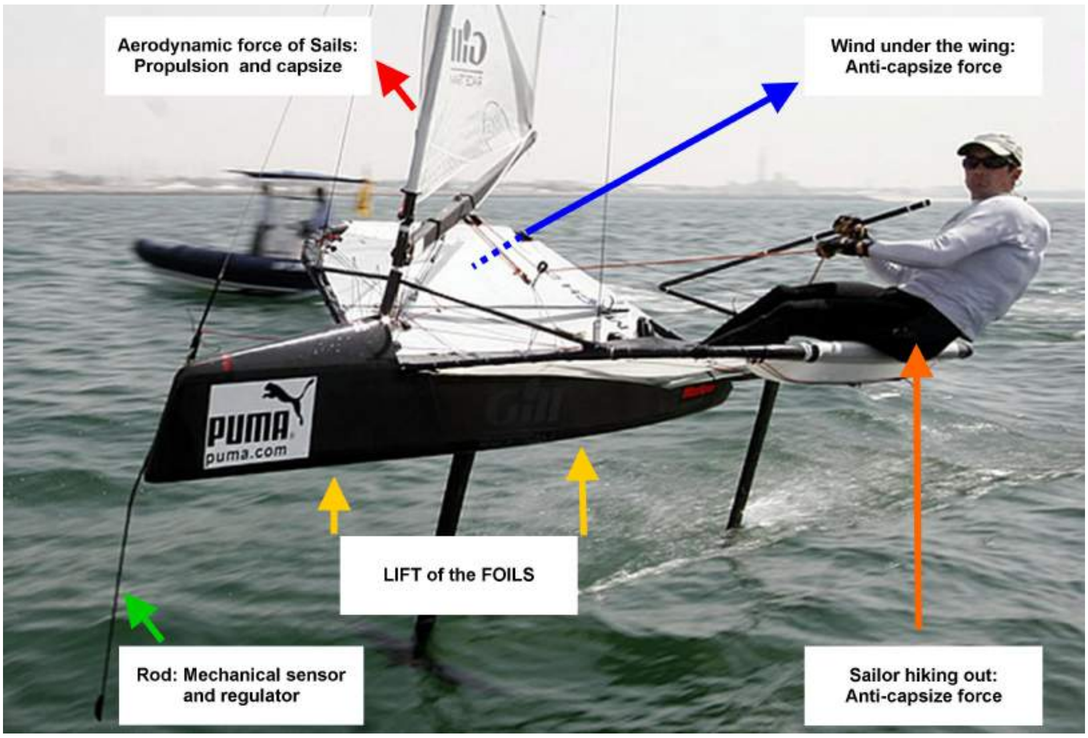
Foils as seen by Jean SANS: Can Yachts Fly?

By Jean SANS - This article is a revised and more complete version, particularly the conclusion, based on Part 2 of the study, published on 22 January 2016 on www.uncl.com.

When we hear of foils on a sailboat, we dream of a yacht levitating over the water.

While flight, with the prior lift-off stage is easy enough on a multihull, we quickly figured out that it was practically impossible on a ballasted monohull, especially if it has a keel.



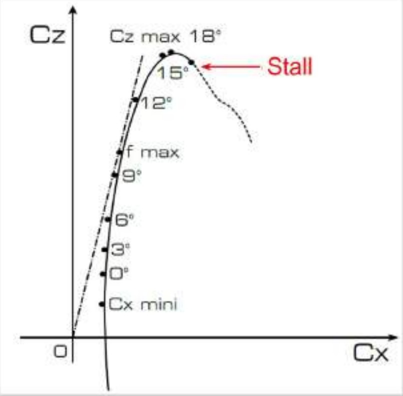
I believe that the **Foiler Moth** is the only monohull that truly flies and <u>can race</u>, meaning <u>freely sail</u> a two or three buoy course. To fly, the boat must overcome Archimedes' principle, the hull must be lifted and leave the water. This means that vertical force superior to the weight of the boat and its crew must be created using the lift generated by the foils.

Here is a reminder of the basic characteristics of a **Foiler Moth**:

- Hull length 3.55m,
- Sail surface: 8m2,
- Rigged weight: 25 kg,
- Displacement when sailing: 130 kg with a crew weighing 90 kg and extras, such as 5 kg of water in the boat, for example.

This means that the vertical force is approximately 60 daN per "T" foil. Two "T" foils are set mechanically (control of a flap on the trailing edge), without electric power. It is a "simple" underwater articulated rod on the bow that controls them.

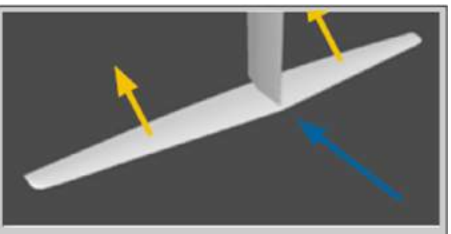
The sailor is a balance artist, whose attitude on board is closer to that of a surfer than a sailor on a "classic" boat. Compared to them, the crews of 49ers look like the sailors of yesteryear.



The angle of incidence is directly linked to the boat's longitudinal trim. Here you can see that the range is relatively small (6° to 12°).

Blue arrow : the speed of fluid (directly linked to the speed of the boat).

Yellow arrow : aero or hydrodynamic lift generated by the foil.



Hydrodynamic lift is broken down into two forces:

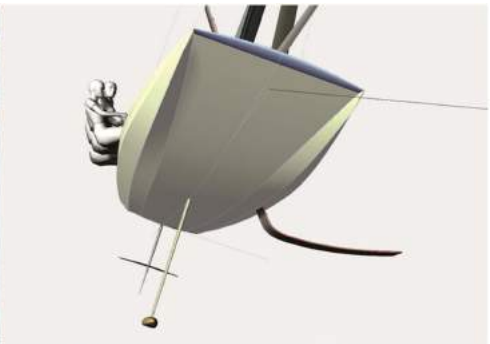
- LIFT (Cz) : the rate of vertical lift
- DRAG (Cx) : the rate of drag that counteracts forwards motion

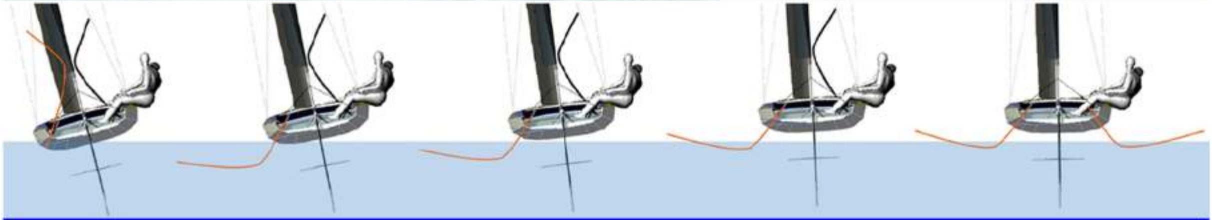
The angle of incidence of the wing sections is the angle compared to the flow of water. Cz depends on the wing sections and the angle of incidence. However, if the angle is too acute, the stall is sudden.

For a maximum Cz (15°), there is a maximum Cx, therefore the optimal incidence must be found with the most favourable Cz/Cx (Lift/Drag) ratio.

Conclusion: without a doubt, the **Foiler Moth** flies, but transposing this "full flight" to a ballasted monohull, even a "super light boat", is likely to remain a pipe dream.

However, the **Quant 23** (it isn't exactly a monohull, even though it looks like one – a monohull must have a hull with a depth that does not decrease as it nears the hull centreline) also flies. In fact, the QUANT 23 is built like a catamaran, as the picture on the right shows below:





QUANT 23 - The different foil settings

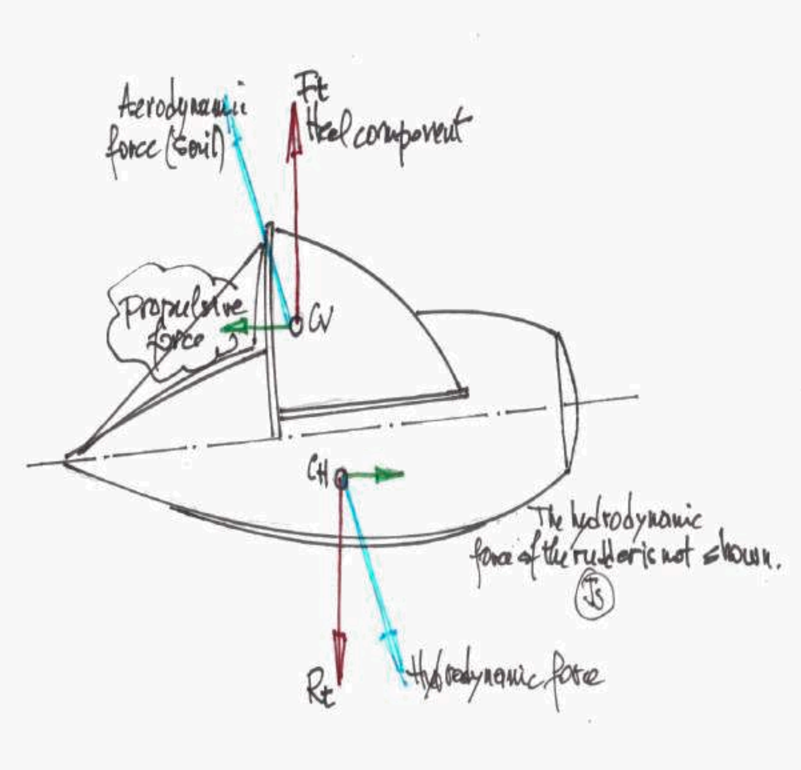
Naval architecture is an absolutely extraordinary science, as with better materials than those at the time, architects could have designed foils and built flying Scows.

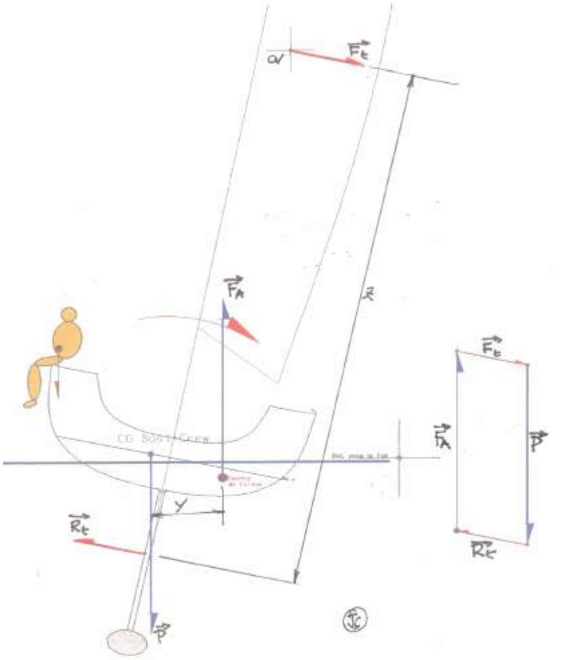
So why do we want foils on a keelboat and what would be the effect(s) on the boat?

Unlike the Moth, where the two foils are on the centreline and produce vertical lift, on a keelboat, the foils are placed on the sides of the hull.

What happens when the foil is active?

First, let's look at the balance under sail of boat WITHOUT foils:





The forces present:

- laterally, only the forces Fc and Rt are taken into account.

- These forces cause heeling.

When we look at the lateral balance of the boat, the **forces that apply** on a boat without foils are the following:

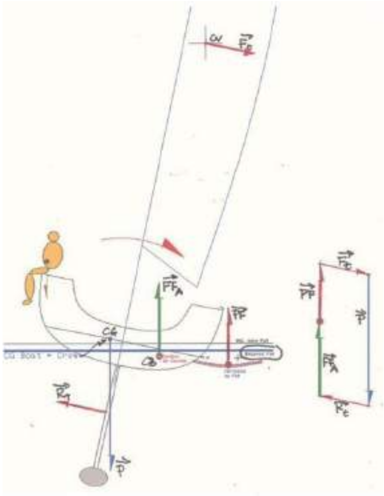
- A component of lift "**anti-leeway Rt**" generated by the keel fin and rudder.

- A component of "**aerodynamic force on sail Ft**" which makes the boat heel:
  - When the boat is balanced at a heeling angle, the anti-leeway component **Rt** and the aerodynamic force on sail component Ft are equal and parallel.
  - In this case the **Ft * z** and **P *y** couples are equal.

- The vertical force **P** (directed downwards) corresponds to the boat's mass, the mast, canting keel, liquid ballasts, etc. This force corresponds to the displacement of the boat and applies to the general centre of gravity which is slightly offset from the boat centreline.

- The vertical force **Fa** (directed upwards) is caused by buoyancy (Archimedes' Principle). This force applies to the centre of buoyancy (centre of gravity of the immersed volume). When the density of water is 1, this volume is equal to the displacement of the boat when sailing. The parallelogram on the right shows the vectorial polygon of the forces present. Because the boat is balanced, the vectorial polygon is closed.

What happens to balance when a foil is used?



We notice: a new force **PF** (foil lift) appears. This new force has a vertical component. In the example opposite, I voluntarily drew vertical lift.

We go from 4 to 5 lateral forces, but as the boat is in static balance, the vectorial polygon must be closed.

This new force **PF** is vertical (its component), it must therefore be inserted vertically between the end of **FFa** and the start of **Ft**.

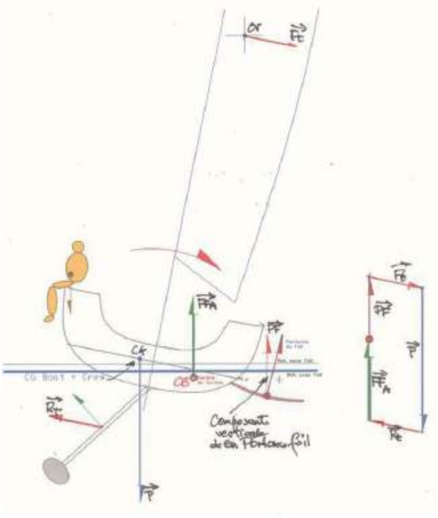
Because **Ft** and **Rt** must be parallel, this results in **PF + FFa = P**, meaning buoyancy drops.

Conclusion: the boat floats "higher", its Archimedean displacement is lower.

The exercise stops the moment the foil leaves the water, and the boat falls back in!

However, a force **PF** which could "lighten" the boat by 10 to 15% should normally improve its performance, despite the drag of the foil. This is what has got the architects thinking.

On a boat equipped with a canting keel, the effect is identical (see below).



Transposing from the Moth to a keel boat

The MOTH is able to "fly" despite its fairly low width. It is an extremely light boat fitted with wings on which the sailor is seated. The mass ratio between the sailor and the boat is almost 3.5 to 1. The sailor can therefore easily heel the boat windward. Because of the windward heel, the aerodynamic force on the sail points upwards, which reduces pressure on the leeward foil.

It is important to understand that keeping the windward heel of the boat is the essential for the boat to lift off the water and fly, with the hull fully out of the water.

So why try to fit foil(s) to a monohull keelboat?

Forget about copying the Moth and fitting a "T" foil on the keel! Indeed, getting a keelboat to heel windward is difficult enough to achieve, and attempting to do so after adding symmetrical foils with a span wider than the beam of the boat would be a nightmare. However the performance of a "heavy" sailboat can be improved, without lifting it completely out of the water, but reducing its immersed volume as we can see in the diagrams.

Moving the foil, and therefore lift, leeward first seems to be the immediate benefit of the foil. It is unquestionable that the righting moment increases with the foil, and the faster the boat goes, the more it increases. We can see that the foil dramatically increases power Two rapid calculations at 13 knots and 17 knots on a 53ft (displacement 9000 kg) equipped with a "DSS" type foil 1.75m^2 , with a lever arm between the centre of buoyancy and the 2.5m foil centre of lift.

- **At 13 knots (6.68 m/s)**
    - the lift is 1400 daN (approximately 1.4T)
    - The righting moment created is 3500 m * daN

- **At 17 knots (8.74 m/s)**
    - the lift is 2400 daN (approximately 2.4T)
    - the lift moment created is 6000 m * daN

For information, the righting moment for this boat at 15 or 20° with the crew hiking out is 7500 m*daN.

Speed increases by 31% and the righting moment by 71%. Of course, it is a theoretical demonstration, but the estimated physical effect is realistic. You can see that the available power, meaning the ability of the boat to withstand greater sail surface increases significantly as the offset foil increases the righting moment. The first reaction is to say: let's increase sail surface.

There's the rub. Although a higher righting moment is caused by the foil, there is especially, because of the distribution of forces in the transversal balance of the boat (see the vectorial polygon), a non negligible reduction in buoyancy, and therefore the boat is lifted. Its Archimedean displacement drops and its real displacement does not change, as the mass of the boat in movement does not change.

The two phenomena are interwoven. The foil does improve the righting moment. It has been shown that buoyancy drops as the sum of this force and the lift of the foil must always be equal to the weight of the boat.

In these conditions, the speed of the boat increases (less wet surface, better ability to plane).

If the speed of the boat increases, the lift from the sails increases (with, let's not forget, this speed squared), therefore the lateral component (Ft) of lift increases and consequently the capsize moment. The capsize moment is balanced by the higher righting moment generated by the foil, since with the increase in speed, foil lift also increased.

We therefore understand that the two forces balance each other (one pushes, the other resist) and the main phenomenon that will enable the significant increase in speed is the lifting of the boat and it breaking out of the water. The peak of this effect is reached when the hull is completely out of the water like on a MOTH.

This transition from the buoyant stage and the "full flight" stage, where the entire hull is lifted out of the water, is very sudden. It almost instantly results in a three or four fold increase in speed, that is not gradual. Of course its perception must be "softer" on a ballasted monohull, but the effect must be almost identical to the effect perceived on a sportboat when it passes the upwind buoy and the asymmetric spinnaker inflates in a 30 knot breeze.

How much lift can be generated by a foil?

The lift of an aero- or hydrodynamic shape is calculated using the following formula:

$$P = \frac{1}{2} * \rho * Cz * S * V^2 \text{ (Force in Newtons).}$$

- V = speed of the shape (here the foil) in the environment (water). It applies in m/s (7.2 m/s for 14 knots)
- S = Projected surface of the foil in m^2,
- ρ = density of water in kg/m^3, or 1025 kg/m^3
- Cz = lift coefficient (0.35 for example)

We note that two parameters are dominant, the **speed of the foil** in the fluid (water) as it is squared in the formula and the **Cz** (lift coefficient), which is relatively unstable.

The **speed of the foils movement** is the boat's speed.

We can easily see that a heavy displacement boat, unable to plane, will not be able to reach a sufficiently stable speed (it must be to kick of the lifting stage) that would enable a significant "lightening" of the boat. However, on this type of boat, the angle of incidence can be increased to increase lift (vertical force), however drag will increase (vector pointing back, therefore a drag). The Lift / Drag ratio is therefore too unfavourable.

The **Cz,** (Lift Coefficient), depends on the aerodynamic profile (generally NACA profiles), the homogeneity of the fluid and the angle of incidence (like how a sail is set by sheeting in or out).

The architect will search for the best **Lift / Drag** compromise by setting the foil on the boat (they define the angle of incidence). We could imagine that the angle is adjustable as is the case on the AC 72, AC45 and MOTH, however it is complicated technically (the method applied on the MOTH cannot be transposed). Piloting would have to be controlled, which will further increase the complexity of the idea. Usually the Cz is 0.30 to 0.35.

Lift	**ρ**	**Cz**	**S m^2**	**V in Knots**	**V m/s**	**V^2**
78 daN	1025	0.3	1.20	4	2.06	4.23
313 daN	1025	0.3	1.20	8	4.12	16.97
704 daN	1025	0.3	1.20	12	6.18	38.19
957 daN	1025	0.3	1.20	14	7.20	51.87
1411 daN	1025	0.3	1.20	17	8.75	76.48

Changes in the Displacement / Length ratio

Let's continue with the 53ft boat with a displacement of 9000kg and LWL = 16m. The Displacement / Length Ratio in homogenous units is equal to DLR (cube root of the displacement / LFLOT), or:

- In "Archimedean" navigation: Archimedean DLR $= (9000)^{1/3} / 16 = 1.300$

- By taking into account a lift that relieves the boat by 1000 kg and considering that the LFLOT drops by 30%, this ratio becomes:

$$\text{DLR Foiler} = (8000)^{1/3} / (16*0.7) = 1.780$$

We notice that with the effect of the foil, the boat tends towards a light displacement, and therefore becomes potentially faster. To understand, imagine that when running, the boat can be lightened by a ton! The wet surface is also reduced, etc.

Look at this photo on which I have highlighted the foil, you can imagine that an object (the boat) is pushed up (red line) and that this lift keeps the boat balanced thanks to the capsize moment, while lifting it.

What future for foils on monohulls?

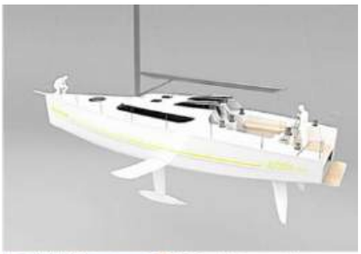
The answer is complicated, as it depends on parameters that naval architecture does not fully control. We can imagine three types of responses:

- Scientific answers that can be provided by designs:
  - What type of displacement for the monohull?
  - What type of yacht (prototype, cruiser-racer)?
  - What type of foil?

- The introduction of the foil in class rules:
    - authorised or disallowed (development of a one design class),
    - rating tax, within a measurement rule for handicap racing, such as IRC,
    - class rules restricting the use of foils.

- Location in the boat:
    - the cost of the foil and the cassette,
    - the volume it takes up in the boat,
    - the weight,
    - the impact on structural calculations.

Will the racing boat of the future look like this picture from FARR YACHT DESIGN?



How can a rule penalise one or several foils?

All rules have a philosophy that they apply to their choices and developments. For example, we can reiterate the main principles of this philosophy for IRC:

- IRC does not forbid anything so long as the boat remains a monohull and respects security rules,
- IRC never penalises a piece of kit, as it doesn't take into account its random use,
- IRC applies a rating tax to each equipment and/or parameter recognised as a factor promoting speed gain as fairly as possible. However it can "encourage" the development of an element or equipment as was the case with the asymmetric spinnaker
- Calculating each rating tax does not take into account the performance of the equipment and/or the parameter in the VPP (Velocity Prediction Program). For example, IRC (like all rules), taxes the surface of a sail, but does not take into account the volume of the sail, the fabric, etc.
- IRC does not tax the intelligence of architects. They are free to design innovative appendages, high performance hulls, etc.
- IRC does not tac the skill of skippers.

However, two methods can be considered to tax foils, and this is true for all equipment:

Method 1

We are searching for an algorithm in the hope that it will simulate and assess as fairly as possible the gain in performance due to the foils. Such an algorithm, which is bound to be complicated, must take into account the hull, sail plan, of course the foil or foils (including the NACA sections used) and change these volumes and masses in two completely different fluids (their density are respectively 1.025 kg/m^3 and 1025 kg/m^3 or a ratio of 1000) without the position of the boat being perfectly defined and constant... a sort of VPP-FOILS.

Supposing it is successful, this method will enable a product to be designed (a foiler for example) and to know its performances to present this product to potential clients. However this method is not a rule, it is simply an assessment tool.

To be able to be used as a Rule, the speed potential calculated for each boat according to its shape, the foils, its sail plan must be converted to a coefficient that will reflect this speed prediction. In the end, this scientific simulation tool will assess the work of the architect, like in an experimental tank for a model.

Method 2

This approach is completely different. It considers that the foil (active part) is the main element of the calculation. It limits the size of the foil at its active span (**Ev**) and the width of its chord (**Co**). Then it calculates the active surface (**S**) of the foil (**EV * Co**).

The general parameters of the boat also enable its potential "Archimedean" speed , as well as its ability to plane (displacement/length ratio, surface/displacement ratio, etc). By combining these two entities we can determine Potential Planing Speed (**Vp**). However, it is not a "VPP" analysis of the hull.

I would like to remind readers that two boats can have identical dimensions and ratios and have very different speeds, the difference is due to the genius of the architect.

From the 3 following parameters:

- (**S**) correlated by a calculation of foil aspect ratio (Ev^2 / S). (S) is the result of the choice of the architect
- (**Cz**) 0.35 for example, the rule fixes this value pragmatically, it changes over time
- (**Vp**), study speed fixed by the rule based on the basic parameters of the boat,

we calculate the potential lift of this boat: $\mathbf{P = \frac{1}{2} * \rho * Cz * S * Vp^2}$

This lift potential represents the theoretic value of the "lightening" of the boat at the speed (Vp) studied. All or part of this lift can be taken into account in the calculation of penalisation of foils. Based on this assessment, a multiplier is integrated in the rule formula.

With this method, the architect is responsible for the performance of the design of foils and their location on the hull. They know exactly the potential speed of their project at all points of sail. They use both the VPP and CFD tools, therefore they are able to design the optimal foil, with a shape and especially an incidence and profile (NACA) that best suit the boat they are designing.

Of course the architect quickly knows how their foil will be penalised by a rule. Well, almost, as they know that the surface and extension are taken into account, but they do not know exactly the potential planing speed (Vp) used by the rule. However, they have an idea of this speed, from the VPP.

In fact this taxation method for foils is identical to that used by all rules to penalise sails, for example. We measure each sail, we calculate and introduce the square root of this surface, correlating with an aspect ratio factor in the rule formula.

No rule has ever taken into account the profile of the sail, the wing sections of the sail, the luff width, etc. Even rules that use VPP consider that a jib is triangular. No tricks (for example tack trimmers on jibs) are introduced in the mathematical model.

Method 2 enables architects to design appendages without any limitation other than knowing that the surface and extension will be used to penalise the use of foils.

Conclusion

The development of foils is interesting, as it opens the door to innovation in naval architecture and the design of cruiser-racer keelboats.

Making monohulls more fun and lively using appendages that should remain financially affordable is a development in the history of yacht racing that must be welcomed.

When I see the work carried out and which is still ongoing on the MOTH and other boats, I understand that there is a lot of inventing to be done on monohull keelboats.

Is it unrealistic to believe that keelboats can dream of lifting off the water?

Jean SANS – 7 June 2016.