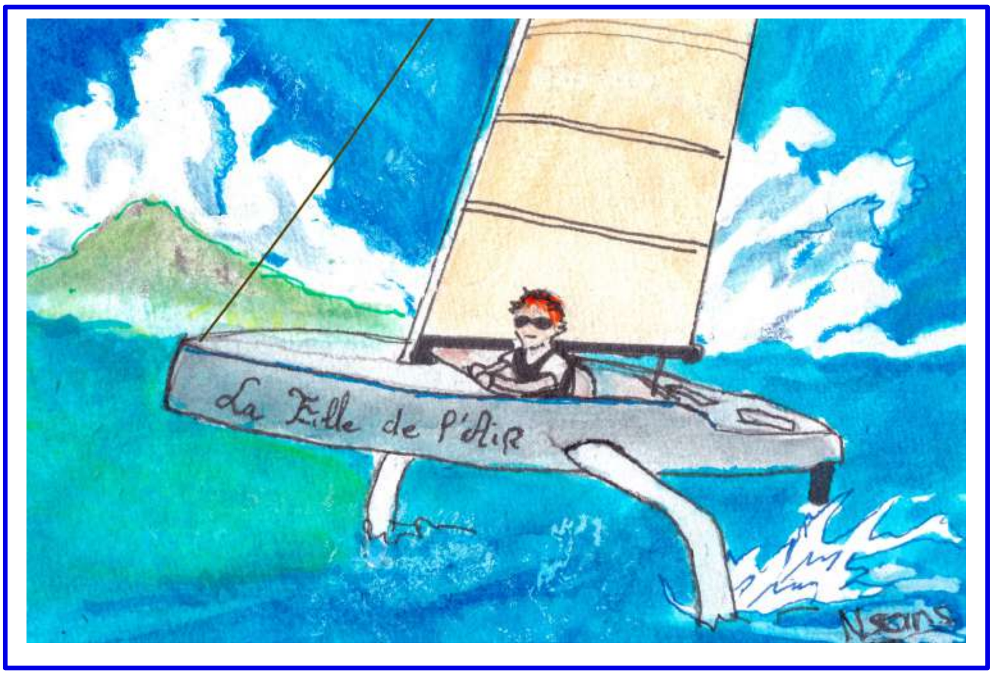
FLYING WITH AN OCEANIC FOILER



Sailing across the water's surface in an ocean-going sailing boat allows you to travel significantly faster than in Archimedean mode. However, because the course is bumpy and the boat's speed depends on the wind, the manoeuvre proves complicated and requires the subtle combination of several appendages to achieve it. Explanations and comments.

Jean Sans.

With editorial collaboration from Patrice Carpentier.

Translated from the French original.

Contents.

Part 1: The technique of stabilised flight

A little on terminology

Sail-powered or motorised foiler: An Archimedean platform supported entirely by one or more foils.
PHR: Horizontal stabiliser. A profiled surface with a symmetrical cross-section, mounted at the tip of the rudder. Depending on its trim (angle of incidence), it generates lift (nose-down action) or downforce (nose-up action).
stingray wings: A profiled surface with a symmetrical cross-section, mounted at the tip of the keel, a bulb or a centreboard. It acts like a PHR.

Lift generated by foils (foiler) versus wings (aeroplane)

The same physical laws of aerodynamics apply to lifting a foiler out of the water as to lifting an aeroplane off the ground.

The foiler or aeroplane remains airborne under the action of three forces:

- The force **Fv** produced by its propulsion (sail or mechanical).
- The force **P, which is** vertical and directed downwards, resulting from its mass (Weight = mass × acceleration due to gravity).
- The aerodynamic lift **Fz** generated by the wing or foil. $\mathbf{Fz = \frac{1}{2} \times \rho \times Cz \times S \times V^2}$

In this formula:

- **Fz** = aerodynamic lift
- ρ = Density of the fluid (kg)
- **Cz** = unit lift coefficient (dimensionless)
- **S =** Area projected onto a horizontal plane
- $\mathbf{V^2}$ = Speed of the moving object, squared (i.e. the speed of the fluid flow around the wing or foil)

The first flight was achieved by the Wright brothers in 1903. In 1910, the Italian engineer Forlanini designed a boat to which he added submerged wings (which would come to be known as ‘foils’). The craft, powered by an internal combustion engine, lifted out of the water and flew on its submerged foils.

Forlanini and the Wright brothers applied the same laws of aerodynamics and the same flight control systems. The only difference between their two craft lay in the fluid flowing around the lifting surfaces: air for the aeroplane, water for the foiler.

In the calculation of aerodynamic lift (**$Fz = ½*ρ *Cz*S*V^2$**) for the wing or foil, this difference is reflected in the value of the fluid's density, expressed as '**ρ**'.

For air, **ρ** varies around 1,230 kg/m³depending on temperature and relative humidity. For water: **ρ** = 1,000 kg/m³ for fresh water and 1,025 kg/m³ for seawater.

The 40-knot glass ceiling

Once the speed required to generate lift is reached, the foiler lifts out of the water. Its speed then increases very rapidly, reaching a glass ceiling of around 40 knots, which appears insurmountable.

This phenomenon of speed limitation is also observed in subsonic jet-powered aircraft[1] at around Mach 0.84 when at cruising altitude (10,000 m). At this altitude, the speed of sound is around 1,070 km/h (300 m/s). Mach 0.84 corresponds to 900 km/h.

These two vehicles, capable of lift over water or air, use identical types of airfoil profiles for their foils or wings. These are cambered asymmetric airfoils, with a relative thickness of approximately 12 per cent (such as the NACA 64-12 or 2412, for example:[2]), mounted on rectangular, trapezoidal or elliptical wing or foil shapes.

In fact, this wall does indeed exist on both types of aircraft, but for very different physical reasons.

On an aeroplane, the limit arises from the transition from subsonic (Mach <1) to supersonic (Mach >1) flight. At this point, the compressibility of the air, shock waves and drag generate vibrations that affect the wing structure and/or cause flow separation phenomena around the upper and lower surfaces. These phenomena lead to a loss of flight.

On a foiler, the foil moves through water, where the speed of sound is around 1,500 m/s. Travelling at 40 knots (20 m/s) through water – which is a completely incompressible fluid – corresponds to Mach 0.013. There is therefore no risk of shock waves.

However, at around 18 m/s (35 knots), cavitation begins to occur on the upper surface and then on the lower surface.

Among other things, these cause the foil to lose lift.

Stall first affects the upper surface (the area of low pressure) and then the lower surface.

---

[1] This applies to jet-powered aircraft; aircraft powered by internal combustion engines cannot reach speeds in excess of 600 km/h or altitudes of 6,000 m.

[2] Various types of aerodynamic profiles are catalogued worldwide. These include the Joukowshi, Eppler, NACA and Göttingen profiles, amongst others, with the NACA types being the best known.

This phenomenon does not depend exclusively on speed, but on the moment when the local pressure on the upper surface (extrados) reaches the level of the saturated vapour pressure PV.

The phenomenon of cavitation is similar 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 lies in the 'driving force' that triggers the phenomenon.

In boiling, the temperature varies at constant pressure, whereas in cavitation, the pressure (on the extrados surface) changes whilst the temperature of the water flowing around the foil remains constant.

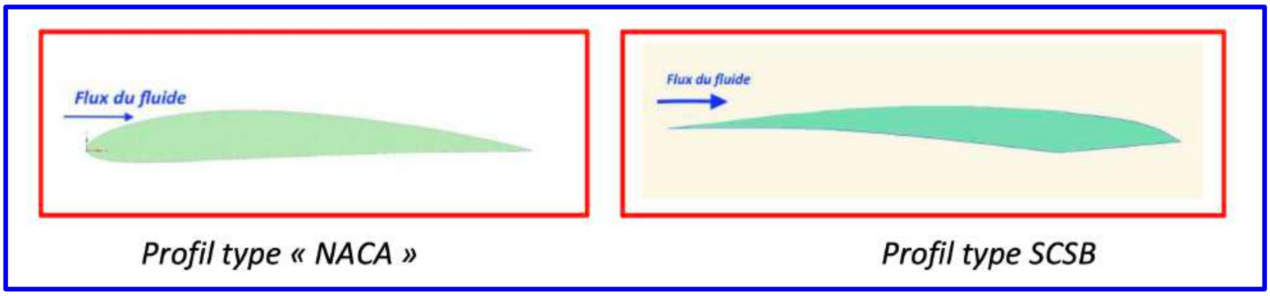
At this point, the water flowing around a foil undergoes a sudden phase change, transforming from a liquid to a vapour. As vapour has a density 55 times lower than that of the liquid, a bubble forms locally on the upper surface; the water flow then separates from the upper surface, simultaneously causing a loss of lift from the foil and erosion of its surface (an increase in roughness and therefore in drag). Cavitation depends primarily on the absolute pressure at the foil's surfaces and the water temperature.

Added to this phenomenon is the risk of ventilation. Ventilation occurs when air is drawn in from the air–water interface at the arm supporting the foil (the connection to the Foiler's hull). The air then flows along the arm towards the foil. This amplifies the hydrodynamic drag forces as well as the structural stresses. All these disruptive phenomena render the system unstable.

In conclusion, for a foiler, the 'wall' is not a physical barrier like Mach 1 for aeroplanes, but rather a hydrodynamic and technological one.

We often hear of foilers reaching speeds of 45 and even 50 knots. This is possible, but the performance is very short-lived because the deterioration of the surface condition of the upper and lower surfaces escalates very rapidly (the surface very quickly resembles 'coarse-grain' sandpaper), regardless of the material (titanium, high-modulus steel, carbon fibre, etc.), leading to an inevitable drop in lift and, consequently, in the foil's performance.

Paradoxically, this speed limit is exceeded by replacing the 'cavitating' profiles of the foils (or wings) with 'super-cavitating' profiles. The shape of the latter's profile resembles a highly elongated, thin-walled curvilinear rhombus.



This family of 'super-cavitating' profiles enable speeds of 100 knots (!!) to be achieved. The difficulty lies not in designing and manufacturing this type of foil, but in reaching the speed at which they become operational.

Indeed, their main drawback is a significant lack of lift at low speeds, which prevents take-off without resorting to complex manoeuvres. Taking off with a super-cavitating profile requires a very high level of temporary propulsion power at the moment of take-off. For example, using a jet engine's afterburner (30 to 40 per cent more power on a Rafale for around ten seconds).

However, whilst afterburner is a feasible concept for a jet engine, it remains a pipe dream for sail-based propulsion.

Foil design and lift management

Before addressing the 3D control of the foiler platform, it is necessary to manage the lift generated by the lifting surfaces.

On a foil or wing, there are four technical levers available:

⇒ **The shape.** This parameter applies only to foils. Visually, this is reflected in their 'U', 'V', 'Y', 'inverted T' or circular arc shapes. With the exception of the 'inverted T', these options allow for a foil that is almost self-regulating. When the foil submerges, lift increases, and vice versa. It is described as 'almost self-regulating' because the response time and damping are not always optimal.

⇒ **The aspect ratio** of the shape (rectangular, trapezoidal, elliptical).
This parameter is fixed at the design stage. The delta shape is excluded, as it applies only to super-cavitating profiles.
The aspect ratio (**AR**) is defined as the ratio of the foil's wingspan squared to its projected area on a horizontal plane.
The performance of a foil or wing increases with the aspect ratio (**AR**).

⇒ **The** angle of attack relative to the fluid flow. The angle of attack of the foil or wing is determined at the design stage relative to the platform or cockpit in a horizontal flight position. Foilers fitted with 'U', 'V', 'Y' or arc-shaped foils are not subject to this constraint.
The skipper can adjust the angle of attack as they wish. For T-shaped foils, the angle of attack is fixed at the design stage.

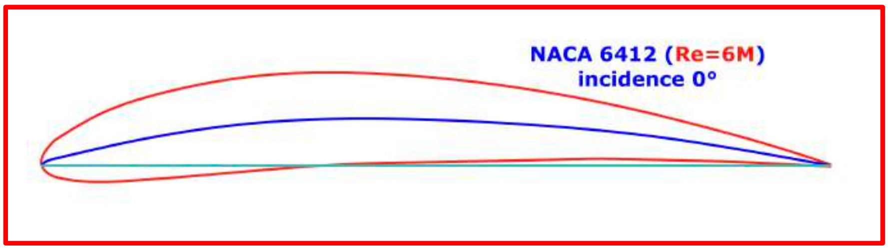
⇒ **The aerodynamic profile** of the foil or wing. This is a choice made by the designer. It defines:

- The relative thickness in relation to the chord of the profile.

  For example, if a **'NACA** 6412' profile is chosen, this corresponds to a maximum camber of 6 per cent at 40 per cent of the leading edge and a maximum thickness of *12* per cent at 30 per cent of the same point.

- The specific lift **Cz** and drag **Cx** depend on the angle of attack selected for the flight attitude.

  In this **Fz** formula, only two parameters are adjustable: **Cz** (the specific lift of the foil's airfoil) and the foil's area **S**, and implicitly its shape.

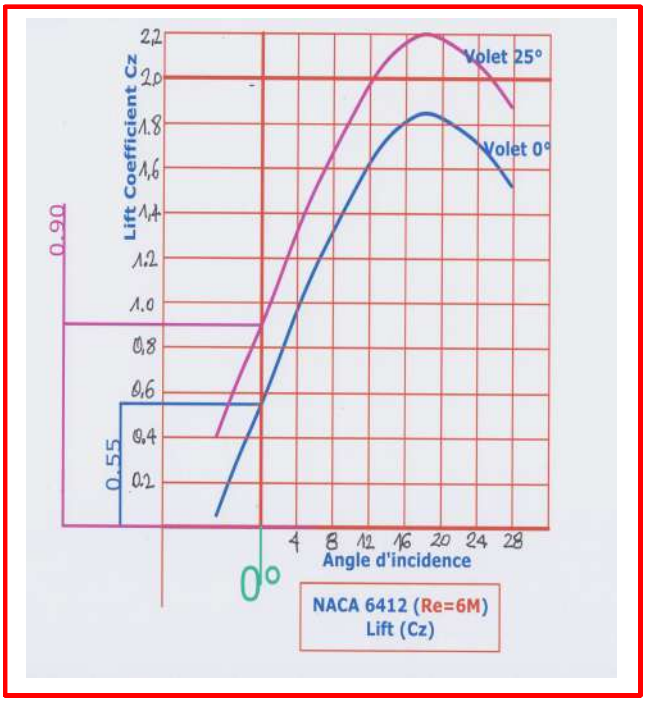


The designer consults the aerodynamic performance table for different profiles to identify the **Cz** and **Cx** values that appear optimal for their project. The choice of **Cz** defines the angle of attack applied to the foil profile.

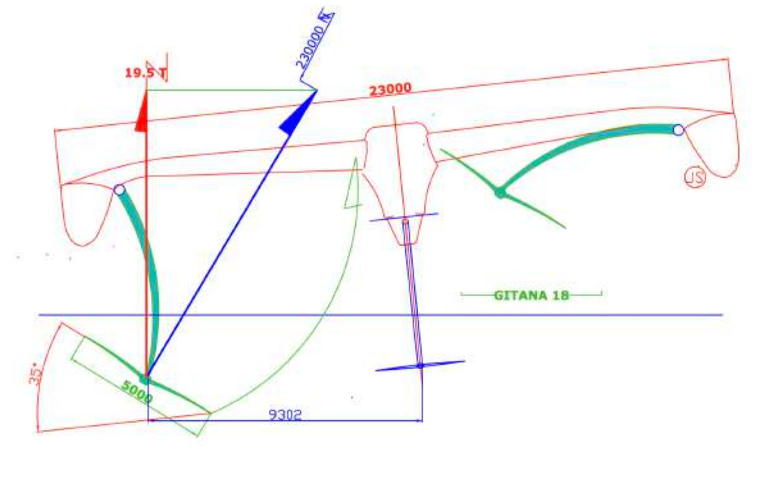
During the design phase, a maximum speed of 35 knots (18 m/s) is set as the upper limit before cavitation occurs.

Adjusting the foil's area and shape (elliptical, trapezoidal, etc.) then enables the generation of vertical lift to keep the foiler airborne.

The designer's choice is determined by the maximum performance sought in stabilised flight. However, the designer aims for minimum drag, which depends on both the camber of the airfoil and the chosen angle of attack (rake). An increase in drag results in more available power.



To achieve, with the new **Gitana 18** launched in spring 2026 (19.5 tonnes, LH 32m, Bau 23m, TE 4.2m, SVoiles: 450m^2/630m^2), the advertised maximum performance figures of around **30–35 knots** at steady speed – **an average of 16.7 m/s and a top speed of 18 m/s** – **a vertical component (lift) of 19,500 kg × 9.81 = 191,000 Newtons** is **required.**



The design of ***the Gitana 18*** *is distinctive as it utilises oriented 'inverted T' foils (like the AC 75s). Whereas the previous generation of* ***ULTIMs*** *used 'inclined L-shaped' foils, which provide them with a degree of self-regulation within a heel angle of 6 to 8°. These 'inclined L-shaped' foils can be retracted by translation.*
However, this 'L' technology requires constant management of the angle of attack, as it is technically impossible to fit flaps to their trailing edge.
The 'T' shape has a fixed angle of attack (5° in this study) relative to the platform in its horizontal position. This is the same design used on aeroplane wings.
This type of 'inverted T' foil, which is symmetrical about a connecting arm, is fitted with trailing-edge flaps, which may be independent. This technology appears to be simpler to control and less energy-intensive than the direct control of the angle of attack used on the 'L'-shaped foil.

The 'T'-shaped foil is inclined at an angle of approximately 35° to the horizontal. This corresponds to an effective lift of 191,000 N / cos (approximately 35°) = 230,000 N.

To achieve this objective, the design team must select a foil profile with the lowest possible **Cx** (drag), whilst maintaining a lift coefficient **Cz** sufficient to ensure a flight speed of 35 knots.

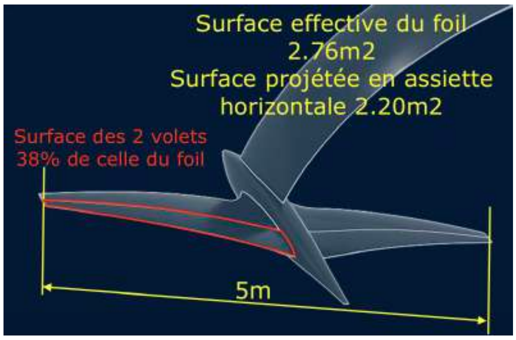
For example, a NACA 6412 airfoil set at 0° (angle of attack) moving through seawater (Re = approximately 6 × 10^6 at 18 m/s) produces:

<u>**Cz = 0.55   and a Cx = 0.045**.</u>

In order to achieve a maximum speed of 35 knots in stabilised flight, and taking into account a platform heel of 5 to 7°, **the Gitana 18**'s foil must produce lift of around 230,000 N, which breaks down into a vertical vector (lift) of 191,000 N (19.5 tonnes) and a horizontal vector (anti-drift).

In this configuration, where the aim is to minimise drag, the foil's flap is set to 0° (the perfect NACA 6412 profile) and the wing is used in lift or downforce mode to control only the platform's heel. This control is important because a change in

heel (positive or negative) affects the foil's lift. By pivoting the foil, the projected area increases or decreases, which alters the vertical lift.
In the lift calculation formula **$F_z = ½ \times \rho \times C_z \times S \times V^2$,** the following parameters are known:



- Desired lift (Fz = 230,000 N),
- Speed (V = 35 knots – 18 m/s),
- Cz (0.55),
- ρ (1025)
- The foil area is 2.76 m^2(corresponding to an aspect ratio AR = 9)

Fz = 252,000 N, which corresponds to the desired flight conditions.

Speed instability in a foiler

It should also be noted that on a sail-powered foiler, the fluid velocity flowing around the foil corresponds to that of the foiler (wind speed). The vector sum of the true wind speed and the wind speed produces the apparent wind.

This apparent wind generates sail lift, which directly affects the Foiler's speed and indirectly affects the lift generated by the foil (at the same Cz). We therefore find that the sail propulsion system is not an engine whose power can be continuously adjusted according to the lift requirement.

A sail-powered foiler suffers from two characteristics that complicate its handling and balance in flight:

- ✓ The uncontrollable nature of the power source (the wind) that enables it to fly.
- ✓ The propulsion vector's position, roughly midway up the mast, which generates significant nose-down torque.

The quest for a low take-off speed

The main objective of a sail-powered foiler is to fly continuously at a speed very close to the maximum speed specified in its design. Calculating and adjusting the parameters required to create these flight conditions ultimately appears to be fairly straightforward. However, it is still necessary that, with these chosen parameters, the take-off speed be relatively low in order to leave the Archimedean domain as ly as possible and enter the flight domain above the water.

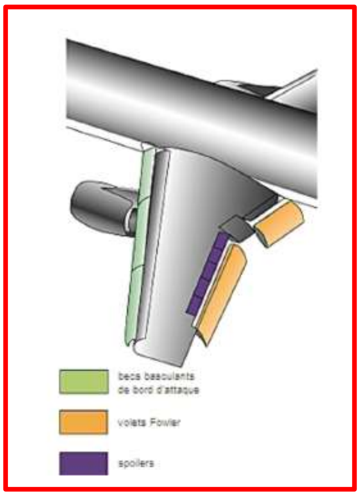
Admittedly, the parameters above (Cz=0.55 and Sfoil=2.76 m^2) allow flight at 18 m/s. Having selected this maximum speed, the designer must also set the take-off speed. On a foiler, the take-off phase follows gradually on from flight in the Archimedean regime. The drag generated by the foil deployed in the water, the PHR on the rudder and the foil fitted to the skim wing hinders this Archimedean take-off phase.

A quick calculation of lift applied to Archimedean speeds of the Foiler ranging between 12 and 13 knots (approximately 7 m/s) yields lift (**Fz**) in the region of 40,000 N. This leaves us a long way short of the target of 230,000 N and the conditions required for take-off.

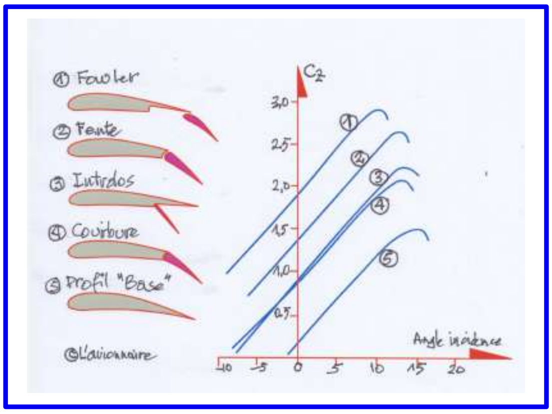
We must therefore make up for this performance shortfall.

The solution is called: **hyper-lift and the use of the 'stingray wing' as a temporary lifting surface.**

This problem of insufficient lift during take-off is not, incidentally, unique to oceanic foilers. Aeroplanes were also quickly confronted with this difficulty.



With hyper-lift, the focus is on increasing the Cz by adjusting the camber of a basic 'aerodynamic' airfoil (the one chosen for maximum speed). On aeroplanes, the volume of the wings allows for the installation and mechanical deployment of flaps before take-off (or before landing). This technique creates two effects: a simultaneous increase in the camber of the wing profile – and thus the **Cz** – and, to a lesser extent, an increase in the wing area. This technology makes it possible to increase the **Cz** by between 45 and 115 per cent of its initial value, depending on the techniques used and the surface areas of the flaps.



In addition to these changes to the wing, the aircraft rotates as soon as take-off speed is reached. This rotation increases the angle of attack and thus the Cz.

The pilot retracts the flaps as soon as the take-off phase is complete; the wing then returns to its original profile, enabling the aircraft to fly at the maximum speed specified by the designer.

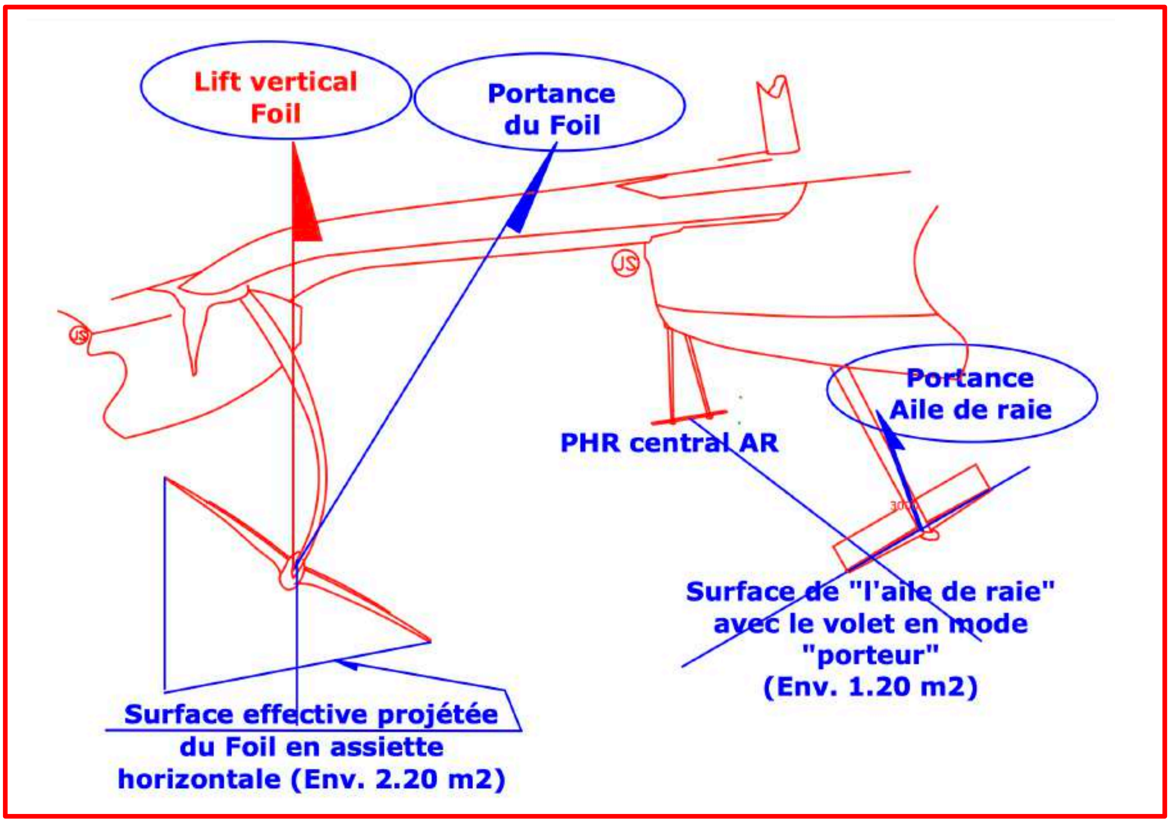
Thus, a commercial airliner takes off at around 250 km/h, with a cruising speed of 850 km/h.

On a Foiler, the foil's surface area cannot be altered, or only marginally: by increasing the roll angle about the Foiler's longitudinal axis. However, it is possible to increase the Cz value by using a trailing-edge flap. This increase in Cz can reach up to 60 per cent of its initial value (that of the undeformed profile). Referring back to the previous example, we can assume that the Cz value of 0.55 becomes 1.1.

For example, at 6.5 m/s, the foil generates a lift force Fz of 66,000 N, which corresponds to a vertical component of 58,000 N.

Increasing the camber certainly produces a higher Cz, but it rapidly increases drag, which requires more sail power…

During the take-off phase, the stingray wing becomes the trump card of a foiling trimaran.



On **the Gitana 18**, the stingray wing takes the form of a horizontal lifting surface with a symmetrical profile measuring 1.2 m² mounted at the tip of the central pendulum centreboard.

The main function of the stingray wing is to control the platform's heel during stabilised flight. Depending on the angle of its trailing-edge flaps, the stingray wing acts either as a lift-generating surface – lifting the central hull – or as a downforce-generating surface – reducing the heel.

With a trailing-edge flap set at an angle of 15–20°, the **Cz** of the stingray wing can reach 0.80. The symmetrical airfoil is less aerodynamically efficient than a cambered airfoil such as the NACA 6412.

At 6.5 m/s, with a Cz of 0.80 and an area of 1.2 m², the stingray wing angled at 20° generates a vertical force of 20,000 N on its own.

Added to this lift is the fact that the skate wing is pendular, meaning it can be tilted into the wind. Its axis of rotation lies in the horizontal plane at an angle of 7 to 10° (known as 'tilt').

When the stingray wing's sail is angled into the wind in this way, the 'tilt' creates an angle of attack that generates lift. This is added to the lift provided by the horizontal lifting surfaces located at its base.

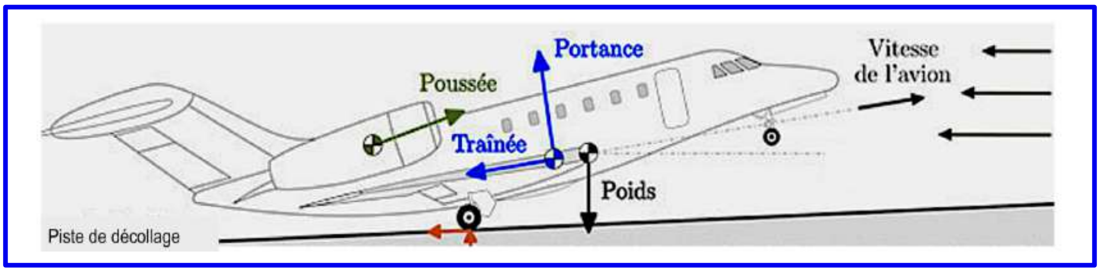
Ultimately, at 6.5 m/s (12.6 knots), by combining the lift from the foil with that of the stingray wing and the centreboard, we achieve a vertical component of almost 80,000 N – which is, of course, still some way short of the 191,000 N required.

But in reality, the transition from 'Archimedes' mode to 'flight' mode is not a binary one.

Even at a speed of 6.5 m/s, the combined lift from the foil and the skim wing produces a vertical lift equivalent to around 42 per cent of the Foiler's displacement. This effect rapidly reduces the wetted area, and therefore the drag on the hull.

Under these conditions, the trimaran accelerates, the apparent wind increases, the trimaran gradually reaches 8 m/s (15.5 knots), and the lift increases… to reach 150,000 N (75–80 per cent of the Foiler's weight).

The climb phase is well underway.



The Foiler reaches take-off speed **V1** and then quickly reaches rotation speed $\mathbf{V_R}$.

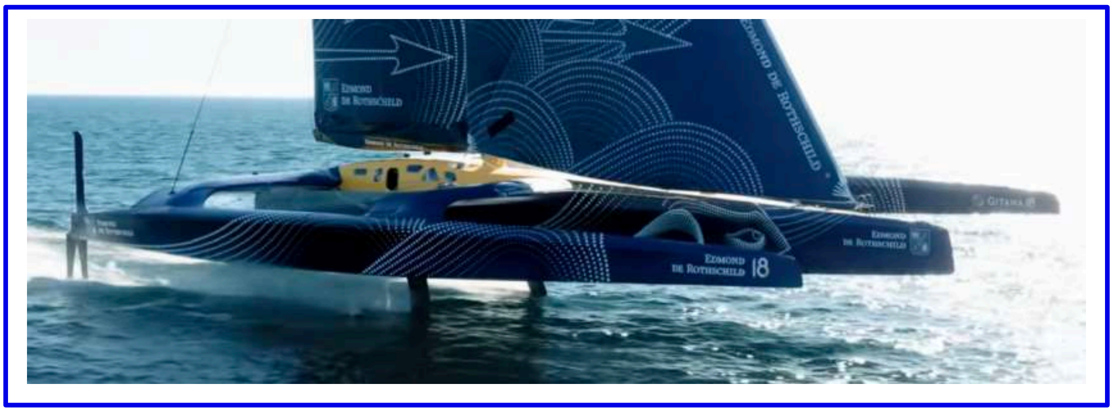
The skipper, like an aeroplane pilot, then gradually rounds off (rotates) the trimaran's trajectory.

This manoeuvre increases the angle of attack of the foil and the skim wing, as well as the Cz of these lifting surfaces. This rapidly amplifies the 150,000 N until the necessary lift of 191,000 N is reached, enabling the Foiler to be lifted out of the water. The skipper performs this round-off by operating the rudder's PHR in 'lift' mode.

The take-off phase ends when the speed stabilises at 18 m/s (35 knots). The skipper then stabilises the platform in horizontal flight, using the PHR (rudder) and the skim wing.

Take-off phases on 27/05/2026

First flight test of **Gitana 18**



Achieving a stabilised flight

A whole new world begins after take-off, once the platform has stabilised in a horizontal plane, listing by a few degrees.

The objective: to fly at a cruising speed of between 15 m/s and 18 m/s (30–35 knots) at a relatively constant altitude of around 2.5 to 3 metres above the water's surface (**Gitana 18** flight certificate requirement).

This final condition is essential for the flight to continue.

Two types of equipment are used to control the aircraft's attitude and altitude.

- The PHR, mounted at the tip of the rudder(s), and the 'raie' wing at the tip of the centreboard. By generating lift (upward lift) or downforce (downward lift), these appendages help to keep the platform horizontal (controlling pitch and roll).
- Adjusting the angle of attack of the foil (in the case of an 'L'-shaped design) or that of the trailing edge flap (inverted 'T'-shaped foil) allows the unit lift coefficient **Cz** to be modified, thereby adjusting the foil's immersion below the water's surface.

In flight, these forces act on a sail-powered foiler in lift on the foil(s):

- The force **Fv** produced by its propulsion
- The vertical force **P,** resulting from its mass (Weight = mass × acceleration due to gravity 9.81 m/s²)
- The aerodynamic lift of the wing or foil. $\mathbf{Fz = \frac{1}{2} \times \rho \times Cz \times S \times V^2}$.

Note: The lift generated by the stingray wing is utilised during the take-off phase. In flight, due to its symmetrical profile, the upward or downward angle of its trailing-edge flap causes it to generate lift or drag (controlling roll and/or flight altitude)

To maintain this equilibrium during the trajectory set by the pilot, the vehicle must always be in motion and the vector sum of these three forces must remain zero at all times in the 3D coordinate system: Ox, Oy, Oz, i.e. they must be concurrent.

It should be noted that the variability of the forces **Fv and Fz,** applied to the centre of the wing and the foil's centre of pressure respectively, affects the platform's equilibrium. Only the force of gravity **P**, applied at the centre of gravity, remains constant in both magnitude and direction. The centre of pressure of a foil is equivalent to the centre of the wing for conventional wings.

Stabilised flight requires that the three parameters – speed, lift and flight altitude – which influence **Fv** and **Fz,** be kept under constant control.

Different approaches to in-flight control

Visual or instrument flight

Flight stability – that is, maintaining a horizontal attitude at a desired altitude (assuming that power remains under control) – requires the pilot (or helmsman) to be able to refer to two reference points:

⇒ **The horizon**

⇒ **A reference for altitude relative to the water's surface.**

Seeing the horizon implies that the Foiler's pilot is flying by sight (VFR). This type of flight appears to be the simplest and most unrestricted, as it is essentially based on the principle of 'see and avoid'.

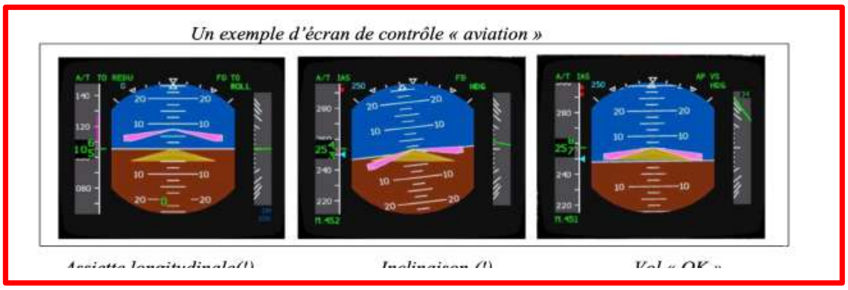
This piloting technique applies, amongst others, to AC75 monohull Foilers and SAIL GP catamarans.

Unlike a foiler, an Archimedean sailing yacht can sail without a 'horizon' reference point (day or night) as hydrostatic principles govern pitch, roll and buoyancy. The helmsman then follows the wind or the compass.

On a foiler, during an offshore race, at night or during the day when visibility is poor, the absence of a horizontal reference creates a new paradigm:

⇒ **Switching to techniques known as 'instrument flight (IFR)**'.

Instrument flight relies primarily on replacing the (natural) horizon with visual monitoring of the cockpit sensor known as the 'artificial horizon'. This topic will be explained in more detail in a subsequent paragraph.



Despite this aid, the visual assessment of flight altitude is lost, which makes flying highly unpredictable, or even impossible. Indeed, the altitude of the vessel may well vary whilst maintaining a perfectly horizontal attitude.

When navigating, the crew (or the skipper in the case of a solo voyage) of an Archimedean sailing yacht controls three parameters:

- Yaw (the course followed) using the rudder
- Heeling, by adjusting the sail area
- Speed, by matching the hull to the wind.

In reality, when conditions are relatively stable, control may well be limited to manually operating the rudder. In fact, the hydrostatic forces constantly acting on the hull ensure the perfect balance of the sailing boat (between 0° and the capsize angle Avs) without any intervention from the crew. 'Steering' an Archimedean sailing boat presents no real difficulties.

On a foiling yacht in flight, flight control is more complex because the yacht's equilibrium in flight is precarious. The laws of hydrostatics no longer apply; everything depends on the three force vectors (lift, weight and propulsion) constantly acting in concert whilst in flight.

This means that the equipment ensuring this balance must be operated by the crew or the skipper (when sailing solo).

These systems are:

- A rudder (yaw control)
- A foil whose lift can be controlled (lift control)
- A PHR fitted to the tip of the rudder to control pitch.
- Sheets to control sail power.
- Possibly a transverse PHR 'skate wing' to control the Foiler's roll.

Note: The weight of the foiler, including the crew and supplies, is factored in as a constant from the very outset of the foiler's design. Based on this weight, the designer selects and calculates the characteristics of the foil's profile and the wing area required to lift the foiler out of the water.

In total, the helmsman or their crew must constantly and simultaneously adjust five controls.

- ✓ The helmsman controls the rudder and the PHR mounted on the rudder
- ✓ The crew member responsible for flight altitude controls either the foil's angle of attack (L-shaped foil) or the angle of the trailing-edge flap (T-shaped foil).
- ✓ Two crew members in charge of sail adjustments (mainsail and jib) manage the power (speed vector).

On an Archimedean boat, the response time between perception and action can be long. On a foiler, the crew's decisions and actions must be taken simultaneously and at lightning speed, as whilst airborne, the slightest error or delay can result in one of the aerodynamic surfaces stalling . Let us recall the incident that occurred on **American Magic** during the 2021 America's Cup or on **Prada** in July 2026.

This type of piloting is extremely stressful and physically demanding. For these reasons, regattas, such as SAIL GP, must not last[3] more than 15 minutes.

An ocean-going foiler is no exception to these flight conditions, even if the cockpit is larger and the inertial forces less severe. The time available for manual steering quickly becomes very limited. External assistance with manual steering becomes essential.

In the case of solo sailing, this appears even more complicated.

Assisted manual piloting

Initially, the pilot perceives two reliable pieces of information:

- ⇒ Their perception of the platform's horizontal orientation
- ⇒ His perception of his flight altitude.

The principle of **assisted manual control** is based on the following sequence:

a) The pilot issues a command by operating a joystick or a multifunction control wheel.

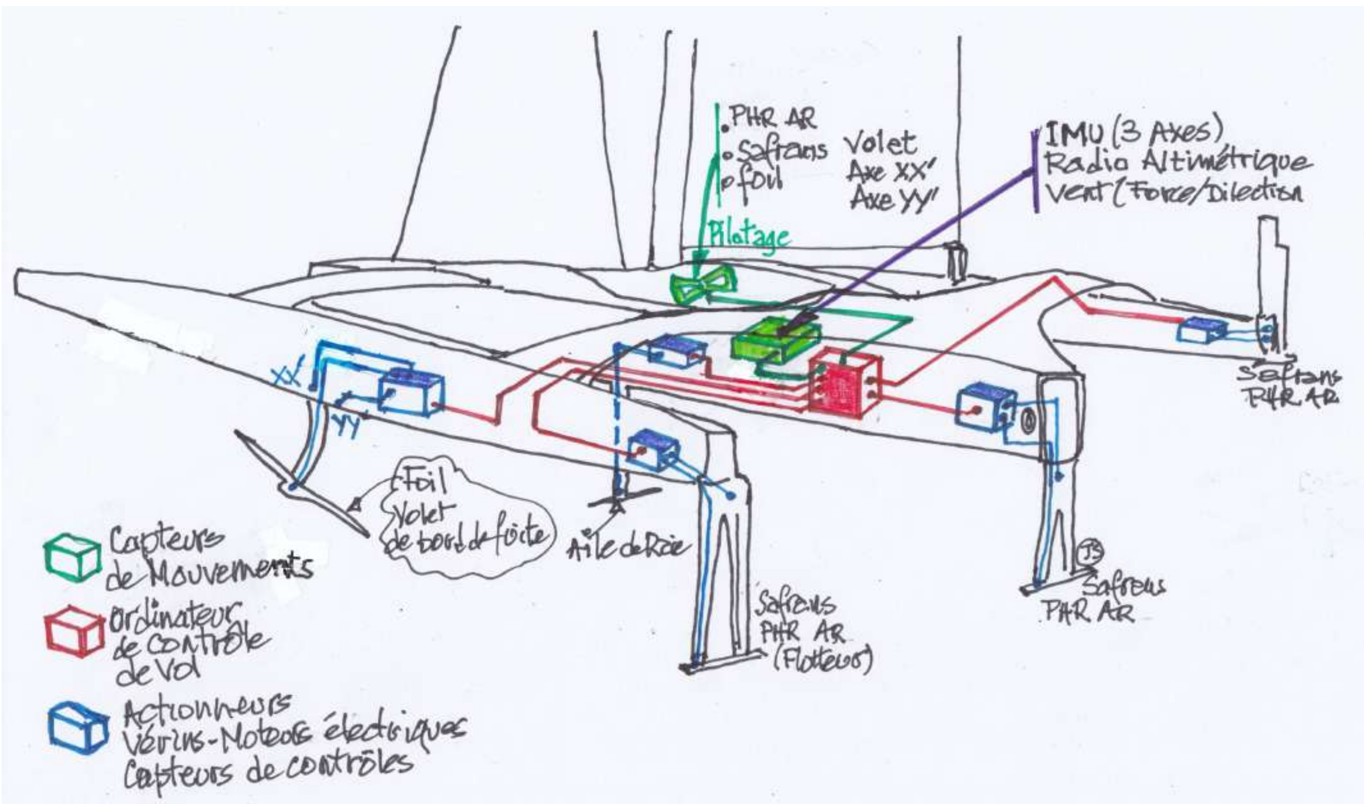
b) Electronic sensors identify this command. In effect, this is the pilot's reaction to correct a flight anomaly or their intention to take a new course.

[3] An aerobatic competition or display is limited to 12 minutes, and all flight controls are operated by cables.

c) This information is transmitted to the algorithms of the on-board flight controller. This flight controller calculates the best overall response to the pilot's request, based on the actual flight situation at time 't' and the Foiler's aerodynamic capabilities. Several actions may be decided upon.
d) These actions are converted into digital data and sent to the hydraulic or electric actuators. The control surfaces move
e) The correction or new course is implemented.

Flight control therefore does not depend on a **direct relationship**, as would be the case with the helmsman of an Archimedean sailing vessel, but on a series of interactions:

- ✓ **Cognitive (intention)**
- ✓ **Computational (calculations comparing the actual state with the desired state)**
- ✓ **Mechanical/hydraulic/electrical (execution)**
- ✓ **Aerodynamic/hydrodynamic (physical reality)**



Layout diagram of this control chain on a foiler.

Further development of this process appears necessary.

Three parameters must be identified:

1 / A horizontal reference

As the view of the natural horizon is not constant, there is a risk of disorientation. Replacing the perception of a distant horizon with the constant reading of an artificial horizon (an 80 mm diameter unit) mounted on the dashboard or even recessed into the skipper's (pilot's) field of vision is a major challenge. This type of equipment requires the driver to focus on reading the vertical and angular markings, which is incompatible with the environment of a foiler's navigation station (vibration, angular accelerations, noise, etc.).

The pilot must be able to track the projection of a 'point' representing their platform in relation to an artificially recreated horizon. Reading graduations forces the brain to convert the values read into corrective commands.

This interpretation is not only too time-consuming, but also potentially inaccurate (reading errors) and, above all, tiring.

Reactions must be intuitive, in the same way that a car driver navigates a series of bends. The decision-making process is based on the driver's perception of the environment, the road layout, and their position in relation to that route. At no point does the driver look simultaneously at their speedometer and rev counter.

On a Foiler, the data provided by the Inertial Measurement Unit (**IMU**[4]) enables the construction of an artificial horizon based on mapping of the sea surface. This horizontal line represents the 'Zero altitude' reference. This reference is entirely different from that used in aviation, where Zero altitude corresponds to the barometric pressure at a specific point on the globe.

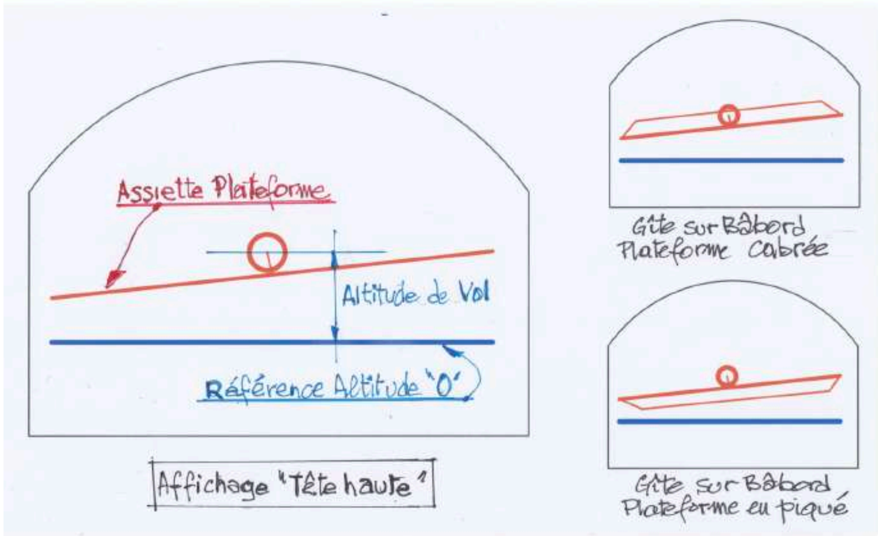
The entire system is constantly synchronised and visible to the skipper.

However, this display must remain constantly within the pilot's field of vision, directly in front of them.

A simplified 'head-up' display system becomes necessary.

Manual piloting becomes assisted manual piloting, as the pilot merely provides an 'intention'. This intention is realised through the pilot's interpretation of what they see on the 'head-up' display, which they then translate into action by manoeuvring their joystick or multifunction steering wheel.

[4] An inertial measurement unit (IMU) is an electronic component. It measures acceleration, angular velocity and orientation using a combination of accelerometers, gyroscopes and magnetometers.



It is worth adding that by using electric winches (to trim or ease) on the mainsail and foc sheets, it becomes possible to adjust the power required to maintain flight stability.

2/ The 'surface' of the water

The water surface serves as the reference surface for determining the Foiler's flight altitude. During an offshore ocean race, this surface, barring very exceptional circumstances, is rarely flat.

Broadly speaking, the shape of this surface can be analysed macro-geometrically (the swell) and micro-geometrically (the chop).

The micro-geometric analysis is superimposed on the swell. However, the identified sea surface is never horizontal due to the underlying 'swell' effect.

These undulating wave patterns (even those of small amplitude) make piloting during the day very difficult. At night, the lack of visual reference points makes flight control impossible or, at best, highly hazardous, even when using standard settings for lift and trim control.

The logical approach is to carry out a dimensional analysis of the waves directly in front of the bow. This method seems natural, except that in the case of an ocean-going foiler, the aim is not to navigate the bow through a wave, but to maintain a stable flight altitude regardless of the wave's amplitude. Our experience of Archimedean sailing clouds our thinking. A foiling craft in flight is not subject to the laws of hydrodynamics, unlike an Archimedean sailing boat, which is governed by them.

A foiler's flight range is between 1.5 and 3 metres above the water's surface. This concept of the water's surface – which is by no means flat – makes it difficult to identify the point used as a reference: zero altitude.

When faced with a wave, the device responsible for attitude detection is confronted with the following dilemma: should the ‘Zero’ point be assigned to the crest or the trough of the wave?

Especially as the detection of the next wave, whose amplitude will inevitably be different, casts doubt on the previous measurement… And so on. The constant shifting of the ‘Zero’ reference point results in a ‘yo-yo’ flight pattern that attempts to replicate a trajectory above the water intended to mirror that of the sea state…

For a foiler, what matters is the physical quality of the fluid surrounding the foil as it moves forward, and the stability of the lift settings essential for flight. Any modification to the foil’s profile (camber adjustment via the trailing-edge flap), made to maintain the flight altitude, creates drag and thus slows down progress.

The transition from one wave to the next, and so on, relies on an algorithm that smooths the lift to maintain the programmed altitude setpoint.

Hence the idea of adopting a predictive approach, often referred to as ‘Look-Ahead control’ or ‘Model Predictive Control’, in order to anticipate the sea surface conditions ahead of the bow.

In fact, it is not the actual state of the waves that interests us – since the lifting surfaces inevitably change underwater – but rather the search for a method that ensures the flow around the lifting surfaces is as uniform as possible.

This predictive methodology is based on the analysis of the sea state that the vessel has just traversed over a given period of time and the associated numerical processing.

It is therefore assumed that the configuration just identified over a given distance will be replicated identically ahead of the bow, covering roughly the same distance ahead.

Mapping the successive waves encountered enables the construction of a fictitious ‘flat’ reference surface that is statistically representative. This reference lies between successive crests and troughs.

By repeating this cycle (measurements and transpositions throughout the Foiler’s progress), a sliding predictive model is created.

The mapping is based on successive 30-metre segments, equivalent to 2 seconds at 30 knots (15 m/s). This distance can be increased.

During this 30-metre stretch, sea conditions are sampled every 0.1 metres or less. For each point, its longitudinal position (x) relative to the start of the mapping operation and its altitude (y) are recorded.

The longitudinal position (x) can be determined using two pieces of data: speed and time: x = v * t.

Methodology:

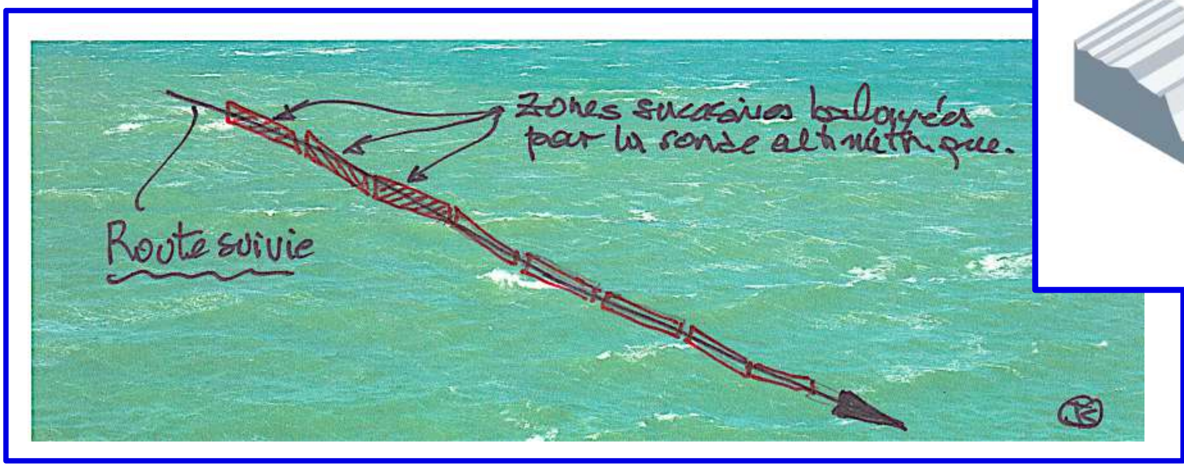
After take-off, the Foiler is stabilised in flight conditions (speed, altitude and horizontal attitude relative to the water surface). These parameters are maintained throughout the initial predictive approach.

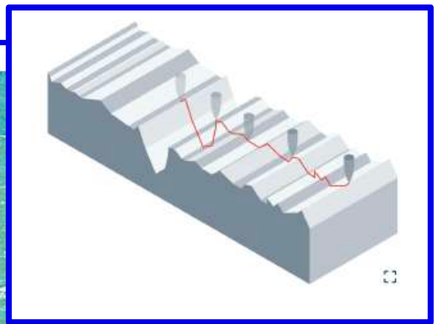
⇒ The Foiler travels for 2 seconds at 15 m/s, covering a distance of 30 m. During this 30-metre section No. 1, the sea state is mapped. From the analysis of this mapping, a guide curve for a left-hand reference surface is derived. This enables a flight altitude to be set. In order to maintain a platform parallel to this left-hand surface, adjustments are made to the PHRs. This information is transmitted to the actuators and/or electric motors that control the foil (angle of attack or flaps) and the PHRs.

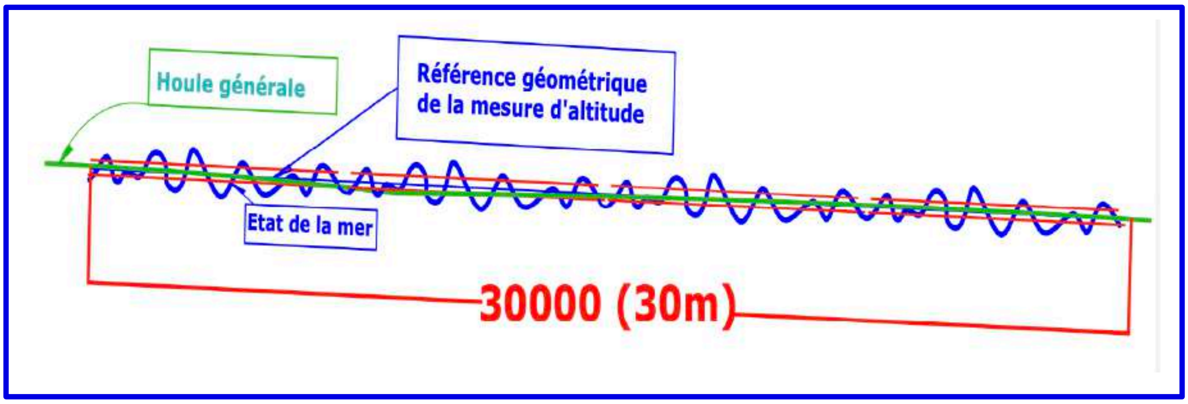
⇒ To tackle the next section, No. 2 – which is of the same length – it is assumed that the sea surface conditions encountered will be identical to those in section No. 1. This means that the settings derived from the mapping of section No. 1 are carried over, enabling a stable flight through the forthcoming section No. 2.

⇒ During the course of Section 2, the actual sea conditions encountered are mapped. At the same time, as the Foiler progresses, the control parameters corresponding to these measurements are recalculated.

⇒ These new parameters are fed into the actuators and/or motors to complete Section 3, again 30 metres long… this pattern is then repeated ‘indefinitely’.



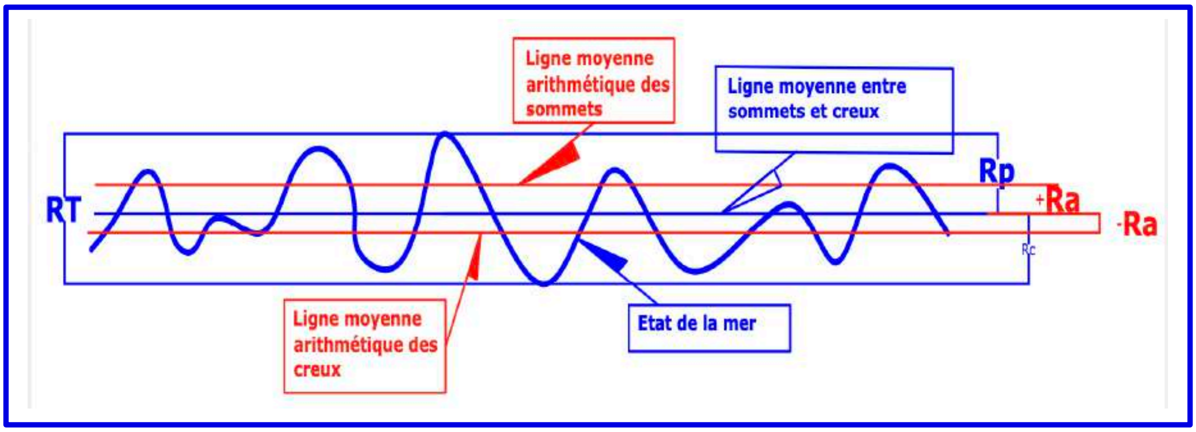




If the dimensional deviations recorded between each new 30-metre section and the previous one are small, we can infer that the amplitude of the sea state is stable.

In this case, it is possible to consider increasing the length of the sections analysed.

Analysis of the mapping



Rp: Maximum peak measured by the altimeter over the analysed length. Rp = ymax. See diagram above.
Rc: Maximum trough observed over the analysed length (see diagram below). Rc = ymin.
RT: Total maximum amplitude measured by the altimeter over the analysed length. This corresponds to the sum of the maximum peak and the maximum trough measured over the analysed length. RT = Rp + Rc.
Ra: Mean deviation, or arithmetic mean of the distances between all successive peaks and troughs. **Ra** corresponds to the difference between this mean distance and the centre line. This mean parameter provides a general indication of sea state over the measured and already traversed length. This value allows the platform to be positioned above the sea surface.

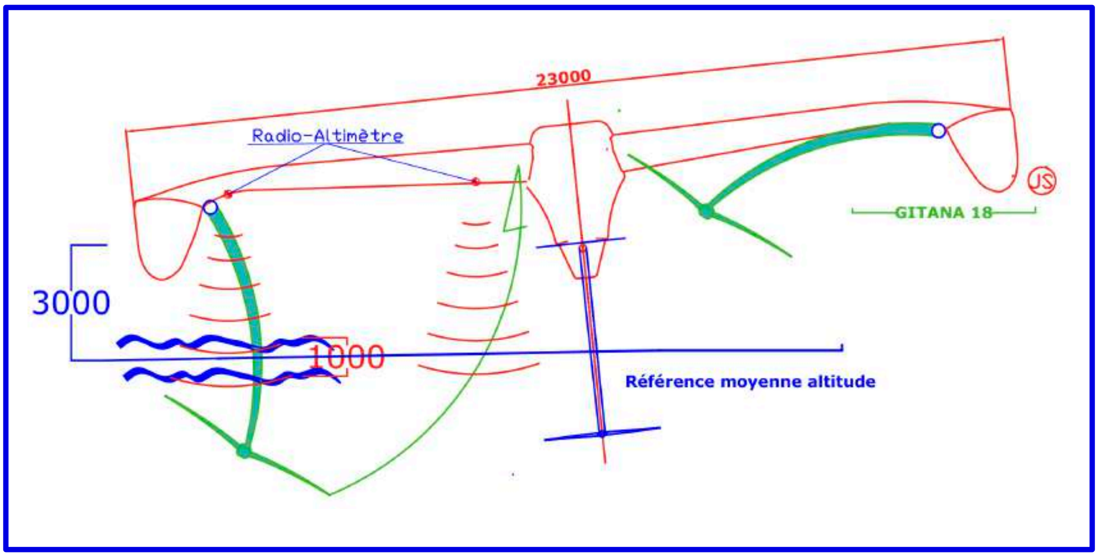
Mapping smooths out the actual sea surface, representing it as an undulating plane limited to the distance travelled, approximately 30 m for an ULTIM Foiler.

3/ Measuring the flight altitude relative to the water surface reference.

This operation, which continues throughout the flight, depends on three parameters:

- ✓ The surface that serves as the reference following successive measurements.
- ✓ The appropriate measuring device
- ✓ The accuracy of the altitude measurements obtained relative to the flight path.

On **Gitana 18**, the altimeter is mounted beneath the leeward float arm, which seems logical given that the foil is positioned directly in line with that float. Another altimeter sensor mounted on the central hull helps to improve the accuracy of the measurements.



The accuracy of the flight altitude, even when measured precisely, depends on the platform's horizontal alignment.

Managing the platform's horizontal orientation (pitch and roll) requires a fixed reference point external to the platform. The horizon is the only natural fixed reference point for a (human) pilot.

As an automated system cannot identify the horizon, it must therefore be provided with this essential horizontal reference so that it can calculate the deviations between the platform's actual position and the horizontal plane.

A gyroscope provides this reference across all three axes. The module that performs this function constitutes an inertial navigation system.

Inertial navigation system technology has evolved from electromechanical models to versions with no mechanical parts, but it remains rather bulky and energy-intensive.

The development of drones has driven research towards new, miniaturised inertial equipment. This has led to the emergence of sensors such as Inertial Measurement Units (**IMUs**).

The specifications of this equipment are astonishing: weight approximately 200 g, size: a 60 mm cube, power consumption: <2 W, offering excellent accuracy at a very affordable price.

The IMU installed on the Foiler's platform thus provides data on acceleration, angular velocity and orientation for every movement in 3D space.

These results are derived from a combination of accelerometers, gyroscopes and magnetometers. An IMU manages all three axes simultaneously, and thus all six degrees of freedom.

Information on flight altitude, combined with changes in attitude detected by the IMU on each axis, enables the algorithm to define the flight settings for the upcoming segment.

However, this heuristic approach will not predict the exact sea state that the Foiler will encounter in the next 2 seconds. But the very short 2-second sampling interval increases the likelihood that the new wave amplitudes to come will be very similar to those the Foiler has just encountered during the previous 2 seconds.

Finding the right altitude measurement device

Whilst the choice of IMU model does not pose any real difficulties, finding equipment capable of measuring a flight altitude of around 2 to 3 metres, with a tolerance range of ±0.25 metres, over a water area that is not particularly homogeneous, is more complex. Added to this is the need to obtain a numerical result.

The target area (the sea) limits the types of equipment to LiDAR, radio altimeters (FMCW) and sonar (ultrasound).

LiDAR (Light Detection and Ranging) uses a distance-measurement technique based on the difference between the frequency of the incident laser beam and that of the beam reflected by the target surface. To avoid penetrating the water's surface, 'altimetric' LiDAR systems operate in the infrared spectrum. They enable highly accurate distance measurements (accuracy of 50 mm) but are apparently more susceptible to sea spray and rain. The **Gitana 18** design team opted for LiDAR.

The **Radio Altimeter** (FMCW – Frequency-Modulated Continuous-Wave Radar) uses frequency-modulated waves. These are highly effective for short-range measurements. This type of equipment is less accurate (70 to 100 mm) than LiDAR, but is largely unaffected by the environment, particularly in a salt-spray atmosphere. Its small size (half a sugar cube) and weight (500 to 700 g) make it widely used on certain drones. Power consumption is around 35 W.

Ultrasonic sonar is not suitable for use. Although inexpensive, simple and reliable, it is greatly affected by wind and, above all, the air–water interface.

Technical opinions in the aeronautical sector seem to favour the **radio altimeter** due to its robustness and suitability for the environment.

In order to be usable in an algorithm, the analogue return signal is sampled and digitised.

The Flight Controller's Algorithms

In assisted manual flight mode, the flight controller's architecture must be conceived as a 3D stabilisation system, rather than as an autopilot (PA).

Broadly speaking, in assisted piloting mode, the pilot[5] (or skipper) transmits a dynamic command to the on-board flight controller. The flight controller's algorithms verify that the command falls within the defined flight envelope, i.e. the physical limits of the Foiler.

The Foiler's designers define the limits of the flight envelope. These limits form the basis for structural calculations and performance predictions, and set the framework for the Foiler's manoeuvrability in flight.

If the pilot's intentions cause the Foiler to move beyond this environment, the flight envelope then re-constrains the flight controller's calculations.

When the pilot encounters an anomaly during the flight or wishes to alter the flight path, they simply express a general intention by manoeuvring the joystick, either to return to the reference spatial state or to move to a new spatial state if they wish to change course. Their manoeuvre may affect:

- Change in heading (yaw) (vertical axis Oy)
- Correction of the flight attitude (pitch and roll). This corresponds to performing two rotations (transverse axis Oz and longitudinal axis Ox)
- Correction of flight altitude (translation along the Oy axis)

[5] **Pilot or skipper… On a foiler, the role of skipper is increasingly merging with that of a pilot.**

The algorithms of the on-board Flight Controller:

- Receive this overall, i.e. non-detailed, intention.
- Check its compatibility with the Foiler's flight envelope**.**
- Calculate the control commands to be sent to the various control surfaces based on real-time data provided by the IMU and the altimetric radar.
- Rank and prioritise these various commands.
- Execute these commands until the data from the IMU indicates that the requested correction(s) have been carried out.

The complexity of these algorithms is evident, firstly because the equations governing flight are subject to the same physical laws as those applicable to aeroplanes, and secondly because the Foiler must fly at a very low altitude of just a few metres above a constantly moving surface.

In fact, when the pilot detects a spatial deviation, they initiate a correction command, which is transmitted to the flight controller. The flight controller's algorithms then adjust the control surfaces to restore the initial stabilised 3D flight position.

If a new route is to be followed, the pilot confirms a 'target IMU'. The same reasoning applies as for trajectory correction.

The return of the spatial position at time 't' to that of the reference spatial state (ideal stabilised flight) constitutes a closed-loop control system.

However, even if the spatial positions (3D angles and altitude) ultimately coincide, the closed-loop control will not simply involve a comparison aimed at achieving perfect alignment.

In fact, the control surfaces fitted to the PHR, the ray wing, the foil and the rudder are not the variables to be controlled directly.

They are merely intermediate actuators. For example, the part of the algorithm that manages flight altitude is not written into the Flight Controller, so as to provide the foil flap with an orientation angle of its own. Its role is to produce an angular variation that reduces the attitude error detected by the altimeter radar, whilst taking into account the actions on the other control surfaces.

Ultimately, the Flight Controller manages a hierarchical set of several nested closed-loop systems. Each loop relates to a trailing-edge flap, with the sole objective of returning to the initial 3D spatial position or the desired position in the event of a new route.

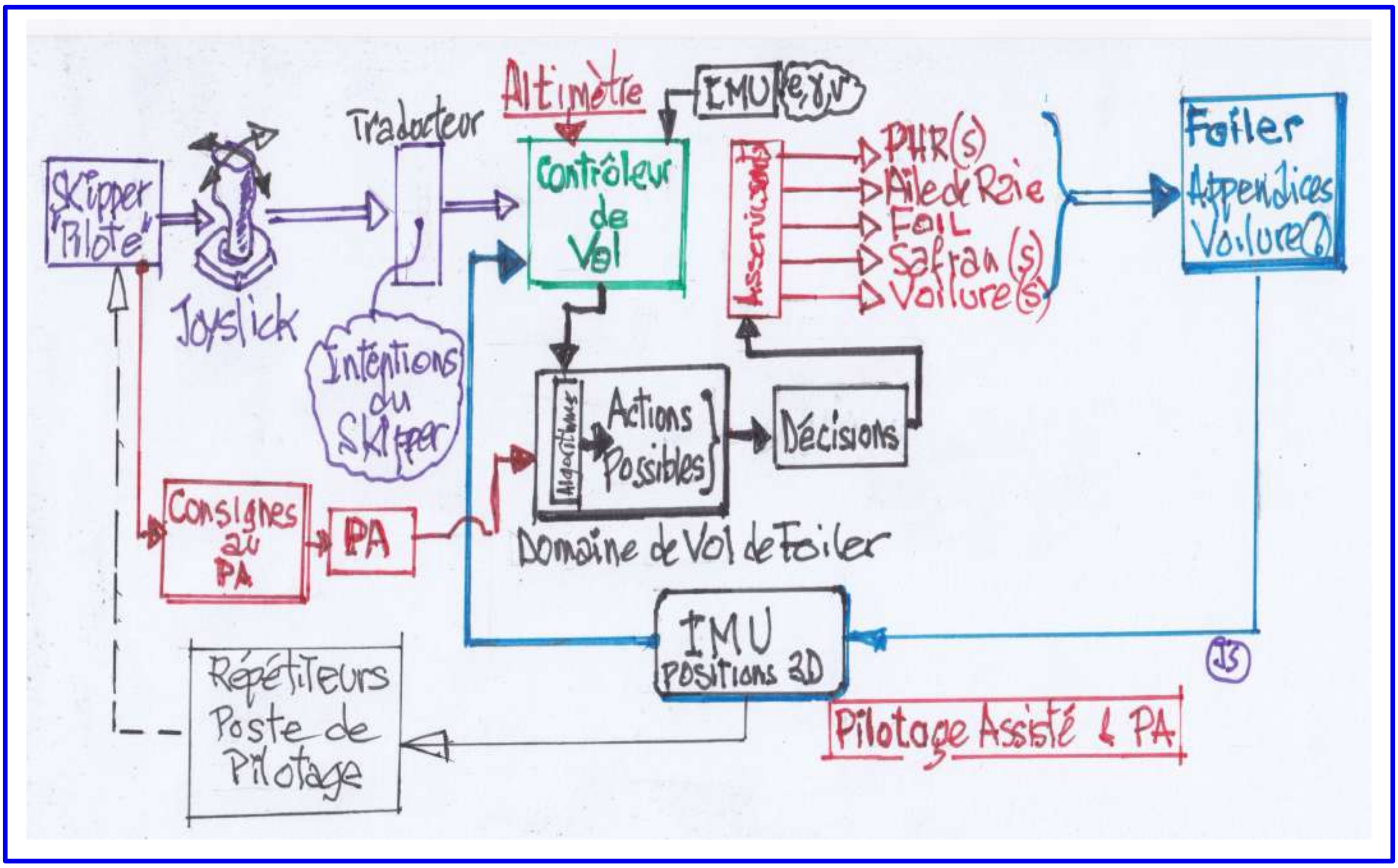
Conclusion: in **'assisted manual** flight' mode, **the pilot**:

- No longer controls the control surfaces directly.
- Merely provides a dynamic intent.

The flight computer, after ensuring that this intention remains within the **flight** envelope:

- 'Closes[6] ' all the loops that control the various flaps of the control surfaces. This means that the angular manoeuvres of the control surface flaps have succeeded in fulfilling the intention expressed by the pilot.
- Converts the intention into a global manoeuvre.
- Stabilises the platform by reducing the error between the current IMU and the reference (or target) IMU.

However, all this assumes that manual control is in use, and therefore that a pilot is paying close attention at all times. If one wishes to eliminate the need for pilot input, the autopilot (PA) must be engaged.



---

[6] **'Closed-loop' in the sense that each control loop has indirectly led to the desired outcome at the IMU level**

Autopilot (AP)

The navigation parameters specified by the skipper replace the dynamic intent that he would previously communicate to the flight controller via the joystick in Assisted Manual Pilot mode. However, this new architecture does not alter the general philosophy of the flight controller.

Adaptation to the new constraints mainly concerns the sensitivity of the autopilot.

Sensitivity refers to the acceptable deviation in spatial positions between **the reference IMU –** which corresponds to the platform's 3D position at the moment the AP is engaged – and that of **the IMU at each instant 't' during the flight**.

The autopilot operates based on the following parameters:

- ✓ Foiler speed
- ✓ True wind speed and direction
- ✓ Reference heading
- ✓ Reference IMU
- ✓ Planned flight altitude

However, the reference IMU, the planned flight altitude and the reference heading are fixed, whilst the other two parameters are constantly changing.

Once this data has been entered into the flight controller, the assisted flight mode cycle is applied:

- Check compatibility with the Foiler's flight envelope.
- Calculate the commands to be transmitted to the various control surfaces based on the real-time data provided by the IMU and the altimeter radar.
- Rank and prioritise these various commands.

Conclusion: in **'PA'** mode, **the pilot**:

- Provides the objectives relating to the flight plan.
- Activates/deactivates the PA

The limitations of in-flight control

In this study of sail-powered foilers, one parameter is overlooked, or rather, considered to be manageable at all times: the available sail power.

Firstly, this power is exerted at a height roughly halfway up the mast and generates two torques. The torque created by the transverse component causes heel, whilst that resulting from the longitudinal component produces propulsion.

This sail lift results from the dynamic combination of two velocity vectors: the true wind speed and the speed of the foiler.

Vent Vitesse (Boat Speed) Noeuds	Vent Vitesse (Boat Speed) m/s	Perte de vitesse FOILER en %	Vent Vitesse^2 (Boat Speed) m/s	Perte de portance en %	Évolution de la portance en Newton
35.00	18.01		324		191000
34.50	17.75	1.45	315	2.84	185582
34.00	17.49	2.86	306	5.63	180242
33.50	17.23	4.29	297	8.39	174979
33.00	16.98	5.71	288	11.10	169795
30.00	15.43	14.29	238	26.53	140327

As the wind speed created in flight by a sail-powered foiler is significantly higher than the true wind speed, the resulting apparent wind produces laminar flow over the sails.

A 0.5-knot drop in wind speed relative to the predicted maximum speed – i.e. -1.45 per cent – immediately results in a 5,400-Newton drop in the foil's lift. For a 1.0-knot drop, the loss of lift reaches 10,000 N, or 1 metric tonne for a displacement of 19.5 metric tonnes. Sail propulsion depends on the true wind, which fluctuates around an average value.

Not to mention gusts, as in strong-wind conditions, wind speed is never stable at sea in moderate winds.

With an internal combustion engine, regulating the Foiler's speed poses no difficulties, as managing the fuel flow resolves the issue.

On a Foiler in flight, the apparent wind vector – comprising the true wind and the wind speed – generates the sail lift.

This lift varies with the angle of attack of the sails relative to the apparent wind vector. Therefore, by adjusting the angle of attack of the sails – without changing their settings relative to the apparent wind – it becomes possible to influence the wind speed, but not the Foiler's speed. Luffing increases the apparent wind and increases speed, whereas bearing away decreases the apparent wind and reduces the Foiler's speed.

By altering the heading by a few degrees, the Foiler has an indirect means of regulating its speed around a target value. This helps to stabilise the foil's lift.

However, whilst this process works well for small variations in true wind speed, it is not suitable when the true wind is highly unstable, particularly as this instability in strength is accompanied by angular variations (luffing or heeling) which disrupt this ability to adjust speed.

In both extreme cases, a drop in true wind speed causes a significant loss of speed and therefore of lift, with the foiler immediately reverting to Archimedean behaviour.

When hit by a strong gust, the Foiler's speed increases immediately, causing uncontrolled lift on its foil. As this situation results in an instantaneous increase in kinetic energy, the Foiler is lifted out of the water and crashes violently.

Controlling speed also involves constantly adjusting the sails. Regulating speed by adjusting the yaw, as described above, appears to be an effective approach.

However, this process must be accompanied by constant adjustments to the sails (trimming in or out) in relation to the apparent wind resulting from the yaws. Fittings suppliers offer winches that wind or unwind the single sheet of the mainsail or jib. Their electric motors allow them to be used in manual IN/OUT mode or to be continuously controlled in response to changes in wind angle.

In servo-controlled mode, this is similar to the throttle of an internal combustion engine. Well, almost, because unlike an internal combustion engine or an aircraft jet engine, the wind is not a fuel that the pilot or the autopilot can regulate to maintain speed and ensure stable lift.

In addition to using yaw manoeuvres to maintain as constant a speed vector as possible, the pilot or flight assistant adjusts the foil's camber by increasing or decreasing the angle of the foil's trailing-edge flaps. By doing so, lift – and therefore flight altitude – is adjusted, but the angle of the flaps increases drag… which in turn reduces speed… which in turn reduces lift… 'Caress a circle, and it becomes vicious' (Ionesco in *Rhinoceros*).

On the Interference of Pilot Actions, which introduces the following paragraph.

The number of movable appendages

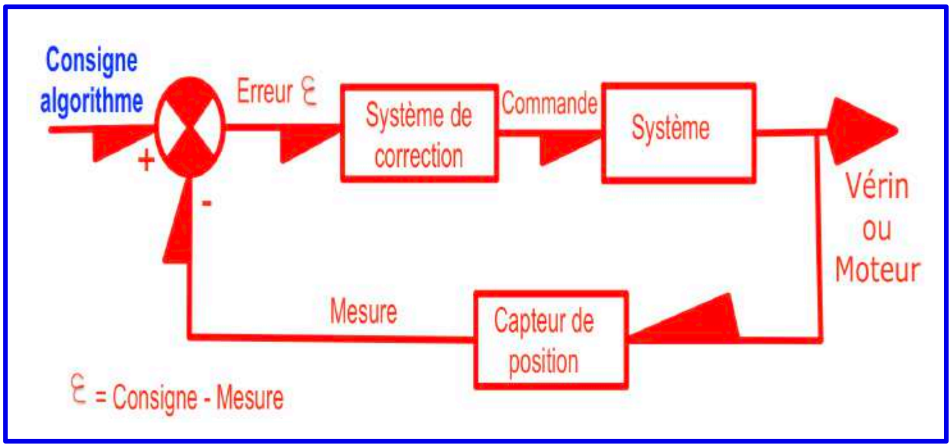
As mentioned at the end of the previous chapter, a change in true wind strength and/or direction results in a change in the available sail force. This variable requires an adjustment to the heading and a change in sail trim in order to maintain, as far as possible, the Foiler's speed.

On a Foiler, speed is the dominant factor in the calculation of lift, as the speed vector is squared in the calculation. A drop or increase in this parameter instantly destabilises the flight conditions.

In the case of an ULTIM trimaran such as **Gitana 18**, a PA requires at least six appendages to fly: the rudder (yaw), the main and jib sail trims (propulsion), the foil trailing-edge flaps, the rudder's PHR (pitch) and that of the skim wing (roll). For a monohull foiler, the skim wing can be replaced by a pendulum bulb keel fitted with symmetrical-profile foils (see **Ferrari Hypersail**).

During this sequence of actions, which must necessarily take place within a very short timeframe, the foiler is travelling at 18 m/s (35 knots); the risk of interactions between the 'aerodynamic' effects of certain appendages becomes a possibility and may destabilise the foiler.

For example, restoring the longitudinal trim (pitch) using the rudder's PHR results in a change to the foil's angle of attack relative to the fluid… which must be simultaneously compensated for by increasing or decreasing the angle of the foil's trailing-edge flap.



Each control system for the appendages – whether hydraulic cylinders and/or electric motors – necessarily uses a closed-loop control system to verify that the displacement setpoint requested by the algorithm is actually achieved. This requires each appendage to be fitted with a position sensor in addition to its drive system. This sensor feeds its actual position back to the control loop.

To improve performance, designers are tempted to duplicate or even add appendages to increase the range of adjustment options.

For example, the active foil arm has two degrees of freedom.

A primary rotation about a longitudinal axis allows the foil to be retracted beneath the platform's net and extended when its lift-generating function is required.

On the AC40 or AC75, this function is of the 'all or nothing' type. On **the G18**, the programming of the actuator controlling the foil's deployment allows, in its final phase, for the deployment angle to be adjusted. This option makes it possible to alter the angle of the foil relative to the horizontal, thereby increasing or decreasing the vertical lift component.

A second rotation of the entire joint occurs about a transverse axis. A actuator allows the foil's angle of attack to be adjusted in order to reduce its initial drag. This manoeuvre provides a slight gain in speed at certain speeds.

It should be added that the two trailing-edge flaps on the foil have independent controls. Thus, adjusting the camber of each half-foil allows the centre of the overall lift to be shifted transversely along the foil. This increases or decreases the righting moment.

In flight, this involves 12 propulsion systems and an equal number of sensors to monitor compliance with the set parameters:

⇒ Foil (4), central rudder and PHR (2), float rudder and PHR (2), skim wing, PHR, tilt mechanism (2), wing control (if applicable) (2).

And that's not to mention the data provided by the two radio altimeters or LiDAR systems, the data from the three axes of the IMU, and the data relating to the sail environment.

All of this technical management falls within the algorithmic architecture of the flight controller. This architecture and the calculations involved are becoming increasingly complex.

The set of control surfaces does not constitute the end goal of the final control loop, which is to align the actual IMU position with the setpoint.

The control surfaces are merely static actuators within an overall dynamic system, subject to violent accelerations as it is constantly in motion.

For example:

- A pitch-up or pitch-down manoeuvre by the PHR attached to the rudder alters the attitude, but also the speed, acceleration…
- Roll alters lift… and thus creates a dynamic effect.
- A change in altitude indirectly alters the attitude… by creating inertial effects
- Etc…

All the flight computer's algorithms are based on the dynamic model represented by the Foiler, and not simply on a geometric correction of the Foiler's position in space, as when moving an object in a stable 3D space.

The IMU, with its built-in accelerometers in particular, enables these induced dynamic effects—resulting from the multiple actions of the control surfaces—to be correlated.

The RRS 52[7] Manual Power

Generally speaking, only the international racing rules and those specifying how a fleet must round the marks are set in stone. The other rules may be modified by regatta organisers.

Rule 52 is one such modifiable rule.

RRS 52 (Racing Rules of Sailing – RRS)

"*A boat's standing rigging, running rigging, spars and movable hull appendages shall be adjusted and manoeuvred solely by the* ***force provided by the crew***."

[7] Rule 52 is taken from the sailing race rules laid down by 'World Sailing', the organisation that succeeded the ISAF. Amendments are made every four years (Olympic cycle).

At the 2013 World Sailing Congress, the phrase *'force provided by the crew'* replaced the former wording *'manual force*'. In fact, the rule specifies that only the physical effort produced by the crew must act directly on the manoeuvres and adjustments. A block and tackle and a winch operated by a crew member comply with this phrase 'force provided by…'. However, the storage of energy is not permitted under Rule 52, even if it is initially generated by the physical force of the crew, such as a cyclist powering a hydraulic pump or an electric generator. This also applies if the energy comes from a wind turbine, even though it is clearly the force of the wind.

With the emergence in the early 1960s of solo and double-handed ocean races, organisers were forced to amend this rule to allow energy other than that produced by the skipper to directly operate the rudder. It is understandable that, in a solo ocean race, the skipper needs to sleep.

The wording of the first amendment to the rule naturally permits yaw control via a windvane, which maintains a steady course. The first autopilots operated in relation to the apparent wind, utilising the reaction of a wind vane acting directly on the helm or on a submerged appendage that adjusted the rudder angle via a system of lines. It was therefore a force not generated by the crew that operated the boat's helm. For a good decade, sail power fulfilled this function.

Gradually, autopilots improved, with the electronic compass replacing the sail-powered system. This innovation made it possible to programme the course to be followed. Thus, a non-sail-powered force actuates the rudder via a hydraulic cylinder, which is in turn controlled by a computer linked to sensors.

As electronics are evolving very rapidly, designers are now offering so-called 'intelligent' autopilots.

In fact, this 'intelligence' is nothing more than a number of electronic filters that dampen or enhance the sensitivity of the response to helm input, depending on the boat's movements whilst underway.

In the next stage, the PA's control unit incorporates several additional parameters: wind speed and direction at time 't'.

The exponential growth in processor processing power has thus completely unlocked innovation, particularly in the areas of autopilots, data processing, etc.

However, these developments rely on electrical power. Paradoxically, it is not so much the generation of electrical power that poses a problem, but the content of the autopilot's computer.

That is to say, the technical sophistication of the algorithms integrated into the autopilot.

As long as the autopilot acts merely to maintain course, sporting fairness is upheld, even if there are filters that regulate yaw to a greater or lesser extent. On the other hand, as soon as data relating to the external environment influences the autopilot's operation – particularly whilst the skipper is asleep, though not exclusively – we enter the realm of augmented reality.

Augmented reality is the superimposition of reality—as represented by the boat's behaviour—onto other elements such as data, 2D or 3D images, videos, etc. An algorithm operating in real time interprets, assembles and enhances this combination, and proposes an evolution of reality.

To give a simple example, a pendulum keel, controlled by hydraulic cylinders or ball screws, can be adjusted according to changes in the course, the boat's heel, the stability curve relative to the hydrostatic model of the hull, anemometric data, etc. Under these conditions, the PA operates in 'augmented reality' mode.

This makes the drafting of Rule 52 very complicated. Highly structured classes such as IMOCA, CLASS 40 or the MINI 6.50 class manage to deal with this issue. However, for Archimedean-measured boats, which by their very nature feature a wide variety of designs – as do the highly varied formats of the races on offer – this amounts to squaring the circle.

This forces organisers to include, in each Notice of Race, a regulatory text relating to Rule 52 that sets out what is permitted.

When the boat transitions to foiling mode, it is no longer possible to control the flight envelope by operating the rudder alone, as this only controls yaw and longitudinal movement.

All six degrees of freedom must be controlled simultaneously: yaw / pitch / roll / translation / yaw / altitude.

This new paradigm requires the drafting of new Racing Rules of Sailing (RRS) entirely dedicated to foilers, which has been achieved for the America's Cup.

In the case of these ocean-going foilers, the regulations must set out the piloting conditions for 'solo', 'double-handed' and 'crewed' configurations.

When crewed, the organisation into watch shifts allows for sailing in assisted manual control mode. This mode of control will be indirect, as it is the flight controller that ensures the final stabilisation of the platform, but it is the crew member who holds the joystick and translates their perception of flight instabilities at time 't' into manual commands. The specific nature of sail propulsion requires the crew on watch to manually adjust the sail in order to maintain speed. This gives rise to a form of comprehensive navigation which, whilst highly assisted, remains dependent on the crew's skill.

Whether sailing solo or even in a two-person crew, a person's physical and physiological endurance limits their ability to pilot a Foiler 24 hours a day, even with Assisted Manual Piloting.

On an Archimedean sailing yacht, it is possible to decouple the tracking of the course from the other functions that ensure the yacht's stability and safety. The yacht's overall equilibrium is governed by the laws of hydrostatics. Its speed, on the other hand, depends on the adjustment of the sails in relation to the wind or the course set in the PA. However, these adjustments allow for a high degree of tolerance regarding their aerodynamic efficiency. Admittedly, this does affect speed. For example, at 10 knots, a 2 per cent loss in speed amounts to 0.2 knots, but does not cause a fatal loss of balance.

Even if the yacht is facing into the wind, turns at an inopportune moment, or is lying flat on the water, there is no immediate danger apart from a complete loss of speed.

Under these conditions, the yaw function – that is, the course to be followed – can be entrusted to an AI.

On board a foiler, it is impossible to decouple lift above the water – which is governed by the laws of aerodynamics – from the course to be followed. This means that the autopilot must manage all the appendages and equipment that ensure this spatial balance.

Under these conditions, the crew's role is almost entirely limited to providing the PA with flight-related data such as the route, altitude, speed, performance curves, etc. Critics will argue that if the PA dedicated to this foiler has access to MTO files, databases and real-time conditions, the on-board algorithm is perfectly capable of continuously determining the optimal route to reach the programmed destination. Ocean racing enters a whole new realm.

PART 2: Foiler Designs

The Origins

The first ocean-going foiling yachts used construction technologies that are now completely obsolete, in terms of materials as well as electronics, micromechanics and computing.

Optimising the weight-to-drag ratio and managing stability in flight are the main challenges to be overcome when designing an ocean-going foiler. The method of steering also appears to be highly complex.

The choice of a monohull design also complicates the design process compared to a trimaran-type platform, which is reputed to be more stable in terms of heel.

During the late 1990s, the ORMA trimaran class saw rapid architectural developments in these 60-foot trimarans, notably with the introduction of curved keels integrated into the floats, making it possible to lift the entire platform out of the water and thus to fly.

However, lifting the trimaran completely out of the water, whilst an important step in flight technology, by no means guarantees a stable flight.

Faced with this temptation to fly – which remained, however, very difficult to achieve with the technological resources available at the time – the ORMA class blocked progress towards flight.

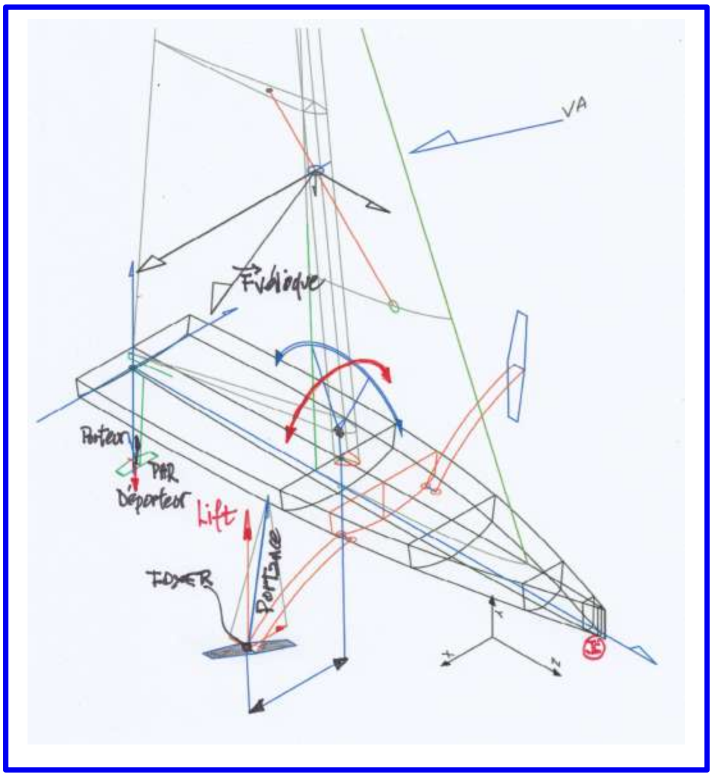
In reality, the ORMA class realised that flight by trimarans was becoming possible. It did not want this paradigm shift. This would also be the case a decade later for the IMOCA class, which drew up regulations preventing monohulls from flying by limiting the number of appendages to five. However, this decision did not prohibit sailing with lifting surfaces.

The relative one-design nature of ORMA vessels allows the class to regulate the lift generated by the use of these laterally curved centreboards, by limiting their projected area on a horizontal plane. ORMA trimarans therefore remain Archimedean.

From the performance of ORMA trimarans, the designers conclude that a catamaran or trimaran platform appears highly suitable for designing a full-fledged ocean-going foiler. It offers a half-width-to-length ratio that favours the moment counteracting capsizing in both Archimedean and flight modes, whilst ensuring that the heel angle remains within the range of 6° to 8°.

Class C catamarans, the AC72s (2012 America's Cup), with a length over all of 26.2 m, a beam of 22 m and a displacement of 5,900 kg, as well as the first-generation F50 catamarans of SailGP, will use L-shaped foils, derived from curved foils. In January 2025, the SailGP F50s will be fitted with 'high-speed T-foils'.

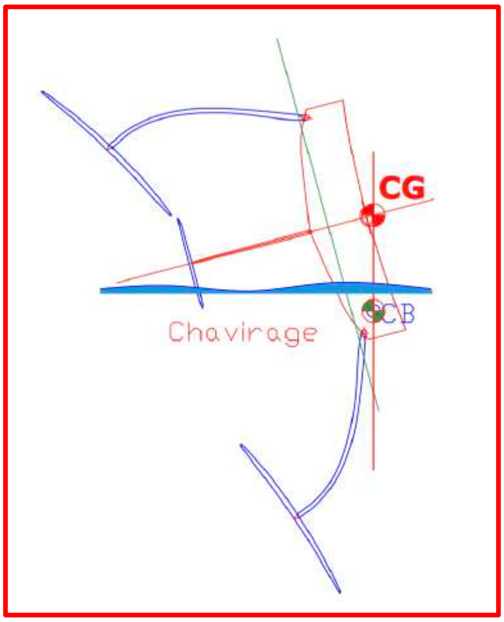
The impact of the AC75 monohull



The decision, in November 2017, to opt for a 21-metre AC75 monohull with a displacement of 7 tonnes – unballasted but fitted with foils – challenges many preconceptions, even though foil-equipped Moths have been darting across the water like dragonflies for several years now.

It should be noted that this AC75 project is designed to sail on a flat, sheltered body of water

The AC75 flies supported by its foil, which is positioned well off-centre on the leeward side. This 'inverted T'-shaped foil is mounted at the end of a curved, oscillating arm. A PHR (Pitch Control System) located at the base of the rudder controls the longitudinal pitch and, indirectly, the angle of attack of the foil relative to the water during a pitch-up manoeuvre.



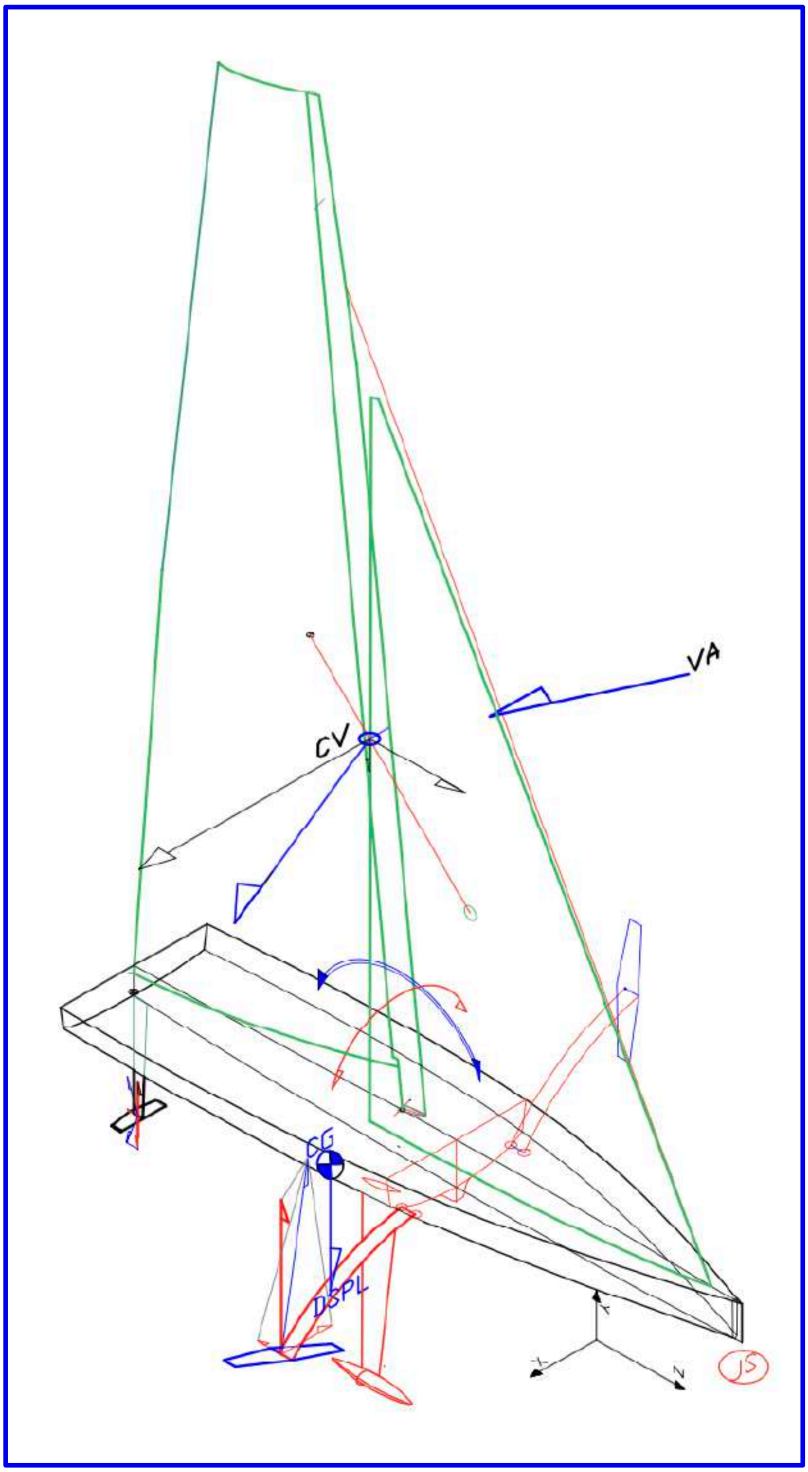
However, this design has the major drawback of capsizing at around 80°, when operating in Archimedean mode, either before take-off or following a loss of control in flight.

This poor stability prevents the global model of an AC75, as it stands – that is, unballasted – from being fully transposed onto an ocean-going foiler.

The reason is simple: an ocean-going foiler may find itself in two situations where it is subject to Archimedes' principles, and therefore at risk of capsizing. These are: when taking off and when landing on the water, when there is not enough wind to fly but too much to ensure stable flight.

It should be noted that, during ocean voyages, an Archimedean monohull must have a minimum capsize angle of around 115–120°. World Sailing mandates the ISO 12217-2 standard for monohulls under 24 metres and, by extension, for larger sailing yachts such as Maxis, which reach 100 feet (30 metres).

A full-fledged foiler designed for ocean racing is no exception to this rule, as it can switch at any moment from flight equilibrium to Archimedean mode.



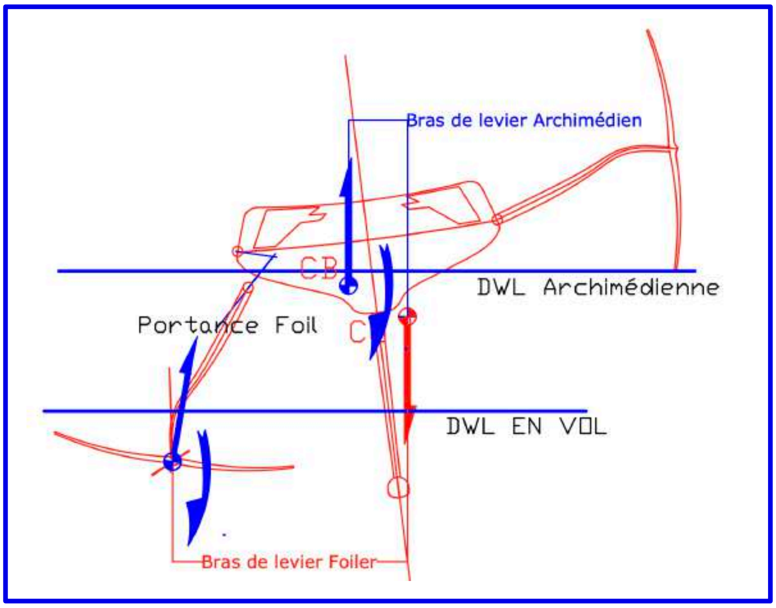
In order to meet this stability criterion, the installation of a bulb at the end of a central keel sail is mandatory in order to lower the boat's centre of gravity and thus achieve a compliant capsize angle. This will be implemented on the first ocean-going foiler monohull, **the Flying Nikka**.

Admittedly, the laws of hydrostatics allow for the design of an Archimedean hull with internal ballast as a replacement for an external keel (whether bulbous or not).

This type of design (similar to an integral centreboard dinghy) requires a more voluminous hull for the same overall length. This results in an increase in displacement, and therefore in weight… the number one enemy of flight. More weight at take-off means an increase in wing area and sail power, and thus additional weight that must be lifted out of the water.

Conversely, a design incorporating a bulb does not increase the foiler's initial planned displacement, as the mass of the bulb is offset by the reduced weight of the hull, deck and internal structure as a whole.

However, as soon as the Foiler takes to the water, the equilibrium equation becomes entirely different from that associated with Archimedean mode. The centre of the hull **(CB),** where the hydrostatic thrust (centre of gravity of the submerged hull volume) associated with Archimedean mode is applied, disappears. It is replaced by the foil's **centre** of lift, where the lift force is exerted.



Consequence: in Archimedean navigation, the righting moment generated by the product of the Foiler's weight and the horizontal lever arm (the distance) between the CG and the CB is multiplied, in flight mode, by a factor of 7 when the Foyer replaces the CB.

Even though, in flight, the bulb no longer serves any purpose in terms of stability, it remains submerged and creates significant drag, which negatively affects speed.

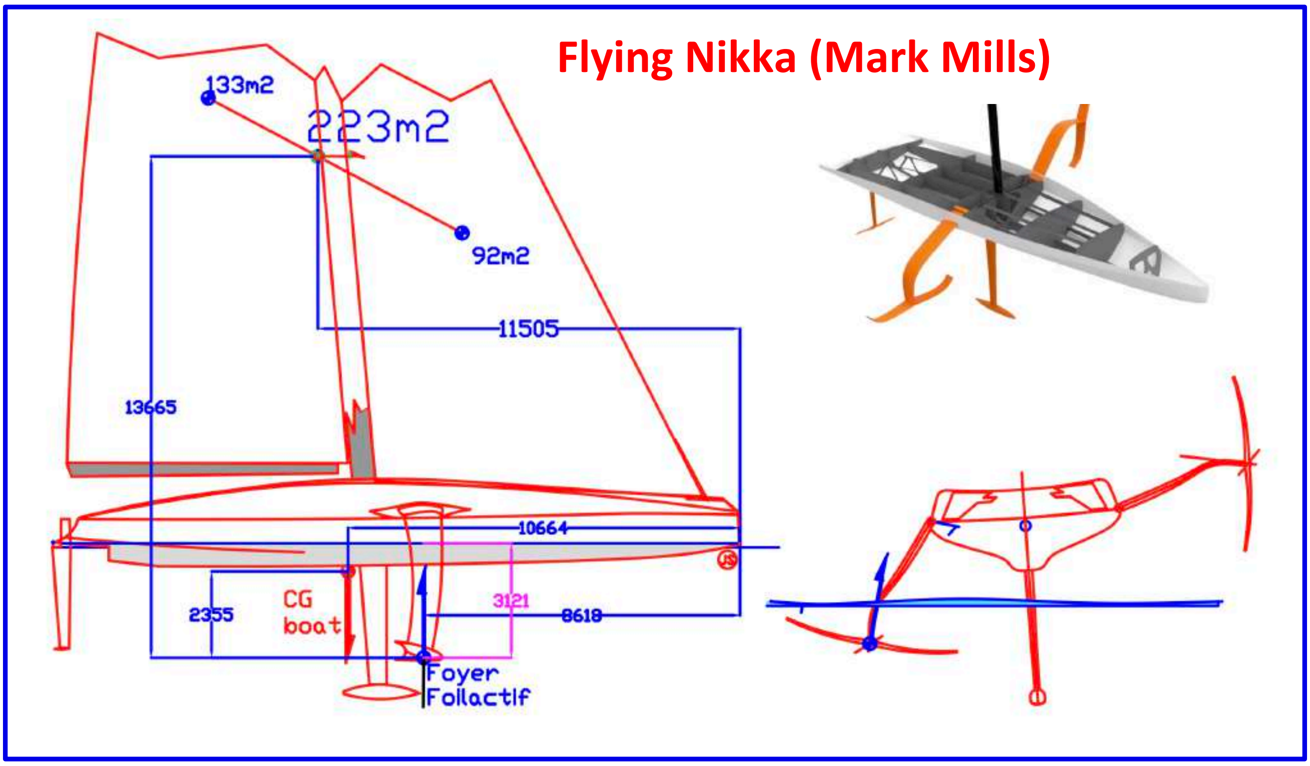
The Flying Nikka monohull foiler

Whilst multihull foilers are being developed – including the creation of the ULTIM Class – it took five years after the launch of the AC75s for a monohull foiler**, the Flying Nikka** (LH 18.72m, displacement 7,450 kg), designed by Marc Mills and his team, to be developed and launched.

The owner's aim is not to design a foiler for ocean crossings, but rather a foiler inspired by the AC75s to compete in coastal offshore races in the Mediterranean, including the Giraglia.

On this project, the manipulation of the foil arms (rotation) uses the same technique as on the AC75s. However, on the version presented at Neuvage, there are no trailing-edge flaps on the foils.

The angle of attack of the foil is achieved by rotating the entire lifting surface.



Flying Nikka (Mark Mills)

These technological choices result in a substantial hydraulic system (operating at pressures of around 500 bar) for controlling the arms, the 5–15° angle of the foils, the PHR and the rudder.

The steering technique employed stems from the sailing programme, which consists of crewed races lasting a single day or a maximum of 24 to 48 hours.

Just like on an Archimedean boat, each member of this Foiler's crew performs a specific role. In addition to trimming the sails to maintain speed at all times, the crew must react continuously to:

- Provide the lift required for flight
- Maintain a horizontal flight attitude
- Maintain the set course.

The crew manually controls the sail propulsion and each of the appendages – the foil, rudder and PHR. Flight stability depends on perfect coordination between all these individual actions.

During flight, the installation of an automated system optimises the relationship between action requests and the operators' response times, and manages the coordination of decisions. This automated system is not strictly an autopilot, but rather a technical aid mediating between the crew's actions and the Foiler's flight envelope. With this system, the crew remains more operational.

Reality shows that this monohull foiler does indeed fly, but its in-flight stability appears very complex to manage. Added to this is the particularly high energy consumption of the control and management systems.

The **Flying Nikka** project appears more to be a full-scale demonstrator than a genuine foiler, ready to sail for several days in an offshore ocean regatta, in sea conditions that can at times be chaotic. However, **Flying Nikka** exists and demonstrates that it can fly. The challenge now is to adapt it to the flight envelope of an ocean-going foiler.

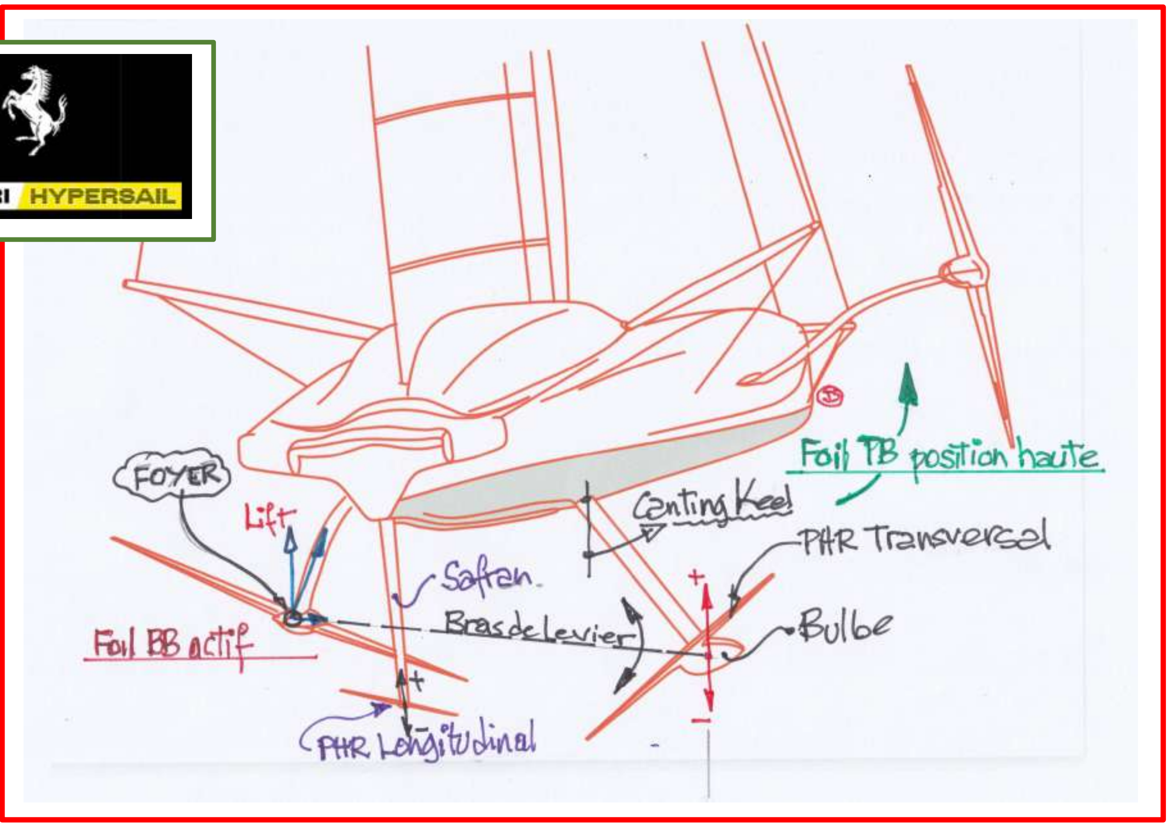
The FERRARI Hypersail project

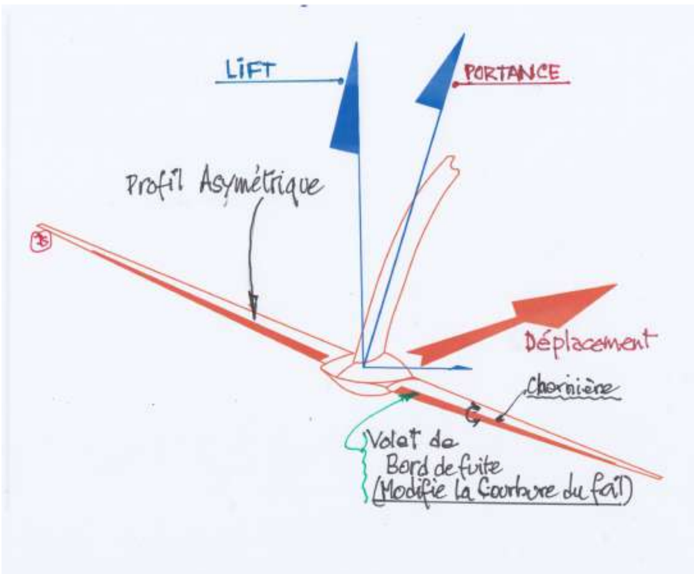
The **FERRARI Hypersail** monohull foiler, the design for which was unveiled in December 2025, utilises an 'inverted T'-shaped foil for its primary lift, just like the AC75s, but innovates by incorporating two lifting surfaces on either side of the bulb of a pendulum keel.

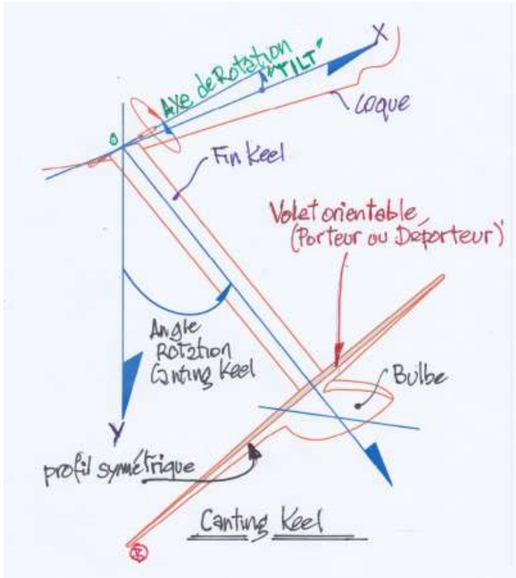
In fact, the **FERRARI Hypersail** foiler adapts the concept, developed on the ULTIMS, of a stingray wing fitted with two lateral lifting surfaces.

The inverted-T foil, on the leeward side, generates maximum lift.

It is possible that the two foils mounted on either side of the bulb also contribute to this lift. I say 'possibly' because these two foils, mounted laterally on the bulb of the pendulum keel, serve another purpose.







'Inverted T' FOIL

Pendulum Keel Bulb and Ray Wing

Indeed, its axis of rotation, situated in the vertical plane of symmetry of the hull, is angled upwards by 7 to 10° (known as 'tilt') relative to the horizontal. This technique was originally developed for IMOCA yachts and was used on **Gitana 18**.

Thus, when the pendulum keel – comprising its bulb and its two lateral lifting surfaces – is angled into the wind by 20 to 25° or more, the tilt of 7 to 10° chosen by the architect during the design phase gives the keel sail an angle of attack, and thus lift, which is added to that of the lateral foils mounted on the sides of the bulb. It should be noted that the flat bottom of the bulb also generates some lift as well as drag.

The profile of the bulb's lateral foils is symmetrical. They are fitted with trailing-edge flaps which, depending on their angle settings (+/-), produce upward lift or downward lift (downforce).

Thus, the foils fitted to the bulb of the pendulum keel can generate lift that adds to that of the 'T'-shaped foil. However, they can also operate in downforce mode, like a PHR, in order to adjust the heel angle.

Setting the foils on the pendulum keel to maximum lift, combined with the lift generated by the leeward foil, improves the take-off phase, which the designers aim to achieve at around 12 knots.

Subsequently, during stabilised horizontal flight, adjustments to the roll and pitch attitudes occur around the centre of pressure of the inverted T-foil.

This is achieved through the simultaneous action of the PHR located at the tip of the rudder and the bulb foils, which act as a PHR controlling roll.

The foil's trailing-edge flaps, located at the end of the arm, allow the Foiler's lift to be modulated and the flight altitude to be maintained.

The revolutionary invention of this PHR – the 'Elevator' – is attributed to the Wright brothers in 1903, who were seeking a method to control pitch. This system for regulating the pitch (pitch-up or pitch-down) of an aeroplane is still in use today.

Often, on sail-powered Foilers, the term 'foil on the rudder' is used to refer to this horizontal control surface (PHR), and it is believed to play a role in the Foiler's lift. This is a mistake, as a foil always generates lift, whereas a PHR – ELEVATOR – can, depending on the pilot's commands, generate lift or downforce; this means that the thrust created is directed upwards or downwards with equal efficiency.

Moreover, the profile of a PHR is symmetrical rather than asymmetrical~~, and~~ it is not cambered, as is the case with a foil (wing). If one wishes to prevent the foil from generating lift, one either deploys a surface flap that disrupts the upper surface, or temporarily sets the trailing-edge flap to a negative angle.

In summary, the design of the **FERRARI Hypersail Foiler** centres on the following appendages:

- An inverted T-shaped foil mounted at the end of each articulated arm. Its **C_Z** varies according to the setting of the trailing-edge flap and the longitudinal trim, particularly during the take-off phase.
- A pendulum keel, whose axis of rotation is pitched up by 7 to 10° relative to the horizontal. This angle geometrically generates lift on the symmetrical profile of the keel sail as soon as the keel is angled.
  The lift produced adds to that of the leeward foil. The bulb at the tip of the keel sail, which remains submerged, creates drag. Its flat bottom generates a small amount of lift.
- A rudder, with its PHR, allows for control of yaw and pitch. This foiler is always designed with a rear centre of gravity[8] , which makes it unstable in the sense that the pilot can respond quickly and, above all, effectively to any change in its in-flight balance.
- Another control surface (lift-generating or downforce-generating) is positioned perpendicular to the keel wing… And this is where the innovation lies: it is located at the bulb. This PHR-Elevator has almost the same span as the foil.
  This illustrates the level of efficiency the designers expect from this appendage. The aim is to generate lift or downforce in order to achieve clockwise or anti-clockwise rotation about the centre of pressure and thus control roll during flight.

That is, 3 degrees of freedom in rotation: R_x(pitch), R_y(yaw), R_z(roll), controlled by the pilot/skipper, and 3 translational movements:

---

[8] See the document 'Speed: a symbol of power through the centuries' (Chapter 30: Balance in flight: Rear-centred or Front-centred) on www.experts-yachts.fr's blog

- Longitudinal translation T_z (the course to be followed),
- Vertical translation T_y (the flight altitude generated by the lift from the lifting surfaces),
- Transverse translation T_x (yaw, indirectly controlled by the transverse component of the lift from the foil and the Fin Keel).

The energy required to fly

Flying Nikka continuously uses an electro-hydraulic thermal power unit (80 kW) to provide the hydraulic power (500 bar) and electrical power required to charge the battery bank. This energy is necessary to ensure control of the appendages and ancillary equipment. It should be noted that the practice of continuously using a generator during regattas is widespread amongst all Maxi yachts.

From the very start of the design of **the FERRARI Hypersail Foiler**, the Maranello's design office opted for total energy self-sufficiency for the Foiler's operation. This means that this Foiler will not use any fossil fuels.

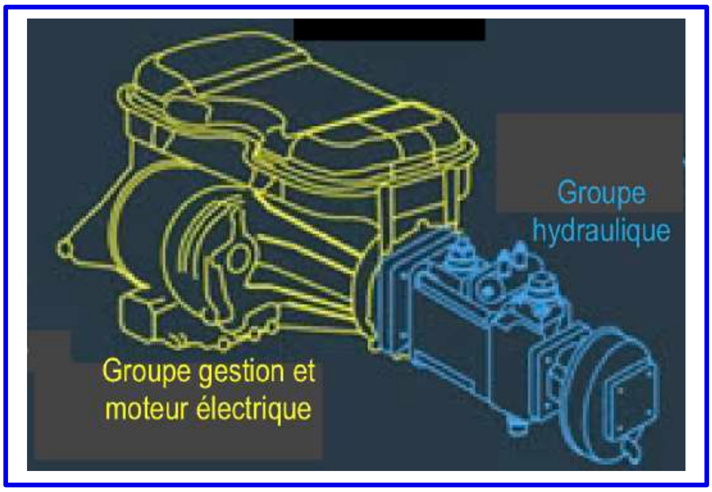
What a challenge! But the design office has two major assets. Firstly, its experience in motor racing with the electric power assistance fitted to F1 cars; and secondly, the launch, in early June 2026, of the first electric FERRARI, named 'Luce'.

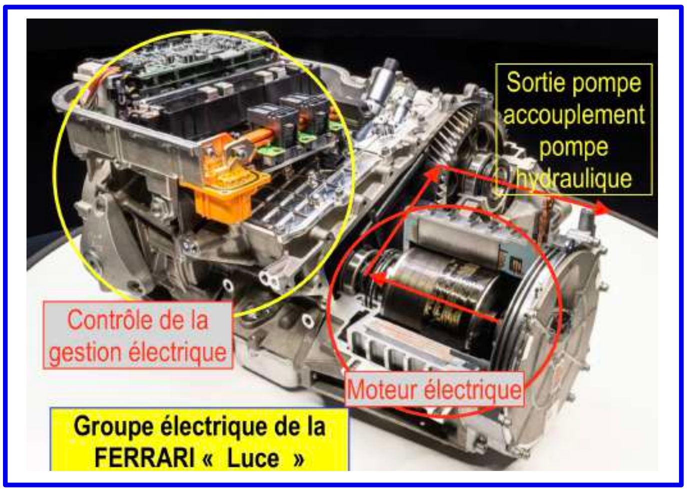
The heart of the Ferrari Hypersail Foiler's overall system relies on two electrical power sources:

- An 800-volt NMC (Nickel-Manganese-Cobalt) lithium-ion battery pack. On the 'Luce' car, this pack has a capacity of 122 kWh. What will the situation be on the **FERRARI Hypersail** Foiler?
- A secondary 48-volt battery pack.

Each of these battery packs powers a hydraulic energy generation system:

⇒ **High pressure**, approximately 500 bar, for the slow manoeuvring of the appendages, namely: the rudder, the foil arms and the pendulum keel. This hydraulic unit (pump) is coupled to a system derived from the FERRARI 'Luce's' aft electric propulsion unit (800 V) (electric motor, coupling and electrical management system).





⇒ **Low pressure** for all the actuator cylinders that must respond rapidly to manoeuvre the trailing-edge flaps fitted to the PHR, the rudder, the foils on the arms, and the foils on the bulb. Electro-hydraulic unit (48 V).

Innovation with the ‘**Winch-by-Wire**’ concept

The design office also decided that the adjustment of the sails should be carried out solely by the force applied by the crew. The BE adopted the fly-by-wire concept, pioneered by Airbus. Fly-by-wire replaces an aircraft’s traditional mechanical flight controls with a system comprising electrical, electronic and computerised equipment. This is referred to as digital flight controls.

The design office has adapted fly-by-wire to create ‘Winch-by-Wire’.

The energy generated by the crew’s muscle power, via the winch handle, no longer directly actuates the mechanical transmission components and/or hydraulic circuits connected directly to the winch heads.

This energy is instantly converted into electrical energy, which is stored and centralised, to be redistributed, at the crew’s request, to the winches used to adjust the Foiler’s sail plan.

The idea stems from the following observation: when a crew member operates a winch, as the tensile resistance on the sheet increases, the rotational movement of the handle slows down and requires greater physical effort.

Winch-by-Wire technology eliminates this fluctuating demand for effort generated by one or more crew members. With Winch-by-Wire, the winches draw on the electrical reserve; it even becomes possible to operate several winches simultaneously and to automate sail plan adjustments. It is the crew’s responsibility to maintain the electrical reserve at a sufficient level.

This energy must be generated

The **FERRARI Hypersail foiler** has two renewable energy generation systems:

- A network of solar panels covering approximately 80 per cent of the entire deck and roof. The surface area is reported to be 100 m².
- Three wind turbines integrated into the transom.

According to the Foiler’s technical team, the wind turbines can be configured and removed depending on the sailing plans.

The use of wind turbines requires a balance to be struck between maximum electrical energy output and the aerodynamic drag produced at high speeds by the entire system. The drag from the three masts and three three-bladed rotors, each some 1.8 metres in diameter, increases with the square of the apparent wind speed, which is far from negligible. It must also be borne in mind that, above a certain rotational speed, the power output of the wind turbine drops.

These two renewable energy generation units supply a power management unit which:

- Directs the energy to charge the battery banks.
- Distributes electrical energy on demand for:
  - Either manoeuvres using high pressure, such as the rudder, the foil arms and the pendulum keel.
  - Or manoeuvres using low pressure, such as the PHR rudder, the foils on the arms, and the foils on the bulb.

However, the Maranello design office, whilst very forthcoming on the technological design of the appendages, trailing-edge flaps and the solutions adopted to achieve energy self-sufficiency during ocean crossings, appears to be very reticent when it comes to the area of flight control.

Energy self-sufficiency contributes nothing to flight stability. The work of Mark Mills’ team showed that **Flying Nikka** could fly, although it was not suited to the ocean environment, let alone solo sailing.

I believe that for the **FERRARI Hypersail foiler**, the design bureau will have no choice but to study a ‘proper’ aerodynamic profile inspired by aeronautical models and to undergo a very lengthy development phase. In my view, this development will involve the design of a proper dynamic flight simulator which can subsequently be hired out to other teams.

Gitana 18

Gitana 18 was born in 2026 from a collaboration between the Gitana design office and Guillaume Verdier.

The platform: A trimaran, built from carbon pre-preg, with around 90 per cent of its components manufactured in a curing oven. This enhances rigidity, which is crucial given that **the G18** is a full-foiler where the appendages that generate lift or maintain trim in flight are concentrated in four areas on the float and the central hull.

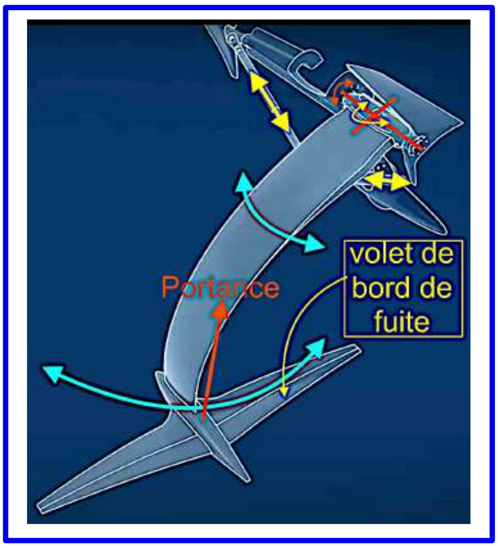
The specifications call for flight at an altitude of approximately 3 metres at cruising speeds of between 25 and 35 knots (13 to 18 m/s). At these speeds, the platform's movement through the air must be taken into account. This has resulted in an optimisation of **the Cx** (drag coefficient), primarily in the central nacelle.

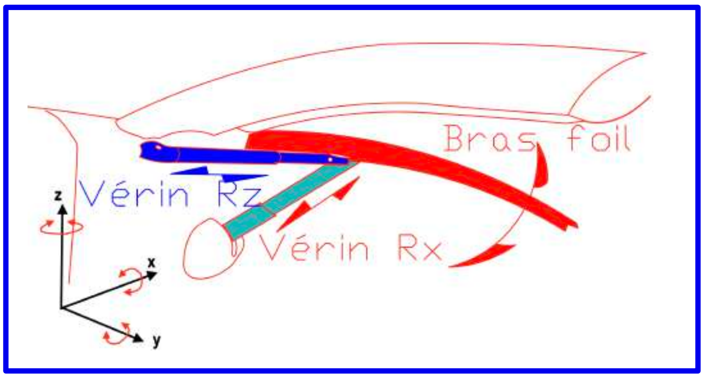
Lifting surfaces:

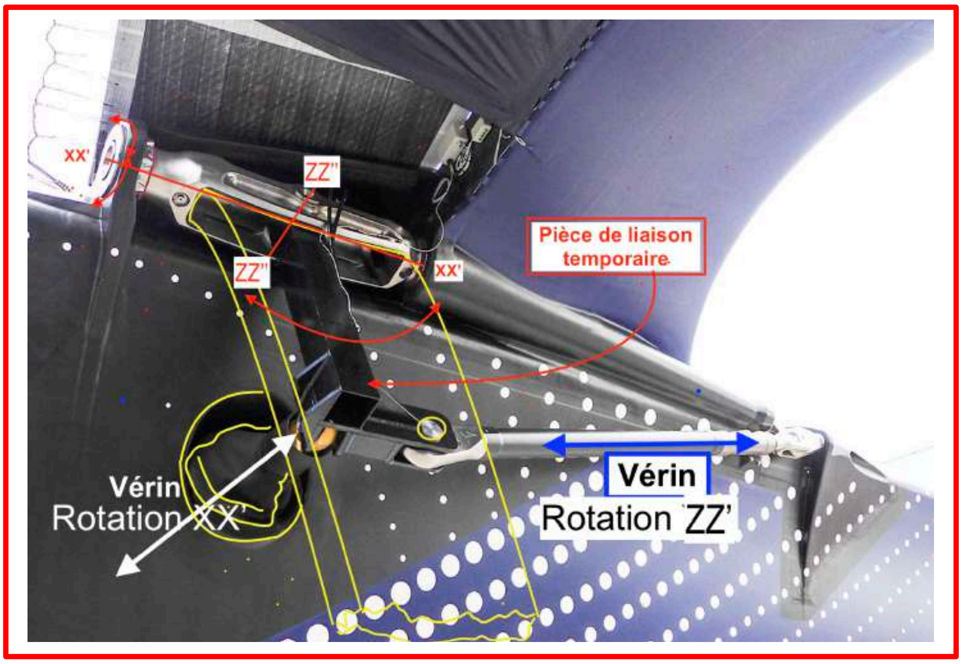
The G18 has moved away from the 'L'-shaped foil technology found on the previous generation of ULTIM multihulls.

The G18 adopts inverted T-shaped foils. The **G18** design bureau refers to these as 'Y-foils'. The support arm for each of these inverted T-foils is not housed in a laminated well within the float's plane of symmetry, but is attached to the end of a pivoting arm whose centre of rotation is located in an area close to the inner edge of each float and slightly behind the front arm. This decision stems from the ULTIM Class rules, which limit the width of the platform to 23 m, including appendages. On **the G18**, the span of each foil is 5 m. This arrangement also protects the foil that is not in use.

In order to fly at an altitude of 3 m, this arrangement requires a relatively long vertical arm, which is subject to significant bending stress and is relatively fragile.







This arm has two degrees of freedom in rotation:

- Longitudinal axis Ox,
- Vertical axis Oz.

Rotation about Ox allows the unused foil to be stowed away. It also enables lateral adjustment of the position of the centre of lift (active foil). The angle of rotation about Ox must, however, remain within the 23-metre width limit imposed by the class rules. This rotation allows the desired righting moment to be adjusted for sailing close-hauled or downwind.

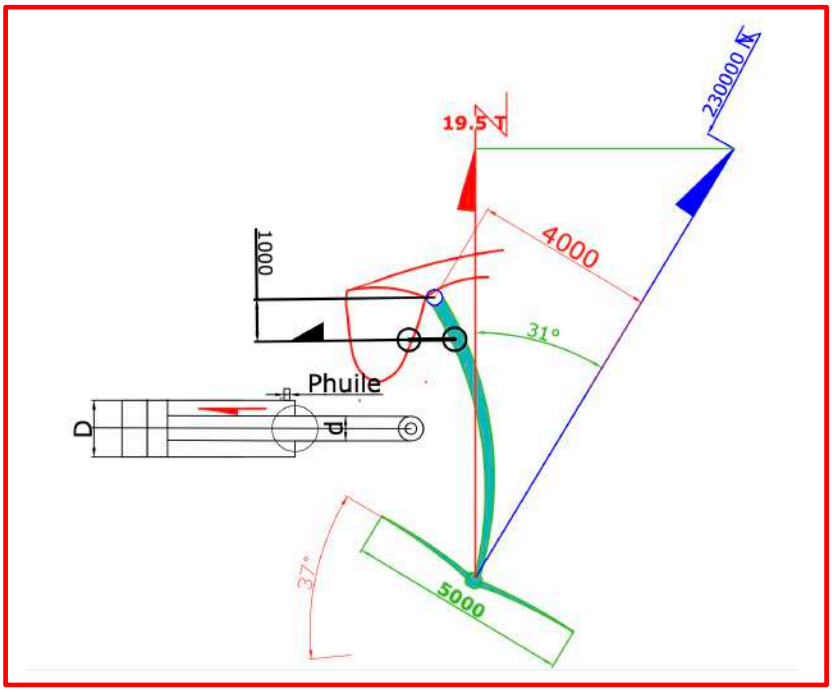
Rotation about Oz adjusts the foil's drag. In fact, the designers choose a basic foil profile similar to an approximately 12% NACA profile, which is asymmetrical and more or less cambered. Once this cambered profile has been selected, its overall shape between the leading edge and the trailing edge at 0° angle of attack becomes fixed.

The more cambered the profile, the better its performance when sailing close-hauled, but this results in greater drag when sailing downwind. Rotation about Oz, by altering its orientation relative to the water flow, helps to reduce this drag[9] , without significantly affecting lift.

Rotations 0x and 0z interact at the end of the actuator that controls the rotation of the foil arm. This requires a spherical joint (ball joint) at this point. A ball-and-socket joint clearly identifies the point of application of force F at the centre of the sphere. However, the angular orientation of force F depends on the possible angles of rotation Ox and Oz. These spatial changes are likely to weaken the head of the piston rod that drives the arm's rotation.

[9] In fact, this rotation is similar to the image of a cyclist adopting a streamlined position whilst going downhill.

This is all the more so given that my assessment of the lever arm ratio in the foil arm's control system is approximately 4 to 1. This means that the torque produced by the lift force – 230,000 N × 4 m – must be equal to that produced by the cylinder – F × 1 m – for the foil to be held stationary.



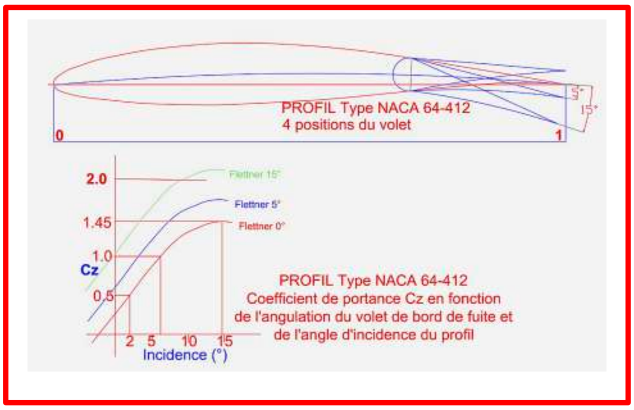
The force F is therefore of the order of 4 times 230,000 N, i.e. 920,000 N or 92 tonnes!

An oil pressure of 500 bar (500 daN/cm^2) in the hydraulic system requires a piston working area of 180 cm^2 (the cross-sectional area of the piston's internal diameter minus the cross-sectional area of the rod) to produce this force.

This corresponds to a cylinder with a diameter of 160 mm and a rod diameter of 35 mm.

This calculation provides an order of magnitude for the forces involved. It is clear that the geometric configuration of the **G 18** foil arm – against which the cylinder must pull in order to move the arm into the extended position and hold it there – is not ideal, as the cylinder rod effectively reduces the force developed by the hydraulic cylinder. However, there is no alternative design that would allow the arm to be folded inwards towards the trimaran.

The foil consists of two asymmetrical wings fitted with a trailing-edge flap. The total wingspan is 5 m. The flap allows the camber to be increased in order to achieve the **Cz** required to lift the foiler, depending on its speed.

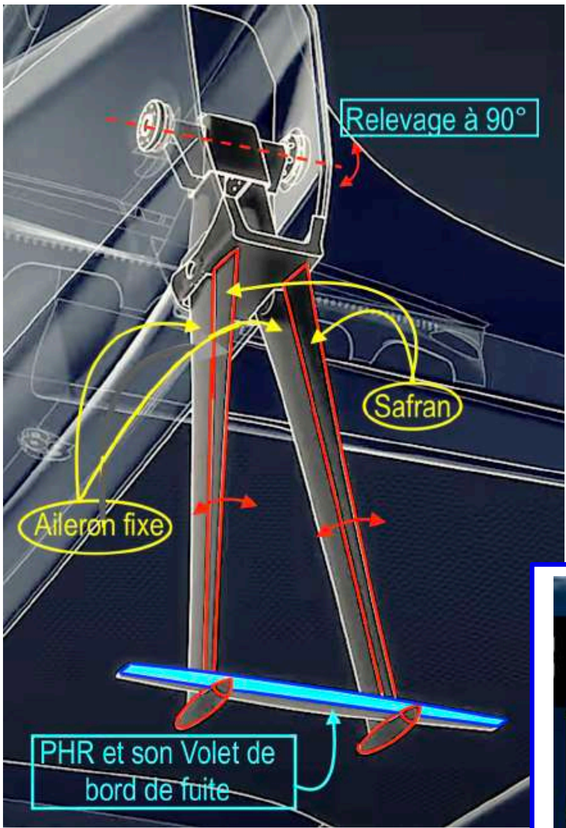


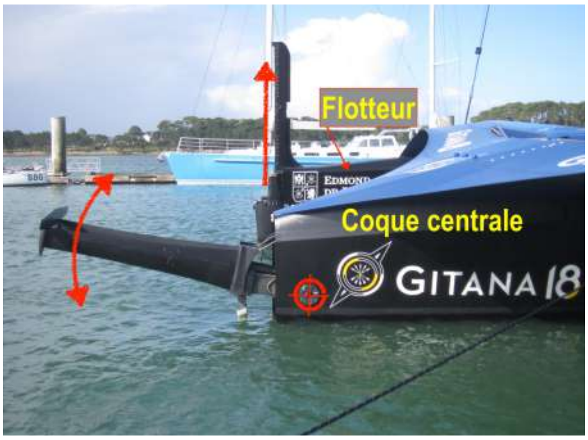
Another distinctive feature of **the G18**'s foil is the independent control of the trailing-edge flap fitted to each wing of the foil. This is an innovative design choice, as it allows, for example, the lift of the outer wing to be increased and that of the inner wing to be reduced on the same foil (with the projection of the sum of the two lifts always remaining at 19.5 T), thereby shifting the resultant force outwards.

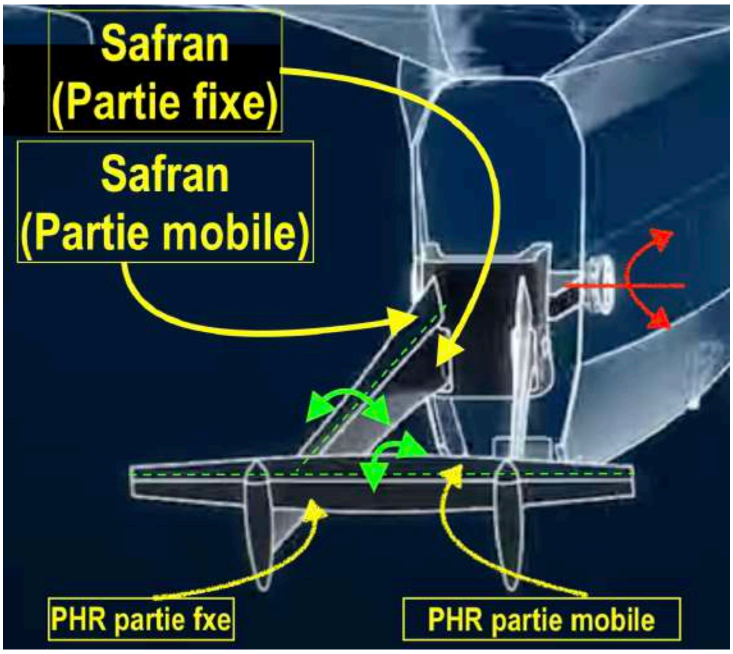
This technique significantly increases the righting moment and allows for the use of more power, where possible.

In principle, the scientific approach described above applies regardless of the type of foiler using a trimaran platform.

Control appendages:







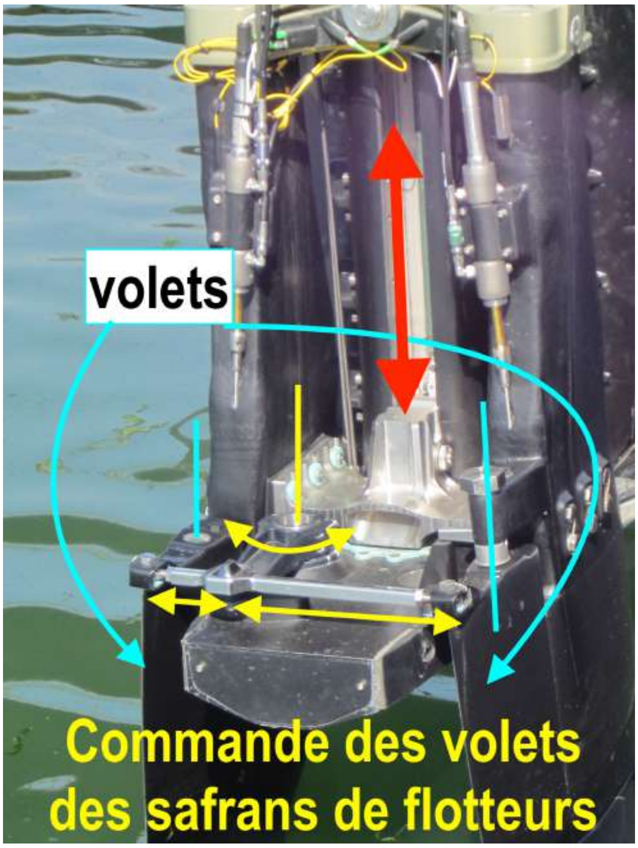
Typically, designers fit trimaran platforms with a Safran/PHR unit on each of the floats and a rudder on the central hull. The Safran/PHR units on the floats can be raised by vertical translation.

The G18 breaks new ground in two ways. The rudders on the central hull and the floats are twin rudders and slightly 'inverted V'-shaped, with an angle of approximately 5°.

Each of these double rudders uses a fixed aileron and a trailing-edge flap and has roughly the same aspect ratio.

A single control system, via a set of connecting rods, adjusts the angle of the trailing-edge flaps.

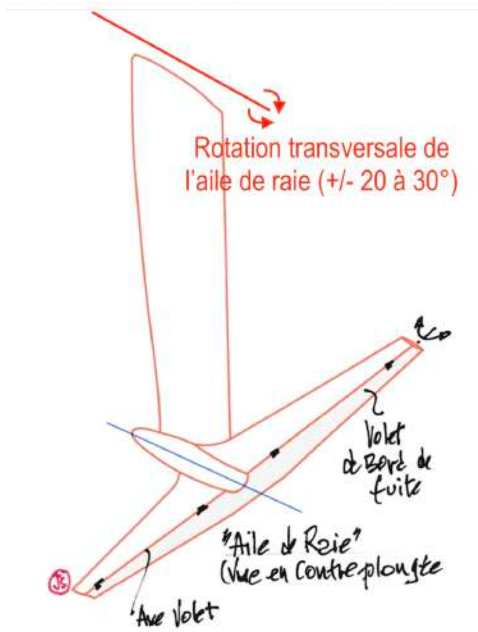
The design of the PHRs is identical: a fixed section and a movable flap.

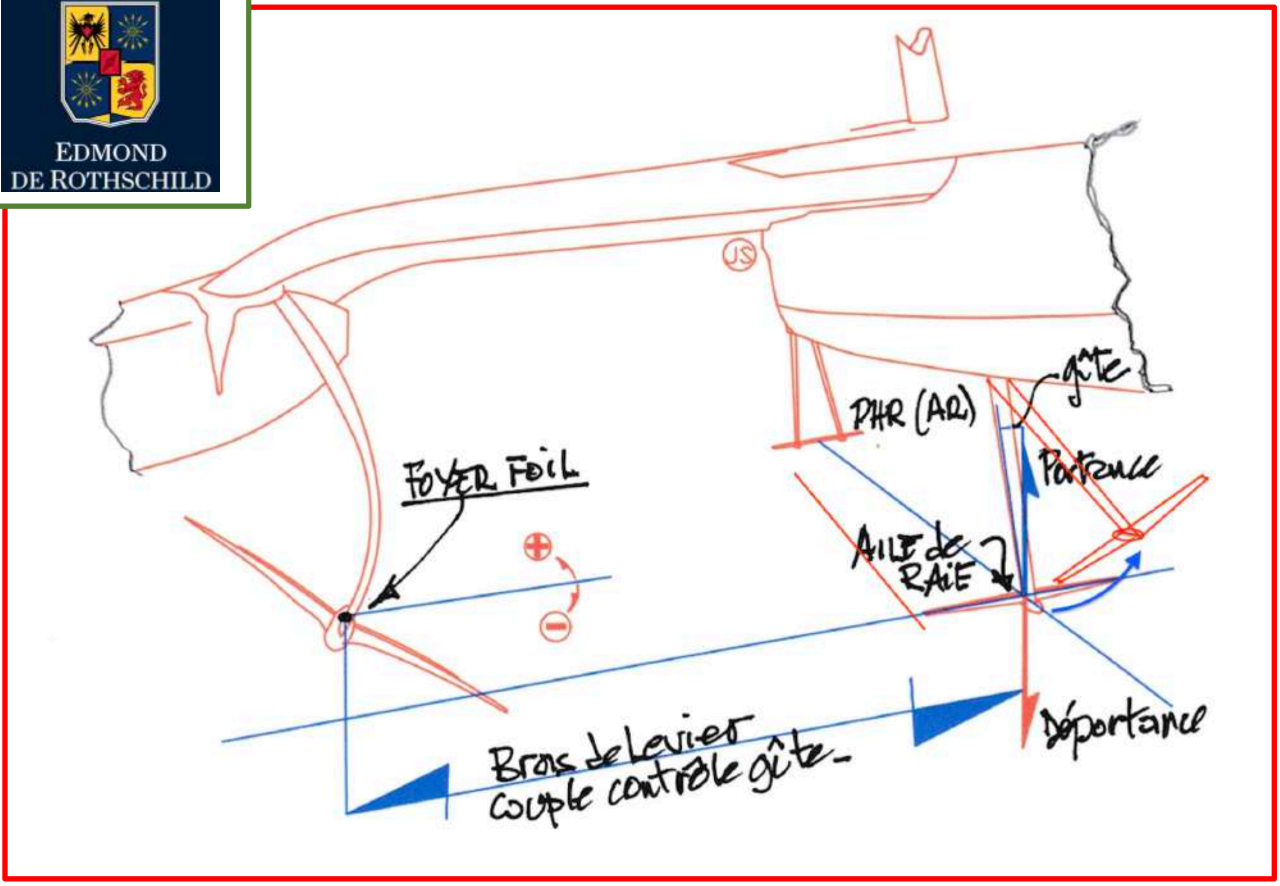


However, whether they are rudders or PHRs, their aerodynamic profiles are symmetrical when the flap angle is zero. A positive or negative flap angle produces only camber, i.e. lift or downforce for the PHRs, or a yaw to starboard or port for the rudders.

The stingray wings:

It has a dual function: to contribute to the lift required during take-off, when the Foiler's speed is low, and to control the amplitude of roll, about the longitudinal axis, whilst in flight, to ensure a trim that allows for optimum sail efficiency.





The pendulum-style wing, angled into the wind, forms a ‘very open V’ lift configuration with the foil, which provides a slightly self-regulating function for flight altitude.

In conclusion

Flying: Icarus burnt his wings trying; the Wright brothers (USA) achieved it in the air in 1903; Forlanini (ITA) did so in 1910 with a foiler on water.

Let’s be realistic. Even piloting an aeroplane is not within everyone’s reach, but it remains possible. Admittedly, the training is lengthy, and not all types of flight and aeroplanes are technically accessible without the necessary skills to manoeuvre in three-dimensional space.

Flying a Foiler is similar to aerobatic flying, albeit with two very specific additional constraints: maintaining an altitude of 1 to 3 metres depending on the type of Foiler, and adapting to erratic propulsive power, all whilst travelling at speeds of between 15 and 18 metres per second.

Added to this are constraints linked to the sporting concept, which requires that participants – ‘men or women’ – remain, at all times, the central figures in this performance. In the case of a motor sport, the ‘machine’ serves the athlete and its design parameters remain limited.

The first time the sporting authority authorises the use of a course-holding system in a solo race—one that acts exclusively on the luff—it introduces a flaw into the conduct of a regatta, as the yacht continues to sail without any control from the skipper. With identical yachts, the quality of the wind vane can make a difference that has nothing to do with 'sport'. The fact that the wind vane quickly becomes a course-holding system does not alter this observation, as the latter still regulates via the luff.

As long as the yachts are Archimedean, the laws of hydrostatics govern their equilibrium whilst sailing. Overall, the system works and is accepted. However, very quickly, crews or solo sailors wish to see beyond the meteorological horizon in order to optimise their navigation strategy.

In 1968, during the OSTAR, a competitor spoke by radio with an MTO expert living in England… 50 years on, skippers are asking ChatGPT their questions via Starlink…

ChatGPT's response to a prompt sent during the La Trinité-sur-Mer–Cherbourg regatta, just before rounding the 'Wolf Rock Lighthouse' mark.

*"I can also carry out a **'navigator-style' route analysis**, using the organiser's chart, the forecasts (Arome, Arpège, ECMWF) and your boat's polar curves to explain, **hour by hour**, where you need to be until you pass Wolf Rock, and then on to Eddystone. This is the sort of analysis that professional route planners generally produce during a race. " ……..*

With foilers, the aerodynamic model replaces the Archimedean model; the foiler, whilst in flight, has no self-balancing mechanism. This shift in scientific paradigm imposes physiological constraints such that the skipper/pilot can no longer rely solely on a course or heading hold to keep their foiler airborne.

More than sleep, it is fatigue and the stress caused by piloting that distract the athletes from their primary role.

The alternative is as follows: either a fully integrated autopilot system modelled on aeronautical design, or a full crew, organised into shifts, responsible for managing the functions necessary for flight and their interdependencies, using algorithmic assistance.

A Foiler is often compared to an aeroplane. The comparison is valid as long as one remains within the physical realm of flight, including aerodynamics and maintaining balance in flight.

However, one factor distinguishes a Foiler from an aeroplane: during cruise flight, an aeroplane can lose or gain 50 metres in altitude without harm; a Foiler does not have this freedom – far from it – as it operates within a space of 1 to 3 metres above the fluid that generates the lift forces enabling it to fly.

In this foiler environment, athletes become reliant on automatic systems that ensure this vertical stability.

Another significant development concerns the very nature of the architect's profession. Until recently, the architect was regarded as the master craftsman. Proof of this is that a ship's design is recognised as a work of the mind. Indeed, the architect receives royalties for every boat built. The design of a sailing yacht involves dozens of paper or digital plans, in addition to the form plan, which truly represents the artist's signature. With the advent of foilers, the technical project has become multidisciplinary.

Hydrodynamics comes into play during the Archimedean phase, which is now minimised as much as possible on a foiler. Next comes the flight phase, defined within the foiler's flight envelope. This raises the need to develop a control system for the foiler. Structural analysis and manufacturing then come into the loop to ensure that everything works in harmony and is properly balanced. This involves a design office working in partnership with a naval architect.

A whole other world… Fascinating.

J.S