



THE 24TH CHESAPEAKE SAILING YACHT SYMPOSIUM
ANNAPOLIS, MARYLAND, MARCH 2022

Progress in development and design of DynaRigs for commercial ships

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ABSTRACT

For most of the past century sailing was (besides very few exceptions) associated with pleasure and racing only. Recently, however, this is changing as the commercial maritime transport sector becomes increasingly interested in direct wind propulsion systems. The reasons are obvious: increasing fuel cost (direct or through emission penalties) and environmental awareness (intrinsic or driven by customer demands). In this paper differences between the design requirements in the commercial market and the pleasure or racing yacht industry are discussed and enhancements to the existing design tools relevant for commercial studies are presented. Sailing yacht studies have repeatedly shown how important it is to design and optimize the aero and the hydro aspects of the vessel in synchrony. This is equally or even more important for commercial ships, where part of the thrust might still come from the engine. Thus, the engine together with economic objectives of the shipping operations enter into the design space. With DynaRigs already having proved highly successful in the pleasure yacht market and possessing key features which are attractive for the commercial shipping, it serves as a good case-study. A few select results are first presented when analyzing the aerodynamic design space alone. Detailed results from several performance analyses via our Performance Prediction Program (PPP) are then discussed as well as some outcomes from the structural analysis to show the importance of combined aero, structure, hydro, and potentially engine as well as economic design decisions. The paper concludes with an outlook on future work.

NOTATION

A	(Sail) Area
AMI	Arbitrary Mesh Interface
AOA	Angle of Attack
BS	Boat Speed
ETA	Estimated Time of Arrival
l_{ref}	Reference Length
AWA	Apparent Wind Angle
AWS	Apparent Wind Speed
CAM	Computer Aided Manufacturing
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics
CSYS	Chesapeake Sailing Yacht Symposium
CWA	Course Wind Angle
DES	Direct Eddy Simulation
DoF	Degree of Freedom
E	Young's Modulus
FEA	Finite Element Analysis

F_i	Force along i-axis
FSI	Fluid Structure Interaction
M_i	Moment about i-axis
OPEX	Operational Expenditure
PBO	Polybenzoxazole
P_e	Effective Power
PPP	Performance Prediction Program
RANS	Reynolds Averaged Navier Stokes
T_h	Hydrodynamic Thrust
TWA	True Wind Angle
WASP	Wind Assisted Ship Propulsion
VMG	Velocity Made Good
VPP	Velocity Prediction Program
ρ	Density of air

1. INTRODUCTION

Commercial (maritime) shipping plays a key role in our economy and thus directly effects our daily lives. 90% of global trade is transported on cargo ships which consume 4 million barrels of oil per day – 4% of the global oil production (International Chamber of Shipping, 2020). Thus, decarbonizing commercial shipping is key in achieving the world’s climate stability ambitions as stated in the Paris Agreement. Currently, different ways of how to decarbonize maritime shipping are being explored. While many of these have merits, using wind energy directly to power ships has three clear advantages: (A) the primary energy source (the wind power) is directly available to harvest. Thus, energy conversion, transport and storage losses are minimized. (B) harvesting wind energy directly on board involves modifications to the vessels systems and its immediate environment only. It does not require the transformation of adjacent and/ or upstream industries. This results in a much more compact technological (and regulatory) challenge. This is in contrast to any alternative fuel solution which will require the creation of a new fuel production industry, as well as modified transportation and storage infrastructure. And finally (C) using wind as a power source for marine transportation has a unique business case advantage: the cost of wind power is, and will stay at, zero. Future fuel prices, which are inherently volatile and largely unknown, introduce a significant degree of investment risk to any fuel powered project – conventional or alternative. Hence, the less a project relies on fuel for its propulsion (i.e., the more propulsive force can be generated directly from the wind), the lower the risk exposure to rising fuel prices.

The DynaRig, one of many means of harvesting wind power for ship propulsion, was conceived in the 1970’s for commercial shipping by Wilhelm Pröhl as a potential offset against rising fuel costs. The key features of this concept are crew safety with no loaded lines on deck, incremental reefing ability and easy and automated handling of furled sails, as well as easy and automated trimming of the sails using only mast rotation to set the sails correctly. Due to the subsequent drop in fuel prices in the early 80’s, this concept never progressed past early wind-tunnel testing (Wagner, 1966), until, aided by the enhancement of modern materials, it was successfully introduced to large sailing vessels by Dykstra Naval Architects, e.g. 89m Maltese Falcon (Perkins et al, 2004) and 106m Black Pearl and followed by extensive load measurements (Roberts and Dijkstra, 2004; Wilkinson, and Robert, 2016). Over the last decade North Sails, the Wolfson Unit, and Southern Spars have conducted several studies on these kinds of propulsion systems. While all three companies come from a background of (racing) yachts, they have recently expanded their expertise into the commercial shipping world. There, North Sails’ unique capacity for numerical modelling of rigs and sails as well as investigating and optimizing the complex interaction of the ship with the “engine above deck” has put them in a key position of bringing the essential sail engineering perspective into these commercial studies. After all, sails are not just a motor that produces thrust, but an aerodynamic system which requires the ships hydrodynamic design to balance forces and moments (most notably side force, roll and yaw moments) in order to create thrust. The Wolfson Unit’s extensive expertise in a range of techniques for both testing and performance evaluation of hydrodynamics and aerodynamics, combined with its technical background in yacht research further enhances this position and transfers well to the assessment of wind assisted technologies on commercial ships. Southern Spars complements the group’s know-how by adding leading expertise on spar and composite design specifically geared to the marine industry.

The core driver of commercial vessels (in contrast to many yacht studies) is cost. That is the need to transport the cargo as efficiently as possible in terms of financial cost and within particular time schedules. Commercial shipping operators have always been aware of wind propulsion, but wind fell out of favor with the lower costs and increased reliability of engines. The balance is now swinging back towards wind propulsion with emission limits, carbon taxes and an overall awareness of the influence of shipping upon climate change. In this paper the tools developed, and some recent results from work on wind powered solutions for commercial shipping, are presented.

2. AERODYNAMIC EFFICIENCY VERSUS COMPLEXITY OF CONCEPT

Before going into the details of DynaRigs for commercial shipping it is important to understand the basic design requirements for commercial ships, trade-offs, and pitfalls, first. Hence a brief introduction of the design considerations around aerodynamic efficiency and design complexity is given in this section.

2.1. Aerodynamic concept

There are currently a variety of different wind assisted shipping concepts, all with their own proponents, at various different stages of technical development and real-world implementation (Chou et al., 2021). Broadly speaking one can distinguish four groups:

- Relatively bluff bodies with manipulation of air flow via power input (e.g. Flettner rotors or Ventifoil)
- Solid wing sails (e.g. WindWings, WindShip or FastRig)
- Soft wing sails with rigid frame mast (e.g. DynaRig or ADD Technologies)
- Soft sails or kites (e.g. SkySails GmbH, Airseas SAS)

The companies listed above are only examples of specific concepts; there are a large number in each category. While it may be thought that one concept will gradually become the clear favorite and dominate the market, much like the Bermudan rig for sailing yachts, the choices and technical challenges are more likely to require different concepts for different tasks. Operational height restrictions and structural implications quickly create the necessity of multiple rigs. This in turn necessitates more integration of the superstructure and the need to operate the rigs such that adverse interactions are minimised - a complex task with apparent wind angles from any direction.

The concept of Flettner rotors for example is both an elegant use of fundamental fluid dynamics and a simple concept to control by altering the rotational speed to change the thrust for a given set of conditions without changing the physical positioning of elements. The aerodynamic efficiency of a rotor in isolation is good (Jones et al, 2019), with significantly higher lift coefficients than other devices. Consequently, there are currently a number of commercial shipping vessels employing Flettner rotors on the water or in planning, such as Norsepower. However, when multiple rotors are placed in close proximity, or next to superstructure, the thrust developed by the rotors drops, and the interaction becomes complex and non-linear. The effect of separation in two dimensions of a pair of rotors is presented in Figure 1, while the effect of a hullform and apparent wind angle upon lift, drag and power can be observed in Figure 2. This interaction between hull and rotor is visualised in Figure 3, where the windward deck edge separation and the extent of the recirculation zone become clear. The effect of the ship is to introduce a secondary flow pattern which interacts with the flow around the rotor causing reductions in efficiency (Figure 2), most dominant at ± 90 deg and -135 deg (wind over the opposite deck edge to the rotor), which is where the ship form creates the largest wake over the rotor. These are large changes in relative performance with apparent wind angle.

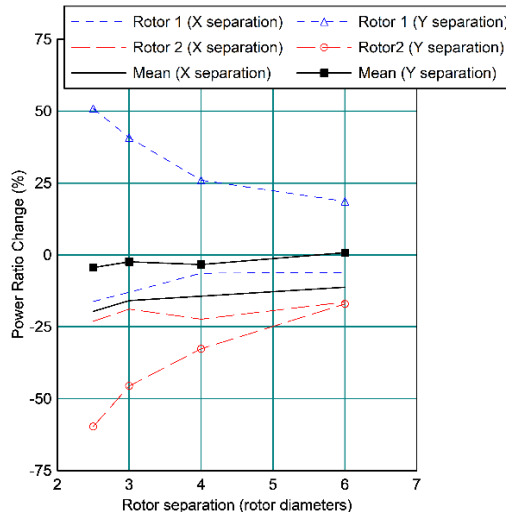


Figure 1 - Change in power ratio for two Flettner rotors, separated in streamwise (x, squares) and transverse (y, circle) direction.

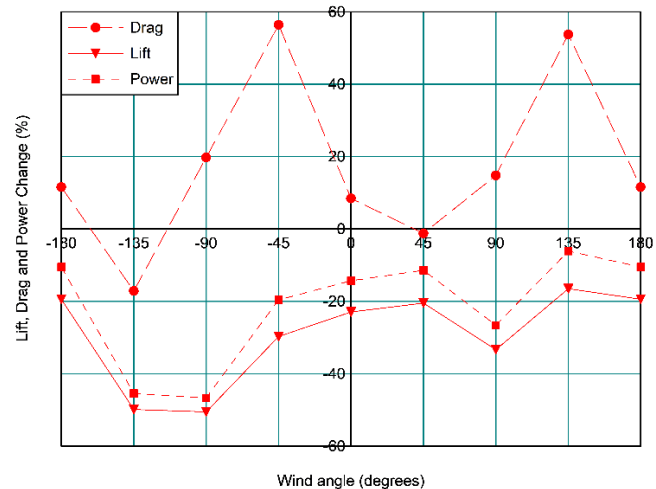


Figure 2 - Change in lift, drag and power for Flettner rotor next to superstructure.

A similar flow visualisation, but with a twin DynaRig instead of a Flettner rotor is presented in Figure 4. The differences in the fundamental flow structure are clear, with the deck separation zone suppressed by the rigs and a larger separation zone to the lee of the ship. Figure 5 shows the flow from the same simulation as that from in Figure 4 but with superstructure blocks added at the bow and for the bridge. While on first viewing there is little difference between these cases (Figure 4 versus Figure 5), careful inspection of the wake structure shows the influence of the superstructure is propagated even half a ship length aft, i.e. in the flow separation between the rigs.

In general, it can be observed that thrust generating components near the deck are of low efficiency, and there are good aerodynamic justifications for keeping them higher, both to keep them clear of the deck recirculation zone, but also to get them into higher wind speeds. However, changes in wind speed with height, as is normal in an atmospheric boundary layer, are a concern for optimising aerodynamic efficiency. Flettner rotors, where the entire device rotates at one speed, become significantly more complex if attempting to optimise for the apparent wind gradient observed when combining ship speed and the atmospheric boundary layer. Wing sails don't need to adjust (from an aerodynamic efficiency perspective) for a change in apparent wind speed, and much like for the Flettner rotor, the effect of deck edge created recirculation zone affects the effectiveness of those sections near the deck. Raising a lifting surface away from the deck is hence beneficial, and also because it transfers moving parts (booms, sails etc.) away from the deck and crew operations.

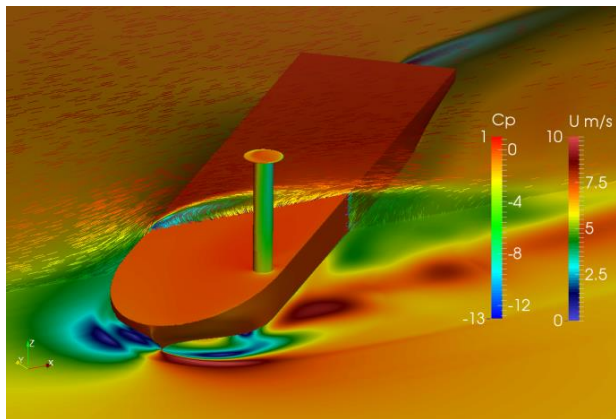


Figure 3 - Simple ship hull form with Flettner rotor (AWA = 45 deg).

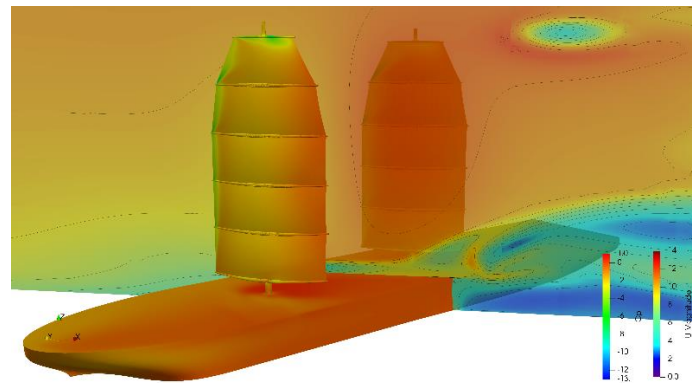


Figure 4 - Simple ship hull form with twin DynaRig (AWA = 45 deg).

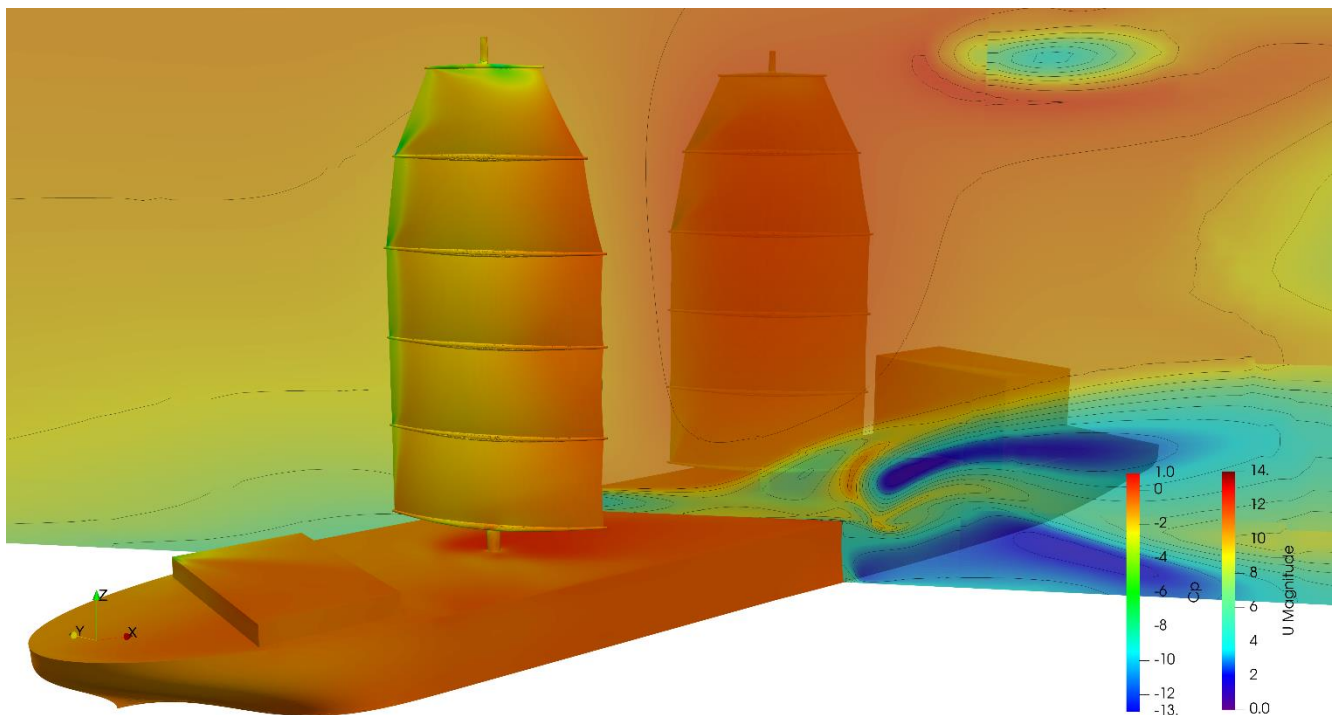


Figure 5 - Twin DynaRig on ship form including superstructure (AWA = 45 deg).

These simple case studies show a divide in functionality of different concepts (lifting wing versus rotating bluff body) from an aerodynamic perspective. In addition, it is clear the interaction of the hull form and superstructure with the propulsive device must be considered to correctly predict performance, all of which requires the use of suitable fluid dynamics tools and techniques which will then allow the balancing with hydrodynamic and engine loads to predict speed. Of course, correct modelling of all aspects, as well as an understanding of their interaction, is required in order to correctly predict performance. However, while the performance of a vessel on the water can thus be characterized, this alone does not yield a full assessment of the design; correct modelling of the structure, understanding of wear, maintenance and operational constraints are also needed in order to correctly assess trade-offs between manufacturing and maintenance costs on the one side and vessel efficiency (speed and payload capacity) on the other.

3. CHALLENGES OF WIND ASSISTED SHIPPING

The traditional approach to modelling a sailing vessel is to balance the aerodynamic forces with the hydrodynamic forces (Figure 6), usually via a VPP, either as a 3 DoF or more often now for racing yachts, 6 DoF problem. While it may appear initially that wind assisted ship propulsion (WASP) poses the same problem, there are a number of design features that make the process more complex. Although some yacht design features are irrelevant for commercial vessels, there is also a set that are unique to the WASP design challenge. For example, one of the most essential aspects to the design of a sailing vessel, that of displacement and stability, is no longer a major driver for the commercial sail propulsion system(s). Design features that are present in sailing vessels already, but are more complex, include leeway, yaw balance, structural requirements, routing and aerodynamic modelling. Engine loading, propeller efficiency, CAPEX and OPEX costs, while already known, are not typically integrally involved in the design of a sailing vessel.

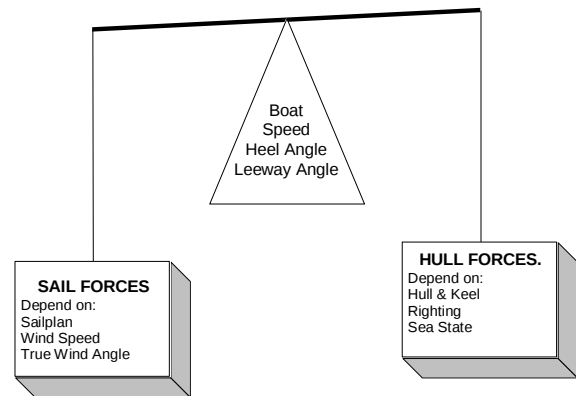


Figure 6 - Sailing yacht design via VPP as a force balance

3.1. Design features with increased complexity

Retrofitted vessels, but usually also new designs, do not have a fin keel. Hence the side force has to be resisted by the hullform, bilge keels and rudders, all of which are low aspect ratio and thus relatively inefficient. The location and size of bilge vortices can be significant in determining of vessel resistance and behavior. Fluid flow modelling of low aspect ratio foils and accurate tracing of vortices is complex, and normally requires higher order solutions such as RANS CFD or tank testing.

Hydrodynamic control of the yaw balance falls usually upon the rudder. As noted above these are typically low aspect ratio, relatively small and in disturbed flow on cargo vessels, resulting in very large rudder angles required to move the longitudinal center of resistance. As well as being inefficient, such large angles induce large and unsteady structural loads. With inconsiderately placed WASP devices, it is thus easy to find oneself in an area of the design space with highly loaded inefficient hydrodynamic appendages – a poor design solution.

Already for a typical sailing vessel we notice that the modelling of the rig(s) in isolation is only adequate in special cases to generate the main aerodynamic behavior, but that the hull generally has a significant influence on the sails. For commercial ships the superstructure is significantly larger, more bluff in shape, and it interacts even more with the propulsion device(s) than already on sailing yachts. A comparison of Figure 7 and Figure 8 shows this. In addition to this change in the relative size of the rig, the shape of the hull exacerbates flow features such as deck edge flow separation (cf. Figure 3). These all combine to require the entire geometry to be aerodynamically modelled by a higher order method capable of dealing with differing Reynolds number scales, bluff body flow and large wake structures as well as the streamline bodies of the lifting surfaces.

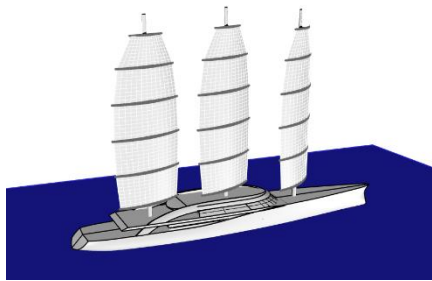


Figure 7 - SY Black Pearl Emulation

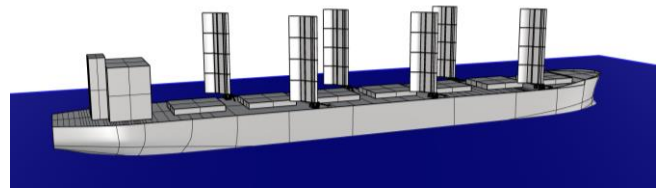


Figure 8 - Bulk carrier with solid wing rigs. image SGS

Routing is a subject well known to the yachting community, and the tools available have increased in power and capabilities over recent years. Today routing studies influence the design of racing yachts (e.g. Vendee Globe entries), but they do not dictate whether a vessel is even built or not as can be the case when assessing a wind assisted cargo vessel. In addition, the number of variables for the route optimization is increased due to the commercial sensitivity and cost/ profit implications of transit time influencing the relative level of dependency upon wind power compared to fossil fuels. Moreover, port operations and schedules required to meet contractual targets can exert an overriding influence.

3.2. Unique design features

Wind assisted shipping currently requires the engine still to provide some of the propulsive force for significant parts of the voyage. Traditionally, with the engine the sole source of power, it is an understood design process to determine the resistance, effective power and then engine power and thus fuel consumption. For a given design speed (dictated by the market forces briefly commented upon above) the engine and drive train can then be optimized for peak efficiency. Off design powering, such as light load and heavy fouling, are given consideration and may alter the peak power location but at a known percentage of time due to knowledge of routes, cargo etc. In the case of wind assisted shipping the engine power for a given speed depends upon the wind speed and direction, both of which can be statistically determined for a given route (and modelled to different levels of accuracy over different time scales), but they are not fixed. This results in a range of engine power requirements, making the optimization process more difficult and, when routing options are incorporated, highly non-linear. All of this requires the design tools to be accurate and capable of processing large datasets. Cascading from the non-unique engine powering ‘design case’ is the requirement for the propeller(s) to maximize efficiency over a broader range of advance ratio and thrust. This ‘detuning’ of the propellers away from one specific advance ratio and thrust can greatly diminish gains nominally obtained by the addition of the rig. One solution is to utilize a controllable pitch propeller. However, this is expensive for large vessels.

Harbor operations are not typically considered in the design of a sailing vessel. Yet, for commercial vessels they are a critical part of the vessel’s reason for existence. Minimizing loading and offloading times and complexities determine a vessels profitability, a partial reason for the rise in containerization. The deck operations for a bulk carrier are fundamentally different to those of a car carrier, and equally different to those of a tanker. Such operations affect whether overhead gantries or cranes are required, relative placement of vessel and dock, what deck-based equipment is needed and even what port facilities can be accessed (e.g. bridge air draught restrictions). This in turn dictates if the wind propulsive device needs to be moved or laid flat on the deck, whether it can be located at the deck edge, and so on. For example, there are concept designs for Flettner rotors on rails (Anemoi Marine) to allow their movement around the deck; this would not be possible with a DynaRig, but DynaRigs can be folded away for greatly reduced windage and increased visibility.

The core reason wind assisted shipping sail technology for commercial vessels has not been previously exploited is the absence of drivers for adoption providing a viable market. That has changed with the requirement for decarbonization, primarily via the imposition of IMO’s Greenhouse Gas Strategy and the Energy Efficiency Existing Ship Index (EEXI) technical measures, which raises the topic which is the final arbitrator: money, and more specifically capital and operational expenditure, or CAPEX and OPEX. The challenge currently is that relatively few wind propulsion devices have been built full scale for modern commercial shipping and those that have do not disclose costs readily. Moreover, the wind propulsive device is normally installed in addition to the engine, so CAPEX will be higher. Voyaging costs, and hence total operational costs, will be lower due to lower energy use (Schinas & Metzger, 2019) and “there is a lack of sufficient performance data for both discussed technologies”. This is not unusual with a “new” technology that is embryonic and expensive; over time it becomes cheaper as production and thus efficiencies of scale increase. Against this is solid data for the installation, running and maintenance of engines and drive trains. As a consequence, the successful implementation of wind assisted shipping is dependent upon outside influences such as regulation and government incentives – just like the drivers behind increasing adoption of green technologies in other sectors and applications.

Most of the topics described above are large enough to be the topics of multiple technical papers in their own right, but will not be discussed further here. They are highlighted only to indicate the range of challenges facing wind assisted shipping, and the fact that end solutions can be counter-intuitive, depending on constraints not normally considered by yacht designers. The skill of balancing forces as per Figure 6 has become a lot more complex, leading to something like Figure 9, with costs moving the balance point between the physical forces present. To date, the economic model has been such that the balance point has made aerodynamic forces & propulsion effectively irrelevant, but the costs, tabled by the IMO (and possibly soon other bodies), are moving the balance point rapidly.

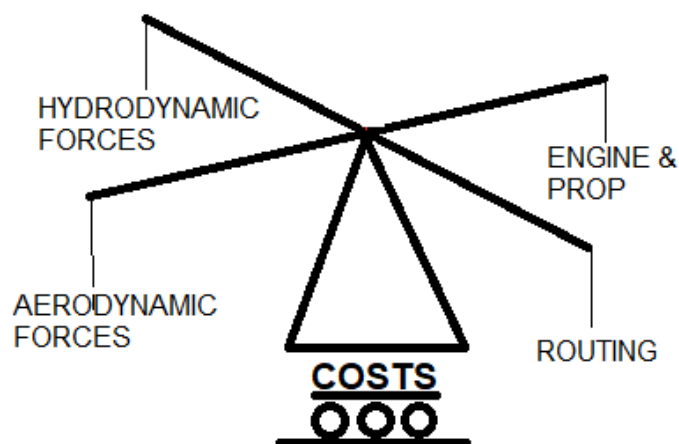


Figure 9 - Design balance for commercial wind assisted vessel

The optimal solution for one type of vessel on a specific route will more than likely be different to the solution determined for a different vessel. Changes in operational requirements or routing can quickly lead to different solutions, but what is critical to addressing the problem is a set of tools capable of correctly assessing the parameters present, and a team with expertise from all disciplines involved: naval architecture, logistics, marine operations, sailing, structural design and materials, ...

4. THE NORTH DESIGN SUITE – ADAPTED FOR COMMERCIAL SHIPPING

The authors (and/or their respective departments) have been collaborating for over a decade to develop the North Design Suite, a family of 14 specialized software modules dedicated to modelling a sailing vessel's behavior on the water. The results obtained have been helping both architects and sail designers optimizing their respective products. While requirements and design challenges for DynaRigs and for commercial vessel in general are different to those for yachts (as explained above and highlighted in Figure 6 vs. Figure 9), the relevant physics are the same. Hence the authors have advanced the Design Suite to correctly model and optimize DynaRigs and are currently working to expand it to other wind propulsion systems.

Figure 10 shows of a typical workflow with the Design Suite. The remainder of this section will provide a brief summary of the core software tools. The necessity of each step in the workflow of this figure will become apparent in the next section, where a set of the most interesting results from recent DynaRig studies is presented.

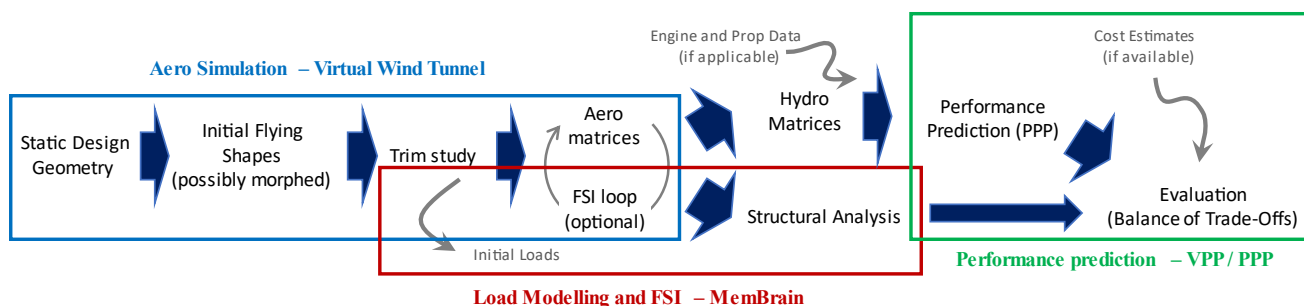


Figure 10 - The North Workflow for Performance Prediction of Commercial Sailing Ships

4.1. Aero Simulation via the Virtual Wind Tunnel

The Virtual Wind Tunnel is a scripted version of OpenFOAM, using a RANS (Reynolds-averaged Navier–Stokes) solver. The RANS equations are time-averaged equations of motion for fluid flow, and while the presence of bluff bodies (e.g. ship superstructure) may be better modelled via DES or equivalent approaches, the computational requirements of DES make RANS the most appropriate approach in an applied design environment. Meshing is unstructured, with a typical full rig plan on a hullform being 20 –25M cells. Boundary conditions incorporate wind profile, vessel speed and leeway to give twisted flow inlets, with pressure and symmetry outflows. The solver is simpleFOAM with kappa-omega ($\kappa\text{-}\omega$) SST turbulence model and ‘lookup’ wall functions (Kalitzen et al. 2005) that have been found to provide acceptable results at relatively high y^+

values. The CFD process is fully automated, with the designer submitting a case and receiving results via an FTP portal. All CFD simulations are run on the Iridis computer cluster at the University of Southampton, with Iridis 4 having 12,200 processors and Iridis 5 over 18,000 processors, allowing many simulations to be run concurrently, while maintaining high fidelity solutions, and correctly modelling complex interactions of different flow regimes (e.g. bluff body flow off a superstructure with the lift dominated flow off twin DynaRigs).

The first step in creating an aero simulation is to generate flying shapes appropriate for the given sail plan and righting moment. For conventional yachts flying shapes are obtained either from previous (similar) studies, or through bespoke FSI simulations for the sailplan in question. For a cost-efficient analysis of DynaRigs North Design Services has developed a unique DynaRig flying shape emulation tool in parametric CAD which can be adapted to match any DynaRig sailplan. Using this tool, full sailsets can be created based on observations from DynaRig yachts in service and/ or from a fully coupled MemBrain FEA simulations model for similar studies. These sailsets can then be tested in the Virtual Wind Tunnel without the need of a complete structural model as would be required for the FSI loop. This way, initial design loads can be calculated relatively quickly and validated against the initial design. The influence of realistic flying shapes will be discussed in the results section.

4.2. Load Modelling and Fluid-Structure interaction via MemBrain

MemBrain is a non-linear FEA software specifically written to model yacht sails and rigs adapted for sailing yacht external aerodynamic simulations. This software interfaces directly with the CAM software that North Sails has written for use in their lofts, meaning the input of sail geometry and structure is as close to reality as possible. Supplied with the pressure field on the sails obtained from the Virtual Wind Tunnel, MemBrain calculates the loads on sails and rig, as well as the deformations. The deformed geometries can then be fed back into the Virtual Wind Tunnel to close the FSI loop. This way, realistic loads, as generated from realistic flying shapes, can be obtained and the rig and sail design can be adjusted to these loads.

Over a number of years MemBrain has been enhanced considerably to be able to model all structural and sail control elements of a DynaRig. Today it directly reports the variables relevant to DynaRig designers, variables that would be impossible to extract from any scale-model wind tunnel testing, such as the chordwise load distribution of the sail on to the yard. This extension allows complex, high-fidelity modeling of a DynaRig, where no simplifications or load assumptions are necessary. Moreover, it has increased confidence in the simulation, and consequently has led to design improvements that would previously (with a lower fidelity tool) not have been possible (see section 5.3).

4.3. Performance prediction via the VPP / PPP

The North Sails Velocity Prediction Program (VPP) is powered by high fidelity RANS CFD force models to capture the unique aero and hydro features of the design(s) under consideration. As with most yacht VPP's the program solves for equilibrium between an aerodynamic and a hydrodynamic force, taking into account other factors such as available righting moment, maximum rudder angles, etc. (Braun and Richelson 2017). Unlike most generic VPPs, the North VPP includes custom / bespoke aero and hydro force models specific to the design in question. This enables the North VPP to capture all of the detailed aero and hydro characteristics that define the character and performance of the vessel to a level of detail not possible using lower fidelity generic VPPs.

Here as well, the situation becomes more complex when concerned with DynaRigs for commercial shipping. Now one is not only concerned about the ship's velocity, but needs to predict and optimize its performance on broader metrics: engine efficiency and fuel consumption, leeway influencing hull drag, stability and cargo holding capacity, ... (cf. section 3). Hence, for WASP studies the general performance rather than "just" the velocity is of interest. Thus, it becomes more accurate to be talking about Performance Prediction Programs (PPPs vs VPPs for yachts).

To turn the existing VPP into a PPP and address the questions specific to commercial shipping, allowances were made not only for windage (e.g. of superstructure not included in the aero models, standing rigging, comms domes and furled headsails if relevant) but also an empirical drag model for exposed propellers, shafts, etc. which were not included in the hydro geometry. The latter includes a drag force and moment which depend on the vessel's speed and operation conditions, with the ability to manipulate the individual propeller contributions to thrust or drag and yaw moment. Since the course stability (the rudder load) can be critical for WASP studies, this resolution of the influence of the propellers on the ship balance is vital for an accurate performance analysis.

5. RESULTS

In this section a summary of results from recent work on DynaRigs is presented. The wind angle is given relative to the course (course wind angle - CWA) which includes leeway as opposed to the true wind angle (TWA) which excludes leeway in the nomenclature. True Wind Speed (TWS) and angle (TWA) are measured at 10 m above waterline.

While this work is all based on the tools described above it has been collected from different studies, hence results from two and three-masted vessels are interspersed. The physics, however, are always the same, as are the principles and general conclusions.

5.1. Influences of the Sail Shape Fidelity

Just as “normal” sails, DynaRig sails pressurized by the wind assume a two-dimensionally curved shape – as a function of sail cut and membrane stretch. One metric to characterize the curvature is the Miter Normal, which is the ratio of the camber at the mid-section of the sail to the chord length at that same section. The results of Figure 11 are based on our parametric sail shape model where we varied the vertical Miter Normal between 0% (flat sail, tight between the yards – green lines in left insert), to 10% (i.e. 10% vertical camber at the mid-section – red lines). All five geometries were run in the Virtual Wind Tunnel. Drive and side forces as well as center of effort (COE) were compared relative to the zero-camber case. Figure 11 shows the results at AWA = 60 deg together with the linear (least RMS) fit for both force components. From the figure it can be seen that for this case higher Miter Normal correlates directly with the aerodynamic forces and most importantly that a good estimate of the flying shape is needed for a realistic force analysis. Note also the change in CoE, which has a direct impact not only on the ship balance (rudder angles) but also on the rig’s torsional loads.

Since more vertical camber also means more horizontal camber, the results from Figure 11 could be interpreted as an indication that the yards for this vessel were too straight. However, one must note that these are results for one wind angle only. A robust design optimization should be based on a routing analysis, with the most probable wind angles, to find the best overall design for the whole operations envelope.

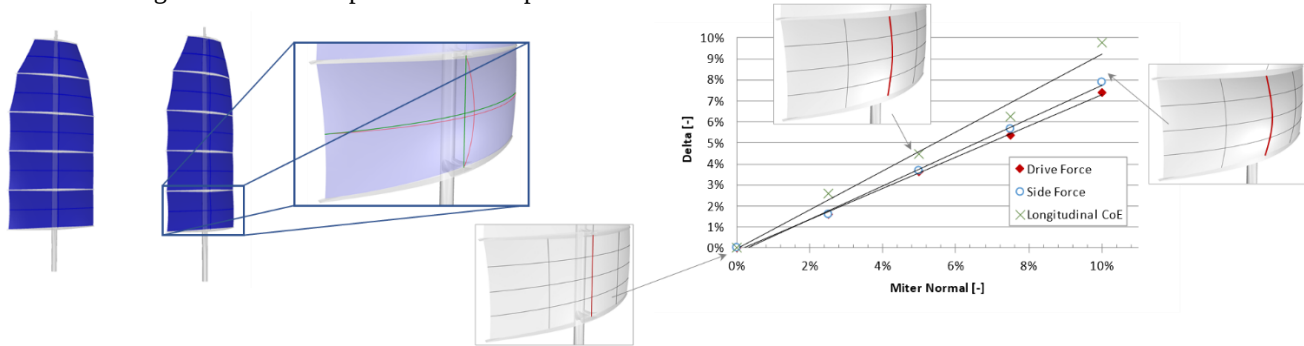


Figure 11 - Evolution of sail forces with increasingly realistic sail shapes (add camber to sails).

5.2. Influence of Rig Trim (Mast Rotation Angles)

Once reasonable sail flying shapes are obtained, “good” sail trims need to be found. Here “good” is determined by the ship’s performance (e.g. speed), but also by operating limitations (e.g. heel limits; dynamic stability of the sails, i.e. luff stability to avoid excessive aging from flutter). For this an initial trim study was performed for each apparent wind angle (AWA). The study was conducted from 30 to 150 degrees of AWA. The true wind speed was increased from TWS = 12 kt at 30 degrees AWA to TWS = 25 kt at 150 degrees AWA. Heel and speed were set such that realistic sailing conditions resulted for each AWA. TWA was adjusted accordingly.

Figure 12 gives an example of a trim study: the abscissa shows the evolution of different trims for the different AWAs as indicated by the gray line (right ordinate in the top graph). The resulting drive forces are shown on the left ordinate (top graph); The lower graph shows the roll (left ordinate) and yaw (right ordinate) moments respectively. Here, a three-masted ship was studied and blue, orange, green bars indicate the force and moment contributions from the forward, mid, and aft mast respectively. Forces and moments are non-dimensionalized by $cF_i = F_i / (0.5A\rho \cdot AWS^2)$ and $cM_i = M_i / (0.5A\rho \cdot AWS^2 \cdot l_{ref})$ respectively, with F_i and M_i the respective forces and moments under consideration, A the sail area, and $l_{ref} = 10$ m a reference length. Note that the way the study was setup allowed investigation of sail trims at realistic sailing conditions. However, it led to a variation in dynamic head between the AWA blocks, which means the forces are not directly comparable between blocks. E.g., comparing AWA = 30 (green box, in Figure 12) to comparing AWA = 60 (brown

box) and inferring that at $AWA = 60$ one obtains roughly double the drive force is not fair, because these two blocks are based on different AWSs.

For $AWA = 30$ deg Figure 12 shows that the first trim case (label A) leads to the highest drive forces. However, for this case the Mizzen Mast is rotated only by 3 deg. Close inspection shows that this low rotation leads to detached flow at the sail's leading edge. While this produces high overall forces in the simulation, in reality it also means an instable, potentially flapping luff. This might deteriorate the real forces, but what is even worse, it will lead to excessive sail wear and early failure. Hence, the PPP rotation angles were limited to AOAs no smaller than six degrees for the subsequent performance study.

Runs #7-9 (label B) effectively show why an aerodynamic analysis alone is not sufficient: these three trim cases all produce roughly the same drive force, however yaw and roll moments are vastly different. Therefore, in a comprehensive PPP case #8 might result in a better performance (less rudder load, less leeway, thus potentially less hydro drag) than its two neighbors (#7 and #9), even though it might have been discarded in a purely aerodynamic study for causing more roll without gain in drive force. In addition, when the increased maintenance costs of highly loaded components are considered the gains of #8 can become even greater.

At $AWA = 120$ deg (blue box) we see that what we would intuitively consider the "perfect" trim (label C, with both rigs just at the verge of stall) leads to sub-optimal drive force and even negative heel – at state that could be very unstable in real life! For good speed and stable sailing, we would want to trim the sails already at this reaching angle well into the stalled regime with considerable suction side separation (label D). As before we again find a very flat peak for drive forces with even the heel moment not changing much (cases #30-33). And again, it will be up to the PPP analysis to eventually pick the trim with the ideal performance, possibly again influenced largely by the vessel's yaw balance.

At $AWA = 150$ deg these same trends intensify: relatively "well" trimmed sails (attached flow, label E) lead to negative heel and sub-maximum drive force while rotating the sails more (cases #44-46) increases the drive force and stabilizes heel. However, these angles now also push the limits of our steady state RANS simulations. Here, conditions are reached, where the ideal trims are found well into the fully stalled flow regime, where typically large vortex structures are shed periodically. Hence, the steady state solver will no longer converge. To get a rough estimate of forces and moments, the results were averaged over several oscillation periods. Obviously, this is a crude and questionable approach but since sailing at these angles is not the most common condition this approach was deemed suitable for the time being. Employing an unsteady solver, or higher order methods such as DES (Wright, 2013) is on the list for future work.

In conclusion it can be noted that this kind of trim study provides an idea of *likely regions* of best trims. A conclusive decision can only be made with a full PPP analysis. One should also note that for this study we manually navigated the trim space. Wrapping an optimization routine around this process to automatically and reliably find the best trims would be an interesting future feature.

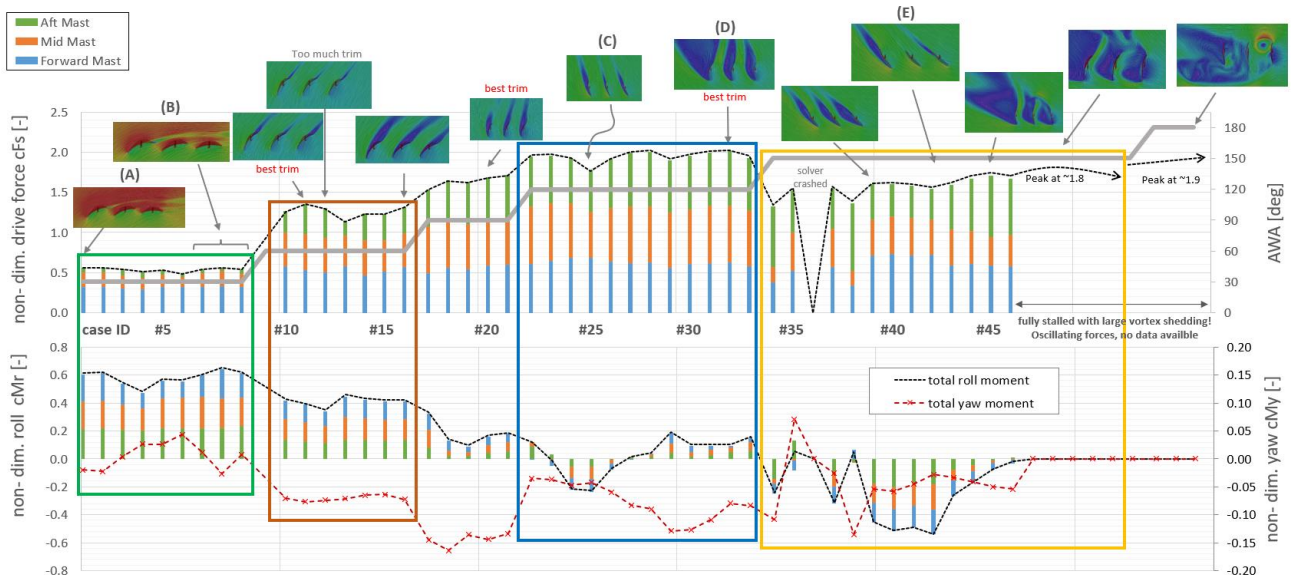


Figure 12 - Example of DynaRig trim study.

5.3. Structural Analysis via MemBrain

The trim study presented in the preceding section provides the base from which the scenarios for a subsequent load case analysis can be extracted. With these initial loads the design can be adjusted and refined early on. In this section some examples are given on results from this analysis and how it has benefited the overall design.

Figure 13a shows the force distribution along the interface between the sail and the yard obtained from the new MemBrain (FEA) simulation vs. the previously used empirical model. Both vertical and horizontal loads, as well as the resultant angle between these forces are shown. Dashed lines show empiric results from the previously used model based on extensive wind tunnel testing. The empirical method, while accurately predicting the overall load across the yard, misses the large force spike at the leading and trailing edge. The fact that on the existing rigs the highest wear of the sails was found at the clew, where the FEA shows the load spike, confirms the superiority of the FEA model over the purely empiric data. Moreover, the angle was simply assumed to be constant in the empirical model – a rough simplification as we see from the FEA results. Considering, however, that this angle is important for proper sail furling and to avoid the sails chafing at the connection to the yard, this has direct design implications.

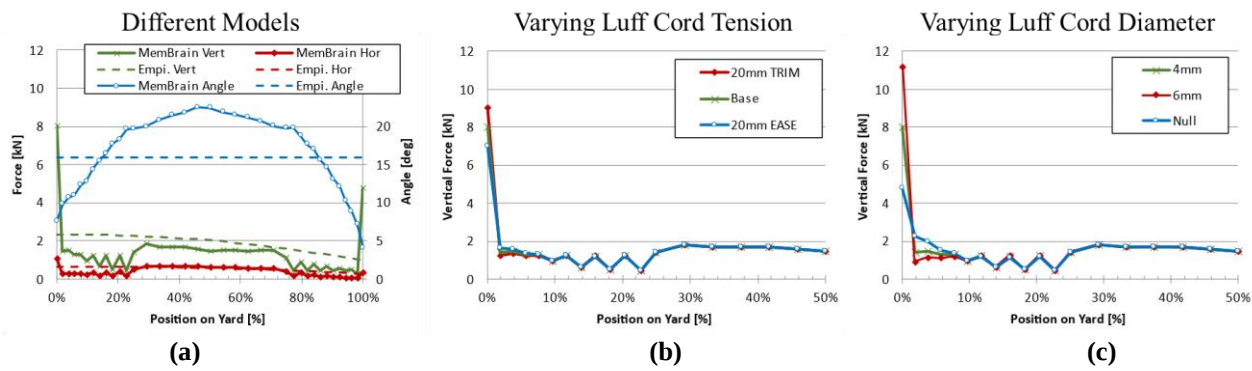


Figure 13 - Force & Resultant Angle Distribution along Yard.

With the results from this analysis, the sail structural design as well as the yard design can be adjusted to ideally match the existing loads – and in turn the new load distribution as caused by the new structural design can be validated. As a first step in that direction, further studies were conducted to determine the sensitivity of this force depending on multiple parameters. This was possible in high detail, because the MemBrain model contained all sail control elements (cf. section 4.2), including the small luff cord that is fitted on all DynaRig sails to prevent luff and leach flutter. Figure 13b and c show results from sensitivity studies conducted on the luff cord trim and size respectively. Both figures show the vertical force component along the leading half of the yard. The trim of the luff cord has a large effect on the peak force (within $\pm 13\%$ for a 20 mm adjustment). Adjusting the cord size, however, resulted in a much larger variation. The standard cord size for this vessel would be a 4 mm diameter PBO line (modulus: $EA \approx 900$ kN). Variations either side of this were assessed with a 6 mm cord ($EA \approx 2800$ kN) and no cord, designated as “Null”. This resulted in $\pm 40\%$ force variation on the baseline 4 mm cord.

5.4. Performance Prediction and Design Enhancement via the PPP

In this study the PPP was run in four Degrees of Freedom (4-DOF). This means the PPP finds an equilibrium between forces in the forward and lateral directions, and moments about the roll and yaw axes. The PPP then finds the “best” sail trim (i.e. the best mast rotations) for achieving maximum speed in the specified sailing conditions while solving for the remaining parameters in the model and observing user-defined constraints (e.g. maximum heel, rudder angle, leeway). The remaining 2-DOF (vertical forces and pitch moments) are pre-balanced in the 2-DOF hydro CFD so they do not need to be solved in the PPP. This approach is appropriate and cost effective for a fixed displacement analysis, i.e. when the aero downforces and pitching moment are a small proportion of overall displacement and do not have a notable effect.

The aerodynamic loads were generated around nominal trim points for each AWA extracted from a trim study similar to the one presented in section 5.2. Here, nominal trims for each AWA were chosen as those which give maximum aerodynamic drive force independent of any constraints. To give the PPP the required freedom to actually find the real best trims, a trim matrix was created, where each mast was rotated by ± 5 degrees from its nominal (aero only “best”) position. This gives three different positions for each mast, therefore there are nine different trim combinations at each AWA of this two-masted study. In addition, heel variations are tested for each AWA with three different trims (nominal and ± 5 degrees). This adds six more points, so a total of 15 different points per AWA, giving a total of 105 aero CFD runs for the 7 AWAs considered. These 105 runs were then solved for each geometry (i.e. each sailset, rig position, mast height, etc.) in the Virtual Wind Tunnel to obtain

the aerodynamic forces. Each CFD run took approximately three hours to solve on 32 cores in the Iridis HPC cluster (96 CPU hours per simulation, or 10080 CPU hours for the full data set). This is already a considerable effort and highlights why this approach of a variation around a set of central points was necessary: while ideally a square matrix of all reasonable trims would be simulated to give the PPP full freedom to choose any trim configuration, this is simply too computationally demanding. With the chosen approach, only a limited subset is calculated. By verifying that the PPP does not drive towards trim points which are not included in the data set, and assuming that the performance surface within design space is smooth (which seems reasonable given the physics at hand), one can assure that potential optima are not neglected in uncharted corners of the design.

5.4.1. Finding the “best” trim

While section 5.2 discussed sail trims (i.e. mast rotations) purely from an aerodynamic perspective, the complete system is now considered: that is the mast trims which actually lead to the highest speed under a certain set of constraints. Therefore the PPP was run at 4-DOF as described in section 4.3 for a sweep of course angles from 50 to 150 degrees at constant wind speed of 12 kt TWS.

Figure 14 shows the resulting AWA at 10 m height and the corresponding boat speed (Figure 14b), together with the mast rotations chosen by the PPP for maximum speed (Figure 14c) and the geometric angles of attack (AOA, Figure 14d). The latter are calculated as the angle between the apparent wind vector at 10 m height and the yards’ chord line. Note that this is only a geometric estimate, as (i) the AWA varies with height and (ii) the influence of one mast on the other (i.e., induced velocities) are not considered. Yet, Figure 14d shows how the ideal AOA varies as a function of the course angle. The reason is that the two rigs interact differently on different CWA and with increasing CWA the aerodynamic drag component becomes increasingly rotated towards the thrust vector. This highlights the importance of actually simulating the rigs in interaction versus simply scaling the data of one rig to model the effects of multiple rigs.

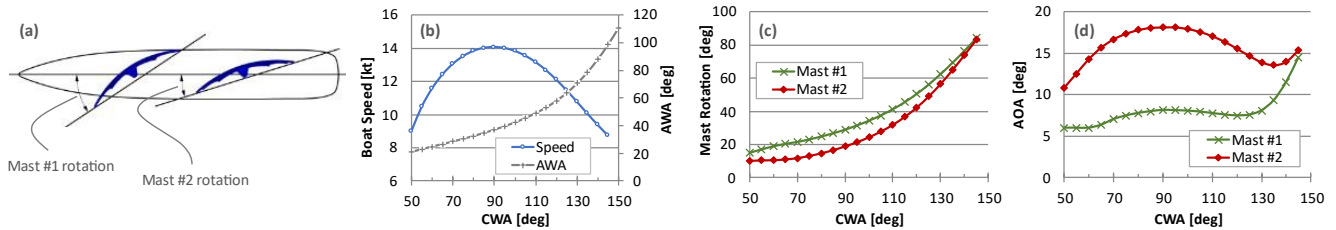


Figure 14 - The PPP finds the ideal mast rotation for the specific hull characteristics for a sweep of course wind angles (CWA).

Particularly interesting is the region of $CWA \leq 60$ deg. Here, the unconstrained PPP would push towards very small angles of attack for maximum speed (AOA = 1.6 deg for Mast #1 at CWA=50 deg). This is the case we encountered during the trim study (Section 5.2, discussion of AWA = 30): While these low angles might theoretically be fast and consistent with CFD results, in reality they result in an unstable, flapping luff. This would deteriorate the real-life forces and diminish speed. Moreover, it would lead to excessive sail wear and early failure – not ideal when overall (life time) cost is considered. Therefore, the PPP was limited to a minimum AOA of six degrees.

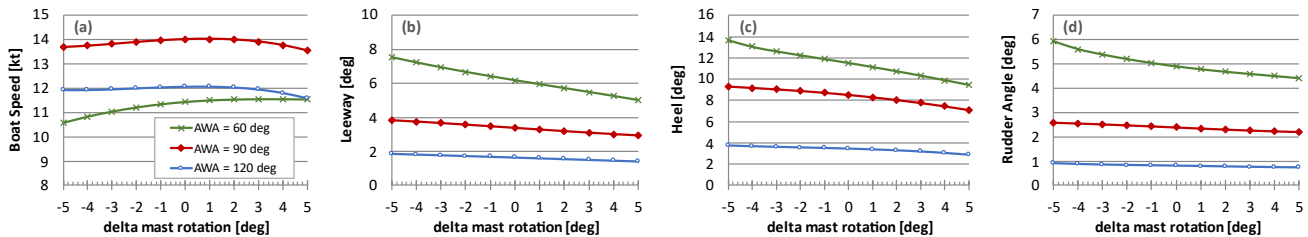


Figure 15 - Ship performance with varying mast rotations.

Figure 15 gives an insight of the variation of the ship’s performance with varying mast rotations. On the abscissa, rotation deltas around the nominal trim are reported. The plots show four performance metrics (speed, leeway, heel, and rudder angle) for three different wind angles. We see that the speed exhibits a relatively flat maximum, while leeway, heel and rudder angle change considerably particularly for the close-hauled course (AWA = 60 deg). For this study – a ship with a rather yacht like hull, relatively long and slender with a prismatic coefficient just over 0.6 and under wind only propulsion – this is consistent with previous experience. However, when these rigs are installed on a dedicated cargo ship with a much higher hull prismatic

coefficient, and operated in a wind assisted propulsion mode, the results of this analysis are likely to change substantially. In that case, hull drag, propeller drag and also propeller efficiency will degrade rapidly with leeway. Moreover, rudder efficiencies and drag will strongly depend on heel and leeway. Hence, the optima are expected to be very different.

5.4.2. Sailing at constant speed

Here the PPP is used to assess the engine power requirement when sailing at different course angles with different wind speeds. For the study at hand the specifics of engine, drive train, and prop were not yet defined. Hence, the power reported is the effective power $P_e = T_h \cdot BS$, with T_h the thrust delivered by the propeller and BS the boat speed.

Figure 16 shows the results for CWAs of 60, 100 and 150 degrees respectively. A target speed of 13.5 kt was set for this project. For CWA = 100 deg (Figure 16b) it can be seen that at 12 kt TWS and above the target speed is exceeded at zero engine power. For 10 kt TWS and below the engine has to be used to achieve the target speed. At around 5 kt TWS, the AWA becomes too narrow for the sails to fly efficiently and the sails will be furled (100% engine power). There are indications that there is a region around 5 kt TWS where it might be beneficial to keep the sails on one mast but furl the sails on the other (see inserts in Figure 16, left). This is because the fore mast deflects the wind on the aft mast. Thus, while the AOA at the fore mast is still sufficiently large, the (deflected) AOA on the aft mast is too tight to fly sails. For a decent yaw balance sails on both masts might be furled partially. The partial furl needs to be investigated in detail and was not included in the aero models yet. Hence, the results of Figure 16 for the area around 5 kt TWS might be somewhat inaccurate.

At 150 deg CWA (Figure 16c) even at 16 kt TWS the target speed cannot be achieved under wind propulsion only. As expected, the required engine power increases with decreasing wind speed. At around 6 kt a partial furl might become beneficial again (not included in the models). For $TWS \leq 6$ kt the ship will rely on 100% engine power to travel at 13.5 kt.

At 60 CWA (Figure 16a), the target speed of $BS = 13.5$ kt will be achieved without engine at wind speeds over 13.6 kt (true). For wind speeds under 13.6 kt the engine needs to be used to achieve the target speed, which quickly moves the (already narrow) AWA further forward. Already at 12.0 kt TWS motor sailing at $BS = 13.5$ kt will already become unfeasible because the AWA becomes too small to allow the sails to fly without flapping. Hence for $TWS \leq 12$ kt the sails will be furled and 100% engine power must be used to keep the speed at 13.5 kt. As discussed before, there will likely be a transition area with a partially furled rig which remains to be investigated.

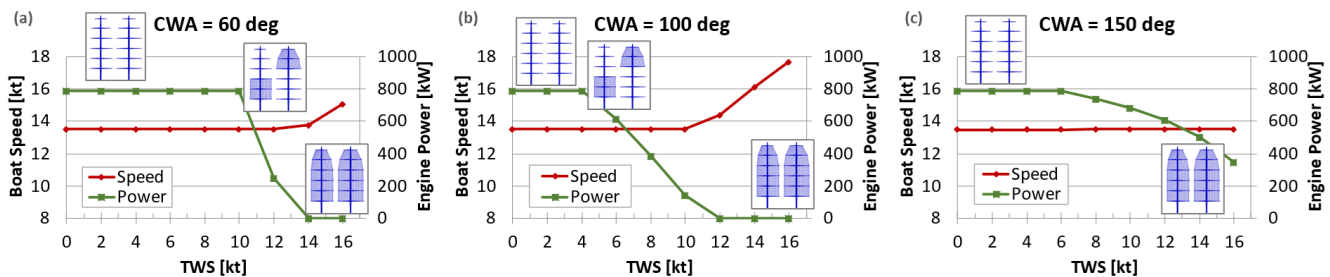


Figure 16 – Motor sailing for minimum passage speed at two different wind angles.

This section presents an initial discussion of required engine power to retain a certain speed. As such, it is meant as an example to show how the PPP can be used to analyze ship power requirements. Obviously, effective power then has to be combined with propeller efficiencies of various thrust and advance ratios as well as with engine efficiency maps to obtain fuel consumption projections. Combining this, further on, with weather and routing statistics will allow a qualified estimate of fuel savings, i.e. OPEX reductions, and thus qualify a potential business case.

5.4.3. Geometry modifications for performance enhancements

In this section results are presented that show how the PPP is used to support the design improvement process and guide decision making. Starting from a baseline hull and rig (blue in Figure 17), the hull was first enlarged and with it the rig moved forward (red); then the rig was enlarged as well (green).

Figure 17 shows the results of a performance analysis for the three hull and rig configurations used to quantify and discuss trade offs between speed and heel on a fact-based level with all stake holders. The data for 12 kt TWS is presented, based on 315 RANS simulations for the aero data for the various rig trims. The 4-DOF PPP was run as described in section 4.3. The PPP was free to find the best mast rotations (within the minimum AOA constraint from above); resulting leeway, heel, and rudder angles were calculated from the force and moment balance together with the associated hydrodynamic drag. The hydro CFD data was provided by Cape Horn Engineering (cape-horn-eng.com).

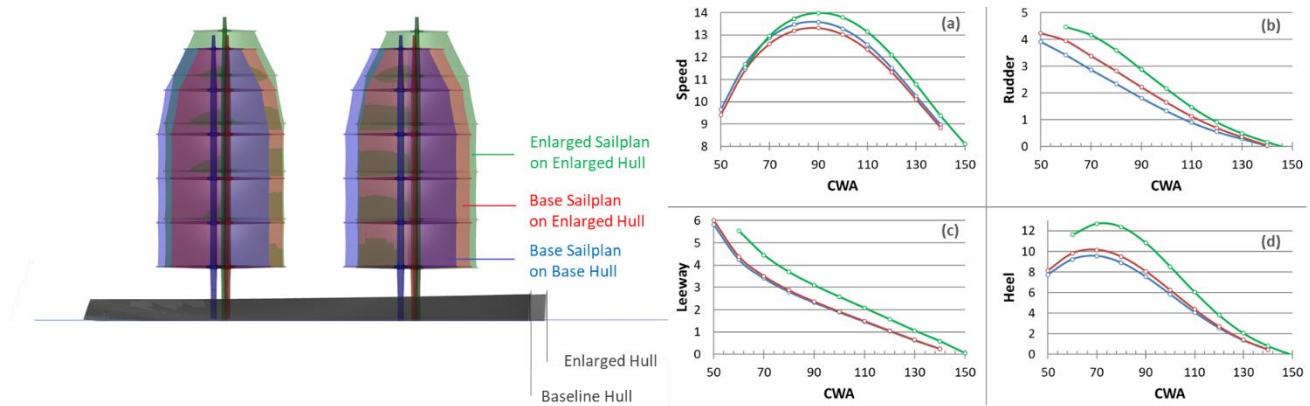


Figure 17 - Performance analysis for different hull and rig configurations at 12 kt TWS.

As expected, enlarging the hull (3.5% longer) while keeping the same rig height (i.e., same sail area) decreases the ship's speed particularly in reaching and upwind conditions (blue vs. red). This reflects the fact that the hydrodynamic resistance is predominantly caused by skin friction drag, with only a relatively small proportion of pressure (wave) resistance. Enlarging the rig (green, 16% more sail area) then over-compensates the losses through the larger hull (red) and leads to a speed above the one initially achieved by the baseline design. This comes, however, at the cost of increased heel.

For a racing yacht, the red option would be a clear loser, while green could be a winner if allowed by class rules and/or the speed gains exceed any rating penalty. For a commercial ship, however, the trade-offs are more complex: Here, a larger hull (red) can mean more payload capacity, which could offset the reduced voyage speed. Moreover, a passage route analysis could reveal that the ship will be mainly operating in downwind conditions where the differences between blue and red design are smaller (roughly 0.15 kt at CWA=130 and even less for higher CWA). While the speed of the green design is higher, it will most likely be also more expensive to build. Moreover, as can be seen from Figure 17 bottom right, the larger rig considerably increases the ship's heel, which has stability implications. For commercial operations it might have an impact on payload capacity, hence reduced revenue potential. With a viable PPP and a specific business model, these questions can now be addressed on a case-specific basis.

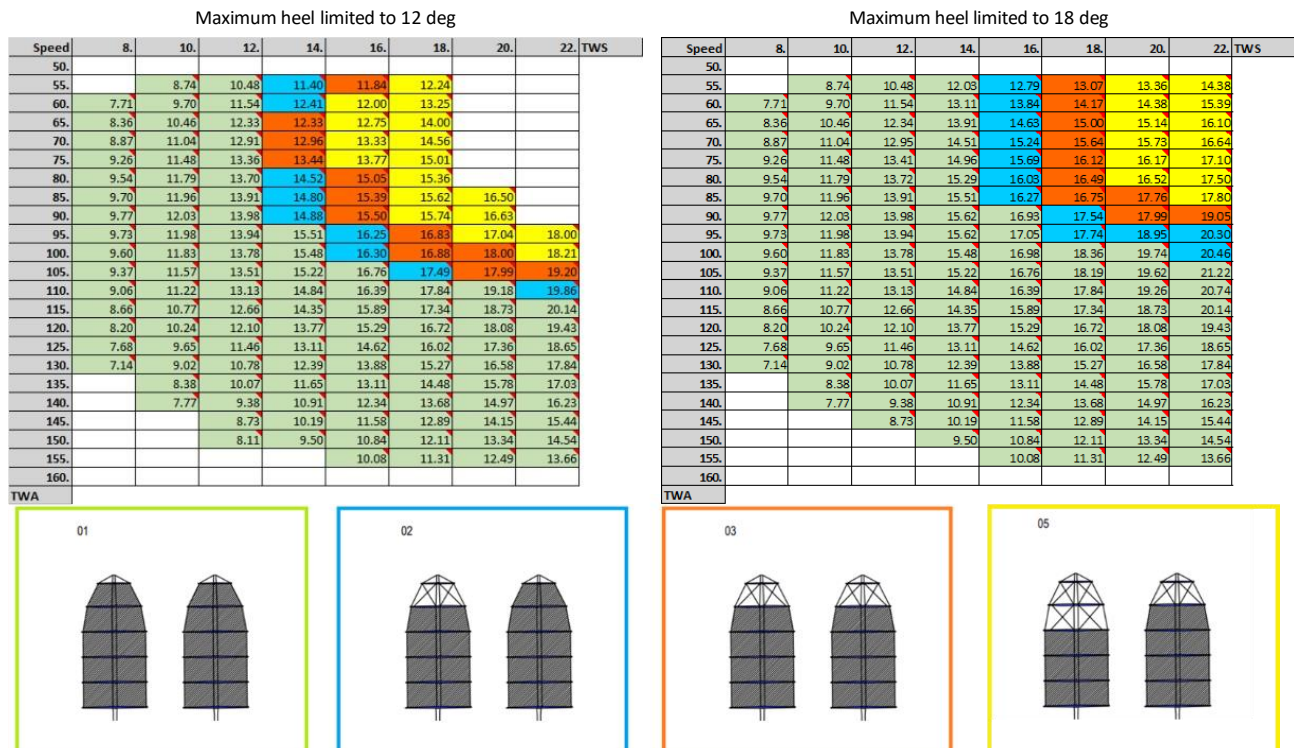


Figure 18 - PPP results: attainable speed polars and required reefing sequence for two different heel limits.

5.4.4. Crossover chart and reefing sequence

Figure 18 shows another example how the PPP can be used for navigating design trade-offs. For this study new VPP aero powering models were run in the Virtual Wind Tunnel for the reefed sailsets. Figure 18 presents best speeds and sailset crossovers for maximum heel angles of 12 (left) and 18 degrees (right). It should be noted that these heel angles may be considered more appropriate to a sailing vessel rather than a modern commercial vessel, but the same principle applies. Colours represent the various sailsets corresponding to the sketches in the lower part of the figure. White/ empty cells in the crossover charts are non-optimal conditions outside of the best VMG limits, or conditions which cannot be sailed with these sail combinations at the imposed heel limit. The polar chart for the 12-degree heel limits could be expanded with the addition of deeper reefed sailsets. This was, however, not relevant for this study.

In a subsequent step these polar tables can now be coupled with route information and expected wind speed and angle probabilities to obtain estimates for the most likely passage time. Then, combining this with cost models for payload capacities at different heel angles, engine efficiencies (how does the propeller efficiency and hull drag evolve with increasing heel?), and structural/ cost considerations, this will lead to a concrete business model. Considering that a higher heel allowance requires a design for a higher maximum righting moment, thus higher rig loads, which in turn lead to increased CAPEX to be able to meet now increased structural demands the question becomes: Does the gain of one or two knots of speed in the high AWS/ low AWA region offsets the additional CAPEX? Or, in the case of wind assisted propulsion: Do the expected OPEX savings from reduced engine power requirements offset the increased CAPEX? Again, these questions are non-trivial. They need to be answered for each ship and its operational schedule individually based on a viable PPP.

6. FUTURE WORK

This paper presents work that is very much in progress and future work has already been alluded to throughout the text. In summary there are currently a number of areas being investigated for further development. The underlying objective is always to either provide greater accuracy to the modelling undertaken and hence to support design improvements and/ or business decisions, or to assess a greater number of parameters, which represent diametrically opposing requirements (i.e. trade-offs) for design decisions, early in the design process. One of these objectives means pushing for greater complexity and more encompassing model boundaries; the other requires simplification in order to process a greater number of cases.

Approaches that will allow greater numbers of parameters to be assessed include:

- The use of a nonlinear Lifting Line model for quick assessment of diverse rig configurations to supply basic aerodynamic data for a performance comparison of different routes;
- An integrated design optimization framework which will vary basic design parameters (rig height and breadth, position, trim) automatically to identify (cost/ revenue?) pareto fronts thus allowing the user to compare a “good” design vs. another “good” one, and not e.g. a badly adjusted Flettner rotor vs. a perfectly tuned wing sail.

More accurate modelling is being achieved via:

- Incorporation of DES and AMI from research investigation into the ‘design process’ CFD to better resolve bluff body flows and the unsteady aerodynamics of large downwind AWAs;
- Extending the PPP to fully include drivetrain parameters to allow fuel consumption to be a design objective. This will include a model of propeller performance curves including impact of leeway angle and propeller and rudder interactions on powering and yaw balance, and could go as far as adding a power generation module for times when wind propulsion provides excess thrust for a given ETA.

7. CONCLUSIONS

With the North Design Suite, notably containing the Virtual Wind Tunnel, MemBrain FSI and structural analysis, and the VPP/ PPP, North Sails, Wolfson Unit and Southern Spars have been well positioned for analysing and optimizing yacht design. Recently the tools have been advanced to meet the growing need for Wind Assisted Ship Propulsion (WASP) studies. It has been discussed that, while similar, the requirements, constraints, and objectives for commercial WASP studies are considerably different from the “traditional” sailing yacht studies. Examples are the trade-off between speed (voyage time) on the one side and CAPEX, and/ or payload capacity (i.e. revenue potential) on the other. By the example of some key results from several recent DynaRig studies we showed how the North Design Suite can be used to navigate these trade-offs. In particular it was highlighted how any analysis which considers the aerodynamic performance only can supply an initial baseline for a design, but that it can not replace a full PPP study of sufficient fidelity to balance the aero and hydro forces. Only such a PPP analysis forms a viable base of a cost/ revenue analysis. The reason identified is that the real optima are largely influenced by the hydrodynamics of the hull (e.g. drag vs leeway), the efficiency map of the drive train (e.g. engine

efficiency vs power, propeller efficiency vs advance ratio) and cost models (speed vs. payload capacity). The presented results show the aero vs. hydrodynamic trade-offs in detail and give an impression how and engine model can be incorporated. A detailed engine and propeller model as well as any cost model are going to be specific to any commercial study and will be implemented in future work.

8. ACKNOWLEDGMENTS

Thanks to Gerry Dijkstra, Damon Roberts, John Brickwood and Andy Shaw for their past efforts in bringing these novel rigs to reality, and especially to Damon, John and Andy for sharing their early work, as well as their ongoing efforts in expanding this fleet under the Southern Spars brand.

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