HYDROFOIL CONFIGURATIONS FOR SAILING SUPERYACHTS: HYDRODYNAMICS, STABILITY AND PERFORMANCE

J-B R G Souppez, Solent University, UK.
J M M-A Dewavrin, Gurit, UK.
F Gohier, Bénéteau Group / ENSCBP University, France.
G Borba Labi, Principal Power, Portugal.

SUMMARY

Hydrofoil-assisted racing monohulls have undergone significant development phases in the past decade, yet very little scientific data has reached the public domain: an increasingly critical issue as the superyacht industry is now looking at the implementation of foils onto leisure vessels. Consequently, three contemporary configurations, namely a Dynamic Stability System, a Dali-Moustache and a Chistera have been towing tank tested to present the first complete characterisation of the hydrodynamic efficiency, quantification of the added dynamic stability and eventually the resulting impact on sailing performance. Furthermore, the considerations inherent to the design and installation of hydrofoils onto superyachts will be detailed. Building on extensive experimental work, this paper provides a comprehensive assessment of current design options with both technical and practical guidelines and recommendations to improve performance.

NOMENCLATURE

$1+k$	Form factor (-).
A	Planform area (m^2).
B_{OA}	Beam overall (m).
B_{WL}	Beam on waterline (m).
$\bar{c}$	Mean chord (m).
C_{T}	Total resistance coefficient (-).
D_{WL}	Design waterline (m).
Fn	Froude number (-).
F_{H}	Side force (N).
L_{OA}	Length overall (m).
L_{WL}	Length on waterline (m).
R_{I}	Induced drag (N).
R_{T}	Total resistance (N).
s	Span (m).
t	Temperature (°C).
T_{C}	Canoe body draft (m).
T_{EFF}	Effective draft (m).
T_{K}	Keel draft (m).
U	Uncertainty (-).
V	Velocity (m/s)
WSA	Wetted surface area (m²).
α	Sweep angle (°).
θ	Heel angle (°).
λ	Leeway angle (°).
ρ	Density (kg/m^3).
AoA	Angle of Attack.
CNC	Computer Numerically Controlled.
DSS	Dynamic Stability System.
DSYHS	Delft Systematic Yacht Hull Series.
FP	Forward Perpendicular.
IRC	International Rating Certificate.
ITTC	International Towing Tank Conference.
LCG	Longitudinal Centre of Gravity.
NACA	National Advisory Committee for Aeronautics.
ORC	Offshore Racing Congress.
VPP	Velocity Prediction Program.

1. INTRODUCTION

The implementation of hydrofoils on leisure vessel was first featured in 1898 on powerboats, before being employed on a sailing catamaran in 1938 under the leadership of the National Advisory Committee for Aeronautics. Then, circa 1954/1955, foiling monohulls emerged, with the Baker Manufacturing Company building various size dinghies. Eventually, the 1960s saw their use in offshore racing. Nevertheless, despite their historical use, the last decade sparked an unprecedented regain of interest, with hydrofoiling yachts featured in several forms in the most competitive and prestigious sailing events, from the America’s Cup to the Vendée Globe.

While significant numerical and experimental work has been conducted by the design and race teams, hardly any technical data has been made publicly available. Consequently, this paper aims to remedy this absence of open source information by providing results for different foil-assisted monohull configurations, whilst also tackling performance prediction and design consideration for their implementation on superyachts.

Firstly, the previous work, aims and objectives, and the foils will be introduced, followed by a description of the experimental setup, as well as the design and manufacturing considerations for the model and three hydrofoils: a Dynamic Stability System, a Dali-Moustache and a Chistera. Then, the towing tank results will be presented in different conditions, representative of upwind and downwind sailing, eventually discussing the hydrodynamic efficiency, added dynamic stability provided, and the overall effect on the performance of the vessel. The advantages and drawbacks of each option will be outlined, finally concluding on practical design considerations and recommendations.

2. BACKGROUND

2.1 PREVIOUS WORK

For offshore racing monohulls, the literature has primarily been focussed on the long-established use of straight asymmetric daggerboards, as summarised by Campbell *et al.* (2014). On the other hand, the design of hydrofoils for flying dinghies, such as the International Moth class, have been extensively investigated (Beaver & Zselczky, 2009). Furthermore, new research emerged in the last few years, targeted at flying catamarans and the optimisation of flexible foils (Sacher *et al.*, 2017) and issues associated with ventilation (Binns *et al.*, 2017), all heavily influenced by the developments in the America's Cup. The literature, however, does not tackle foil-assisted monohulls.

The past couple of years also saw the first large scale production of an offshore racing vessel with hydrofoils, namely the Figaro Bénéteau 3, and more recently the first superyacht fitted with a Dynamic Stability System (DSS), namely the Baltic 142. Moreover, 2018 marked the addition of foil measurements as part of the International Rating Certificate (IRC) racing rule, reflecting contemporary practice in racing craft design. This shows the strong interest of yacht and superyacht designers for foiling technology, and the necessity for published data relative to their efficiency, stability and overall effect on performance.

2.2 AIMS AND OBJECTIVES

The experimental investigation into foil-assisted monohulls aims to quantify the hydrodynamic efficiency and ascertain the added dynamic righting moment provided, to ultimately predict the velocity. Three main contemporary designs will be tackled, namely the DSS, the Dali-Moustache and the Chistera foils.

2.2 (a) Dynamic Stability System

The DSS is a retractable transverse foil deployed to leeward, the intention being to increase the righting moment, but also to reduce the pitching moment, allowing a more comfortable sailing. Unlike the Chistera and Dali-Moustache foils, the DSS only provides vertical lift due to its solely horizontal planform.

2.2 (b) Dali-Moustache

Based on the IMOCA racing yacht design, the Dali-Moustache is a V-shaped foiling daggerboard, intended to improve stability, while contributing to both the side force and vertical lift, the latter reducing the effective displacement of the vessel. The other advantage of the foil is the decrease in the pitch angle of the boat, improving the longitudinal stability and sea-kindliness (*i.e.* damping the pitch motion).

2.2 (c) Chistera

Finally, the Chistera foil is based on the Figaro Bénéteau 3 one-design class. In contrast with the Dali-Moustache, the Chistera has an inward-facing V-shape, that also provides both vertical lift and horizontal side force, together with additional righting moment.

3. EXPERIMENTAL TESTING

3.1 MODEL

The tank testing of the different configurations has been performed on a purposely designed hull (Dewavrin, 2018), first towed bare, before the keel and bulb were added; finally, each foil was evaluated. The main dimensions for the 1:10 scale model, representative of a 50ft sailing yacht then use to extrapolate the findings onto superyachts, are presented in Table 1

Hull Particulars	
Length overall - L_{OA}	1.52 m
Length on waterline - L_{WL}	1.43 m
Beam overall - B_{OA}	0.47 m
Beam on waterline - B_{WL}	0.34 m
Canoe body draft - T_{C}	0.06 m
Keel draft - T_{K}	0.36 m
Wetted surface area - WSA_{H}	0.39 m^2
Keel Particulars	
Span - s_{K}	0.266 m
Mean chord - $\bar{c}_{\mathrm{K}}$	0.068 m
Planform area - A_{K}	0.018 m^2
Wetted surface area - WSA_{K}	0.037 m^2
Section	NACA 64-012
Swept back angle - α	3°
Leading edge distance aft of FP	0.636 m
Bulb Particular	
Chord - $\bar{c}_{\mathrm{B}}$	0.270 m
Wetted surface area - WSA_{B}	0.023 m^2
Horizontal section	NACA 65-017
Vertical section	NACA 65-012

Table 1: *Tank testing model dimensions.*

General modelling and scaling laws are driven by Froude's similitude theory. Equality in Froude number between model and full-scale will ensure that gravity forces are correctly scaled. However, this implies that the vessel and appendages will operate at a too small Reynolds number, thus not replicating the full-scale laminar to turbulent transition. As a result, transition will artificially be triggered using sandpaper strips, in accordance with the International Towing Tank Conference (ITTC) procedures (ITTC, 2017).

3.2 HYDROFOILS DESIGN AND LOCATION

The general dimensions and locations of the hydrofoils were based on a parametric study of the existing vessels they are featured on. The cross-sectional shape is a critical design consideration as it directly affects the lift and drag characteristics. For consistency, and in order to compare the hydrodynamic results, the same section was employed for each foil, namely the NACA 63-412. This is commonly used for small craft, such as the International Moth (Beaver & Zselczky, 2009) and was chosen due to its high lift to drag ratio (Abbott & Doenhoff, 1959) and the relative ease of manufacturing.

Table 2 presents the main dimensions for the three foils and their leading-edge location, longitudinally aft from the forward perpendicular (FP) and vertically upwards from the design waterline (D_{WL}). Note that the spans given are for the entire foil, not accounting for its actual immersion at a given heel angle.

Dynamic Stability System	
Span - s_{DSS}	0.232 m
Mean chord - $\bar{c}_{\mathrm{DSS}}$	0.070 m
Planform area - A_{DSS}	0.016 m²
Wetted surface area - WSA_{DSS}	0.034 m²
Leading edge distance aft of FP	0.742 m
Leading edge height above D_{WL}	-0.016 m
Dali-Moustache	
Span - s_{DM}	0.368 m
Mean chord - $\bar{c}_{\mathrm{DM}}$	0.058 m
Planform area - A_{DM}	0.021 m²
Wetted surface area - WSA_{DM}	0.045 m²
Leading edge distance aft of FP	0.488 m
Leading edge height above D_{WL}	-0.016 m
Chistera	
Span - s_{C}	0.364 m
Mean chord - $\bar{c}_{\mathrm{C}}$	0.056 m
Planform area - A_{C}	0.020 m²
Wetted surface area - WSA_{C}	0.043 m²
Leading edge distance aft of FP	0.488 m
Leading edge height above D_{WL}	0.142 m

Table 2: *Model foil dimensions.*

The positions of each foil along the hull can be visualised in Figure 1 (a), with underwater views of the DSS, Dali-Moustache and Chistera respectively shown in Figures 1 (b), 1 (c) and 1 (d) respectively. Note the forward position of the Dali-Moustache: unlike the racing yachts, it is located further forward to fit within the overall beam when retracted, and importance consideration for leisure vessel, further discussed in Section 7.3.

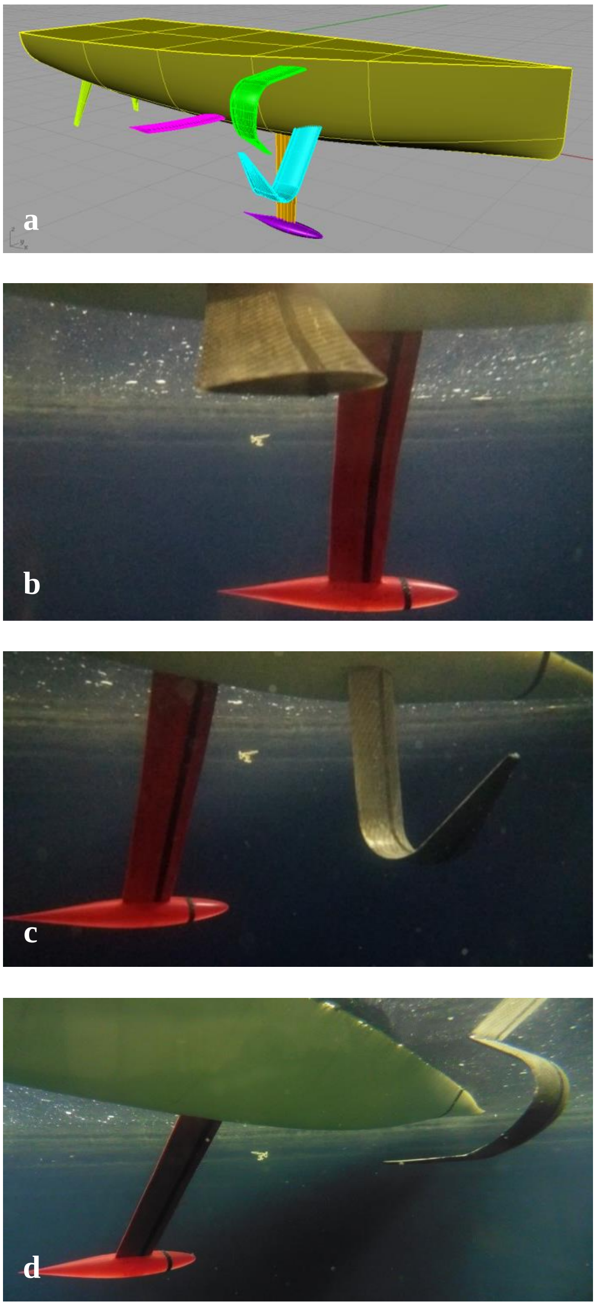


Figure 1: *(a) 3D view of the appendages on the designed model. Underwater view of (b) the Dynamic Stability System, (c) the Dali-Moustache and (d) the Chistera foil.*

3.3 MANUFACTURING

The hull shape was CNC cut on a 5-axis milling machine out of 32 kg/m^3 polystyrene. The hull was hand laminated with two layers of E-glass woven roving having a total combined dry weight of 300 g/m^2 and epoxy resin. Then, it was sanded to a smooth finish, equivalent to that achieved by 400 grit wet and dry sandpaper, as per the recommended ITTC procedure (ITTC, 2017). Geometric tolerances were well within the required allowable +/- 1 mm for the overall length, breadth and depth (ITTC, 2017).

The keel was constructed out of thin laser-cut plywood, then laminated and faired. One outer layer of epoxy resin was applied for coating.

The model keel bulb and hydrofoils were manufactured out of ABS resin using stereolithography on a ProJet 3600 Max 3D printer. This was required to achieve the necessary +/- 0.2 mm tolerance on such complex 3D geometries (ITTC, 2017). Moreover, their location was accurately ascertained to respect the permitted 0.5 mm variation in position (ITTC, 2017). To strengthen the foils and ensure no deformation under dynamic loading, a layer of high modulus 200 g/m^2 twill carbon fibre and epoxy resin was applied and vacuumed consolidated at 1 atm.

Finally, all components were fitted with a 5 mm wide sandpaper strip located to replicate the full-size flow regime, as the model hull and foils would be operating at a much lower Reynolds number in the towing tank. Indeed, while the Reynolds effects on hydrofoils are not well-understood and consequently there is no current full-size correction for a smaller geometry being tested, the best practice across fields of fluid dynamics is to ensure that transition is replicated at model-scale where expected at full-scale. The use of studs or sandpaper strips to artificially trigger transition is, therefore, deemed suitable (Jackson & Hawkins, 1998), and is recommended by the ITTC (ITTC, 2017).

The locations of the rough strips were established based on the ITTC recommended Reynolds number as a function of the model/appendages length and Froude number (ITTC, 2017).

3.4 EXPERIMENTAL SETUP

The experiments were performed following the ITTC Recommended Procedures and Guidelines for Resistance Test (ITTC 2014), and were undertaken in the Hydrodynamic Test Centre at Solent University. The main characteristics of the towing tank utilized are presented in Figure 2.

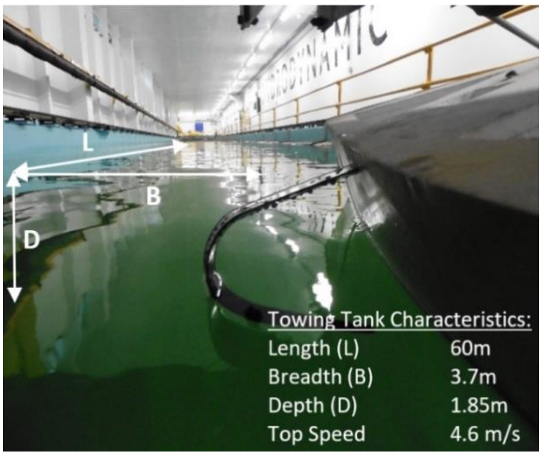


Figure 2: *Towing tank characteristics (Souppez, 2018).*

For the characterisation of the hydrodynamic efficiency of each foil, the runs were performed for a defined speed, at a constrained heel and yaw angle, with the vessel free to heave and trim. Conversely, to quantify stability, the model could heel freely, as later described in Section 5. The drag, side force, heave and trim (or heel for the stability investigation) were measured with a precision of five decimal places, and the data sampled at 1000 Hz over a minimum of 6 seconds, or longer at the lowest speeds where a greater data acquisition window was available.

The installation of the model on the towing carriage and the measurement devices are depicted in Figure 3. The drag, side force and trim are measured by potentiometers (P), while the heave is quantified thanks to a linear variable displacement transducer (LVDT).

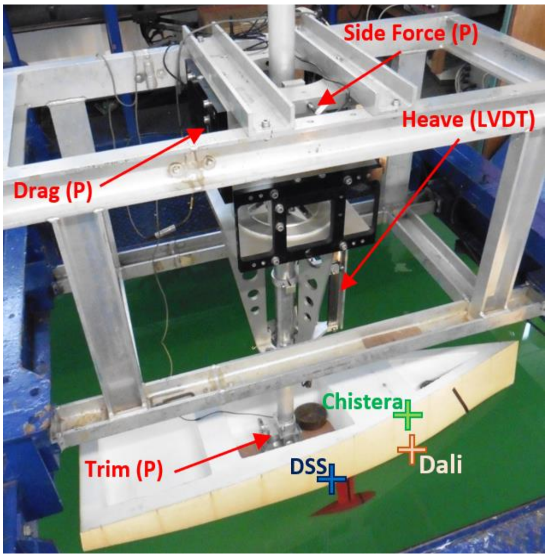


Figure 3*: Model installed on the towing carriage (Dewavrin & Souppez, 2018).*

3.5 TEST MATRIX

The test matrix was defined after running a standard Velocity Prediction Program (VPP), where the hydrodynamic model was based on the Delft Systematic Yacht Hull Series (DSYHS) (Keuning & Katgert, 2008).

The intention was to establish a relevant set of testing parameters representative of upwind sailing on the one hand (low speed, high heel, high leeway), and downwind sailing on the other (high speed, low heel, low leeway), with also higher Froude numbers to be more in line with the performance of racing yachts (0.35 to 0.70).

Additional tests were undertaken in the first place to establish the form factor, 1+k, based on the Prohaska method suggested in the ITTC procedure (ITTC, 2014). Moreover, a preliminary study investigated the best Angle of Attack (AoA) for each geometry. In this instance, the AoA is defined as the angle between the chord line of the foil at its root and the design waterline.

Once acquired, the model scale data was scaled up to full-size (ITTC, 2011). However, prior to comparing the results for each configuration, an uncertainty analysis was performed to ensure the reliability of the data collected.

3.6 UNCERTAINTY ANALYSIS

Based on the ITTC recommended procedures and guidelines for Type A uncertainty analysis (ITTC, 2014), the experimental precision could be quantified. The parameters under consideration are the wetted surface area (WSA), speed (V), water density (ρ), total resistance (R_T) and associated coefficient (C_T). The uncertainty U, of each parameter i, and inherent components j, is labelled $U_{(i,j)}$. An example of broken-down uncertainty analysis for a resistance test undertaken at 2.25 m/s (Fn = 0.60) is shown in Table 3.

Wetted Surface Area – WSA (m^2)	**0.453**
Model uncertainty - $U_{\mathrm{WSA,MOD}}$	0.781%
Displacement uncertainty - $U_{\mathrm{WSA,BAL}}$	0.025%
Wetted surface area uncertainty - U_{WSA}	0.782%
Velocity – V (m/s)	**2.322m/s**
Calibration uncertainty - $U_{\mathrm{V,CAL}}$	0.002%
Data acquisition uncertainty - $U_{\mathrm{V,DAQ}}$	0.002%
Velocity uncertainty - U_{V}	0.003%
Density – ρ (kg/m^3)	**998.403**
Temperature - t	19°C
Temperature error - E_{t}	1.316%
Density uncertainty - U_{ρ}	0.010%
Total Resistance - R_{T} (N)	**11.049**
Calibration uncertainty - $U_{\mathrm{R_T,CAL}}$	0.002%
Fitting uncertainty - $U_{\mathrm{R_T,FIT}}$	1.288%
Data acquisition uncertainty - $U_{\mathrm{R_T,DAQ}}$	4.937%
Misalignment uncertainty - $U_{\mathrm{R_T,MIS}}$	0.934%
Resistance uncertainty - $U_{\mathrm{R_T}}$	5.186%
Total Resistance Coefficient - C_{T}	**0.024**
Resistance coefficient uncertainty - $U_{\mathrm{C_T}}$	6.245%

Table 3*: Example of uncertainty analysis.*

4. HYDRODYNAMICS

4.1 ANGLE OF ATTACK INVESTIGATION

Early tests were conducted to investigate the impact of the AoA of the foils. By design, they can be given a pre-set angle; many racing yachts are also typically able to adjust foils by up to +/- 7°; thus, a smaller study investigating the performance at a range of AoA was devised (Kitching, 2018).

The DSS was set at 0°, 4° and 8° AoA, while the Dali-Moustache and Chistera were tested with 0°, 8° and 16° AoA. It is important to mention that the angles defined here are at the root of the foil, the portion that would be controlled on the yacht. In the case of the Dali-Moustache and Chistera, these do not reflect the actual angle adopted by the hydrofoils, which is smaller due to the curvature and twist. The aim is to assess the optimum AoA, to then perform all the tests in their respective ideal condition, thus comparing the best possible performance for each configuration.

The investigation revealed that, when using a DSS, while a larger AoA resulted in an increase in heave and a reduction in displacement, this came at a cost in terms of resistance. Overall, a DSS with no AoA appeared to be the best solution. This is consistent with the properties of the NACA 63-412 foil that exhibits the highest lift to drag ratio at 4° for the tested Reynolds number. Despite the foil having no initial AoA, the vessel trim, ranging from 1° at low speeds to 5° at higher speeds, implies the section will naturally operate close to its most efficient AoA. It could, however, be deemed appropriate to offer some degree of control in order to alter the angle at low speed, and reduce it for the higher downwind speeds, while retaining the optimum operating angle.

For the Dali-Moustache, an increase in AoA did contribute to an increment in heave, resulting in a lower resistance. This was achieved for an AoA of 8° in upwind conditions (θ=20°, λ=2°+) and 16° downwind (θ=10°, λ=0°), with however a decrease in side force. Variations in the AoA, therefore, alter the contribution of the lift that goes towards the side force or heave. This is particularly interesting as these foils are fitted on canting-keel yachts. Upwind, the fully canted keel will provide vertical lift but less side force; which the Dali-Moustache could easily make up for.

Finally, the Chistera exhibited a better side force and heave with an angle of 16°. The impact on resistance was nevertheless negligible, thus suggesting better sailing performance will be achieved with a higher AoA.

As a result, it can be stated that for best performance, the DSS should be operated at the lowest AoA possible, while the Chistera is more efficient at a higher AoA, ensuring stall is not reached. As for the Dali-Moustache foil, variations in AoA allow to either boost the side force and reduce the heave, sensible for upwind, or raise the vertical lift at the expense of the side force, a suitable option for downwind. Consequently, the rest of the study was conducted with the most efficient AoA for each foil configuration and sailing condition.

4.2 INDUCED DRAG FACTOR

The performance of appendages can be quantified by plotting the induced drag factor, *i.e.* the side force squared versus the total resistance. For the results to be meaningful, they must be compared to the typically required upwind side force.

In this instance, the 'upwind sailing' line corresponds to the vessel operating in 16 knots of true wind (*i.e.* the upper end of Beaufort 4, after which the boat would be expected to reef), at a true wind angle of 35°. The results in typical upwind sailing conditions are presented in Figure 4 (data point at λ = 6° not shown for the Dali-Moustache).

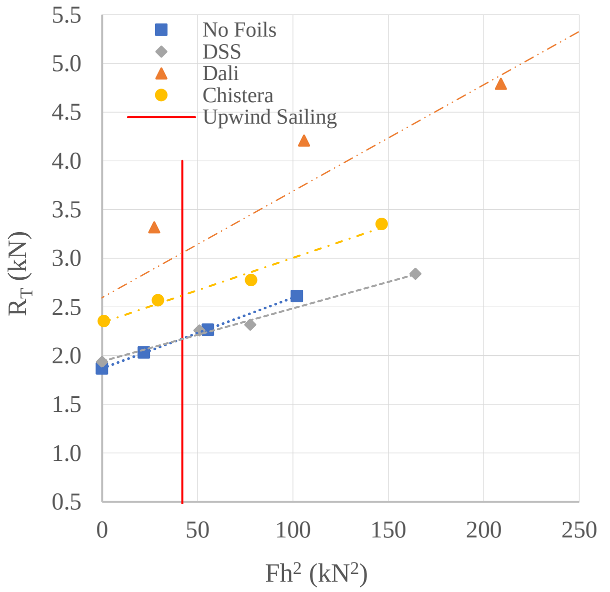


Figure 4: *Induced drag factor for a typical upwind condition, Fn = 0.35 and θ = 20°; data points at λ = 0°, 2°, 4° and 6°.*

Firstly, it is interesting to notice that the Dali-Moustache is the only one able to provide significant side force with no leeway. While this is no surprise for the keel alone or DSS, it could have been expected of the Chistera to be able to generate more side force thanks to its asymmetric profile without any leeway. The present results, however, demonstrate it is not the case.

Regarding the contribution of each foil to the overall side force upwind (θ = 20°, λ = 4°), the Chistera provides 15% and the Dali-Moustache 45%. Those values are consistent from Froude numbers for 0.35 to 0.50.

The best performance in terms of generating side force for minimum drag is achieved by both the keel alone first, and then the DSS. However, looking at the side force that would be required to sail upwind, the keel only is superior in that portion where the realistic operation of the vessel would occur. Furthermore, this is assuming the keel only contributes to the side force, thus neglecting the asymmetry of the waterplane area, the rudder (if weather-helm is achieved), and foil (if fitted).

Under the limitations presently considered, the configuration without any foils appears more hydrodynamically efficient. Nevertheless, despite creating more resistance, the Dali-Moustache and the Chistera would contribute to reducing the leeway angle; this could permit the vessel to sail a shorter distance on an upwind course.

4.3 EFFECTIVE DRAFT

The hydrodynamic performance of yacht appendages is quantified using the effective draft, T_{EFF}, derived from the theory of induced drag on a lifting surface, mathematically:

$$T_{\mathrm{EFF}} = \sqrt{\frac{F_{\mathrm{H}}^2}{\pi \rho V^2 R_{\mathrm{I}}}}$$

Where:

- T_{EFF} Effective draft (m).
- F_{H} Side force (N).
- ρ Density (kg/m^3).
- V Velocity (m/s).
- R_{I} Induced drag (N).

It can be noted that the ratio $F_{\mathrm{H}}^2/R_{\mathrm{I}}$ is, in fact, the reciprocal of the induced drag factor slope. The DSS having the lowest slope, it naturally yields the highest effective draft, as presented in Figure 5.

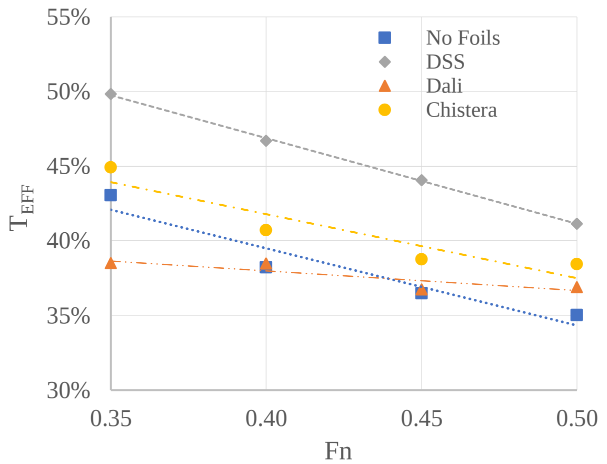


Figure 5: *Effective draft at θ = 20°.*

Those results should, however, be moderated with the previously identified fact that, within the normal sailing operation, the best configuration is achieved without foils. It would, therefore, be recommended that the best design option is assessed solely on the induced drag factor and in relationship with the expected side force to be provided in upwind conditions, as in this case the use of the effective draft has been proven to be misleading.

4.4 HEAVE

So far, the data analysis has been focused on the total drag and side force, critical upwind, but not accounting for the vertical lift generated by the foils. The measured heave, in both upwind and downwind conditions, is presented in Figures 6 (a) and 6 (b) respectively, where 0 heave corresponds to the static heave of the vessel.

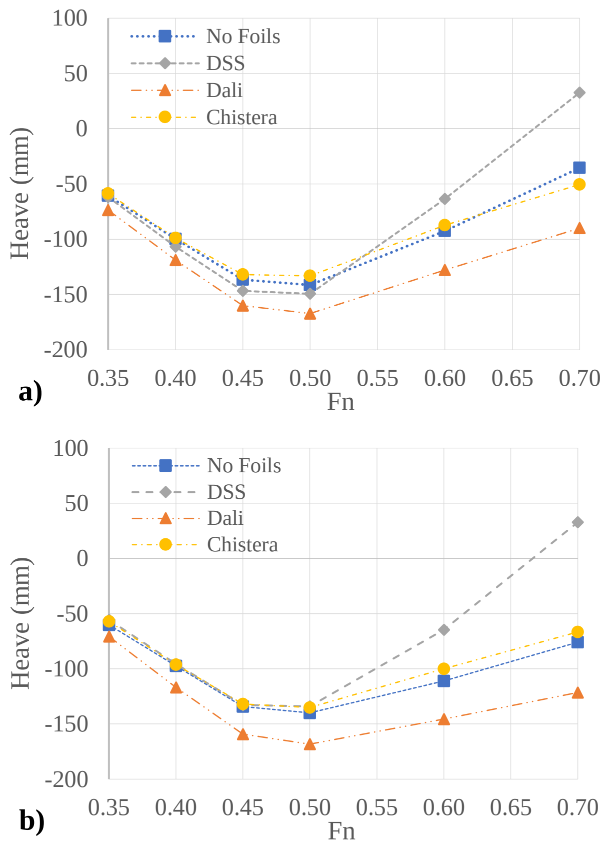


Figure 6: *Heave for (a) upwind (θ=20°, λ=4°) and (b) downwind condition (θ=10°, λ=0°).*

The DSS, that primarily generates lift upwards, appears to be the best at reducing the effective displacement of the vessel. Moreover, due to its presence closer to the longitudinal centre of gravity (LCG), a greater portion of the lift contributes to reducing the displacement, although negligible for typical cruising Froude numbers. Conversely, the Dali-Moustache and Chistera produce a higher trim, since they are located further forward and thus the lift induces a higher pitch moment. On the other hand, the Dali-Moustache, which proved to generate the most side force (albeit with a drag penalty) did not appear to significantly lift the vessel out of the water and was recorded to have greater negative heave than the boat without foils in this experiment.

4.5 DISCUSSION

The towing tank testing of the three main options for foil-assisted monohulls has been conducted for a range of upwind and downwind conditions. The purely hydrodynamic analysis provided experimental evidence of the effectiveness of hydrofoils and yielded a number of important results.

Firstly, the induced drag factor appears a more sensible method to assess the ideal configuration compared to the effective draft, as the former enables to identify the typical operating range of the yacht in terms of side force, whereas the effective draft could suggest an erroneous interpretation.

Then, to generate a given side force, the boat without foils will create a lesser resistance than any of the three geometries tested.

The Dali-Moustache foil is the only arrangement that creates significant side force without leeway. This is surprisingly not the case for the Chistera and was expected for the DSS. Moreover, below a Froude number of 0.50, the vertical lift is not sufficient for the displacement to be reduced. Past that Froude number, the DSS develops the most vertical lift (in addition to the one generated by the vessel reaching semi-displacement mode). Moreover, at any Froude number, the Dali-Moustache performs worse than the configuration without foils.

Finally, when investigating the effects of an increased AoA, the Chistera appears to respond better to a higher angle. The DSS, however, operates best with no AoA, as the vessel's trim allows the section to operate very close to its ideal lift/drag ratio. Finally, the Dali-Moustache functions optimally at a moderate AoA upwind (8°) and a higher AoA downwind (16°). A varying angle of incidence can, therefore, be beneficial on a Dali-Moustache foil to boost either the side force or the heave.

Overall, building on the experiments undertaken and hydrodynamic data gathered, it appears that, for foil-assisted monohulls, no resistance advantage over a design without foils could be achieved, thus demonstrating their inefficiency under the present test conditions and inherent limitations, namely the pure hydrodynamic efficiency of foil-assisted monohulls.

Nevertheless, the increasing presence of hydrofoils in offshore racing yachts and now cruising superyachts suggest there are indeed strong advantages. These observations and present experimental results, therefore, call for further work to tackle the stability and performance aspects, and identify where the benefits of foils truly are, so that their design can be better refined, and the most suitable configuration selected for a vessel's operating profile.

5. STABILITY

5.1 INTRODUCTION

The tests undertaken for the purpose of quantifying the added dynamic stability were performed in conditions representative of upwind $(\theta = 20°, \lambda = 3°)$ and downwind $(\theta = 10°, \lambda = 0°)$ sailing. The slightly reduced leeway in the upwind condition was dictated by the free-to-heel setup that could not cope with the larger side force generated for higher leeway angles.

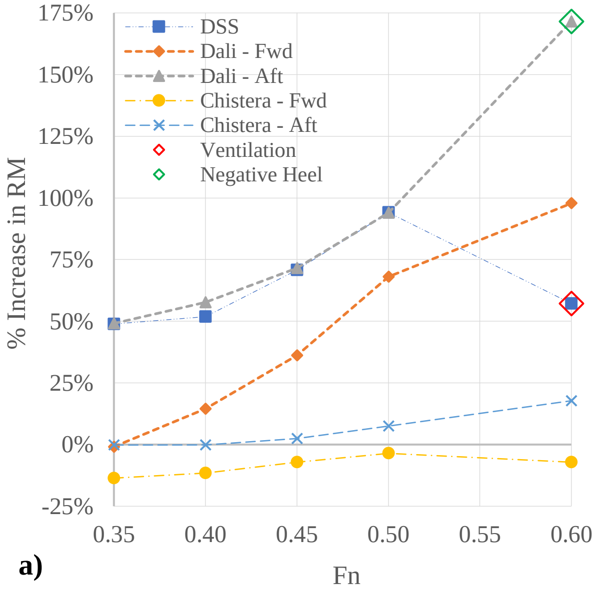
These experiments featured a new aft position for the Dali-Moustache and Chistera. This would not allow the foil to fit within the maximum hull width as intended in the previous experiment, but could provide greater stability and thus be of interest for racing crafts.

It must also be emphasized that the heel angles quoted correspond to the dynamic angle adopted by the yacht without hydrofoils, tested at a given speed. This, therefore, required trial and error to assess, for each Froude number, the transverse ballast location and inherent starting static heel angle, so that the vessel would reach the desired dynamic angle once towed.

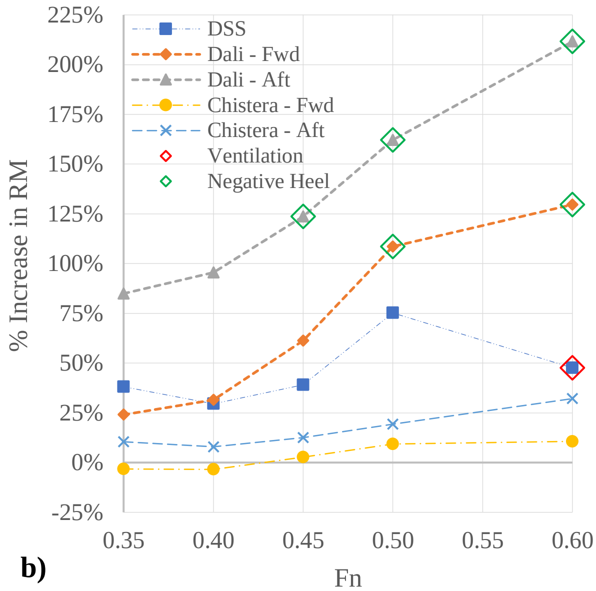
5.2 RIGHTING MOMENT

For this particular test campaign, the vessel was not constrained in its heel angle. The righting moment provided by each foil was quantified from the change in heel angle measured. Firstly, an inclining experiment was conducted on the model fitted onto the towing tank carriage to establish the position of the centre of gravity. This information was then combined with the model geometry in a large angle stability analysis to determine the righting moment at every heel angle. The difference between the righting moment with and without foils, therefore, gives the dynamic contribution to the stability of the yacht. The results, in the form of the added percentage of righting moment compared to the hull fitted with a keel and bulb only, are presented in Figures 7 (a) and 7 (b) for upwind and downwind respectively.

The Dali-Moustache foil in the aft position proved to be the best in terms of generating righting moment at any heel angle; it must be noted that in certain cases, the foil was able to bring the boat back beyond the upright and into negative heel; those results should, therefore, be considered with care. Upwind, the performance of the Dali-Moustache is matched by the DSS, the latter suffering from ventilation issues due to the proximity with the free surface at the highest Froude number, hence the sudden decrease in righting moment. On the other hand, the Chistera foil only provides minor improvements downwind and reduces the dynamic stability in its forward position upwind.



a)



b)

Figure 7: *Added righting moment provided by the foils (a) upwind and (b) downwind.*

For both the Dali-Moustache and Chistera foils, the aft position is far better in term of the contribution to added dynamic stability, primarily because it is located further away from the centerline. The aft location should, therefore, be preferred, provided practical considerations do not dictate a forward position, for example, so that the retracted foil fits within the overall breadth for mooring purposes, a vital aspect for cruising vessels.

Finally, the experiments demonstrated that a yacht or superyachts subject to a given heeling moment onto which a suitable foil is added will benefit from a drastic increment in stability, with however no decrease in drag.

5.3 RESISTANCE

The results proved very consistent with the original hydrodynamic efficiency experiment in that the lowest resistance is always achieved without foils. Indeed, despite the vertical heave (only significant from $Fn = 0.5$), the reduced displacement and wetted surface area are never sufficient to overcome the added resistance and induced drag of the foil. Notably, the configurations providing the most righting moment, namely the Dali-Moustache in both conditions and the DSS upwind, also have the most drag, as shown upwind in Figure 8 (a) and downwind in Figure 8 (b).

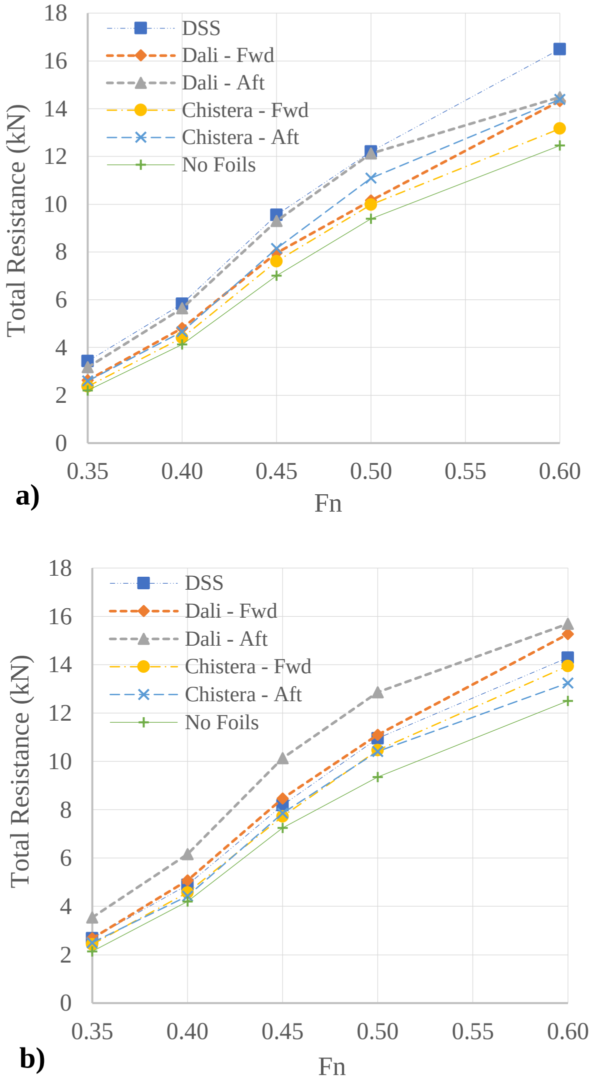


Figure 8: *Total resistance (a) upwind and (b) downwind.*

The resistance is a vital factor in the performance of a yacht: for a given drive force, the vessel with the least resistance will be the fastest. Furthermore, for upwind sailing, side force is critical. Interestingly, the Dali-Moustache generated the most side force in its aft position, while the Chistera did so in its forward position. Remembering that IMOCAs feature a Dali-Moustache aft and the Figaro Bénéteau 3 has a Chistera forward, the fact that each one is located in the position developing maximum side force could imply this is the parameter designers have been trying to improve for optimized performance. For the Dali-Moustache, the aft location is also the best position to generate stability. It is however not the case for the Chistera foil, which could suggest its primary objective is not to improve the stability but provide additional side force. Ultimately, this would allow the vessel to sail closer to the wind, and thus travel a shorter route into the wind. This will be further analysed in Section 6.4, taking into account the effect of the leeway angle on upwind performance to compare the theoretical sailing times on the water around an upwind race course.

5.4 DISCUSSION

The investigation into the ability of hydrofoils to create dynamic stability provides an insight into the added stability due to various configurations and positions. The present work is consistent with the earlier findings relative to the hydrodynamic efficiency and provides tangible arguments regarding the influence of foils on stability.

5.4 (a) Dynamic Stability System

The DSS demonstrated a very effective contribution to the righting moment upwind. In this particular instance, for $\theta = 20°$ and $\lambda = 3°$ at $Fn = 0.35$, *i.e.* a typical upwind sailing condition at the upper end of upwind speeds, a reduction in heel angle of 4.73° was measured. This is in agreement with the findings of Welbourn, inventor of the DSS: *"I figured out a simple rule way back at the very beginning of all this, and you should be looking to optimize the foil for about 5 degrees heel equivalent of RM at the top end of typical upwind speeds"* (Welbourn, personal communication, 14 December 2017).

5.4 (b) Dali-Moustache

The Dali-Moustache in the aft position (where it is found on racing yachts), revealed the best ability to add stability and reduce heel angle. While the DSS is limited by ventilation issues due to the proximity with the free surface, the Dali-Moustache proved to be able to bring the vessel past upright, thus demonstrating its efficiency at low heel angle, characteristic of downwind sailing. Since this configuration is seen on IMOCAs, primarily optimized for downwind, it is no surprise to see it perfectly suited for this point of sail. Moreover, the added stability explains the reason behind the latest generation of IMOCAs being narrower (Beyou, 2017): with the tremendous dynamic stability provided by the foils, the form stability due to the width of the vessels can be decreased, in turn resulting in a yacht with lower wetted surface area, but also a lighter weight thanks to the diminished size.

5.4 (c) Chistera

The Chistera exhibited a greater contribution to stability in its aft rather than forward position, the actual amount however being the lowest compared to other configurations. The advantages of the Chistera in the forward position, where it is found on the Figaro Bénéteau 3, are a lower drag and greater side force upwind. This would, therefore, suggest its design is targeted at a faster boat, able to sail with less leeway upwind. This would also explain the previously not understood reason for the new Figaro Bénéteau 3 featuring a heavier and deeper keel despite the foils (Dewavrin, 2018). This can now be explained as compensating with weight stability for the minimal increase in dynamic stability. Practical considerations also drive the forward location of this foil, as discussed in Section 7.3.

5.4 (d) Findings

The DSS appeared to be most suited to upwind sailing, and a very similar reduction in heel angle compared to the rule of thumb developed by the DSS' inventor has been observed. Downwind, or at low heel angles, the proximity to the free surface negatively affects this configuration, with limited stability gains.

The Dali-Moustache is creating the most righting moment in all conditions, especially in its aft position. This justifies its presence further aft on racing yachts, as well as why the latest generation of IMOCAs can afford to reduce the form stability of the hull, now mostly relying on the tremendous dynamic stability of the foils.

The Chistera foil in its forward position proved less efficient stability-wise. This would, however, explain why the new generation with hydrofoils features a deeper and heavier keel. Nevertheless, with a greater side force and lower drag upwind, it could be suggested that this is where the benefits of this configuration reside.

With the knowledge of hydrodynamic efficiency of these foils and the characterization of the added righting moment, the understanding of hydrofoil-assisted monohulls has been strongly extended. The final element to be ascertained is the overall impact on performance. Indeed, added stability will increase the power to carry sail, but it has also been shown to enlarge the total resistance. Similarly, greater side force will make for a shorter distance upwind, but again at a cost in terms of induced drag. Consequently, the development of a velocity prediction program able to capture the various behaviours of the foils will be tackled, to eventually establish their significance to the overall sailing speeds.

6. PERFORMANCE

6.1 INTRODUCTION

While the hydrodynamic and stability influence of the various foils have been quantified, the sailing speeds remain to be assessed. Velocity prediction programs have been successfully employed for the comparative performance of racing yachts (Thomas & Souppez, 2018) as well as cruising vessels (Guell & Souppez, 2018), but current commercial packages do no account for the effect of hydrofoils. Consequently, a dedicated VPP was developed (Borba Labi, 2019).

6.2 METHODOLOGY

The three degrees of freedom VPP (surge, sway, roll) relies on hydrostatics and stability input. On the other hand, the Offshore Racing Congress (ORC) methodology (ORC, 2017) was adopted to quantify the sail forces, and the DSYHS regression equations provided the hydrodynamic hull resistance model (Keuning & Katgert, 2008). For the hydrofoils, Glauert's biplane theory corrected for proximity with the free surface was utilised (Daskovsky, 2000), implementing correction coefficients based on the towing tank results obtained previously. Indeed, the empirical nature of the mathematical model representing the forces generated by the foils does not account for all the variables, hence the addition of an efficiency factor to bring the theoretical prediction in line with the experimental results for the various degrees of freedom considered.

The heave has been neglected in this instance has it was previously shown to be beneficial for typical sailing Froude numbers (see Section 4.4), and a significant reduction in displacement would not be expected on superyachts, as it is on some of the small and light racing crafts.

The VPP developed, having the architecture depicted in Figure 9, was first validated for non-foiling vessels against commercial packages to demonstrate its validity and suitability, before analysing the behaviour of hydrofoiling yachts.

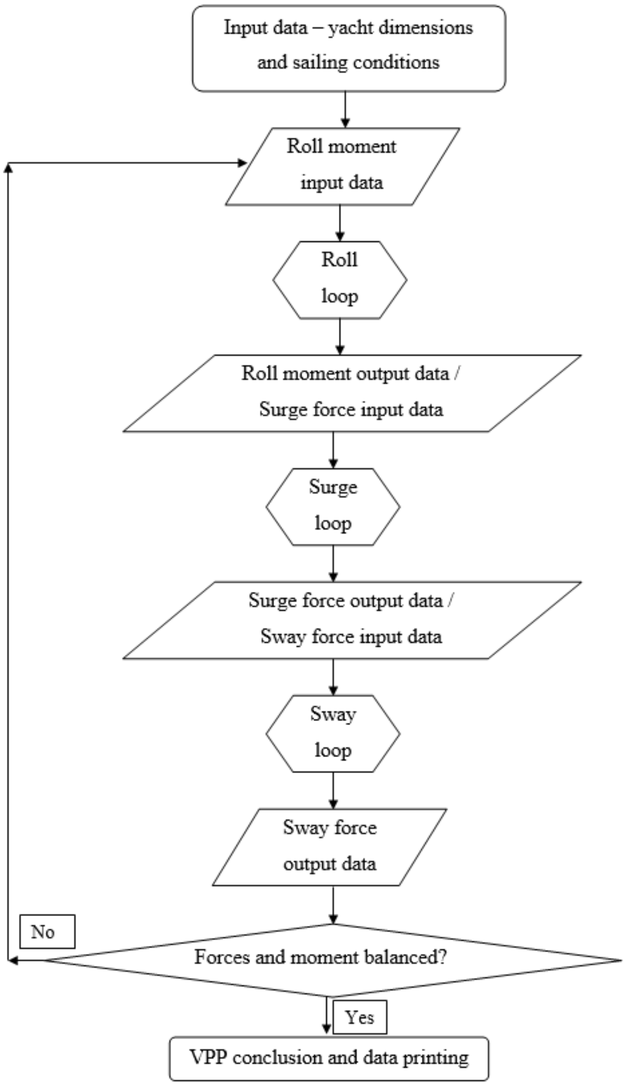


Figure 9: *Structure of the VPP (Borba Labi, 2019).*

Due to its nature and underpinning theory, this VPP is solely intended for foil-assisted yachts (*i.e.* not fully flying), and is best utilized at an early development stage, for the purpose of performance assessment, as illustrated in Section 6.3, but also hydrofoil design optimisation later highlighted in Section 6.4.

6.3 RESULTS PRE-OPTIMISATION

The initial assessment was conducted on the foil geometries as tested in the towing tank. The intention being to translate the experimental measurements into a quantifiable performance on the water.

6.3 (a) Upwind

In upwind conditions (mainsail and jib) for a low wind speed of 8 knots, the overall performance of each foil is very similar, with an increasing advantage in boat speed. The main difference, however, lies in the heel angle adopted by the vessel (Figure 10), highlighting the added stability of the Dali-Moustache, resulting in a lower heel angle.

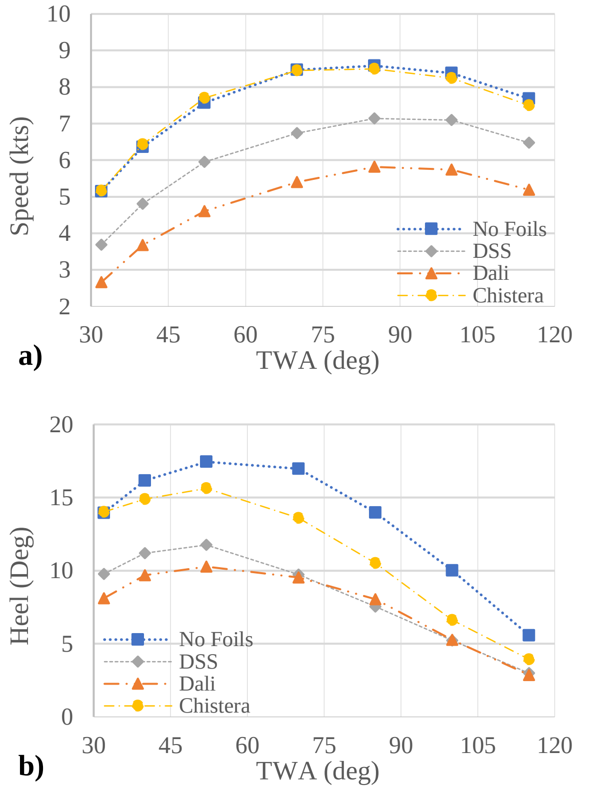


Figure 10: *Upwind boat speed (a) and heel angle (b) in 8 knots true wind speed.*

In low wind speeds, the small angles of heel are not yet optimum for the DSS, which provides greater stability further away from the free surface as the boat heels over more in stronger wind. This is reflected in Figure 11, where the vessel fitted with a DSS has the lowest heel angle. In terms of performance, greater differences are now shown, with the Chistera achieving higher velocities.

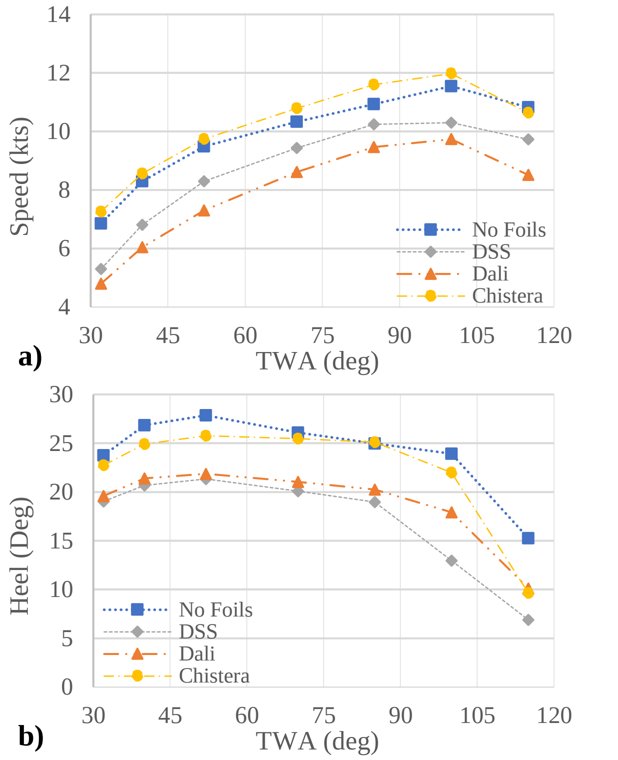
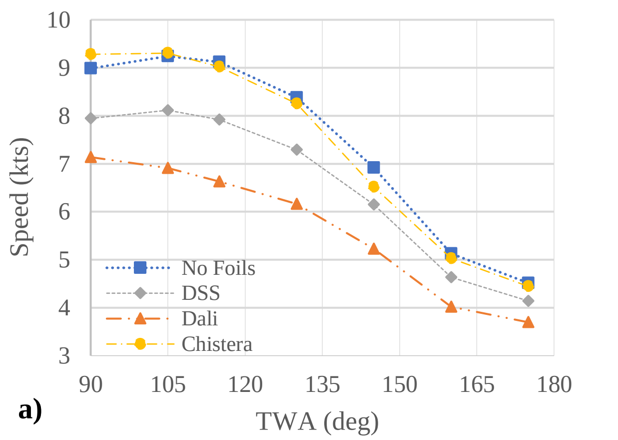


Figure 11: *Upwind boat speed (a) and heel angle (b) in 16 knots true wind speed.*

In those conditions, the pure boat speed is only superior to the vessel without foils when fitted with a Chistera. The DSS and Dali-Moustache do however contribute to a much lower heel angle, which could be seen as more suitable in cruising conditions for comfort.

6.3 (b) Downwind

In the downwind case (mainsail and spinnaker), the results are less sensitive to the wind speed. Both low (Figure 12) and high (Figure 13) wind speeds depict identical trends, with the Chistera performing best, but at a higher heel angle. Here again, only the Chistera proved able to surpass the boat speed of the yacht not fitted with hydrofoils.



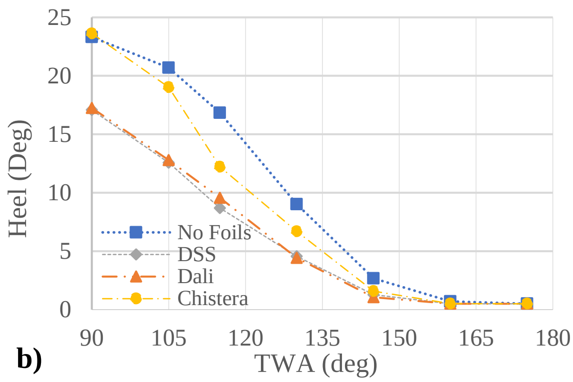


Figure 12: *Downwind boat speed (a) and heel angle (b) in 8 knots true wind speed.*

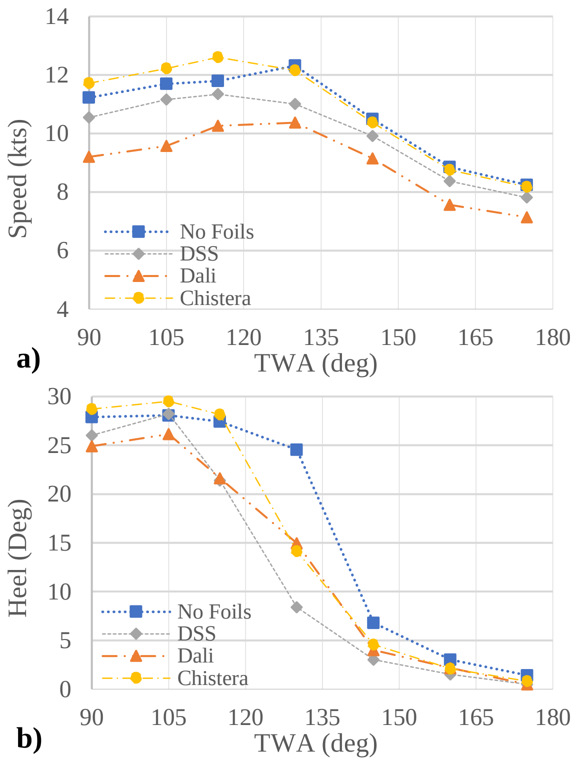


Figure 13: *Downwind boat speed (a) and heel angle (b) in 16 knots true wind speed.*

Those results are however not sufficient to ascertain the Chistera foil as the best performing one in all conditions. On the one hand, an identical vessel has been considered, when added sail area could, for instance, be fitted on a boat equipped with Dali-Moustache or a DSS due to the significant added righting moment. For a given heel angle, those two configurations would have more power and thus achieve better speeds. In addition, the leeway angle would be considerably reduced if the yacht was fitted with a Dali-Moustache or Chistera. On the other hand, the comparison presented is for a given foil design that has not been optimised. The original towing tank tested geometries resulted from a parametric analysis to ensure their representative nature, but in light of the new experimental findings and the VPP created, their design can be refined. Consequently, the specifications of each hydrofoil will be altered to achieve an optimum geometry before re-assessing the performance.

6.4 RESULTS POST-OPTIMISATION

The VPP created permits to conduct a parameter study of the hydrofoil geometries with the aim of maximising performance. The design optimisation was targeted around some key features, namely: the span, aspect ratio, the angle of the foil to the hull and angle between its two part for the Dali-Moustache and Chistera.

The results showed that very little improvement could be made on the initial Chistera geometry that already appears to be extremely efficient; this explains its superiority in the previous presented section. On the contrary, significant performance optimisation could be achieved with both the DSS and Dali-Moustache. The gains between the original tank tested versions and the VPP optimised ones are presented for 16 knots of wind upwind and 18 knots downwind in Figure 14.

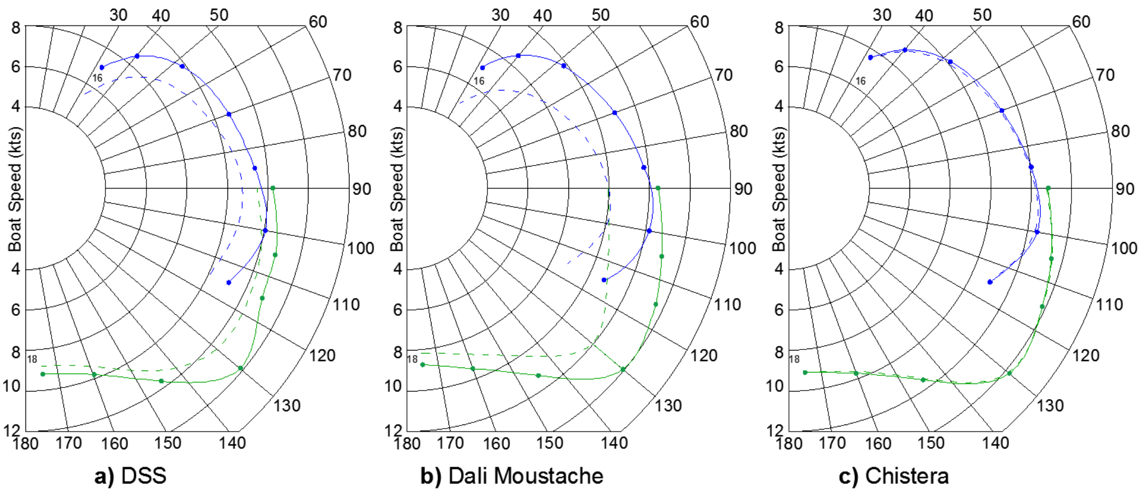


Figure 14: *Polar plots for the original (dashed line) and optimised (solid line) boat speed of the (a) DSS, (b) Dali-Moustache and (c) Chistera.*

Lastly, as all VPPs, the presented one should be considered qualitatively, allowing to compare the performance of various boats, rather than quantitatively. Indeed, although similar results between VPPs and sea trials can be achieved (Souppez, 2014), there is now evidence to suggest the force coefficients employed as part of VPP models and originating from wind tunnel tests could be flawed (Souppez *et al.*, 2019)

Nevertheless, this illustrates the crucial importance of the qualitative VPP at early design stages. Having reached an optimal geometry for each configuration, the performance of the three vessels could be compared again, yielding very interesting results. Indeed, with the optimised hydrofoil designs, virtually no differences in velocity or heel angle were present, as illustrated for an upwind case in Figure 15.

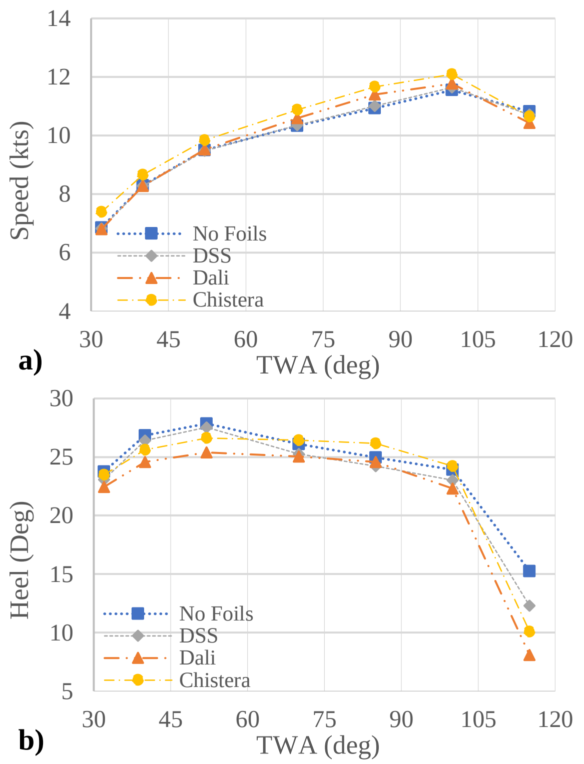


Figure 15: *Upwind boat speed (a) and heel angle (b) in 16 knots true wind speed for optimised hydrofoils.*

Therefore, it appears that provided the design of the hydrofoil is optimised, similar velocities can be achieved, irrelevant of the actual configuration employed on the vessel. However, the comparison must also consider the leeway angle, with a strong difference between the arrangements not creating side force (no foils and DSS) and those that do (Dali-Moustache and Chistera), the later having a much smaller leeway angle, as quantified in Figure 16.

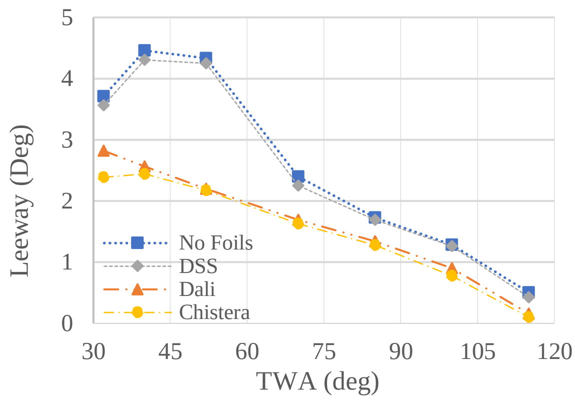


Figure 16: *Upwind leeway in 16 knots true wind speed for optimised hydrofoils.*

With this information, for a one nautical mile upwind course, the Chistera would be the first at the mark, followed by the Dali-Moustache 27.2 seconds behind, and then the vessel without foils and the DSS, respectively 44.3 and 44.7 seconds later. This therefore provides a clear comparison of the actual performance on the water of the various designs.

6.5 DISCUSSION

An empirical VPP tool able to account for the effect of hydrofoils was devised to quantify the sailing performance and demonstrate the significant impact of their optimisation on boat speed for foil-assisted monohulls. One of the key findings is that, for designs that have been ameliorated, there is no configuration superior to another in terms of velocity, including a yacht without foils. However, there are strong differences in terms of performance on the water, with a clear ranking between the different options.

It is worth noting that this study assumed that the design of the yacht remains constant. In practice, the amount of sail area or hull shape could be refined based on the specificities of each hydrofoil, as tackled in Section 7.5.

Nevertheless, the choice of which option to be installed on a yacht or superyacht is also subject to practical considerations.

7. PRACTICAL DESIGN CONSIDERATIONS

7.1 INTRODUCTION

Since the same performance can be attained for any of the three hydrofoil configurations investigated, the practical design considerations are vital factors to consider. These primarily revolve around minimising the loss of internal volume, ease of mooring and preventing marine growth on the foils. These also supplement elements normally considered as part of the development process, such as issues associated with cavitation and ventilation, or the structural loads, although these are currently beyond the scope of structural design regulations (Souppez, 2018).

7.2 INTERNAL VOLUME

Accommodation volume is always limited and must be maximised, even on the largest mega yachts. As a result, the intrusiveness of the hydrofoils should be minimized. To that effect, the DSS is the easiest to fit, as it can easily be concealed under the floorboard, even on small crafts (Guell & Souppez, 2018), thus having very little impact on the interior volume. The Chistera, and to a greater extent the Dali-Moustache, however, induce in a much larger loss of volume.

Of course, the physical size of the yacht itself play a large role. At present, only the DSS has been featured on superyachts, which would appear a sensible solution to avoid the loss of internal spaces, but also for mooring and maintenance reasons.

7.3 MOORING

An additional factor to consider in implementing hydrofoils onto superyachts is the ability to fully retract it within the overall breadth of the boat for mooring. Not only is it more expensive and harder to find suitable berth for a wider vessel, but hydrofoils are fragile, and should be protected.

A hydrofoil such as the Dali-Moustache protrudes beyond the overall beam of the vessel, thus requiring a larger berthing space as well as suitable protection for the hydrofoils. This also implies the deck edge will be further away from the quayside, which could represent a loading/unloading issue.

Consequently, it could be seen beneficial to prevent this situation. In the case of the DSS, the foil retracts and can be stored within the breath of the hull. This generally governs its position further aft, where a greater breadth is available. On the other hand, the Chistera, which still practically protrudes once retracted, is located forward, where the boat is narrower so that the outer extent of the foil remains within the overall breadth.

Irrelevant of the size of the vessel, preventing the hydrofoils from sticking out of the hull's overall beam in the harbour is to be considered by the designer. This can also help prevent marine growth and thus minimise maintenance by keeping the foil dry.

7.4 PREVENTING MARINE GROWTH

The performance gains obtained from the hydrofoils rely on a high lift to drag ratio. Unfortunately, the development of marine growth on its surface sharply hinders its effectiveness. The hydrofoil's surface should, therefore, remain smooth; the easiest way being to keep the hydrofoil dry when not in use.

On racing yachts such as the IMOCAs the foils will remain submerged even when retracted. This issue is alleviated by the fact that racing yachts will be regularly cleaned, and a high level of maintenance will be available ahead of the race start. A racing class such as the Figaro Bénéteau 3, equipped with Chistera foils, would also be expected to benefit from this.

For a more leisurely application of hydrofoils, which represents most of the sailing yacht industry, a more maintenance-free solution should be reached. Here again, the ability of the DSS to fit within the hull shell and the Chistera being mostly outside of the water when retracted provide strong practical arguments for their use.

7.5 DISCUSSION

The selection and design of a given hydrofoil configuration should consider all aspects, from the performance to the more practical elements. With the ability to fit within the hull's overall breadth, be kept away from the environment when retracted and minimal loss of internal volumes, the DSS appears as an easy system to install and has currently been the most widespread form of hydrofoil on sailing yachts and superyachts.

Nevertheless, other hydrofoil configurations can lead to alternative design philosophies. The Dali-Moustache for instance, shown to provide the most added dynamic righting moment, has led to new hull design for the IMOCA class. Indeed, the latest vessels feature narrower hulls, with less form stability, no longer required thanks to the foils. This also diminishes the build cost and weight as the surface area and size of the craft is effectively lowered.

8. CONCLUSIONS

Extensive experimental hydrodynamic testing has been performed on three contemporary hydrofoils in order to further the knowledge of hydrofoil-assisted monohulls, for application ranging from small racing yachts to cruising mega yachts.

Firstly, the hydrodynamic efficiency investigation revealed that, despite their contribution to the vertical lift and side force, none of the tested configurations could achieve a lower drag that the hull without hydrofoils.

This prompted further work to quantify the added righting moment provided, in a free-to-heel setup. The results showed that, while significant dynamic righting moment could be created, this came at a strong drag penalty.

In order to ascertain how the previous findings influence the overall speed of the yacht, which is of paramount importance, a dedicated velocity prediction program was developed. This tool allowed to define the comparative performance of the various foil types, but also to conduct a parameter study and refine their design. Upon optimisation of each hydrofoil, it appeared that none could provide a greater speed than the others.

Furthermore, it is interesting to note that, for foil assisted-monohulls where the foil does not a provide significant reduction in heave (particularly on superyachts where the lift force is very small compared to the vessel's displacement, and would not occur until a higher Froude number, as demonstrated experimentally), the actual boat speed remains virtually unchanged. There are however some strong benefits in terms of reducing the heel angle for comfort and leeway for performance that can be very attractive. Overall, looking at the race time on an upwind course, the Chistera would win, followed by the Dali-Moustache, and eventually the DSS, the later achieving a similar time as a yacht without foils.

Finally, the practical considerations that could influence the selection and design of the most appropriate arrangement have been outlined, revolving around the ability to retain internal volume, ease of mooring and the prevention of marine growth.

These novel findings provide new insights into the design of hydrofoil-assisted monohulls. Future work will, however, consider the impact on the design of the vessel itself. Indeed, all configurations were tested on an identical hullshape and sailplan. In practice, a narrower hull with less drag and less mass could be designed thanks to the added dynamic stability. Moreover, a greater sail area could be implemented as the power to carry sail has been increased, eventually resulting in a faster yacht.

In addition, research into the seakeeping characteristic of the vessels should be undertaken, with a potential reduction in motions experienced for greater comfort and lower structural loads.

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11. AUTHORS BIOGRAPHY

Jean-Baptiste R. G. Souppez is the Senior Lecturer in Yacht Design and Composite Engineering at Solent University, teaching on the prestigious *BEng (Hons) Yacht and Powercraft Design, BEng (Hons) Yacht Design and Production* and *MSc Superyacht Design*. He contributes to the European Master in *Integrated Advanced Ship Design* (EMship+) as a Visiting Professor and Research Supervisor, and is also the UK Principal Expert in Small Craft Structures, in charge of representing the interests of the British Marine Industry in the development of international structural regulations (BS EN ISO 12215). His research in fluid dynamics features twisted flow wind tunnel, towing tank, wave and current flume, particle image velocimetry, laser doppler anemometry, and full-size instrumented testing, as well as a range of numerical methods.

Juliette M. M.-A. Devawrin is currently a Graduate Design Engineer at Gurit Composite Engineering, UK. She is working on pre-studies and structural engineering solutions for composite structures in glass fibre and carbon fibre reinforced polymers on various projects such as sailing and motor boats, superyachts, vehicles and transportation, architecture and renewables. She is also conducting an experimental research on naval composite structures for Gurit internal development in the scheme of her graduate programme. During her studies on the EMship+ master in Ship Design, she conducted experimental research in fluid dynamics at Solent University, featuring modern hydrofoils-assisted monohulls hydrodynamic efficiency.

Florian Gohier presently occupies the position of apprentice engineer in composite engineering between the ENSCBP (Bordeaux Graduate School of Chemistry, Biology and Physics) and BJ Technology, Bénéteau Group, France. He is responsible for the structural calculations of hulls, hull liners, decks, deck liners and composite components manufactured by the Bénéteau Group.

Gaetan Borba Labi is currently a mooring engineer at Principal Power, Portugal. His responsibilities include the analysis and design of mooring systems for offshore platforms used in the Eolic industry of energy generation. His previous experience features numerical modelling of fluid dynamic problems and development of tools for the velocity prediction of hydrofoils-assisted monohulls.