow Banque *Populaire* to cross the line first.

On the other hand, the foils on “SVR Lazartigue” appeared to perform better in the first part of the race, but not enough to compensate for the lack of performance at the more upwind speeds.

In absolute terms, all foilers, whatever their characteristics, have the same speed potential (around 40 knots), provided, of course, that they have the necessary power and sail area.

27. Deforming the shape of the foils to replace the flaps?

For decades, and still today, trailing edge flap control systems have used rods, cables, hydraulic actuators and, for the last twenty years or so, electric actuators combined with ballscrews. But the general philosophy is still based on articulated flaps that are mechanically deployed or oriented to modify the local camber of the foil profile.

It is obvious that as soon as a hinge is fitted to a foil, the linkage locally destroys the flow of air or water and generates unnecessary drag. What's more, the camber effect is identical along the entire length of the flap in relation to the body of the foil, which is generally trapezoidal.

This means that the chord length of the foil profile varies. It's true that several independent flaps can be fitted longitudinally, but this requires new cuts in the foil, additional control mechanics... and even more drag (see photo on previous page).

In aeronautics, engineers have imagined the possibilities of adapting the wing to the conditions of flight. As far back as 1906, the Wright brothers[21] designed an adaptive wing to control the flight of their "Flyer" biplane. They twisted the wooden structure of each wing by adjusting the tension of the cables between the biplane's two wings.

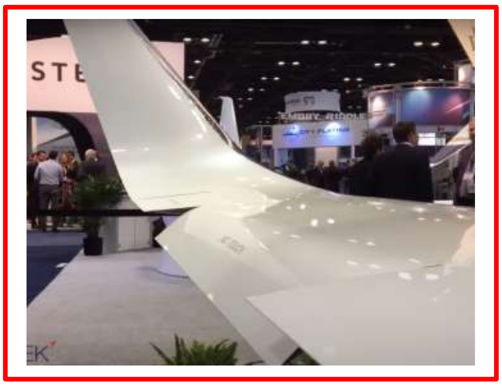
Inspired by the deformation of birds' wings in flight, the engineers are looking at ways of applying this principle to the overall surface of the wing, in order to eliminate all the external mechanical links that separate the body of the wing from the trailing edge flap(s).

This research has led them to focus on two modes of flight control, known as "macro-adjustment" and "micro-adjustment". The first mode concerns piloting, i.e. the pilot's decision-making actions, such as turning and altitude. The second, which is much more subtle, concerns instantaneous variations in attitude caused by the environment (airflow).

With this second mode, we return to the flight of birds, which manage this type of instability with the movements of their feathers, particularly at the tips of their wings.

---

[21] The Frenchman Clément Ader carried out flight experiments in France from 1873 on his plane *La chauve-souris* (a few flea jumps, due to a steam engine!!!, but there were no other types of engine) and, from 1890, proposed a deformable wing concept to ensure flight stability.



This design implies that sensors send information on the evolution of the flight (attitude, etc...) to an inertial unit which communicates with a computer. This computer then adapts the wing's internal mechanism to correct these micro-instabilities in flight. These operations are transparent to the pilot. The first "macro-adjustment" mode, which depends on the pilot (or PA), is superimposed on the second mode (micro-adjustment).
https://youtu.be/bC5BUuDFhmg

Admittedly, the volume and internal structure of a boat foil are not those of an aircraft wing. But the levitation of a boat on foils and the flight of aircraft are closely linked by both the laws of physics and those governing the conduct of stabilised flight. We can imagine that these ideas of morphing wings will one day appear on foils.

28. The state of the art in full foiling ocean monohulls

Finding technical solutions to improve performance, and therefore speed in particular, is the objective of competitors and designers alike. The architectural options of the last twenty or thirty years, in terms of shape, canting keel, materials, sail plan and sails, have unquestionably improved boat performance.

These performances are rapidly converging towards an asymptote for at least two reasons. The limits of the Archimedean physical model and the competition environment, where classes (under pressure from organisers and riders) are moving towards increasingly restrictive box-rules.

During the VENDÉE GLOBE, for almost two decades, the watchword has been downwind speed (the fascination of the 12,000 miles to be covered in the Indian and Pacific Oceans). However, the 7,000 miles or so (out of 28,000) that separate Cape Horn from the Bay of Biscay, sailed mainly upwind, could prove decisive in the final victory.

If we add the randomness of the weather conditions encountered, we have to admit that during all these VENDÉE GLOBEs, the average speeds progress relatively slowly compared to the technical progress invested in the boats.

They will increase from 10 knots (1989) to 13.8 knots (2012). Replacing the daggerboards with foils in 2016 will take her up to 14.6 knots.

So how do you achieve a significant performance gap?

Is a **full** ocean-going **foiler monohull** the solution?

Specifying "integral" is important, because it implies that the flight is piloted: which translates visually into navigation with a horizontal attitude.

To date, no monohull with the ability to fly fully, i.e. entirely in stabilised flight, has taken part in a Transat, with the exception of certain Mini 6.50 foilers mentioned above

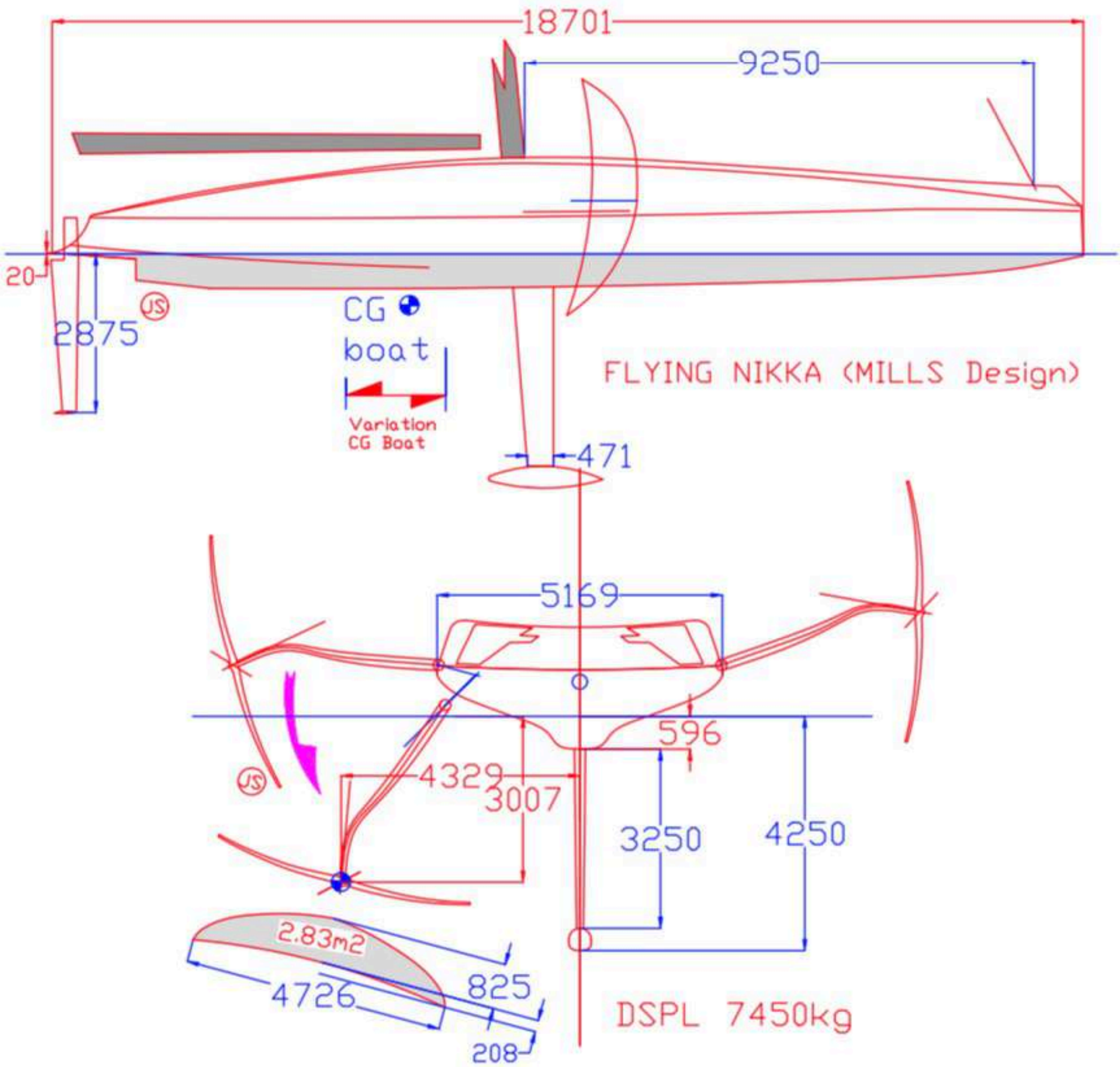
IMOCA monohulls do not fall into the category of full foilers, since the rules, by limiting the total number of steerable appendages, de facto prohibit pitch control using a horizontal stabiliser (PHR). It should be noted that the idea of installing a horizontal stabiliser without any degree of freedom on the rudder does not ensure stable flight.

Antoine Koch[22] recently published an exhaustive study on the conditions for full flight on an IMOCA boat. He comes to the logical conclusion that, without a horizontal stabilizer, IMOCA boats can only benefit from the random and uncontrollable lift produced by their foils and the pendulum keel.

[22] Antoine Koch is a naval architect and navigator.

FLYING NIKKA

JS drawings based on public documents



"The Flying Nikka, designed by a team led by Marc Mills, will be sailing in offshore and inshore regattas in the Mediterranean (2024 season). It's a 60' boat that's considerably lighter than the light displacement of an IMOCA and also a little less veiled: 233m^2 compared with 260m^2 on average for an IMOCA.

On the other hand, 'Flying Nikka' is less ballasted than an IMOCA, her bulb weighing in at 1700 kg compared with 2600 kg.

SIMULATION de DÉCOLLAGE FOILER						
TYPE de FOILER	FLYING NIKKA		D'après documents publics			
LHT	18.71	m				
Masse BW (Kg)	7450					
Poids en daNewtons	7308.45					
Hull speed Take Off (1 foil)	4.65	m/s	9.04	Nœuds		
Foil Area sailing (Chaque foil)	2.83	m2				
Corde	0.825					
ENVERGURE	4.726					
ASPECT RATIO (AR)	7.89					
Transcription essai en soufflerie du 64-412						
Angle d'incidence du Foil Maximal	8					
Cz "infini" FOIL NACA 64-412	1.238					
Coef unitaire Cz avec cet angle d'incidence	0.939					
Evolution du décollage sur l'angle d'incidence du Foil (Rake)						
Navigation juste avant le déclenchement du Take OFF			Nœuds	9.0	m/s	4.63
ANGLE INCIDENCE FOIL en dégré	1.00					
Cz "infini" FOIL NACA 64-412	0.541					
Cz "AR" (avec flap) FOIL NACA 64-412	0.411					
LIFT en daN	1276	daN	-6032			
TAKE OFF (beginning)	LIFT		Vitesse			
1 FOIL actif Incidence : voir ci-dessous			Nœuds	9.0	m/s	4.63
ANGLE INCIDENCE FOIL en dégré	5.00					
Cz "infini" (avec flap) FOIL NACA 64-412	0.983					
Cz "AR" FOIL NACA 64-412	0.746					
LIFT en daN	2319	daN	-4990			
TAKE OFF 75%	LIFT		Vitesse			
1 FOIL actif Incidence : voir ci-dessous		daN	Nœuds	16.0	m/s	8.23
ANGLE INCIDENCE FOIL en dégré	2.50					
Cz "infini" FOIL NACA 64-412	0.716					
Cz "AR" FOIL NACA 64-412	0.543					
LIFT en daN	5333	daN	-1975			
TAKE OFF 100%	LIFT		Vitesse			
1 FOIL actif Incidence : voir ci-dessous		daN	Nœuds	21.6	m/s	11.11
ANGLE INCIDENCE FOIL en dégré	1.00					
Cz "infini" FOIL NACA 64-412	0.541					
Cz "AR" FOIL NACA 64-412	0.411					
LIFT en daN	7352	daN	43			

Caractéristiques principales du Foiler.

Vitesse de décollage choisie

Caractéristiques du Foil

Suivant l'angle d'incidence du foil, on détermine le Cz pour une aile de longueur infinie, que l'on corrige en fonction de son « Aspect Ratio ».

Calage du foil (Incidence 0°) en début de décollage.
Lift généré par l'asymétrie du profil du foil.

Augmentation de l'incidence du foil
Augmentation progressive du Lift.
Diminution de la trainée de la coque.

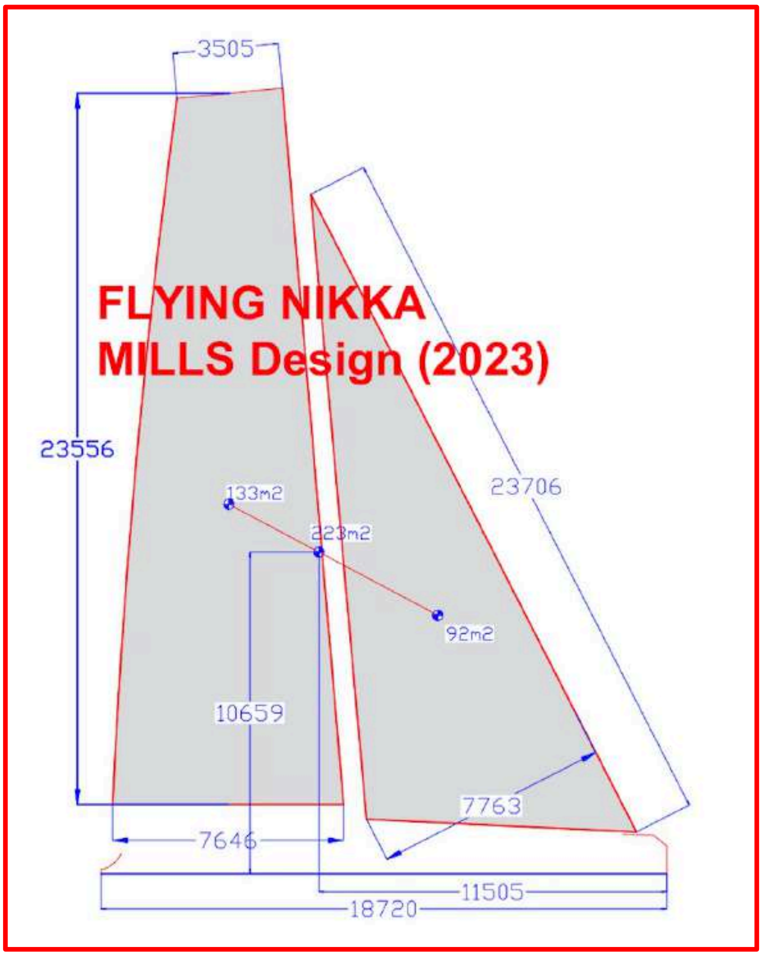
La vitesse augmente, donc le Lift aussi avec le « carré de la vitesse », ce qui permet de diminuer l'angle d'incidence.

La coque est entièrement hors de l'eau. Il faut alors stabiliser la hauteur de vol en jouant sur l'angle d'incidence.

This foiler is based on the AC75 concept, with the addition of a keel fin and bulb to give it oceanic stability when sailing in archimedean mode.

Under sail, Flying Nikka shows good speed potential (25 to 30 knots). It is supported by a single foil carried by an articulated arm at the level of the hull dead-works. The construction uses epoxy/carbon composite applied in a vacuum. However, the foil does not have an adjustable flap on its trailing edge, as is the case with AC75 technology.

Rather than using trailing edge flaps on the foils, Mark Mills' team has opted to install a mechanical joint at the link between the arm and the foil, which allows the angle of incidence of the foil to be altered by +/- 10° by means of a hydraulic cylinder installed in the arm.



This solution is possible because the foils with a 2.8m2 and 4.726m wingspan have a top chord of around 820 mm for an aspect ratio of 7.80 (the aspect ratio of the AC75 foils of 2024 is close to 12 to 13). The thickness (12% of the chord) of the foil's upper chord makes it technically possible to implement this articulation and a sufficiently large lever arm to lighten the power of the control jack.

The Wing / Weight ratio at take-off (and in flight), in homogeneous units is approximately 0.763. This is for an overall aspect ratio (mainsail + jib) of 2.47. These calculations apply to laminar regime operation and correspond to the apparent wind. For comparison, an AC75 (2024) has a ratio of 0.780.

Key figures

In flight, the 80 kW Yanmar diesel engine (4 to 5 L/h at 1700 rpm / 35 kW) ensures the operation of the hydraulic system (pressure of 500 bars) via an attached piston pump.

In order to limit the expansion of the oil under the effect of the rise in temperature resulting from the movement of the oil in the pipes and in the hydraulic pump, a fairly large volume oil tank is used.

This volume of oil is used to cool it in order to eliminate the pernicious effect of expansion, which reduces the precision of the linear movements of the cylinder rods.

All this translates into a payload of some 400 kg (engine, pipes, jacks, tanks, etc.), not to mention the 120 to 130 litres of diesel fuel needed every day (with a planned range of 750 litres), since flying requires permanent electrical (pilot, electronics) and hydraulic power generation.

The owner commissioning 'Flying Nikka*'* allowed Mark Mills and his team to embark on the design of an ocean-going foiler monohull. Intellectually, the adventure is interesting. On the other hand, the ecological balance sheet must surely be pretty poor, both because of the carbon composite construction (hull, mast, sail, rigging, etc.) and because of the constant consumption of fossil fuels to ensure the functions required for stabilised flight.

But whether it's a Moth, an AC75, or a full foiler (multihull or monohull), you have to steer these machines a few dozen centimetres above the surface of the sea. Which is not always, or even rarely, a flat surface when sailing offshore.

29. Archimedean mode vs. full foiler mode

On a "good old" Archimedean sailboat, even at full speed in surf mode under asymmetric spinnaker at 35 knots, 3 brains are enough to steer:

The helmsman, the crew member on the mainsail and the person in charge of the spinnaker sheet. The helmsman feels the boat under his feet (or under his arse, if he is seated) and at the touch of the helm (soft, hard, neutral...).

The two crew members perceive the speed, interpret the pennons, the refusal of the spinnaker's leading edge, etc. All this visual and physical information is automatically translated into reactions: rudder angle, trim, etc. The rest of the crew can contribute to maintaining a heel which limits the asymmetry of the hull. The rest of the crew can help to maintain a heel that limits the asymmetry of the hull.

If a steering error is made, usually a lack of responsiveness, or a faulty appendage, it is very often possible to manage the mess. However, sometimes the situation completely escapes the helmsman and the crew. In this case, recovery becomes impossible. The straight trajectory is transformed into a gyration, the boat goes down violently, the crew suffers and then takes the decisions they deem appropriate.

The Archimedean laws come into play simultaneously and bring the boat back to its basic trim (0° heel), barring exceptions (exceeding the Avs angle) and whatever the attitude of the crew.

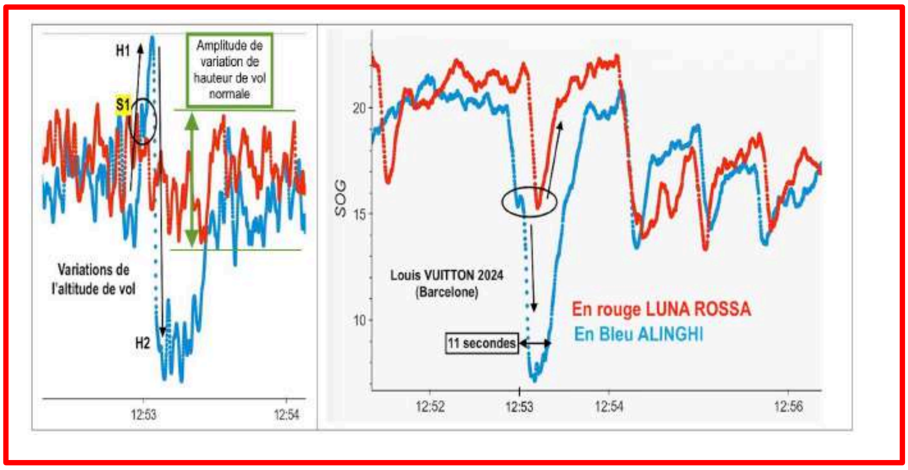
In Archimedean, the time available between **perception**, **decision** and **action** is long enough for the system to work. The speed of the boat remains within a reasonable range and helps to make it possible for man to steer the boat for a long time.

Increasingly sophisticated autopilots (APs) provide reliable course-following. In fact, there are two states to consider when following a course. There is the final objective: the course to be followed for "x hours" and the boat's performance at each instant "t". While the PA is very well suited to the 'course' objective, we know that the helmsman is still the best person to get the very best out of his boat every length sailed.

Today, the internal algorithms of an AP connected to a navigation centre adapt the instantaneous route taking into account the current conditions and the objective to be reached.

No matter how technically advanced the PAs are, they do not manage the evolution of hydrostatic equilibrium, since this function is devolved to the physical laws of the Archimedean model.

With a foiler, you change world and, above all, environment, as the 'boat' leaves the Archimedean environment to enter a totally discontinuous environment.



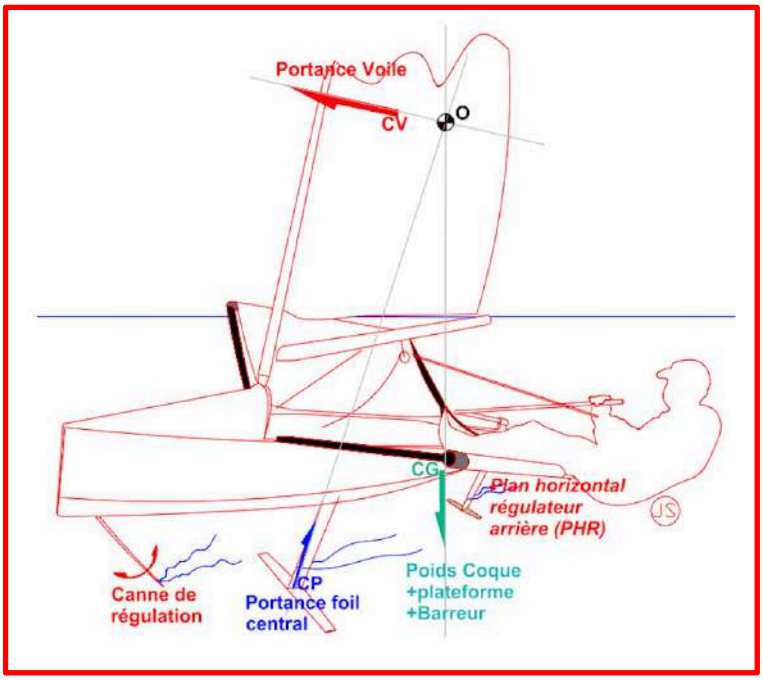
During the Vuitton Cup preview of the 37th AC, the recordings of the altitudes and speeds of *Luna Rossa* and *Alinghi* following each other at around 30 knots during a race show the importance of the reliability of the PHR action.

The graph on the right representing the flight altitudes shows (12:53 in H1) a nose-up platform (loss of PHR action). This pitch-up occurs in 2 stages, since S1 shows an attempt by the pilot to recover.

This pitch-up is followed by an instantaneous fall, a loss of altitude (return to Archimedean mode) and a drop in speed (right graph) to 7m/s (13 knots).

30. In-flight balance: Reverse or forward centring?

The in-flight balance of an ocean foiler is obviously similar to that of the Moth (35 kg for the boat and 80 kg for the crew), but because of scale effects, the balance conditions of the Moth are not fully reproducible on an 18 to 20 m, 7500 kg monohull.



Let's return to the general theory of theft.

<u>The forces at play (aircraft)</u>

⇒ The lift forces are applied at the centre of thrust (CP).

- The main lift is produced by the wings. This lift is applied at the focal point of the wing profile, i.e. approximately 25% behind the leading edge. It is broken down into 2 forces: a vertical force directed upwards and a horizontal force directed backwards (drag).
- Secondary lift also exists. This is the lift produced by the longitudinal shape of the fuselage. Its point of application corresponds approximately to the longitudinal position of the centre of gravity of the fuselage profile, including the rear vertical control surface. Note that the secondary lift is very low compared with that produced by the wings.

⇒ The "forces that pull" the aircraft towards the ground applied in G1 or G2.

- In fact, there is only one force. It is the force created by the mass of the aircraft (F = Mass in kg X 9.81). It is expressed in Newtons (N). This force is applied at the aircraft's centre of gravity (weight estimate). Calculations identical to those carried out on a boat.

⇒ The "control" forces applied to the PHR.

- This is the lift generated by the rear control surface (PHR). This lifting surface has a symmetrical profile. This control surface can have a positive or negative angle of incidence, which means that the PHR is either weight-bearing or weight-lifting, depending on the piloting conditions. This results in a nose-down or nose-up movement of the aircraft.

⇒ *Propulsion force*

- It is parallel to the axis of the aircraft and points forward. Because of its small eccentricity in relation to the axis of the aircraft, it has little effect on flight stability. This is not the case on a sailboat, where its point of application is halfway up the mast.

Degrees of freedom, focus

Flight stability depends on managing the 3 rotational degrees of freedom: yaw (vertical axis rotation), pitch (transverse axis rotation) and roll (rotation around the axis of the aircraft). These 3 axes converge at a point known as "focus", so the aircraft, and by analogy the foiler, have a centre about which they pivot.

On a foiler, given that only the foil, the PHR and the rudder tip move through the water, the aerodynamic effects on the hull are relatively negligible. The focus of a foiler is located on the active foil, around 25% aft of the leading edge.

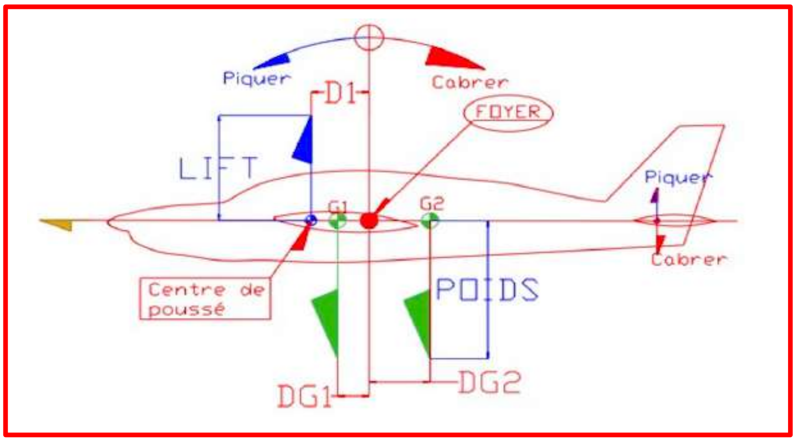
The effects of lift, weight and associated torques in relation to the focus.

This comes down to 2 torques: that created by the lift applied to point CP and that produced by the action of the aircraft's mass applied to the aircraft's centre of gravity (G1 or G2).

As **the lift is** always in front of the centre of gravity, this torque always pitches the aircraft up. The lever arm (D1) is virtually constant. The value of the corresponding torque therefore depends solely on the lift, and therefore on the angle of incidence of the wing profile.

The mass of the aircraft (apart from that of gliders) is not constant, since it consumes fuel. However, in relative terms, the fuel mass is small compared with the aircraft's laden weight. The torque created by the aircraft's mass around the centre of gravity depends on the longitudinal position of the aircraft's centre of gravity. It is the longitudinal position of this point that determines flight stability.

Where the centre of gravity is in front of the focus (point G1).



The balance is as follows:
LIFT * D1 - WEIGHT * DG1 = 0
The position of G1 is set globally by the designer.

As the lengths of the 2 lever arms D1 and DG1 are constant in stabilised flight, we adapt the incidence below this balance. We compensate for this tendency to dive by turning the PHR nose up. As the PHR lever arm is very large, the angle of incidence of the PHR will be very low: this will produce very little drag.

In the event of a momentary loss of lift, the torque generated by the weight causes the aircraft to pitch down. The pilot or the PA recovers by pitching the PHR up.

Balance is deemed to be "stable". This is known as forward centring.
As a result, the aircraft becomes less manoeuvrable.

Where the centre of gravity is behind the focus (point G2).

The balance is as follows:

LIFT * D1+ WEIGHT * DG2 = 0

The lengths of the 2 lever arms D1 and DG2 are always constant in steady flight.

It all depends on the manufacturer's choice of G2 position.

The WEIGHT * DG2 torque causes the aircraft to pitch up, which can become uncontrollable despite the pilot's nose-down action on the PHR (the PHR surface area is relatively small, and although the lever arm is large, the torque produced may not counteract that of the aircraft's weight multiplied by DG2) .The aircraft pitches up more, and the angle of incidence increases until the wings stall.

With an <u>aft C of G</u>, the balance becomes 'unstable', but gives the aircraft excellent manoeuvrability.

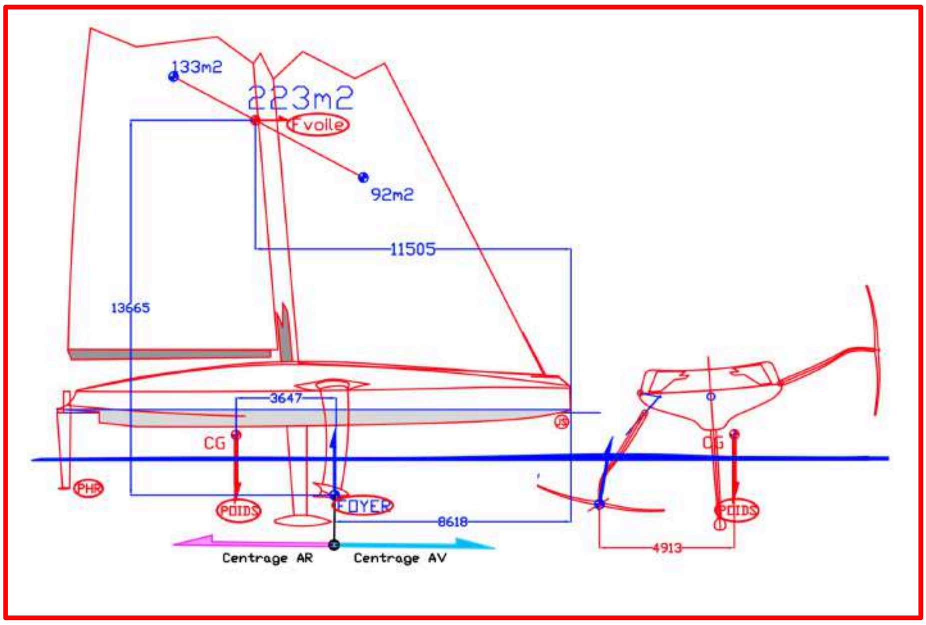
<u>**Note**</u>: the propulsion force an aircraft has very little effect on equilibrium because its point of application is very close to the axis of the aircraft and its direction is parallel.

Finally, this assembly evolves in the same environment, i.e. a mass of air with constant density, although this varies with the flight altitude. In conclusion, **to be stable, an aircraft** must be designed with a "**Forward C of G**". <u>Only fighter and aerobatic aircraft are designed with an aft C of G</u>, as they must be able to modify their trajectories instantaneously.

But let's get back to our ocean foiler... The number of forces and their spatial positions are virtually identical to the configuration on a Moth.

By moving the foil of the ocean-going monohull foiler to leeward, the architect creates a righting moment which opposes that generated by the transverse component of the wind lift. In terms of righting moment, the leeward foil lift produces the same effect as the leeward float of a trimaran.

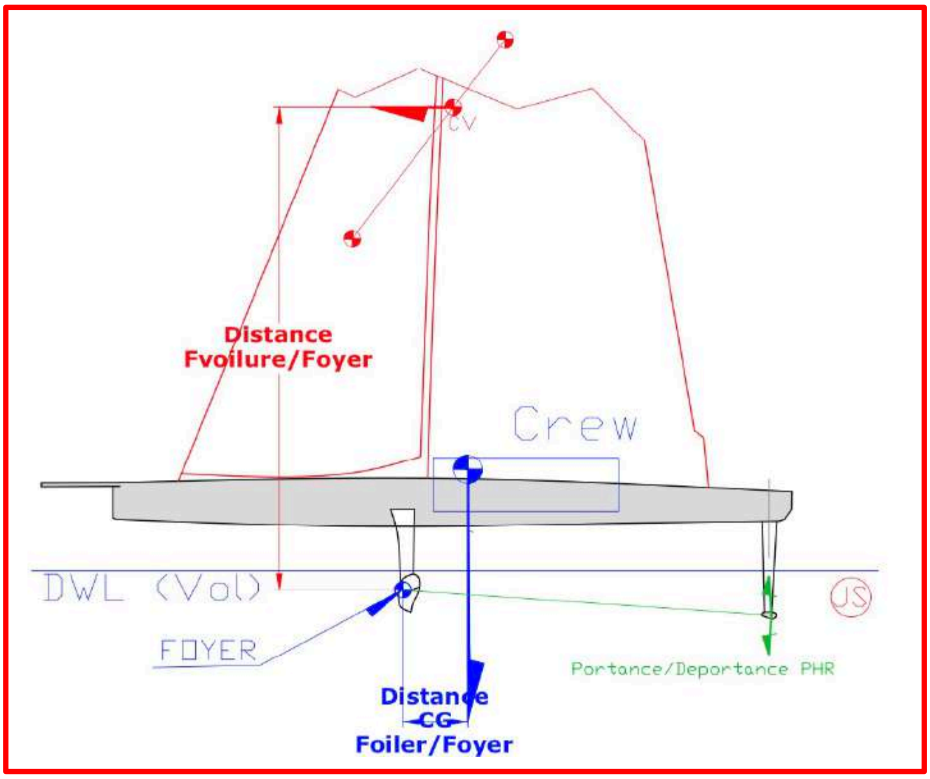
If we want to reason by analogy with the equilibrium in flight of an aircraft, we need to locate the longitudinal position of the focus, roughly on the foil, then that of its centre of gravity and finally the point of support of the veils force.



This is highlighted in the drawing above.

On a foiler, the resulting hydrodynamic focus between the respective centres of lift of the foil, the PHR and the submerged part of the rudder in flight, does not move back very much in relation to that of the foil.

This results in an overall foiler focal point that can be assumed to be the same as the foil profile focal point (25% AR of the leading edge).



In-flight balance therefore comes down to taking into account only the torques produced by the propulsion force (// to the trajectory) at the centre of the wing and the action of the weight of the foiler applied to the centre of gravity.

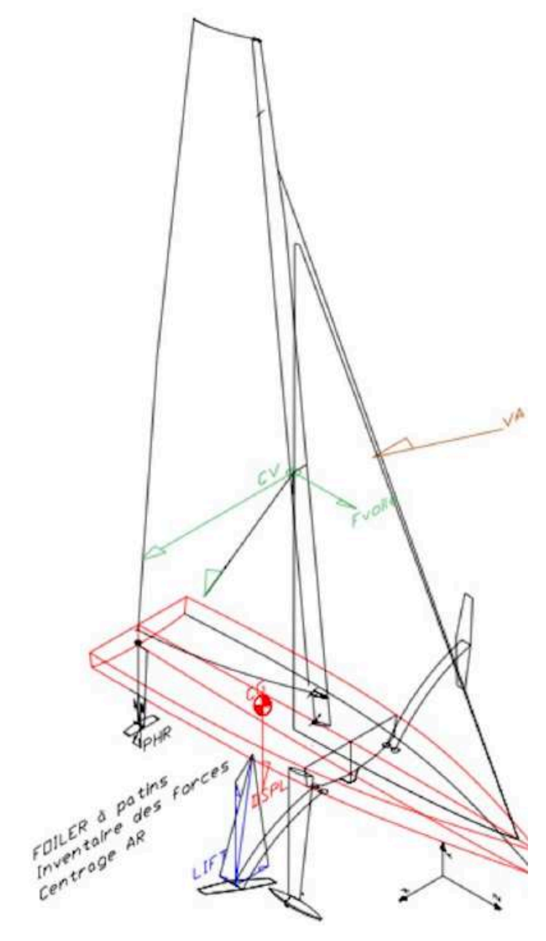
So **Fvoile * 13.665 - (7450 *9.81) * 3.647 = 0.**
With a rear centre of gravity, this gives a propulsion component (Fvoile) of **19505** Newtons.

It is immediately clear that the hypothesis of a forward centre of gravity on a foiler is strictly impossible, because in this case the two torques (**Cvoile and Cpoids**) would be in the same direction: which would lead to the foiler tumbling over the nose

In the conditions of a rear centre of gravity, the pilot must always try to be at the point of equilibrium such that the Fvoile torque and the Weight torque ensure an almost perfect balance. To reach this position, he plays with the lift or offset of the PHR.

The fact that the foiler is unstable, and therefore very manoeuvrable, means that it has very short reaction times, and therefore a very 'linear' horizontal flight.

	FLYING NIKKA vs MOTH	
LHT	18.70	3.55
LFLOT	18.60	3.55
ANGLE du VENT VRAI / Bateau	50.00	50.00
VENT VRAI (TWA) (Nœuds)	20.00	20.00
VENT VRAI (TWA) (m/s)	10.29	10.29
VENT APPARENT (AWS) (m/s)	14.38	11.95
VENT APPARENT (AWS) (Noeuds)	27.95	23.22
VENT APPARENT ANGLE (AWA)	33.24	41.28
Surface de voilure (m2)	233.00	8.00
Force Aéro (Newton)	43361	1028
Force propulsive (N)	14830	351
Force laterale (N)	37551	890
Puissance de propulsion (Watt)	80284	831
VITESSE ARCHIMEDIENNE (nœuds)	10.52	4.60
VITESSE ARCHIMEDIENNE (m/s)	5.41	2.37
JS 17/08/2024		



This manoeuvrability is also enhanced by the fact that the PHR is positioned well aft of the centre of gravity. This means that the lift or offset required to produce the torque needed to maintain the horizontal attitude will require a very low angle of incidence, and therefore very little drag.

On the other hand, you very quickly come to the technical limit of the flight of all these foilers. Indeed, while an aircraft, because of its flight altitude, has a margin of evolution in vertical manoeuvres which normally allows it to recover from a stall or another incident linked to the instability of the environment, a foiler is trapped by its low capacity for variations in flight altitude (50 to 80 cm).

Flying with such a small vertical amplitude, and what's more, when there's sea, requires constant, highly responsive piloting.

On the Moth, the skipper achieves this by moving to windward and longitudinally on the trampoline: this continuously shifts the Moth's centre of gravity. This action, combined with the skipper's constant adjustment of the PHR and the automatic flight attitude management system (stick on the bow), enables the Moth to fly horizontally at a very stable altitude. But remember that the ratio between the weight of the rigged Moth and that of the skipper is around 1 to 2.6.

Obviously, changing the CG position of the boat continuously on a monohull foiler is totally impossible.

Conclusions

At first sight, it may seem paradoxical to abandon stability of flight (remember that we're sailing in 3 dimensions, so with 6 degrees of freedom) in favour of manoeuvrability. In fact, this decision is justified by the fact that the foiler pilot must respond immediately, using a minimum of energy, to faults affecting the performance of the appendages or variations in the maritime environment.

Secondly, unlike an aeroplane, the pilot of a vee foiler is not in control of the (vee) power available. As a result, a significant variation (a drop in wind speed or vice versa) in the propulsion force, which is not necessarily under the control of the crew, can instantly result in a loss of control and a stall of the foil. It is clear that the return to the Archimedean domain must favour a fall to the stern and not a stall.

Flight stability also means controlling pitch and yaw. These two degrees of freedom depend on the hydrodynamic efficiency of the PHR and rudder. A ventilation effect on the rudder that spreads to the PHR renders these two appendages totally inoperative in 2 seconds.

This mainly causes the platform to pitch up if the "Weight torque" is greater than the "Sail torque", or to pitch down if the values of these torques are reversed.

The pilot's two thumbs seem to continuously actuate the PHR's lift or offset at the same time as the foiler's trajectory.

In practical terms, the very high position of the centre of the wing in relation to the centre of gravity means that a foiler has to be centred at the rear.

31. Steering: Man, or Machine

When piloting an ocean foiler in full flight, the pilot abandons the safety aspect of the Archimedean environment. They discover the importance of the horizontal flight plane (attitude and altitude) as a visual reference point, in the knowledge that there is no active safety in flight.

If the foiler loses the hydrostatic effects (lift) provided by its lifting surfaces, it crashes. In flight, at the moment of crash, the foiler's transition to and return from Archimedean mode results in speed differentials dropping from 30 to 35 knots to 6 to 8 knots and perhaps even less in a matter of seconds. During this sudden transition, the stored kinetic energy falls by a factor of 3.5. The platform, rigging and crew are all affected by this sudden slowdown.

Is man capable of piloting an ocean-going foiler?

In Archimedean mode, manual piloting on sight has long used technical aids. Apart from nautical charts, compasses and stopwatches, the first real advances were radio beacons, then speedometers, anemometers and wind angle, initially apparent, then, as soon as the compass became electronic, the true wind obtained using an integrated calculator.

Over the years, as electronics have evolved, these visual aids (screens) have become more and more common. However, in this Archimedean mode, the helmsman retains his natural reference to verticality, day and night, enabling his brain to visualise the horizontal plane... Even without any horizon reference. Note that in Archimedean mode, you can steer a yacht in complete safety using only your sensory perception of the wind (i.e. you follow the wind).

Moth regattas on bay courses show that well-trained skippers are always flying and are real tightrope walkers on the water.

However, transposing this steering system to an offshore or inshore foiler at 30 or even 40 knots (15m/s and 20m/s) in full flight is much more complex to manage.

Manual piloting of an ocean foiler is still possible, but only under certain conditions. Indeed, despite the use of technical piloting aids, there are situations where the pilot loses the external references necessary to maintain correct flight stability

This results, for example, in the loss of horizon identification when visibility deteriorates. The technique of visual flight (VFR[23] *, Visual flight rules*) is based on the pilot's vision of all external references and a few instrumental references.

The perception of the horizon forms the basis of the pilot's decision-making and the processing of information identified by the brain.

---

[23] In aviation, pilots navigating in VFR mode must have a minimum visibility of 1500 to 8000 m and remain clear of clouds (at a minimum distance of 1500 m horizontally and 300 m vertically).

Identifying the information needed for flight stability is a multi-sensory process, with vision remaining the primary element. All visual perception is processed in the pilot's brain simultaneously with non-visual information perceived via other sensors (the inner ear, muscles, supports, joints, etc). All this contributes to producing a correct interpretation of the situation.

The difficulties caused by reduced visibility cannot be resolved by reading instruments alone, but by simultaneously and correctly decoding non-visual sensations perceived even though the brain is no longer fed by the usual images it receives from outside.

But on the other hand, and this is where the difficulty lies in human flight management, what the optic nerve transmits to the brain is not enough for the pilot to have exact situational awareness. Without additional non-visual information, spatial disorientation can occur, even for a very short time

Piloting an ocean-going monohull foiler in full flight will require fairly lengthy practical training. In fact, more and more AC75 pilots are spending hours in front of a flight simulator. This practice is also appearing in the piloting of IMOCA boats, even though this type of boat does not fly. However, it will never be physically accessible to everyone.

So why is it that full-ocean multihull foilers (almost exclusively the longer and wider trimarans) actually fly, while full-ocean monohull foilers flounder?

The answer lies in the lateral stability of a trimaran's platform which, thanks to the laws of hydrostatics and its surface area on the water, always remains close to the horizontal and allows the lifting elements to be installed over a large area. In this way, the flight attitude close to the perfect flight plane becomes easier to control and correct using dedicated engineering.

<u>The Machine is added to Man?</u>

On the face of it, replacing **the man/pilot** in a regatta with a 'machine' seems absurd, because you might as well be racing with Virtual Skipper. However, the complexity of the integral foiler means that this aid has to be incorporated.

The analysis developed above highlights the fact that although man is not intrinsically the weak point in "runaways", it simply shows that **in the time allowed by the speed of the machine for decision-making**, it is very difficult for the pilot to manage the appropriate manoeuvres. It's not that the pilot doesn't know what to do, it's just that his senses don't allow him to control the situation.

For example, humans have a very poor perception of acceleration in a horizontal plane. The important thing is not the perception of the speed itself[24] , but the perception of the moment when the foiler begins to accelerate (or decelerate). This perception of acceleration defines the origin of a series of actions to be taken so that the future flight equations remain operative.

If the pilot does not perceive an acceleration or identifies one with a very slight delay, the actions taken may not the vehicle from going off course.

But perceiving acceleration is not enough. Quantifying this acceleration or deceleration must be part of a structured manoeuvre that corresponds to the in-flight equilibrium to be achieved in the following seconds. This implies the existence of a predefined flight envelope linked to this manoeuvre.

At that moment, the "Machine" intervenes.

32. From controlling a route on the ocean to controlling a foiler in flight.

During navigation, for a long time the point of departure was the only perfectly identified point. After the astrolabe came the octant and then the sextant, which were used to measure the height of a star above the horizon at a precise time (in the morning, for example).

From this measurement, combined with the star's bearing in relation to North and an estimated point on the boat's position, the navigator calculates an intercept and a height line.

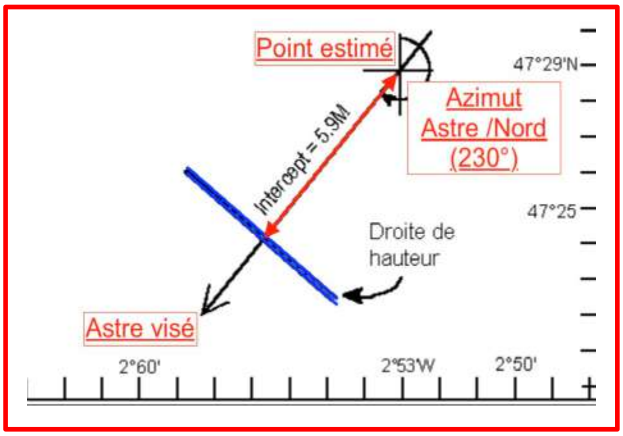
At the end of a measurement, the navigator knows, at best, that he is on this height line.

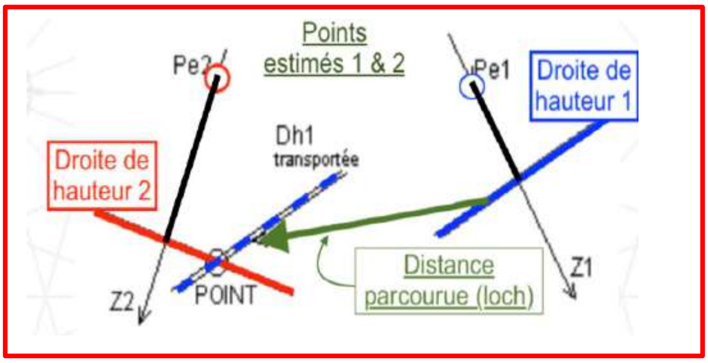
To find out their position in longitude and latitude, navigators must repeat the same operation in the evening before sunset or at midday (meridian).

All you have to do is translate the height line in the morning from the heading and the route taken (loch) so that the two height lines intersect and give the boat's Cartesian position.

---

[24] In a train, the fact that the stabilised speed is 150 or 300 km/h is completely unnoticeable as long as there is no braking (deceleration).





This method of offshore navigation was used until the 1950s/60s, despite the invention of the mechanical gyroscope in 1852. This device is based on the gyroscopic effect produced by a disc rotating at very high speed around an axis. Once launched, the disc tends to resist all changes in the spatial orientation of its axis of rotation.

The simplest and most telling experiment to understand this gyroscopic effect is to hold a bicycle wheel by its hub at arm's length and ask a third party to spin it at a fairly high speed. If, during the rotation, the person holding the wheel tries to tilt it to one side, he or she perceives great resistance to changing the wheel's initial spatial position.

It is this moment of rotation (speed) and the movement around the peripheral mass axis (rim + tyre) that generate the opposition to this movement.

This physical characteristic can only be exploited if we are physically capable of quantifying the variations time and in the 3 dimensions of the angles in relation to the initial position and of the accelerations. The interface between the mechanical effect and its evaluation is very slowly finding a solution, first with analogue


Gyroscope d'un Boeing 737

sensors, then much later with the transition to digital.

Until the 1970s, the mechanical basis of gyroscopes formed the backbone of inertial control units (ICs). This highly sophisticated, heavy, bulky and energy-consuming equipment, whose gyroscope (disc) rotates at 25 or 30,000 rpm and moves in the 3 mutually perpendicular X, Y and Z axes, was abandoned in the early 2000s in favour of components such as fibre optics, lasers and electronics.

This type of equipment is rapidly becoming miniaturised and, above all, much more energy-efficient. For example, the iXBlue control unit, which uses 3 networks of laser gyros (each with several kilometres of fibre optics) and 3 accelerometers, is roughly the size of half a tin of sugar cubes.

In navigation, the route taken to the port of arrival remains the objective of inertial navigation systems. This applies initially to ships and then to aircraft ([25]). However, the actual route taken by the mobile, calculated from the data provided by the inertial unit, remains subject to the accuracy of the sensors and the gyroscope (whether mechanical or other technologies). An inertial unit provides a very precise quantification of roll, pitch and yaw between each deviation from the course (in 3D). The inaccuracies (less than 0.1°) of the roll and pitch implemented at each minute variation in spatial position are used in relative mode.

On the other hand, those affecting the yaw accumulate in the construction of the route and cause an actual deviation from the theoretical route. Over time, this generates a drift.

At present, inertial units produce a yaw drift of:

- Normal: 0.1 to 0.01°/h   Aeronautical: 0.01 to 0.001°/h
- Submarines[26] : 0.001 to 0.0001°/h

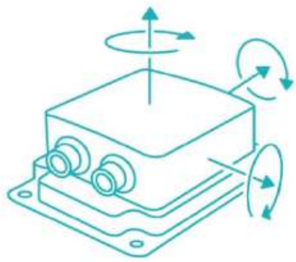
Today, this 'route' function seems almost superfluous, since the GPS (USA), Galileo (EUR) and Glonass (RUS) systems give your position in space in real time. These satellite positioning systems enable the inertial units to be

[25] For a few decades, aircraft crossing the oceans were equipped with a dome where the navigator made the astronomical points.
[26] Since nuclear submarines are only on the surface on departure and arrival (at the same base), it is impossible to readjust their inertial units, which is why the angular sensors are so accurate.

recalibrated, thereby compensating for yaw drift. Note that electromagnetic pollution does not affect inertial units.

Although the 'road' function is often seen as the most common use for inertial navigation systems, this type of equipment is also used for rocket stabilisation, since during a vertical launch, the thrust of the engines and the weight of the rocket[27] (mass *g) plus the air resistance on the rocket body must be opposite and rigorously on the same line. To maintain this balance, the flow of thrust-generating engines is steered continuously using data supplied by an on-board inertial unit.

By integrating micromechanical elements, sensors, actuators and electronic components on a silicon substrate, engineers are revolutionising the design of inertial units. The result is MEMS technology[28] , which enables an inertial unit to be kept to an absolute minimum (volume reduced to around 300) and, above all, to be mass-produced.



Other benefits include lower energy consumption and cost, as well as greater reliability and robustness.

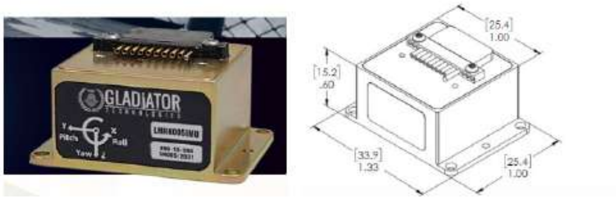
These MEMS units have a weakness in terms of trajectory tracking.

The drift is much greater than on Giro-laser power units.

This 'defect' is not necessarily a problem, since an on-board GPS allows the initial position to be recalibrated at regular intervals. However, this equipment provides accuracy of less than 0.1° degrees for pitch and heel angles.

All these developments and technical characteristics will make it possible to assess and control the horizontal flight of foilers.

Electrical	
Input Voltage	+3.8 V to + 5.5 V Max (single sided)
Power Consumption	250 mW Typical / 400 mW Maximum
Mechanical	
Mass	19 grams
Size	Metric: 2.54 x 2.54 x 1.52 = 9.81 cm³ US: 1.0 x 1.0 x 0.6 = 0.6in³



[27] With every meter of elevation, the fuel level drops and the weight decreases.
[28] MEMS stands for Micro Electro-Mechanical Systems.

33. What applications on an AP?

In-flight piloting constraints require the AP to continuously correct pitch (PHR) and roll (heel) so that the flight pitch is as close as possible to horizontal and the heel (depending on the wind) generates a lateral orientation of the foil such that lift does not decrease.

Only an inertial power plant can regulate these two conditions in accordance with the flight altitude constraint of a few tens of centimetres above the water, while moving at speeds of up to 15 to 20 m/s.

In this flight configuration, the basic variable remains the instability of the boat's speed, since it is linked to the wind power, and therefore to the actual wind in terms of strength and/or direction.

All the lights are green when, with the AP engaged, the boat is stable in flight.

If at any time the true wind speed decreases or increases, the flight becomes unstable.

The immediate translation is a fall or increase in lift, since lift depends largely on boat speed ("V^2" in the lift calculation formula).

At the same time, the boat's pitch and heel (platform) are affected. With less power, the boat collapses at the stern, the angle of heel decreases and the drag from submerged components increases.

Conversely, with more power, the stern of the boat becomes lighter, the heeling moment increases, the efficiency of the rudder suffers, the PHR moves closer to the surface (less homogeneous fluid) and its efficiency decreases.

By comparing the actual attitude during navigation with the horizontal reference provided by the inertial unit, it is possible to re-establish a situation that conforms to the flight plan. The result of the information produced by the AP algorithms depends on the accuracy of these corrections, which are essentially linked to the sensitivity of the inertial unit (IC). The control unit then transmits the information to the rudder control actuators, the foil profile or incidence camber actuators, and the PHR in order to restore the optimum flight attitude.

34. Reminder of piloting modes (in flight mode)

There are three possible control modes:

- **<u>Manual steering</u>** by a helmsman and crew. This type of steering concerns the instant "t". It optimises the boat's performance according to the wind at that moment and the sea state encountered, while maintaining the most correct altitude and flight attitude possible.
  The course to follow is underlying in the sense that it remains an overall objective. This means that the heading at any given moment may be

different from the "target heading". This type of flying is suitable for visual flight rules (**VFR**). Moths or AC75s, which race on a very limited stretch of water, use this mode, but it is unsuitable for ocean-going monohull foilers as soon as they consider sailing offshore.

- **Assisted manual piloting.** By "assisted" we mean assistance in the form of algorithms and also physical assistance (jacks, etc.). This means providing assistance with analysis, decision-making and action. Assisted manual piloting does not use an AP. The orders given by the pilot are sent directly to the "Flight Director" (algorithms) which calculates its own actions according to the possible flight envelope. This is known as a "**Short Term Loop**". A "Short Term Loop" generates fine control, length by length, of the foiler's flight path. The assistance provided can be graduated according to the sporting requirements imposed.
- **The autopilot** manages the Heading[29] or Way Point imposed, the actual flight conditions and the necessary wind power chosen by the pilot, without optimising the foiler's performance. This is known as a "**Long Term Loop**".

Assisted Manual Pilotage

At present, steering assistance systems are fitted to full foilers in very different ways.

In assisted manual piloting, the idea is to design a sort of 'shadow' system that acts between the pilot's commands and the actual commands from the actuators manoeuvring the appendages, in order to achieve the desired objective.

This system becomes a "**flight director**". Its function, if we simplify it, is to keep the foiler horizontal above the water at as constant an altitude as possible, while respecting the 'flight envelope' established by the engineers

This "**flight envelope**" depends on the wing area of the foils, the profile chosen, and therefore their unit coefficient of lift (Cz), as well as the efficiency of the trailing edge flap, the weight of the foiler, and so on.

[29] The course is set by the skipper, either in relation to the true or apparent wind, or in relation to the polars.

It manages:

a) The mechanical elements that control the Micro-Trajectory[30] (3D evolution)
b) Engine power: foiler speed (i.e. the speed of the fluid passing around the foils).
c) Foil lift: the lift you need.

Each of these 3 parameters has its own tree structure, linked by "bridges".

In practice, how is the relationship established between the pilot and the "flight director"?

The flight director assists the pilot in his task of piloting in assisted manual mode.

So, when the pilot initiates a manoeuvre and/or a change in trajectory at a given time 't' during a defined route (heading), he does not act directly on these actuators (flaps, actuators, etc.) but provides the 'flight director (algorithms)' with an **intention**, which may be: a nose-up, a nose-down, a very temporary change in the route (yaw), a change in power, etc. The 'flight director (algorithms)' is then able to modify the trajectory of the aircraft.

This intention is analysed by the "flight director", then compared with the foiler's "possible flight envelope", the current external conditions and the foiler's instantaneous flight parameters.

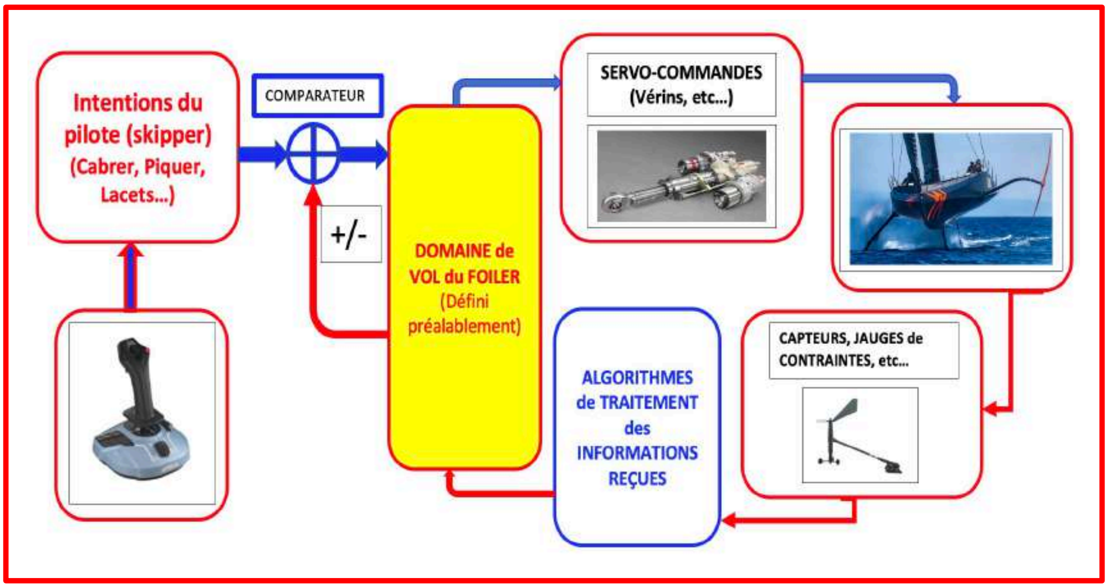
At the end of the analysis, the information is sent to the appendages and power control elements.

The system is such that the results are constantly compared with the targets to be reached (closed loop). All this follows on from each other, adapting as the foiler moves in 3D (flight)

It seems obvious to me that, very quickly, foilers will be actively controlled by processors.

For the moment, this is practically forbidden by the race and class rules, but given the gains in speed and above all safety to be expected from the automation of foiler steering, it's only a matter of time before these barriers come down.

[30] We could say that the Micro-Trajectory is that which corresponds to the few dozen metres travelled, which follow one another ad infinitum. The Macro-Trajectory is the route to be taken (the course).



The Ultim 'Edmond de Rothschild' has already broken free from the rules of the Ultim class for a time. In the America's Cup (AC), this type of assisted steering is forbidden in races, but it has been used to develop steering algorithms and train the crews to try and do as well as the algorithm!

Today, the measurement rules for ULTIMs authorise the use of a servo loop during record races. This means, for example, that the PA can control the aft lifts fitted to the float and central hull rudders.

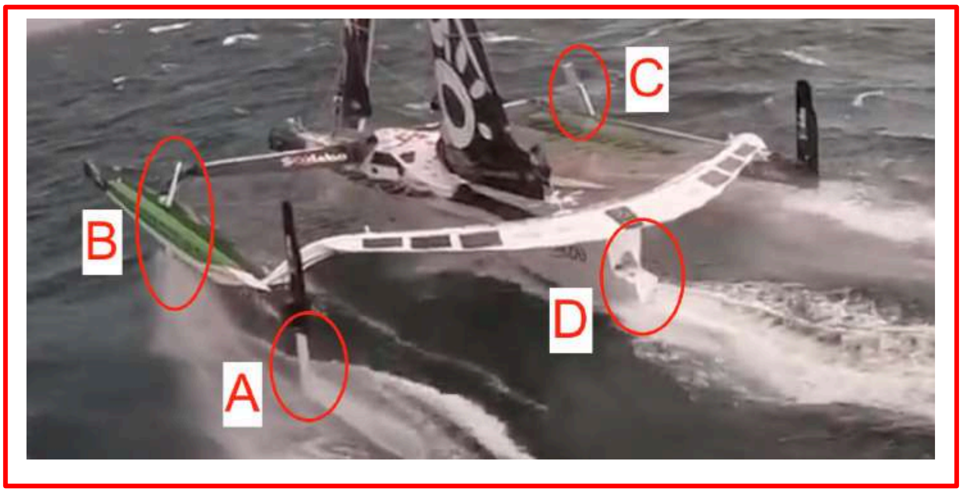
Two SODEBO videos from December 2024 published during the Jules Verne Record (just before rounding the Cape of Good Hope and then on the approaches to the Kerguelen islands from a drone) provide information on how the ULTIM is steered by a crew and how it behaves at sea.

The crew member on watch is constantly manoeuvring a transverse wheel which acts on the trailing edge flap of the stingray wing. In his commentary he says "*I control the centreboard riser*". During the video, we can see the wheel on his back oscillating almost constantly.

On the video taken from the drone, at '**A**' you can clearly see that practically the whole of the leeward rudder is out of the water, just short of the PHR (in fact the whole float is supported).

In "**B**", the foil is fully down, with only the lifting goat visible.

In "**D**", the lower end of the transom of the central hull is at the waterline. In '**C**', the foil is in its highest position.



Controlling the height of the central hull by acting on the effective lift or offset of the foil fitted to the daggerboard (known as the stingray wing) allows this hull to be raised or allowed to fall by its own weight. This action regulates the heel angle by a few degrees, but above all prevents the rear control surfaces (PHR) from being too close to the surface in a highly disturbed flow (water + air bubbles).

What does the pilot do?

In aeronautical visual flight rules (VFR), in addition to seeing the horizon in front of them, pilots control their attitude using the "Aircraft / Horizon" imagery (inertial sensor) displayed on a screen.

It sounds simple. However, the reality is more complex, because on a sailing foiler the power parameter (i.e. the speed) available is very difficult to control, since it depends on the strength and direction of the wind at time 't'.

The wind propulsion vector is potentially less important than the aerodynamic lift of the sail. This makes the foiler underpowered, despite a large sail area. A large part of the aerodynamic lift is 'converted' into drift (hence the risk of capsizing).

All these constraints mean that assisted manual piloting is possible with a crew, but very uncertain single-handed.

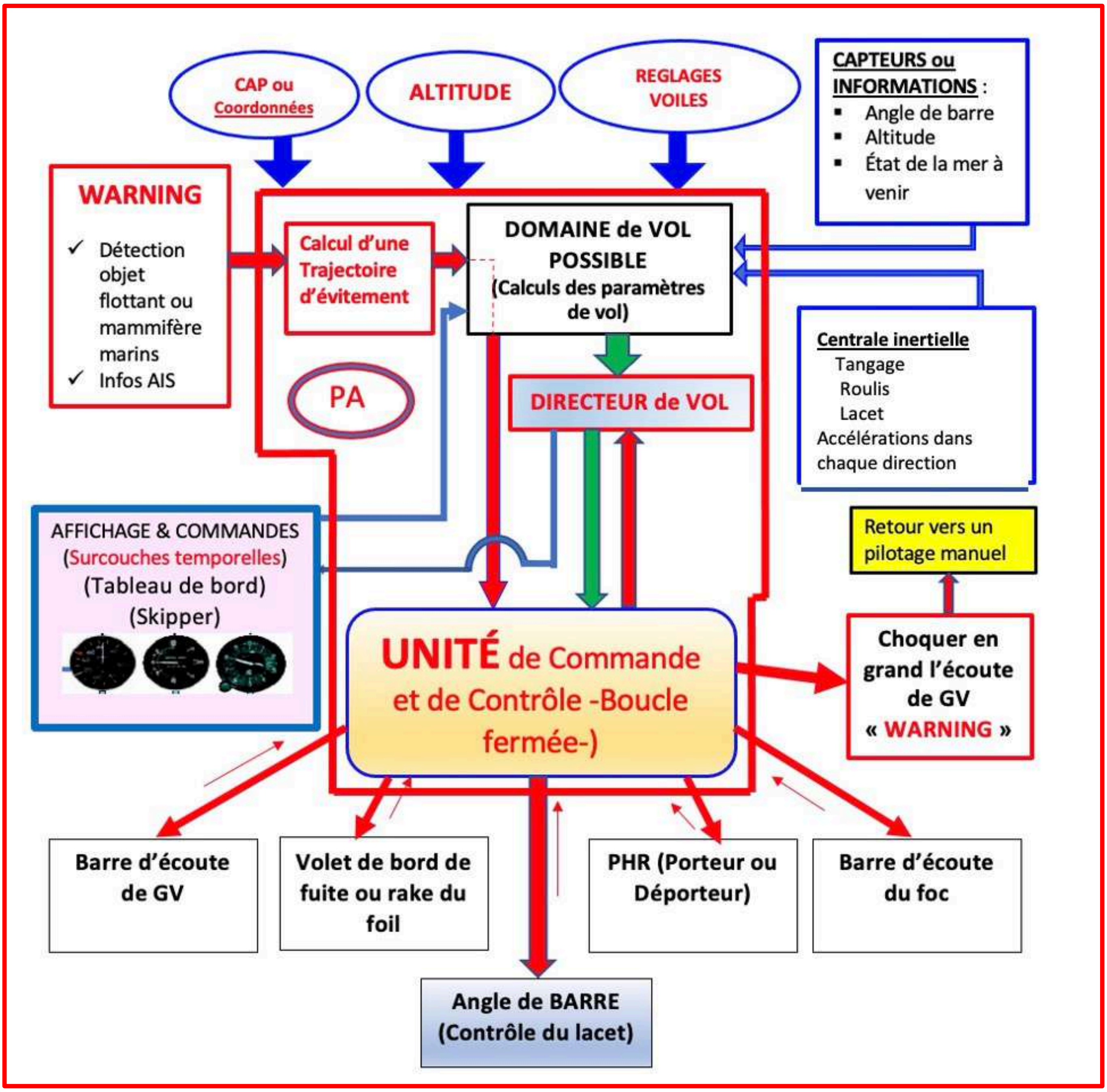
Piloting in "autopilot" (AP) mode

In autopilot mode, the skipper hands over complete control to a 'box' that includes the 'Flight Domain' and the 'Flight Director'. This 'box' then delivers the necessary information to the Control Unit, which executes and controls the actions.)

Together, they form the "PA".

The skipper sets three parameters:

- **The course (or a Way Point)**
- **Setting the basic sails**
- **Flight altitude**



Setting a course or Way Point is the main objective in a regatta.

The constraints associated with flight altitude, flight attitude (horizontal) and wind speed (lift of the lifting surfaces) make the design of an autopilot for a full foiler monohull very complex.

The foiler's flight attitude depends on the speed of the flow of water around the lifting surfaces. It is used at power 2 to calculate vertical thrust.

In theory, a drop or increase in foiler speed, for example from 25 to 24 (or 24 to 25) knots, or 4%, produces a drop or increase in lift of 7 to 8% and, therefore, a high risk of the skipper losing control of the foiler.

The shape of the foil, through its camber modified by the trailing edge flap or its spatial alignment (modification of the angle of incidence) influences the unit lift (***C_z***) of the airfoil. This is also reflected in the lift (vertical lift) in the calculation.

Given the importance (power 2) of the airspeed parameter, in the event of a drop in airspeed, you need to act quickly to maintain lift: the key to flight altitude

On a foiler, three types of action can be envisaged to regulate speed:

- ✓ Either act on the geometry of the foil by increasing the camber, or directly on the angle of incidence.
  This adaptation modifies the unit coefficient of lift, but remains relatively limited in quantitative terms (6 to 10%). In addition, too much camber or too much angle of attack can lead to a stall.
- ✓ Or modify the fluid flow speed, i.e. the foiler speed.

The best and quickest solution optimal and quickest solution is to very temporarily the course of the foiler by a few degrees (luffing) in order to keep the apparent wind as keep the apparent wind as constant as possible. This reasoning also works the other way round: i.e. when the speed increases (reefing). In this case, you have to bring the boat down.

- ✓ In other words, continuously adapting the propulsion of the sails, by adjusting the main sail settings and the way they interact with each other.

All that remains is to provide the AP with data relating to the current external environment and its changes. At present, the current racing rules have to be largely rewritten so that this 'Ideal AP' can be used both offshore and inshore.

35. Data acquisition

Navigation in hover mode remains highly unstable and depends on the precision of the AP's steering. The steering algorithm certainly respects the 3 basic instructions above, but it also and above all depends on the effects of the external environment on the foiler.

There are therefore two families of data:

- Data specific to flight conditions, from sensors or equipment installed on the foiler
- Data relating to the immediate environment.

Data from sensors or equipment:

They are collected from sensors installed on the foiler:

- Mechanical stress evaluation gauges
- GPS data and heading
- Anemometer, wind vane. The speedometer (for Archimedean conditions)
- Acceleration in the 3 axes (linear and rotational acceleration)
- Angular values for pitch, roll and yaw
- Flight altitude. This information, which is essential for stable flight, is very difficult to quantify because the platform of an integral foiler is not always horizontal, particularly because of its heel and also because the surface of the water is far from being a perfect plane.

Environmental data.

- The physical environment in front of the foiler. First of all, there are the other vessels generally identified on the AIS. The significant speed differential with these vessels generates close-quarters situations that can quickly become problematic. There is also the possibility of collisions with marine mammals or floating objects. The speed of foilers amplifies the level of damage resulting from these collisions. AIS makes it possible to manage surrounding vessels and to be identified in the navigation zone.
  The alarms allow avoidance decisions to be taken. However, the detection of marine mammals or wrecks beyond fifty metres from the bow (3.3 seconds at 15m/s) seems difficult and, above all, unreliable.
  And even if detection were effective, the decision to avoid, and especially the trajectory to choose in such a short space of time, seems illusory.
- The state of the sea in front of the "bow".
  A good knowledge of the terrain that the foiler flying at an altitude of about 1.5m will encounter in the next 3 or 4 seconds (i.e. about fifty metres to cover) seems necessary in order to ensure that it is piloted under PA in accordance with the flight envelope. This presupposes a highly responsive system for detecting and analysing the surface of the water.

There are on-board systems for recognising and quantifying the shape of the water in front of the foiler, using digital cameras or laser scanning. However, these on-board technologies (often still at the prototype stage) require technological resources that are complex to install, expensive and very energy-intensive.

Mathematics offers a possible solution based on heuristic functions. A heuristic function is a mathematical tool which classifies the events perceived at time "t" (for example the state of the sea, the wind, etc.) and which, by means of a comparison algorithm (logical successions of "yes/no") with configurations previously acquired while sailing, proposes a solution for what is going to happen at "t+1".

In simple terms, this means: "*I've just been through 3 successive waves and I've just analysed their characteristics. By associating these 3 waves with previous learning and history, I can predict possible developments in the waves to come (i.e. the 4th and 5th waves), and adjust the AP and appendages to cope with this prediction*".

As well as providing a specific solution required at time 't', the interconnections between the algorithms integrate it into the overall database. This continuous enrichment of the database is known as learning and generative AI (Artificial Intelligence).

AI, provided it is embedded (we'll come back to how AI works in a later chapter) becomes a possible recourse for finding an approximate solution to problems when predictive analysis or real-time detection methods prove impossible to implement. [31]

So, we trade optimality, completeness, accuracy or even precision of what we should be doing in an ideal mode for the speed of decision of the corrections to be anticipated and applied to the steering of the foiler.

In the end, the solution produced and implemented on the AP appears to be good enough to solve the problem in question: steering the sailboat in an optimal way. However, it will not be the best of all the solutions. We can only hope that it is as close as possible to the exact solution and that it remains viable because it is very reactive.

[31] When the boat is flying at 15m/s, it is very difficult to detect and avoid potholes and other obstacles in front of the bow and especially in front of the lifting surfaces.

The fact remains that an AP capable of providing control in these conditions depends on technical elements (sensors, inertial unit, power unit, position sensors, algorithms) of a high technological level and, above all, homogeneous characteristics.

36. How a "universal" AP becomes "MyPA

The designers graft and correlate the AP with the physical reality of each boat onto the general AP diagram described above.

Not all hulls have the same characteristics: length, maximum beam, forward shape, transom width, displacement, sail area, etc. Other parameters such as the moments of inertia on each of the 3 axes X, Y, Z, the Archimedean speed polars, the position of the CG (centre of gravity), the rear centre of gravity evaluation, are also used to calibrate the AP.

At this point, the simulator work begins. Dozens of hours flying in the simulator will enable us to validate all this technology and establish the flight envelope specific to this foiler.

Then the tedious sea trials begin. During these tests, the team compares point by point all the work carried out in the simulator and validates it. Normally, at the end of the trials, the flight envelope is established.

Based on this AP in osmosis with the boat, the designers also offer 'personalised algorithmic overlays' which allow the skipper, once the AP is engaged, to finely adapt the information generated to the current conditions, which may be slightly different from those theoretically predicted in the algorithms. And this despite the trials

These overlays focus mainly on the reactivity between detection and adjustment actions. Designers often propose wind filtering in order to clip the angular instability of the wind and its strength. In other words, the aim is to adjust the AP so that it does not respond instantaneously to a shift in the wind. Some AP designers refine performance with more technical overlays that superimpose the basic setpoint (the heading) on the boat's actual speed polars. The aim is then to weight the heading or polar criteria in the route options taken by the AP. Some AP manufacturers are talking about intelligent functions.

37. There's a lot of talk about AI on the pontoons

In the previous chapters I referred restrictively to AI. These days, the press is all abuzz about Artificial Intelligence (AI), which is supposed to replace human beings by helping, replacing and proposing different solutions to problems of all kinds.

Coastal and ocean racing are no exception to this craze. But first, let's be clear about the meaning of these words.

A few reminders: An algorithm is a sequential sequence of instructions which, when supplied with data by an operator or a sensor, enables a problem to be solved (calculations or other types of results). The function of an algorithm is unique. The concept of an algorithm dates back to an invention by a Persian mathematician around 900 AD. A time when no one had even imagined computer science.

AI is not a new concept. Alan Turing[32] laid the foundations in the 1950s by proposing to dissociate the algorithmic, i.e. sequential, analysis that produces the results of calculations from the conceptual and cognitive approach, and thus to build machines that come close to human intelligence.

For Alan Turing, what is calculable will always give the same result. On the other hand, the non-calculable can evolve in unpredictable ways. A typical example of the non-calculable is the sudden changes in air masses in meteorology.

Developments in technology (data centres, super-fast processors, etc....) are now enabling the development of AI in the public sphere.

How does AI work?

AI includes algorithms such as **Machine Learning** and **Deep Learning.** These types of algorithms can be useful for managing an offshore race (piloting, weather, controls, etc.).

Machine Learning consists of letting algorithms discover recurring elements in the data sets available to us. This data can be numbers, words, images, calculation methods, etc. A Machine Learning algorithm learns autonomously to perform a task or make predictions from this data. What's more, they improve their performance over time. Once trained, these algorithms can find recurrences in new data.

Deep Learning is a subset of Machine Learning, in other words an improvement in the way we learn.

It uses algorithms designed to learn from large quantities of data, operating in a way that is vaguely similar to the human brain (let's not be too pretentious). These are known as artificial neural networks.

---

[32] Alan Turing (1912-1954): British mathematician and cryptologist who laid the foundations of artificial intelligence. He is best known for his work on the cryptanalysis of the German coding machine during Ww2.

In fact, they are layers of electronic nodes similar to neurons[33] in the human brain. Materially there is an input layer, one or more hidden layers and an output layer.

Each time a node is passed through, an algorithmic analysis triggers the following alternative: blocking of the information or transmission to the next layer, etc... All the way to the output layer, which produces the result. A Deep Learning model uses hundreds or thousands of hidden layers. The aim of Deep Learning is to improve the automation of one or more tasks.

On the other hand, Machine Learning, like Deep Learning, requires enormous computing and storage capacity because it processes very large quantities of data. For a long time, only data centres could provide both storage capacity and computing power. To meet the needs of video game computing, manufacturers have created new processors that work in parallel with the CPU (Central Processing Unit) that equips all PCs.

Two types of processors:

The **GPU (Graphic Processing Unit)**: created for graphics processing and photos (video games), it can also execute billions of calculations simultaneously and repetitively.

The **nPU** (**neurol Processing Unit**): similarly, **nPUs** are specifically designed to accelerate calculations associated with neural networks, and therefore Deep Learning. These units can handle the matrix and vector calculation tasks found in possible navigation algorithms.

GPU processors dedicated to graphics are relatively power-hungry, consuming around 350 to 500 Watts without counting the PC, so they cannot be taken on board a boat. On the other hand, nPU processors, specifically designed for calculations, consume 10 times less power (30 to 50 Watts). It is therefore conceivable that they could be installed in a PC and taken on board an ocean-going sailing boat, even a monohull foiler. Even assuming that 2 PCs are taken on board (redundant system), this is limited to 200 watts (PC + nPU + storage).

[33] The brain is made up of 100 billion nerve cells, called neurons. Together, they form a highly precise wired network that perceives and transmits information.

In a nutshell...

The **nPU** and, a fortiori, the **GPU** are the essential components for AI today, as they enable parallel and specialised calculations to be carried out.

These types of processors can also be used to design algorithms that interpret the data in the knowledge base and, using general or specific strategies, automatically link them together to solve a given problem.

At the moment, AI can be divided into a number of areas, but this classification may well evolve:

i. **Controlled learning**: given a question, an algorithm analyses existing and verified data and, by sequential successions of "true or false", proposes one or more results to the question.

ii. **Uncontrolled learning**: in this configuration, the algorithm explores the data, whatever it may be, without any control over its veracity in relation to the question. From these results, the algorithm proposes the most logical possible combination of all the data. The result is necessarily heavily influenced by the programmer, i.e. human intelligence.

iii. **Learning from mistakes**: Analysing a mistake or incident to identify and link the causes of the event.

An algorithm can therefore list everything that should not be done in a specific situation. Following a proposed action, this algorithm suggests a response by comparison with what you should not do.

In this way, we are progressively and theoretically moving towards faultless predictions in response to a very precise action.

Using AI on foilers

Artificial intelligence (AI) can certainly play a role in foiler design. AI's ability to analyse huge amounts of data means that it is possible to determine the state of the art before the start of a design, based on sailing, expertise in materials, theses on hydrodynamics and aerodynamics, It can then become a working tool for architects and engineers throughout the design and production process. However, AI alone will never produce the 'foiler of the century', without the talent of the people who hold the pencil.

Other possible uses include routing, even if this is carried out from the boat's chart table. AI can provide an evolution of current meteorological data augmented by a scientific analysis of previous data over several years.

AI and Autopilots?

Currently, APs use algorithms based on fixed rules and traditional control models. While it is not certain that AI will play a direct role in the technical design (at hardware level) of APs, it seems clear that AI offers the possibility of improving the learning phases of an AP, and therefore its optimisation, through its ability to analyse large volumes of data compiled from many hours of practice on a simulator (successes, failures).

In the near future, developments in AI will enable a PA to simultaneously manage the steering of the foiler and real-time checks on the equipment (mast, rigging, etc....) to prevent mechanical breakdowns.

The development of AI and its incursion into the management of the AP's piloting is in conflict with the racing rules (RRS), the wording of which only concerns human action and not algorithms.

38. The RRS[34] 52 - Manual Energy:

"A boat's standing rigging, running rigging, spars and movable hull appendages shall be trimmed and manoeuvred solely by the power supplied by the crew."

Rule 52 of the RRS (Racing Rules of Sailing) needs to be amended in order to pilot a foiler (in flight) by day or night, and even more so single-handed. This rule imposes the exclusive use of muscular energy for all types of manoeuvres on a boat, even a foiler.

For decades, organisers have been adapting this rule to allow energy other than that produced by the skipper to drive certain appendages. This derogation applies to single-handed and double-handed races, and allows the rudder to be controlled by a PA.

Other equipment such as pendulum keels can also benefit from an exemption and be operated by the jacks. However, these operations must never be associated with the PA or another PLC.

Racing is a mechanical sport. The constant evolution of technical developments to improve performance contributes to the enthusiasm of crews for regattas. This scheme works very well when the boats remain in the Archimedean domain. When the boat becomes a foiler, its speed gap is 80 to 100%.

---

[34] RRS: Acronym for Racing Rules of Sailing (international rule)

This new paradigm requires a rethink of the RRS, including rule 52, to take account of foiler piloting techniques. But talking about energy, which we can see is not always purely manual, leads us to talk about daily energy consumption and its corollary, production.

39. Energy required on board an ocean foiler....

Over the years, the demand for energy has grown in order to keep pace with technological developments and to ensure the operation of all the equipment on board,

This is especially true for ocean-going monohull foilers, which must be piloted using an autopilot system that controls all the parameters that manage flight attitude.

A few reference points based on the AC75 foilers and the IMOCAs (Archimedean monohulls supported by two lifting surfaces), although their types of sailing are very different.

An **AC75**, which must be flown in visual flight, uses four cyclists to produce the energy required to ensure flight in compliance with amended rule 52 of the RRS[35] . Experiments at show that one cyclist can produce around 1100 watts for 30 seconds, or 530 watts for 5 minutes, or 400 watts over 20 minutes. Four cyclists therefore develop a potential power output of 1300 to 1600 watts over the 30 to 40 minutes that each regatta lasts.

That's energy of 1450*(30/60) = 725 Wh over 30 minutes.

Extrapolating, a foiler of this type that we wanted to sail 24 hours in a row would consume an average of 34,000 Wh/day of energy (1450 * 24).

A latest-generation **IMOCA** consumes nearly 7000 Wh/day, or 80% less than an AC75 over 24 hours. This comparison only gives an order of magnitude of the respective consumptions. In fact, the type of sailing influences the amount of energy needed by each type of boat to sail. For example, unlike an AC75, which can undertake around thirty tacks or gybes over a 30 to 40 minute race, an IMOCA limits these types of manoeuvres. During the 2024/25 Vendée Globe, Charlie Dalin carried out 25 gybes between the Cape of Good Hope and the South of New Zealand (6,500 miles).

A tack or gybe on an AC75 is characterised by a 65° tilt of each of the two arms, whereas on an IMOCA the keel is limited to a rotation of around 36°.

---

[35] However, this rule 52 is more or less adapted by the organiser.

Like the IMOCA boats, the AC75s use hydraulic jacks for these operations. But that's where the comparison ends. The 4 cyclists on the AC75s act on the internal pressure of one or more hydraulic accumulators, which drive each of the actuators controlling the foil arms.

The windward keel of an IMOCA boat uses a special process. For each manoeuvre (tacking or gybing), the first phase is carried out by gravity up to the boat's 0° heel, then the electrohydraulic pump takes over to send the keel into the wind (70A at 24V for around 2 minutes, i.e. a developed power of 1680 W and 56Wh per manoeuvre).

Service batteries or super-capacitors power an electric motor coupled to a hydraulic piston pump (250 to 300 Bars) to carry out these keel manoeuvres. The decision to use super-capacitors is justified by the very short recharging time of 4 to 5 minutes, using energy from the service batteries.

To keep the flight as stable as possible, manoeuvring the foil arms (AC75 and integral foiler of similar general design) requires a great deal of responsiveness and therefore electro-hydraulic power, as well as an identical infrastructure on each arm.

In addition, this type of design with side foils means that both foils have to be operational for a short time, so the jacks are under pressure every time the boat tack or gybe.

General electricity consumption items include:

⇒ The installation of an inertial unit and its peripherals (micro inertial units of the NEMS type have a permanent power output of 1 to 3 W, or 72 Wh/day),
⇒ Navigation instruments, including the PA,
⇒ IT equipment (mainframes, screens, etc.)
⇒ Lighting, ventilation, watermaker and any ballast pumps,
⇒ A set of sensors, PLCs and data acquisition systems to continuously monitor changes in the mechanical stresses on the platform, PHR, foil flaps, mast, rigging, arms, keel sail and PA.
⇒ PCs equipped with nPUs (200 W)
⇒ Storing data on a high-capacity SSD hard disk (8 to 10 TB) requires between 5 and 7 W, or 144 Wh/day.
⇒ Satellite communications.

The total balance is close to 800 W, or around 19,000 Wh/day.

This energy consumption is not in itself exceptional for a 19 metre foiler with a displacement of 7 to 8 tonnes and a theoretical sailing speed potential of 35 to 40 knots at all times. It's never more than the equivalent of a small electric radiator.

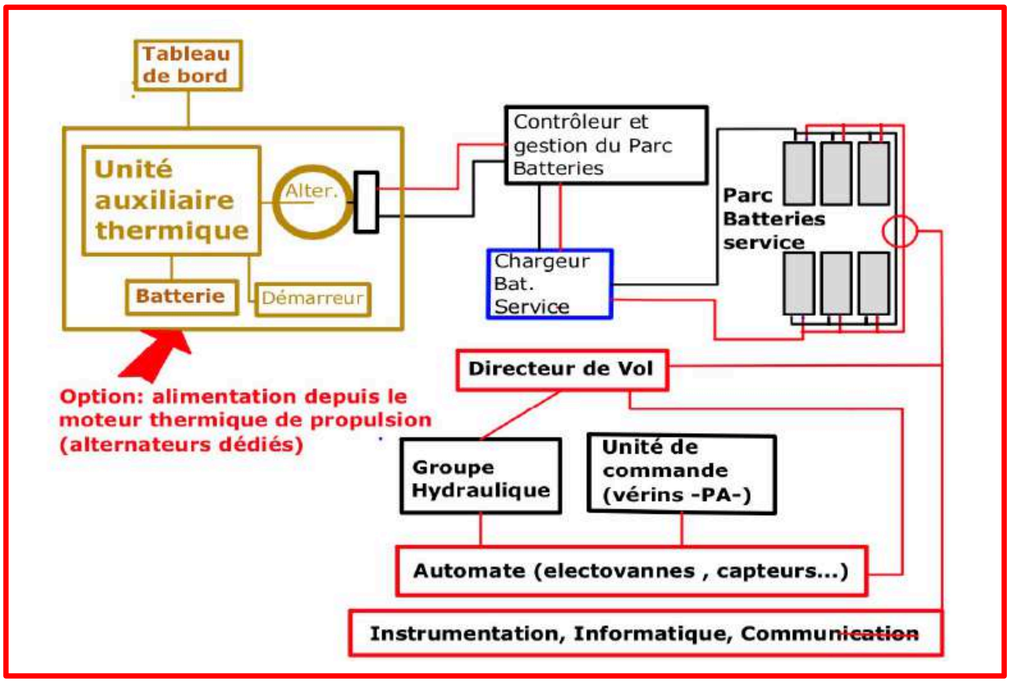
To have electrical energy on board, it has to be produced and stored. There are two reliable solutions for providing continuous power.

Either the combustion engine is used as the mechanical source, to which a suitable alternator is coupled, or a generator set is used solely for the permanent production of electricity (Auxiliary Power Unit).

The difference between the two production methods lies in the way they are used. In the first case, the combustion engine (30 to 40 kW, 1500 cm3) runs only when the electrical level of the battery pack reaches the low limit allowed by the type of battery (lead, lithium, other, etc.), i.e. one to two hours a day depending on the capacity of the on-board service battery pack and consumption.

The other solution is based on a generator set (battery + engine + alternator) that operates continuously. Based on a 200 cm^3 diesel engine with a power rating of 2 kW, the genset provides the electrical power required to consume 0.15 litres per hour at mid-range.

An independent generator also provides a redundant energy production system, since in the event of a generator failure, we can switch to the propulsion engine.



This power generation system uses only hydrocarbons (GO) as an energy source to produce electricity. Since the technique of full flight requires a reliable power supply for all the equipment needed for piloting (including the AP), the autonomous generator appears to be the best technical solution.

An improvement in carbon footprint is possible. Port manoeuvres and any safety interventions require the foiler to be fitted with a propulsion engine. Traditionally, this is powered by an internal combustion engine.

Replacing the internal combustion engine with an electric motor of around 15 kW (around 20 hp) seems possible by combining an increase in the capacity of the battery pack with the operation of the genset. This configuration imposes a fairly rigid protocol for using the available energy, between the capacity of the battery pack and that produced by the genset. However, the electric range will never be the same as that offered by diesel, but it will be sufficient for port approaches and manoeuvres.

The use of solar panels, tidal turbines (difficult to install on a foiler) and wind turbines can reduce the amount of fuel consumed. Wind-generated or photovoltaic electricity is intermittent and uncontrollable. It is conceivable to combine all these means of production, but for a foiler whose weight is enemy number 1, this would appear to be prohibitive. This approach therefore seems unsuitable for a full foiler.

These last chapters deal with flight conditions, piloting modes, assistance from a PA, the introduction of AI, the energy required, the maritime environment... So many constraints which complicate ocean navigation on a monohull or multihull foiler. Can we then ask ourselves the question raised in the following chapter?

40. Does the quest for speed justify the constraints associated with flying?

The technical management of the flight applied to ocean-going multihulls (ULTIM trimarans) is working well, although the authorised level of automation is different between offshore races (World Sailing's basic rules) and records such as the Jules Verne (rules specific to each record). The performances obtained appear to be fairly close to the predictions we were looking for.

Today, average speeds of 24 to 28 knots over long distances are becoming commonplace. They are between 35 and 40 knots when sea state and wind strength allow.

However, the environment and the specific nature of these multihull foilers are confronted with certain constraints.

Firstly, collisions with marine mammals or floating objects.

The consequences of a collision with a floating 'object' depend on the kinetic energy stored by the boat, whether Archimedian or foiler, and on the speed, trajectory and mass of the obstacle encountered.

The latter parameters are highly unpredictable. An empty 40' (12.19m) container weighs around 3 tonnes and has a volume of 70 m3. Its maximum mass can reach 25 tonnes. Its drift speed is very low.

The highly varied nature of the containers' contents and their buoyancy make it impossible to assess the consequences of such a collision. Ships report the loss of containers to the maritime authorities, who set up surveillance of the area.

Récupération par filet et mise en surfût.

Photo : Central Command for Maritime Emergencies Germany (CCME)

For marine mammals, it's much the same problem. A whale, rorqual or sperm whale weighs between 140 and 15 tonnes, depending on the species. A calf weighs 2.5 tonnes at birth...

On the other hand, many floating objects, often isolated, such as logs and metal or plastic drums, are frequent sources of collisions.

In sailing, collisions with objects have always existed. However, the consequences are less catastrophic on Archimedian yachts.

The increase in speed from 8/12 knots to 28/30 knots changes the kinetic energy stored by the boat

$$E = 0.5 * m * V^2 \quad \text{(E in Joules, m in kg, V in m/s)}$$

Here are a few examples:
*100-foot monohull. E = 0.5*28000* 7.71^2 = 833000 Joules (15nds)*
Trimaran ULTIM E = 0.5* 16000 * 15^2 = 1800000 Joules (30 knots)
*60' monohull E = 0.5*9000* 6.1^2 = 171000 Joules (12nds)*
Foiler 60' E = 0.5*8500*15^2= 956000 Joules (30 nds)
E = 0.5*8500* 17^2= 1224000 Joules (33 nds)

In the formula for calculating energy "E", the expression for speed squared (V^2) multiplies the energy by 4 when the speed doubles and by 9 when it triples.

It is also certain that over the last 30 years, the number of floating objects lost at sea each year has followed the curve of globalisation. In 1989 (first Vendée Globe), 0.65 million containers (TEU[36]) were circulating around the world. By 2023, this figure will have risen to 22.6 million. Without following the same progression, the probability of collision risk has increased very seriously.

The combination of the two phenomena (speed and probability), amplified by the wingspan of the foils, and the presence of the PHR contribute to significant material damage in the event of a collision.

Of course, structural engineers take safety factors into account, but they can in no way guarantee that recesses and appendages will withstand the shear forces resulting from these types of collision.

Next, the conditions for manual visual flight.

Having experienced slipping along at 16/18 knots under an asymmetric spinnaker in a Melges 24, I think that piloting a foiler above the waves is surely the grail for the helmsman.

Steering a monohull on a schedule can be very physical, but is still accessible to those who love racing. When sailing, even at high speed, apart from controlling the velelic force by playing with the sheets and the course to steer, the laws of hydrostatics manage the dynamic balance of the boat.

As we saw earlier, sailing a monohull foiler while flying above the water excludes the boat from the Archimedean domain, and therefore from the laws of hydrostatics, and brings us back to the permanent equilibrium of a solid subject to 3 forces: Vessel thrust - Weight of the boat - Lift of the foil.

[36] TEU: Twenty-Foot Equivalent Unit (Container 6.09 m long)

With a crew, piloting an ocean-going monohull foiler by sight (during the day), as is done on an AC 75 (America's Cup), i.e. with just assistance to modify the physical state of the appendages, seems very difficult, mainly because of sea state linked precisely to the ocean environment.

For a monohull foiler crew sailing in visual flight mode at speeds of around 35/40 knots, night-time or blind navigation becomes complicated, if not impossible.

The difficulty of maintaining easily identifiable physical horizontal reference points disturbs or annihilates the helmsman's control of the flight attitude.

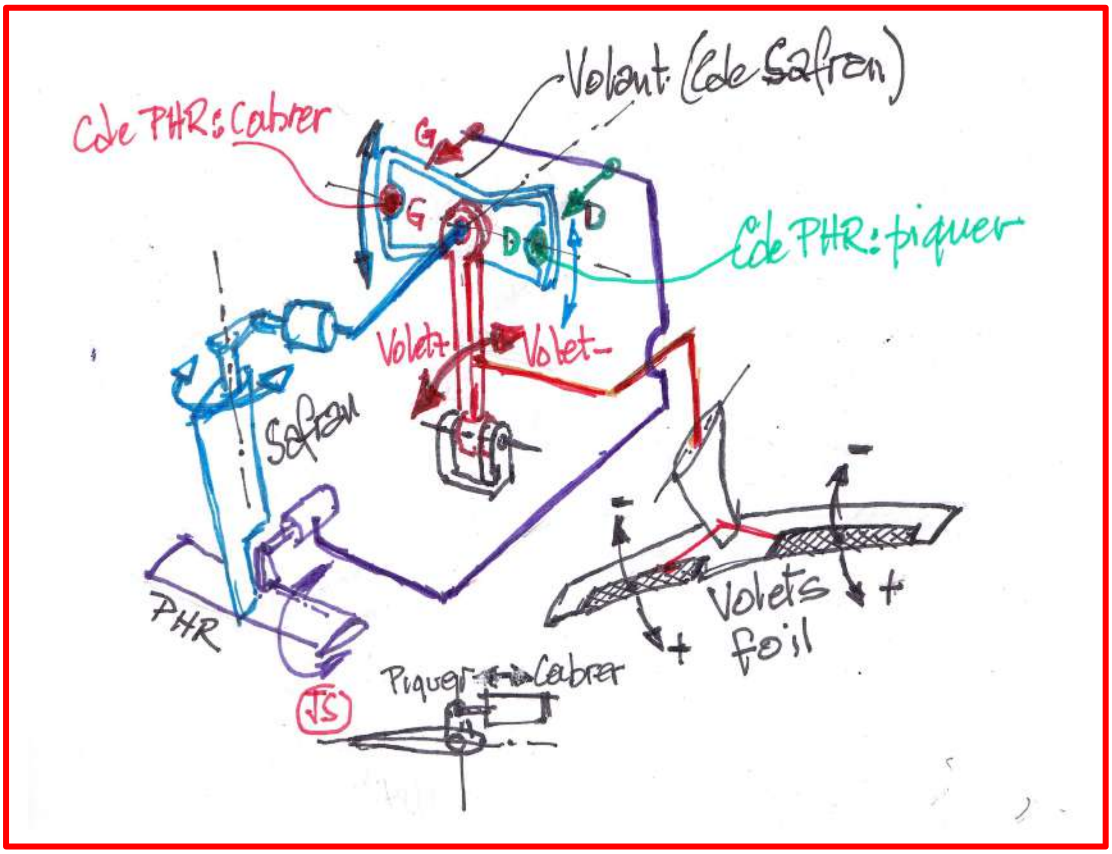
Piloting using only on-board instruments (altimeter, artificial horizon, compass) implies:

A. *That the kinematics implemented on the Moth at helm level (heading) and the PHR control system, which controls the boat's horizontal position in flight (nose up, nose down), be reproduced on the foiler*. Technically, the solution of a steering wheel that operates the rudder, combined with 2 push buttons on this wheel (left and right thumb +/- on the PHR) to operate the PHR control cylinder, works. This configuration exists on the AC75 and GP50.
B. *That a control to control the flight altitude by modifying the lift of the active foil be installed*. Ideally, this control should be linked to the column supporting the steering wheel (the helmsman pushes forward to descend and pulls back to climb) by adding a joint at the base of the column around a transverse axis.
C. *Whether the sails are trimmed by one or more crew member*

At first sight, the helmsman's management of functions A (Heading and PHR) and B (foil lift) would appear to be very similar to those carried out by an aircraft pilot using the rudder pedals (feet) to control the wing flaps and simultaneously pulling or pushing the 'stick' to manoeuvre the PHR (pitch up/down) while manoeuvring the steering wheel to control the yaw.

On a foiler monohull, in visual flight, the cockpit can be inspired by that of an aeroplane. The helmsman manages 3 functions simultaneously (heading, PHR, foil flaps). The advantage of entrusting total control of the foiler reduces the response time for adjusting the flight conditions to practically zero.

The helmsman with full control can compensate for slight variations in wind speed by luffing or leeing around the initial heading.



In the event of strong wind variations, the crew intervenes.

The unique feature of foiler flight is its low flight altitude (of the order of 1m to 1.5m). This implies a flight height fluctuation margin of a few tens of centimetres (+/- 30 cm max). This small fluctuation makes it difficult to adjust the lift of the foil(s).

The sea state also complicates the assessment of the flight altitude. In addition to this need for very meticulous manual piloting, you have to pay constant visual attention to three screens: the artificial horizon, the compass and the altimeter.

This very fine piloting configuration does not exist on an aircraft where instantaneous variations in altitude can reach several metres.

In a single-handed, manual visual flight situation, the skipper cannot abandon this position in order to trim the sails. This constraint effectively prohibits manual piloting single-handed.

These two constraints - the risk of collisions and manual visual piloting - do not preclude crewed sailing on these ocean-going multihull foilers. However, the restriction on visual flight in good visibility limits the scope for sailing.

On hydrofoil monohulls, there is also the need to manage transverse trim (heel), which must be regulated by adjusting the sails. Of the two components of buoyancy, transverse buoyancy is by far the more important.

Unlike Archimedean monohulls, which can be steered manually whatever their size, day or night and even without visibility, it is virtually impossible to steer a monohull foiler manually.

The high transverse stability generated by the surface of the platform of an ocean-going foiler trimaran means that this constraint of blind steering can be more or less overcome.

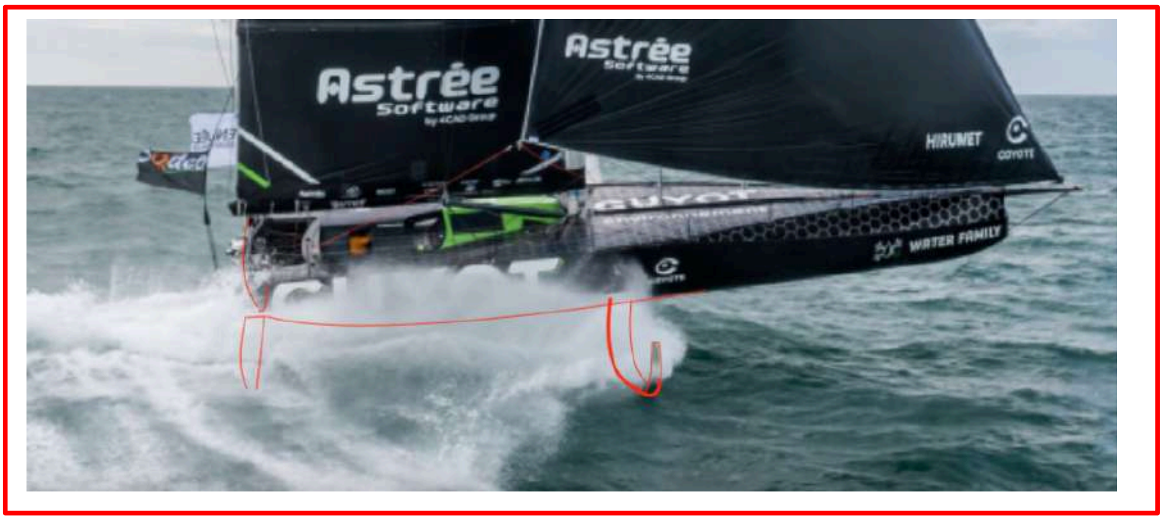
On the other hand, on a trimaran, the surface swept by the leeward foil, the daggerboard fitted with a stingray wing and the two active T-shaped rudders (float and central hull) are all appendages exposed to collisions. The incidents experienced on the ULTIMS show this.

AP-assisted flight

The main constraint is still the same: managing the trim of the ocean-going monohull foiler in relation to the horizontal when sailing at night or in poor visibility.

As already mentioned, only an inertial system combined with servo-controls to manage the appendages can ensure stabilised flight.

41. IMOCA boats: foiler or not foiler?



The idea of racing around the world became a reality in 1973, but with a crew, on IOR[37] boats largely controlled by the Anglo-Saxons. The IOR design favours hulls with relatively high displacement, and therefore limited Archimedian speeds.

[37] See the book "ÉVOLUTION de l'ARCJITECTURE NAVALE en COURSE au LARGE durant le 20(ème) siècle et les années de transition au début du 21ème". https://experts-yachts.fr/blog-js.html

From the end of the 70s, the idea of freeing oneself from the restrictive rules of the IOR and extending the playing field of racing to all the oceans reigned in the offshore racing environment.

Skippers and architects created the BOC Challenge (the race included 3 stopovers) in 1982. In 1989, Philippe Jeantot, who had won the first two BOC Challenges (149 and 134 days), proposed the Vendée Globe, but without stopovers or assistance. Downwind speed became the DNA of this offshore race, which left Antarctica to starboard, as early as the BOC Challenge and even more so with the creation of the Vendée Globe.

Base Devis de poids IMOCA

Description à déduire	masse	/Axe (x)	/DWL (y)	/ PPAR (z)	m*x	m*y	m*z
Plateforme	2.400	0.000	0.500	7.680	0.000	1.200	18.432
EQUIP FIXE	1.170	0.000	0.380	5.550	0.000	0.445	6.494
VOILE de QUILL	0.980	0.000	-1.600	7.690	0.000	-1.568	7.536
BULBE	2.590	0.000	-4.350	7.530	0.000	-11.267	19.503
Gréement complet	0.480	0.000	11.000	6.790	0.000	5.280	3.259
Foil 1 rentré	0.250	2.300	0.730	8.900	0.575	0.183	2.225
Foil 2 sorti	0.250	-3.300	0.060	9.000	-0.825	0.015	2.250
GO + etc	0.350	0.000	-0.150	5.000	0.000	-0.053	1.750
BALLAST AR	0.560	2.100	0.265	2.430	1.176	0.148	1.361
DIVERS + voiles	0.600	0.000	2.500	5.000	0.000	1.500	3.000
Total	9.630				0.926	-4.117	65.809
	masse	/Axe (x)	/DWL (y)	/ PPAR (z)			
CG	9.630	0.096	-0.427	6.834			

Architects then embarked on an unconventional and alternative approach to naval architecture. It was especially after the first Vendée Globe (1989) that totally unbridled innovations appeared, which certainly led to gains in speed, but resulted in very typical designs (flat deck, low freeboards, tiny roof, fragile keel sail), which generated a lot of accidents. The organisers and managers of the future IMOCA class are becoming aware of these drifts and are intervening to curb these architectural ardours.

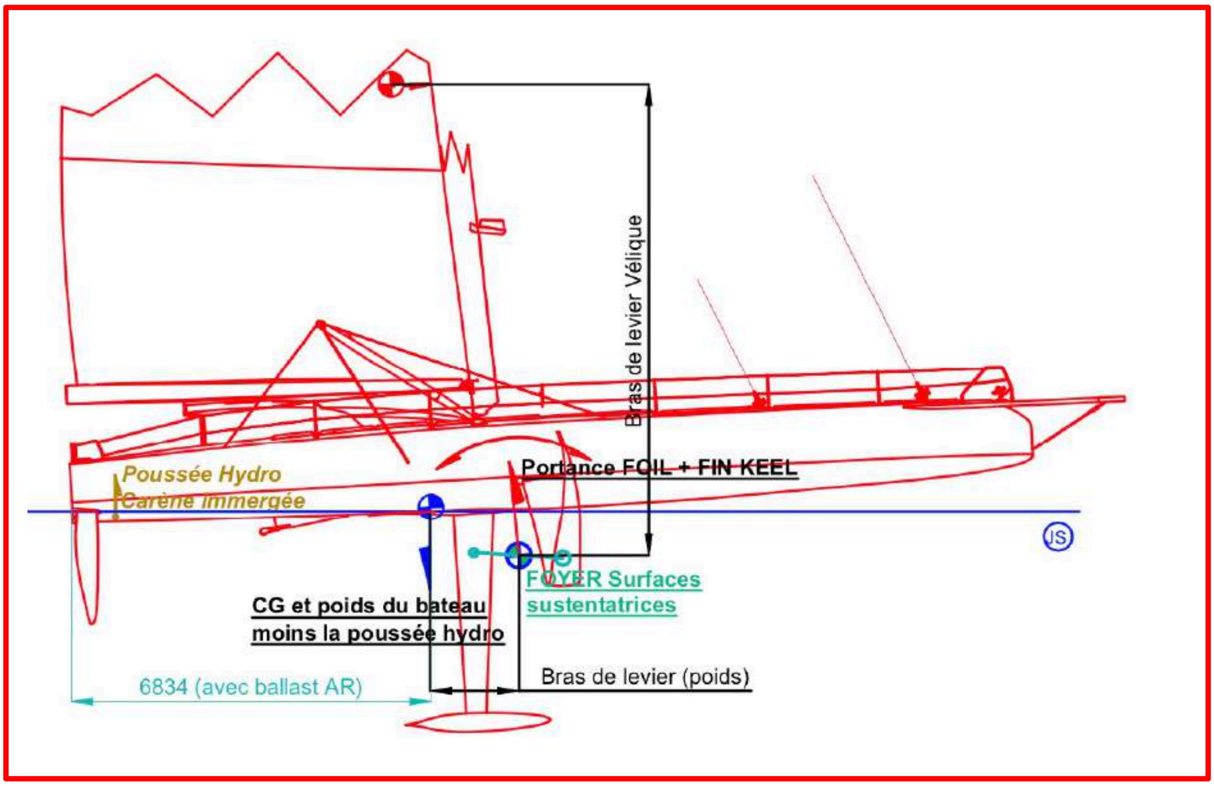
The long evolution of IMOCA yachts actually began in 1998 with the official creation of this class.

Until 2014, the hulls remained Archimedian and stabilised. The idea of introducing[38] foils on IMOCA hulls was born around 2013/14 (between the 2012 and 2016 Vendée races).

The IMOCA class approved the use of foils, but restricted it drastically by limiting the number of movable appendages to 5 (2 rudders, 1 canting keel and 2 foils) and by restricting the number of degrees of freedom of the foils. During the 2015 Transat Jacques Vabre, the few IMOCA boats equipped with foils showed that, despite their complex technical development, foils are making progress in terms of performance.

[38] In 2014, the UNCL published the state of the art on the use of foils on ocean racing monohulls.

In the 2016 Vendée Globe, 7 out of 29 IMOCAs are equipped with foils. At the finish, the rankings were clear: the top 4[39] were equipped with foils. Armel Le Cleac'h won and set the new record in 74 Days.



This raises the question of defining this new type of architecture. Do these new IMOCAs belong to the 'semi-foiler' or 'full foiler' category? The international sporting classification distinguishes between these 2 types: for the semi-foiler, the hull still plays a role (hydrostatic phenomenon) in generating the righting moment, and for the full foiler, the hull is completely lifted out of the water.

As an IMOCA boat does not have a PHR (Horizontal plane Regulator) fitted to its rudders, it is impossible for it to fly horizontally in a stabilised and controlled manner. An IMOCA is therefore a semi-foiler.

This means that the aft volume of her hull always remains partially submerged when sailing and that the Archimedean rules apply, taking into account not only the hydrostatic thrust of the submerged hull and the weight of the boat, but also the "foil thrust - keel sail thrust" component applied to the barycentre of the foci of these two forces.

[39] Banque Populaire, Hugo Boss 3, Maître Coq II, St Michel/Virbac.

This translates into the following vector equality[40] :

$$\mathbf{F_{foil\text{-}finKeel} + F_{hydrostastic} - Masse_{bateau}*9.81 = 0}$$

Avec les foils ancienne génération au VG 2020

When this vector equality is broken, the semi-foiler reverts to a 'pure' Archimedean sailboat, as shown in this photo of Hugo Boss.

As in all motor sports, the trend is always to design 'bigger' to gain more performance. As a result, between two Vendée Globe races (2016/2020), the surface area of the Foils is increasing... the forward shapes are getting bigger, the masts are moving back, and the mainsail leech is getting closer to vertical.

In addition, the fact that the keel sails and masts are shared means that designers have fewer architectural choices.

<u>Why these changes</u>

The combination of lifting surfaces and hulls with more buoyant forward shapes means that the sail plan has to be adapted and the boats' centre of gravity moved further back. Designs are tending more and more towards uniformity, amplified by the constraints of the IMOCA rules. Practically the only freedom to innovate is to play with the shape and span of the foils. This has led to the IMOCA class legislating after the 2020 Vendée Globe to regulate the 'volume' of foils, but without forcing the teams to cut or scrap the foils already built.

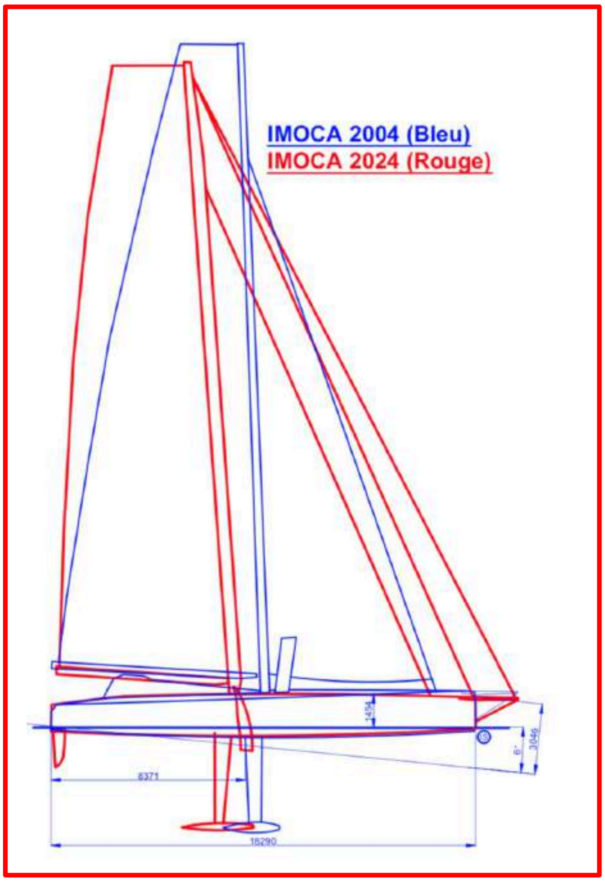
[40] In the case of an integral foiler, the vector equality is: $\mathbf{F_{foil\text{-}finKeel} - Masse_{bateau}*9.81 = 0}$

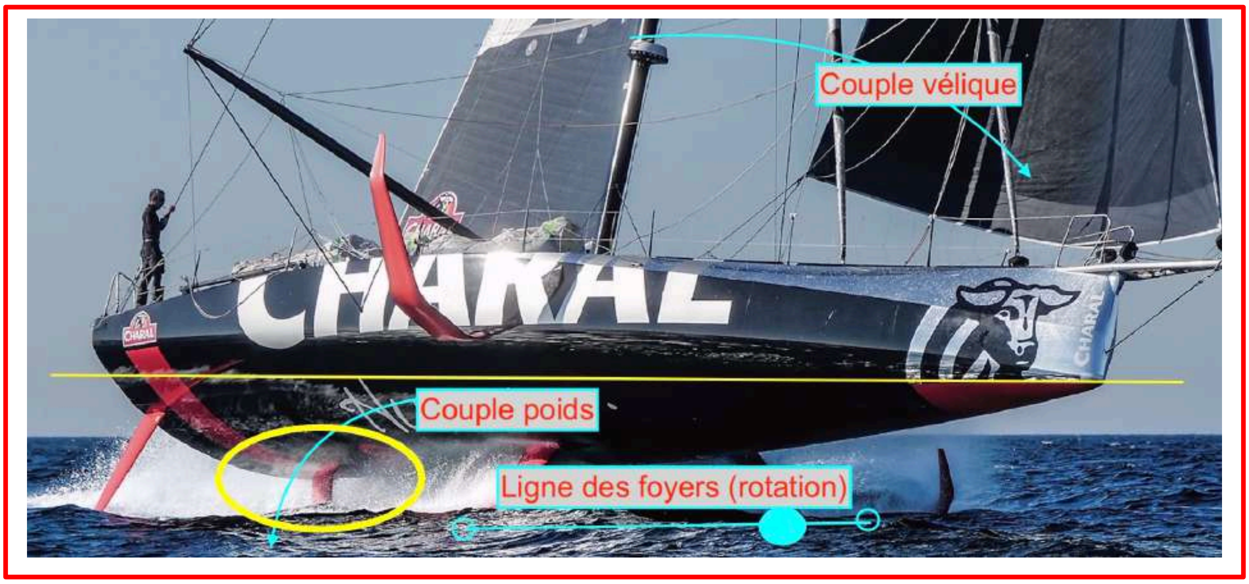
This famous PHR

The IMOCA class rule prohibits the fitting of PHRs on the rudders of IMOCA boats.

Knowing that the in-flight balance of an integral foiler requires pitch control (nose-up or nose-down action) with a Horizontal Planing Regulator (HPR), an IMOCA without a HPR will be sailing in an archimedean environment with a submerged aft hull volume and a very nose-up pitch.

However, can an IMOCA sail at its full speed potential in full foiler mode, which corresponds to a horizontal longitudinal flight attitude?





As the photo above shows, flying "fully" appears to be technically possible.

To simplify, balance in flight results mainly from 2 torques around the line of focus of the lifting planes (keel and foil).

Or :

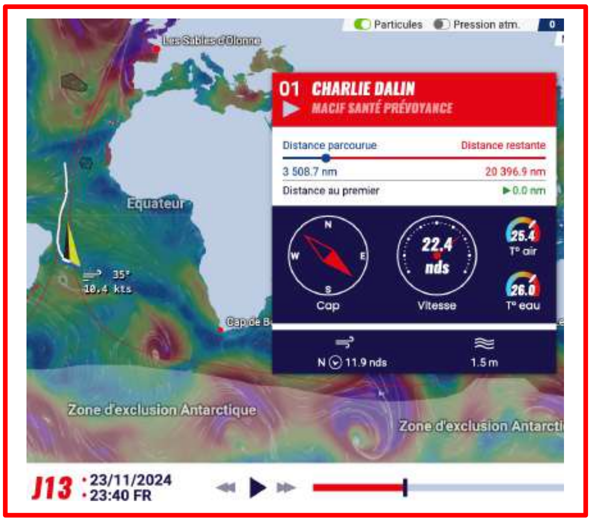
- The veiled torque
- The weight of the boat

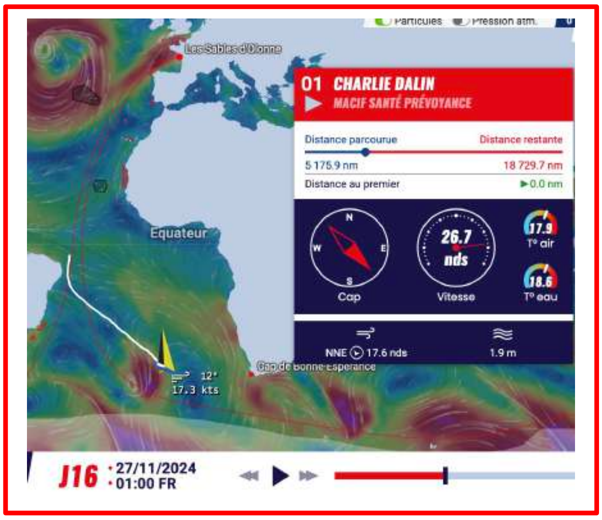
The perfect balance between these two couples can exist, provided that the wind is very regular and the sea state is perfectly flat. However, this equilibrium configuration is short-lived. In this configuration, the foiler will reach speeds close to the 40-knot barrier for a few seconds or minutes.

The inevitable collapse of the balance will brutally cause either the bow to sink or the transom to crush, resulting in a drastic drop in speed and, above all, a relatively long time to get the boat back on course in Archimedean mode. All this assuming no material damage. But in this spatial configuration, the reliability of the steering managed by the AP is illusory, as it only acts on yaw (class rule).

The record (27/11/2024) set solo by Sébastien Simon over 24 hours at 25.55 knots (613.33 miles) represents a fine performance, especially as it was achieved during a Vendée Globe, which is more of an endurance race .

This performance is corroborated by the maximum speeds, which often hover around 23/25 knots, of the winning trio and other IMOCA boats at the same time in the South Atlantic.





ZONE : SOUTH ATLANTIC

Charlie Dalin's performance between J13 and J18 (23/11/2014 to 28/11/2024):

Trajectory superimposed on the great circle route.

Distance covered: 2565 miles

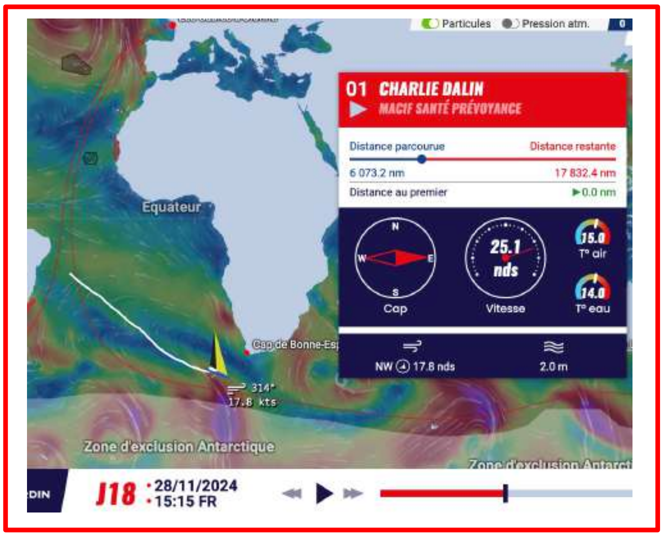
Elapsed time: 110 H

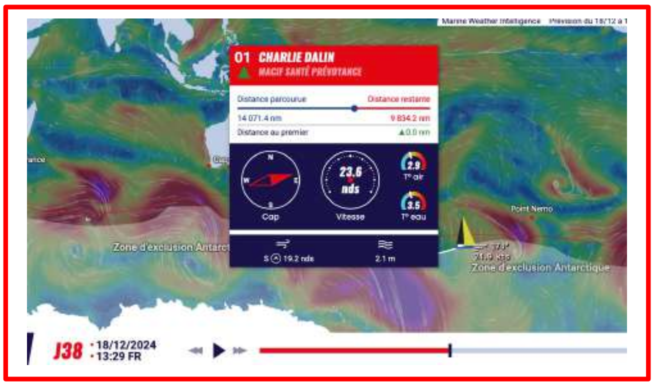
Average speed: 23.31 knots or :

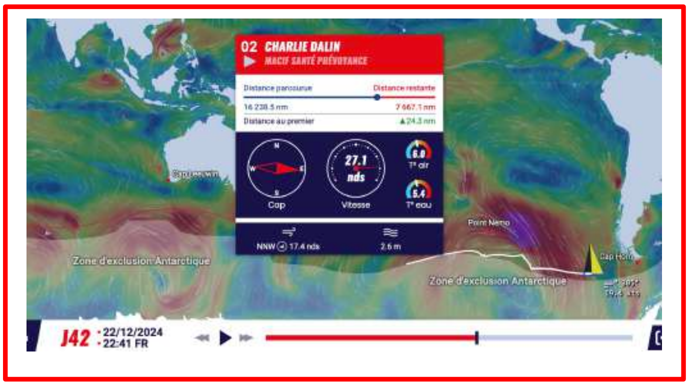
23.31 x 24 = 559.63 miles

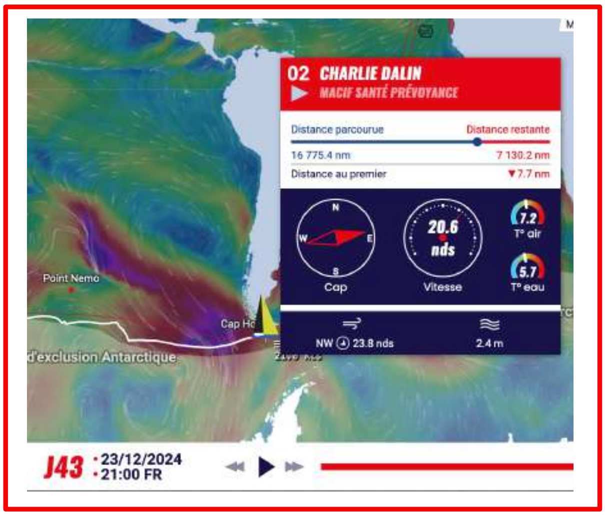
Average per 24 hours: 554.4

(23.1 x 24 = 554.4)









ZONE : SOUTH PACIFIC
Charlie Dalin's performance between J38 and J43:
Trajectory superimposed on the ice boundary.
Distance covered: 2700 miles
Elapsed time: 128 H
Average speed: 21.09
Average per 24 hours: 506.25
Maximum recorded speed: 27.1 knots

These readings, like the averages achieved by the top 3 on their actual routes for the whole of the course (between 17.2 and 17.9 knots), show that the semi-foiler design is 30% more efficient than that of the IMOCAs with canted lateral daggerboards (speed of 13.7 knots over the bottom established during the Vendée Globe 2024 by Tanguy le Turquais).

However, overall, the speeds of semi-foilers remain well below the potential of a full foiler.

The following questions arise? :

⇒ Should we go through the transformation from a semi-foiler to a full IMOCA foiler?
Or
⇒ Improve the design of semi-foilers in terms of drawings and controls on the lifting surfaces currently used?

Converting an IMOCA semi-foiler to an IMOCA full foiler

In theory, it is technically possible to upgrade the current design of IMOCA boats to a **full foiler** model, but for this to happen 4 conditions must be met:

a) Make major changes to the class rules (in particular by authorising more than 5 appendages).
b) Be able to fly horizontally, which means installing a PHR on the active rudder and slaving it to the AP.
c) Be able to measure and manage a flight altitude with an amplitude of variation of 40 to 60 cm, or even less.
d) Agree to give control of the full foiler to an AP who manages the overall spatial balance of the foiler (blind flight). In other words, give the PA control of all the equipment (yaw, power, foils, altitude and flight stability).

Of these 4 constraints, item **d)** appears to be the most prohibitive, as **it transfers all control of** the foiler to an automaton, contrary to the current rule which limits the AP's action to yaw control only.

It's hard to imagine the IMOCA class accepting these sailing conditions. Indeed, these technological constraints completely distort the original idea of the Vendée Globe, as imagined by Ph Jeantot and his friends in the BOC Challenge.

Some people are talking about installing a 'fixed horizontal stabiliser' on the rudders instead of a PHR. This appendage, which must have a symmetrical profile, is totally unviable.

To reduce drag as much as possible, this stabiliser must be set parallel to the sailing trim corresponding to an IMOCA speed below archimedian speed (sailing in light winds).

As soon as the wind increases in intensity, the boat gradually lifts off the windward side under the effect of the tuliped front forms and the keel sail angled to windward (effect of the tilt[41] of the keel pivot axis). If the foil is deployed, the lift of the leeward foil is added.

These vertical forces cause the hull to pitch up around its aft area, and the stabiliser switches to lift mode, immediately generating drag and therefore braking.

[41] Tilt is the angle between the axis of rotation of the canting keel and the boat's horizontal attitude. This angle is approximately 6° and is anti-clockwise.

In strong winds, the foils, given their size, become overpowered. As a result, the pitching of the IMOCA boat increases and the stabiliser becomes increasingly buoyant. These two vertical forces, 'foil lift' + 'rear fixed stabiliser lift', to which must be added 'keel sail lift', then cause instability and a loss of control of the IMOCA, until the water surface is pierced and the lift collapses completely.[42]

To think that a fixed horizontal rudder stabiliser would solve the problem of flight on an IMOCA boat is tantamount to asserting that a rudder immobilised in line with the hull would make it possible to follow an absolutely straight trajectory and do without a PA.

Introducing the semi-foiler foil in a dynamic environment.[43]

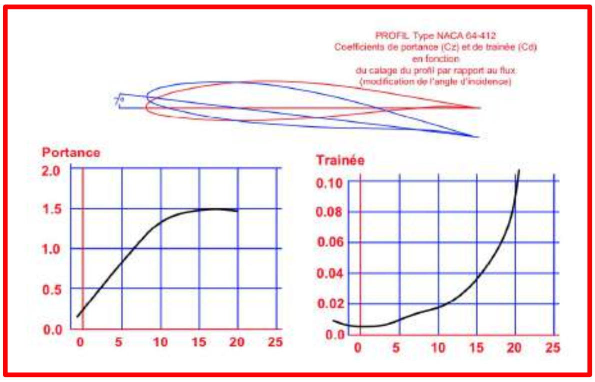
As already mentioned, the IMOCA rules prohibit any modification to the foil profile by means of flaps or morphing (see § 27). Only L-shaped foil geometries are permitted.

The class rule allows 3 degrees of freedom:

- Translation of the body known as the "tip". This part, which has a constant cross-section, slides into the hull. It emerges from the hull through a fixed opening called the 'gate' in the class rule.
- A "rake" rotation gives the foil an angle of incidence limited to 5° in relation to the flow of the fluid in which it is moving.
- The foil can be pivoted around the longitudinal axis of the boat to change the spatial position of the tip.

These 3 degrees of freedom must be controlled manually using simple mechanisms (sic). This class rule makes it impossible to continuously adjust the angle of incidence of the foil, on which lift depends, and thus to avoid periods of overpower or the opposite.

The skipper can only look for an average setting valid for the coming hours of sailing



[42] This same phenomenon of loss of lift would also occur on an aircraft that maintained take-off angle of attack until an altitude of around 15,000 m and then broke through the atmosphere in an attempt to penetrate the stratosphere.
[43] Paragraph developed in collaboration with Robert Lainé.

Between two consecutive fixed settings, the flow of water due to waves, pitching and rolling modifies the real incidence, and therefore the unit coefficient of lift Cz (see § 26) and, as a corollary, the coefficient of drag (see opposite).

The longitudinal trim of a semi-foiler is characterised by hydrostatic pressure on the aft area of the hull. A sudden increase in lift from the foil and keel sail causes rotation around the volume close to the transom. These lifting surfaces are located on average 8.30 m from the point of the transom.

When the IMOCA is sailing at 20 knots (10.3 m/s), a vertical speed of 1.0 m/s at foil level generates a variation in the angle of incidence of 4°44 . [44]
The foil set at 5° to the horizontal generates a Cz of 0.75.
An increase of 4°44 transforms the angle of incidence from 5° to 9°44, generating a Cz of 1.15.
The lift curve shows that a Cz of 1.15 approaches the rounded shape of the curve, leading to the stall value Cz= 1.4 and the instantaneous loss of lift.

But as the angle of incidence increases, so does the drag. The unit coefficient of drag increases from 0.0067 to 0.0145. That's a 2.16-fold increase, while lift increases by only 1.5 times (0.75 to 1.15).

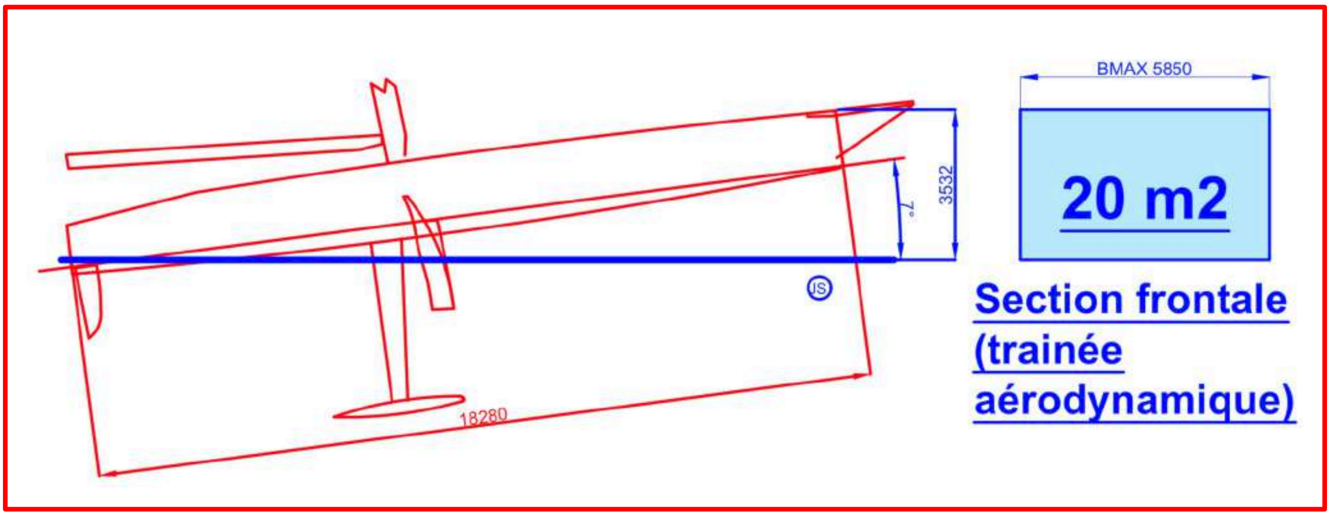
⇒ Initial incidence of foil: 0.75 / 0.0067 = 111.94
⇒ Dynamic impact of the foil: 1.15/ 0.0145 = 79.06
In other words, an efficiency loss of -29%.

The pitching up resulting from this dynamic effect increases the frontal dunnage of the hull, and therefore the drag, which in the worst-case approaches 20m2. It's true that in this very nose-up configuration, the wetted surface area of the hull is reduced, but I'm not sure that the balance in terms of speed is positive.

With this pitch and 10 to 15° of heel, the coachroof fairing, apart from providing protection and comfort for the skipper, has little aerodynamic effect.

---

[44] Result obtained from the time taken to cover 8.30 m at 10m/s (0.805s) and the rise in speed of the foil at 1m/s in the same time.



Overpower : Cabrage

Ideal pitch (low pitch)

Comment by Thomas Ruyant, skipper of "VULNERABLE":

Top speed" is not the goal. What we want above all is average speed over time. Because, sometimes, the boat can go up to 36 knots but if we fall back to 12, the compromise is not good. But if we find a stable speed of 25-26 knots, that's perfect.

<u>What type of pitch adjustments are possible under the IMOCA rules for a semi-foiler?</u>

Let's start with the assumptions:

- The boats are permanently under autopilot (AP)
- The AP, however "intelligent" it may be, only controls the yaw.
- The incidence of the foil must be set manually and cannot be controlled by the trim or other parameters such as wind strength (detection of oversteer).
- Because of their size, the foils used often appear to be overpowered.

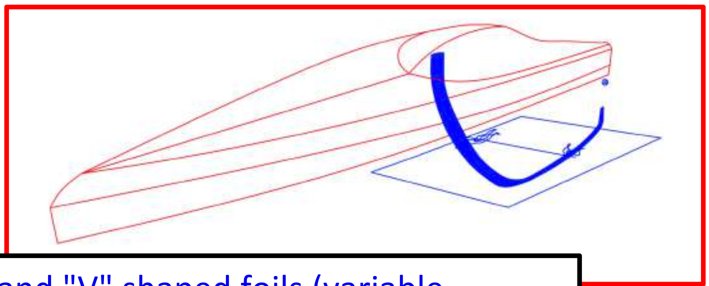
On the basis of these assumptions, the only possible options are as follows:

- Design foils that are less extreme dimensionally.
- To find a technique for regulating the lift of the active foil without affecting the angle of incidence preset for the current conditions.
- Achieve this control without using a servo connected to the PA. This amounts to imagining self-regulation of the foil's lift.

Variable submerged surface

The bearing surface of the foil that counts is that which is in the water. Since air has a density 800 lower than water, we will neglect the lift of the part of the foil outside the water.

To adjust the foil's lifting surface, this surface must be inclined in relation to the surface of the water (incidence). The higher the foil rises, the smaller its surface area, and vice versa. This solution is as old as hydrofoils because it is self-regulating and simple to implement. As speed increases, the thrust generated by the foil increases, the foil rises out of the water more and thus reduces its surface area: this reduces the lift until the new equilibrium point is reached.



U" and "V" shaped foils (variable submerged surface)

However, this solution has a number of limitations:

- The first limit comes from the ventilation (see §19) induced by the foil as it crosses the air-water interface. This phenomenon can lead to a sudden loss of lift, even at low speeds.
- The second limit comes from the uncontrolled variation in lift as the foil crosses the waves. When it encounters the front of the wave, the sinking of the foil increases and the same effect occurs on the lift. The boat rears up
  After passing the top of the wave, the submerged surface of the foil suddenly decreases, causing the boat to nose down.
  In the case of short waves of limited amplitude, a vibratory regime is created at the rhythm of the waves: a phenomenon to be taken into account when calculating the boat's structure.

When the waves are of greater amplitude, a sudden fall of the boat (collapse of the lift) occurs after the top of the wave. The speed of the vertical fall increases the incidence of the flow on the foil beyond 12° (see above), and the foil suddenly stalls. The boat's hull falls back into Archimedean mode. The process starts again with the next wave...

Trailing edge flap

This is the technology used in aeronautics, but also on the Moth Foiler and the AC75. The trailing edge flap (§ 15) modifies the camber and modulates the lift. The advantage is that, depending on the angle of the flap (positive or negative), the foil changes from lift to drag, which regulates the foil's altitude in relation to the surface of the water. But for an IMOCA, the installation of a flap is firstly prohibited by the class rules and secondly, even if this prohibition were lifted, the 'L' shape of the foils makes the installation of a trailing edge flap technologically extremely complex and probably unreliable.

Ventilation of the upper surface

On a NACA-type profile, the top surface of the profile produces 75% of the lift and the bottom surface 25%. A possible and effective solution is to create a phenomenon of controlled ventilation by injecting air from the core of the foil onto a defined surface of the top surface. In this ventilated area of the upper surface, the air replaces the water, locally destroying the lift. This causes the foil to fall in a controlled manner.

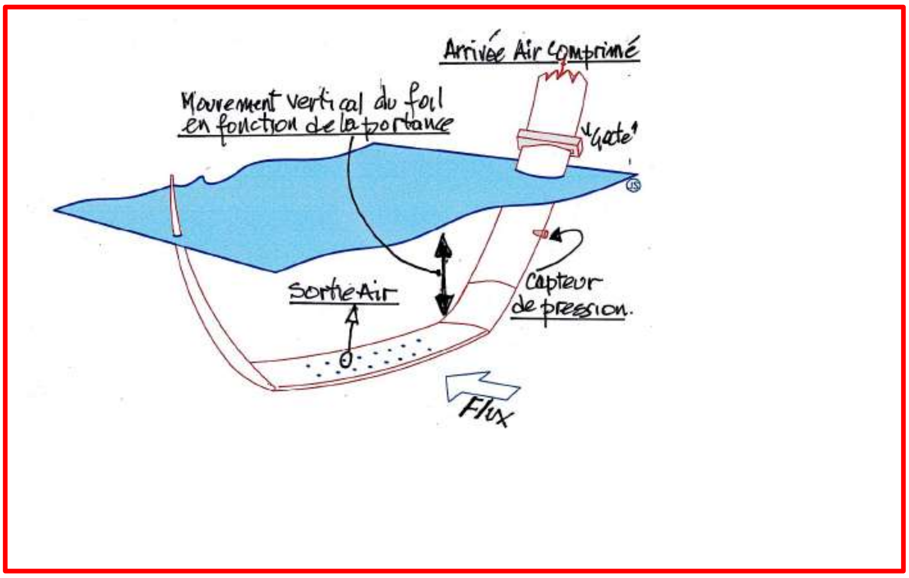
With the foil submerged, when the ventilation effect is removed, the water layer is re-established almost instantaneously and the foil regains its initial lift

This control method assumes that the lifting surface of the foil is in a zone that is deep enough in relation to the air/water interface.

The idea is to design foils with a lift zone that is more or less horizontal to the usual angles of heel.

Technically, the system can be very simple. A compressed air unit (5 to 6 bars) connected to a hose (internal diameter 16 mm) feeds a 40 cm long clarinet integrated into the horizontal part of the foil. This clarinet feeds a dozen 8 mm diameter nozzles fitted flush with the surface of the upper surface (virtually no drag). All these components are moulded into the foil's core.

A pressure sensor embedded in the leading edge of the shaft, connected to a control box, controls the solenoid valve that sends compressed air to the top surface. As soon as the pressure sensor is close to the water/air interface (the horizontal part of the foil approaches the surface), the pressure drops and the solenoid valve lets the compressed air through.



Under the effect of the ventilation created on the upper surface, the lift drops and the immersion of the foil increases. Pressure increases and the solenoid valve closes. Water replaces the air and ventilation of the top surface is stopped. The foil regains its initial lift. The management of the top surface ventilation automatically regulates the immersion of the foil in relation to the water/air interface.

The management of the top surface ventilation can be technically improved, but its self-regulating principle is retained.

42. Faster and faster... through the centuries, but ...

It's a fact that over three millennia, the speed and development of boats have never stopped increasing. However, regardless of the era and especially the technological environment, we can see that during each period, speed gains stabilise more or less quickly, as if the technology of the time was in its infancy and no longer allowed progress to be made. It then became necessary to change the paradigm.

This was the transition from galleys propelled mainly by oarsmen to square-rigged sailing vessels.

Over the next two and a half centuries, scientific analysis improved hull designs. Sailing warships and merchant ships with hull lengths of up to 90 metres sailed the oceans.

Towards the middle of the 19th century, several events came together simultaneously: work on hydrodynamics and its corollary, the passage of hulls through the water, the industrial revolution which led to the reliability of the steam engine and the discovery of the propeller. For a hundred years, maritime gigantism had no limits.

Each of these periods saw unbridled scientific and technological development, making anything seem possible. However, despite the technological and financial excesses of these projects, speed gains have stalled.

At the crossroads of the 19th and 20th centuries, the aeroplane was born. Immediately after the first flights, engineers dreamt of applying this technique to water. The idea was not far-fetched. Water and air are two fluids, albeit of different densities. However, some people are asking themselves the following question: a wing supports an aeroplane in the air, so why shouldn't a boat fly if it is equipped with a wing (foil) that moves in the water? The hydrofoil is becoming a reality.

But the desire to fly led others to create a kind of aircraft-ship, a disproportionately large hybrid machine. The first of these was the Ekranoplan[45] , designed in the 1960s and built by the Soviets. The adventure lasted just over twenty years, although projects still exist today.

We had to wait until the middle of the last century to see the first hydrofoils explode the speedometers. Here again, reality (the price of energy) or pragmatism (maintenance, collisions with floating objects) brutally reminded designers.

Sailors then took up the concept and embarked on the "foiling" adventure. It would take almost 60 years to finalise a sailing foiler capable of flying on ocean voyages.

Today, the technical developments of full or semi-foils for ocean sailing appear to be fairly mature and reliable. However, we are discovering that an 'aero' (subsonic) foil inexorably cavitates and loses all its lift when the speed approaches 40 knots (see §20 above). In theory, this wall can be overcome by using super-cavitating airfoils, but the velic power required for take-off is not (and never will be) available with velic motricity. There is no such thing as a post-combustion wing.... So, we'll be stuck with cavitation-type foils. In these conditions, full foilers, whatever their length and weight, will fly at more or less the same speed as long as they have equivalent $weight^{1/3}/sail^{0.5}$ ratios.

[45] https://www.lecurionaute.fr/ekranoplan-geant-avion-bateau-russe-effet-de-sol/

We have also observed that flying a few tens of centimetres above a body of water agitated by waves seems to be beyond human capabilities. This is all the more true in the case of a solo offshore race. The assistance of a PA becomes essential. This PA must act on all the factors that enable the yaw, pitch, roll and flight altitude to be controlled.

The rules of offshore racing (the use of manual power to manoeuvre a boat, even a foiler) currently prohibit the continuous control of horizontal flight by APs. Of course, these rules can be amended, but then the whole philosophy of offshore racing changes paradigm. To date, only ULTIMS are exempt from the racing rules during record races (Jules Vernes Trophy).

This is the limit of the exercise. Transferring flight control from a full foiler to an AP is tantamount to eliminating the human pilot, leaving him or her solely to choose the routes via the Grib prediction files. This is without taking into account the possible intervention of AI in forecasting the evolution of these files. In this context, the future of full ocean foilers seems to me to be unviable from a sporting point of view.

On the other hand, semi-integral foilers can still make considerable progress, provided they abandon the quest for maximum speed, close to the 40-knot barrier, as this quest for speed generates permanent hydrodynamic instability resulting from the uncontrollable pitching of the 'boat', and makes it impossible to achieve consistent, stable average speeds on the high seas.

This evolution involves self-control of the lift of the upper surface of the foil's active surface (see § 41 above) as a function of its immersion. This means regulating the hull's pitch up to a more stable attitude and thus improving average speeds, while leaving the AP with exclusive control of the programmed route.

This technique seems much more flexible than having the skipper 'choose' a fixed value for the 'rake' for each section of the sail. This choice of foil incidence is never correlated with the power developed at each moment by the pre-set sail.

Lorient 14 February 2025
J.S