The art of model testing: Using CFD to adapt traditional tank testing techniques to a new era of wind propelled shipping

Laura Marimon Giovannetti*, Frederik Gerhardt, Martin Kjellberg, Martin Alexandersson, Sofia Werner

* SSPA Sweden AB
Chalmers Tvärgata 10, Gothenburg, Sweden
e-mail: Laura.Marimon@sspa.se – Web page : https://www.sspa.se

ABSTRACT

Hybrid testing is an experimental technique that can be used to test ships and marine structures when both hydrodynamic and aerodynamic effects are important, for example for wind powered or wind assisted ships and sailing vessels.
SSPA is currently developing an experimental method using hybrid testing involving fan forces added to ship decks to simulate sails to assess the course keeping, seakeeping and manoeuvring performance of a wind powered ship. For conventional motor ships there are well established test methods and knowledge on how to scale the results from model to full-scale. For a wind propelled ship however, the driving force is no longer located at the propeller shaft but high above deck and at another longitudinal position that could vary with true wind angle and speed. Moreover, there is a large side force coming from the aerodynamic forces of the wingsails that needs to be counteracted with lifting surfaces underwater. The side-force and yaw moment are much more prominent than in conventional vessels. The combination of those factors will influence the manoeuvrability and course keeping, especially in waves.
Having built up the research tools for predicting and simulating the behaviour of a full-scale vessel, making the model sail in a similar way as predicted for the full-scale vessel remains a challenge because of the difference between Froude scaling and Reynolds scaling applicable for the hull and lifting surfaces respectively. Using Computational Fluid Dynamics (CFD) to understand the scale effects in model tests for a wind powered ship and developing a methodology for determining the fan parameters that correctly model the ships behaviour and performance are the key objectives of the research study. The art of model testing encompasses the need to learn from different techniques to ultimately achieve the best agreement between model tests and full-scale results in terms of accuracy, repeatability, cost, and speed. Learning from preliminary experimental tests, through studies on CFD and ultimately paving the way to new testing methodologies is the main aim of the current paper.

Introduction

In 2018 shipping accounted for around 2.89% of globally produced CO2 emissions with an estimated increase of 90% to 130% by 2050 compared to the baseline year of 2008. Such projections have placed the topic of decarbonising shipping on the forefront of the global policy making agenda. The International Maritime Organizations (IMO) reached a milestone agreement in April 2018 and aims to cut greenhouse gas emissions by at least 50% by 2050 compared to the 2008 level. To achieve this ambitious goal the international community is examining various measures to enhance the energy efficiency of the maritime transport sector. One area of significant interest is the use of wind assisted ship propulsion (WASP). Several WASP-concepts are currently being developed or re-discovered. Such modern technologies range from "Flettner-rotors" over kites and suction sails to rigid sails that resemble vertical aircraft wings (WASP Report D 5.B, 2020).
Before this background a Swedish consortium, consisting of Wallenius Marine (industry), KTH Royal Institute of Technology (university) and SSPA Sweden AB (research institute), is working on a technically and commercially viable concept for the world largest sailing ship. This "Wind Powered Car Carrier" concept, called *Oceanbird*,(Figure 1) will have five 80-metre-high wing sails targeting emission reductions in the order of 90%.

Figure 1. The Oceanbird concept

When studying the seakeeping and manoeuvring performance of such a sailing ship it is necessary to account for the sail forces. Reasons for this include:

- Sails will change the manoeuvring characteristics
- If the sails are included (or modelled) manoeuvres like tacking and jibing or crash stops can be studied experimentally.
- For a constant ship speed, the thrust from the sails will unload the propeller. This reduces the suction on the aftbody (decrease in thrust deduction factor). Such effects need to be taken into account in a power prediction.
- Aerodynamic damping and inertia of the sails affect ship motions directly and added resistance in waves indirectly. An understanding of these effects is required to make power predictions

While seakeeping and manoeuvring tests are very common for conventional cargo vessels, relatively little has been published on such tests for commercial sailing ships. Instead, one has to look at the field of yacht design to find relevant information. As discussed by Eggers seakeeping and manoeuvring of yachts can be studied during "free sailing" tests, be it in model or full-scale (Eggers, et al., 2012).

Several attempts to conduct full-scale tests with sailing yachts have been reported ((Binns, et al., 2008); (Clark, 2014); (Day, et al., 2002); (Masuyama & Fukasawa, 2011); (Masuyama, et al., 1993); (Milgram, et al., 1993)). During such full-scale tests one usually faces the challenge of accurately measuring environmental conditions like wave heights and true wind speed.

Free sailing tests with models of yachts are relatively rare. The main difficulty here lies in the application of the aerodynamic forces from the sails. Equipping the model with scaled-down sails and using fans to blow wind over them is beset by a number of problems. Firstly, it is difficult to create good-quality uniform air flow in a model testing basin. Secondly, scale effects are very difficult to handle in such an approach. The hydrodynamic forces require Froude scaling whereas the aerodynamic forces are mainly Reynolds number dependent. Achieving similitude for both in the same experiment is next to impossible. Nevertheless, such an approach has recently been taken. As reported by Eggers (Eggers & Kisjes, 2019) a makeshift wind tunnel was installed under the carriage of a seakeeping basin. Results showed that the measurements were contaminated by aerodynamic blockage effects from the model and that the flow quality was poor.

Another technique to apply the sail forces is to tow the model at the sail centre of effort (Eggers, 2018). It is, however, uncertain how the towline interacts with the model, especially in waves and during quick changes of direction.

A third solution is to propel the model by means of an airscrew/fan mounted on a short mast. This was reported to work well for a sailing yacht in calm water as well as in waves (Gauvain, 2019). Tsukada et al. (Tsukada, et al., 2017) report on a similar method to study wind loads on conventionally propelled cargo ship. Here multiple fans are used to simulate win forces (drag) acting on the superstructure of conventionally propelled merchant vessels.

It is this "fan-propulsion" method that was used to study the seakeeping and manoeuvring behaviour of the ship from Figure 1. To this end a 5-metre long model of *Oceanbird* was equipped with two fans that simulate the wingsails of the full-scale ship, see Figure 2.

Figure 2: wave test5s with a model of Oceanbird. Note that the wing sails have been replaced by fans/airscrews.

The target values (magnitude and direction) of the sail forces come from an in-house VPP and are generated by adjusting azimuth angle and *rpm* of each fan individually. This makes it possible to produce the desired combination of driving force, side force, and yaw moment.

Such an "hybrid testing" approach can produce high-quality results but poses one major challenge: How to scale the aerodynamic side forces (from the sails) in comparison to the hydrodynamic forces from the rudders and appendages? To achieve similitude of wave-induce forces during seakeeping tests the model-speed needs to be Froude-scaled. This results in Reynolds numbers of the appendages that are usually two orders of magnitude smaller than the full-scale values. To make matters worse the full-scale values, $Re \approx 40 \cdot 10^6$, are supercritical (i.e. above the value of $\mathrm{Re} \approx 1 \cdot 10^6$ where lift and drag characteristics of lifting surfaces become *Re*-independent) whereas the model rudders operate at approximately $Re \approx 0.16 \cdot 10^6$, i.e. in a range where lift and drag drastically change their behaviour (Hoerner, 1965). As a result of this "Reynolds-number mismatch" it can be expected that, at identical rudder angels, the model rudder will create a side force that is lower than the one of its full-scale counterpart (Schmitz, 1967).

In the first part of this paper, these scale effects on the rudders are examined in detail using RANS CFD simulations, in both towed (i.e. sailing) and propelled (motoring) condition. The second part of the paper then discusses ways to over-come or reduce these scale effect in model tests. Figure 3 illustrates a number of strategies how the above "mismatch" of side forces can be overcome. In the current paper we will investigate the "green" approach shown on the RHS, i.e. we will present a methodology to decrease the aerodynamic side force from the fan to compensate for the reduced side force from the rudder.

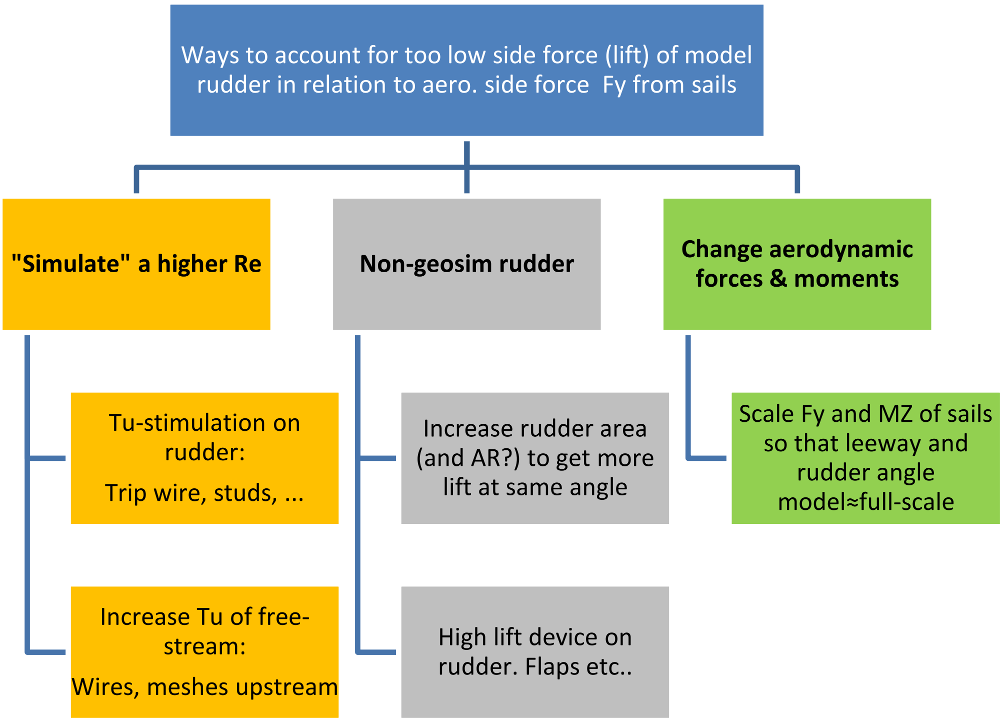

Figure 3: Strategies to overcome the scaling differences.

Experimental methodology

The experiments described in this paper were carried out using the hybrid-testing technique explained above, see also (Gerhardt & Santen, 2021).
The ship model was manufactured from the plastic foam material Divinycell and coated and painted.
The model is equipped with a conventional two-propeller open shaft propulsion system and twin rudders as well as fans that simulate the sail forces, see Figure 2.
The full scale sail plan centre of effort is located about 30 m above deck. Because of the limited vertical clearance between the model and the carriage of the test facility, the masts of the fans had to be relatively short. The resulting error in heeling moment and angle was estimated and found to be negligible because of the large initial stability of the hull.
All tests were carried out in SSPA's Maritime Dynamics Laboratory (MDL, Figure 2). This facility is purpose-build for manoeuvring and seakeeping tests and has a basin with the dimensions 88 m x 39 m and a maximum water depth of 3 m. A multi-motion carriage for model control and data acquisition spans the width of the basin. During a typical free-sailing test the model is accelerated by the carriage and, at the right speed, released from it. The model then continues self-propelled and autopilot-controlled in the desired direction and at the desired (Froude-scaled) speed.

Figure 4 shows the coordinate system used for evaluation the experiments.

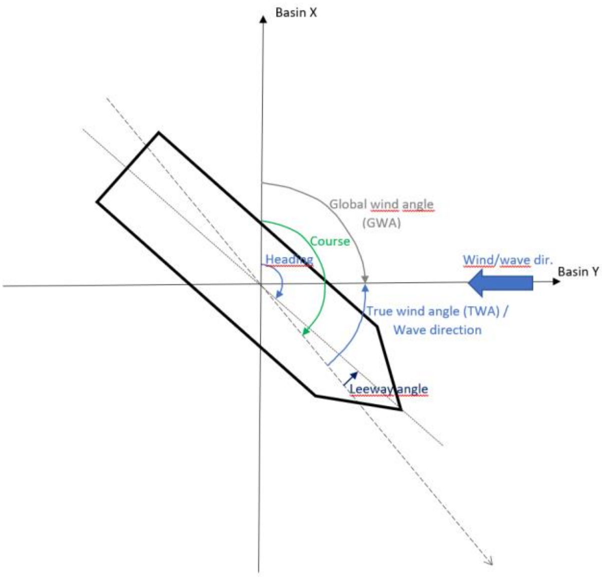

Figure 4: SSPA experimental test in Marine Dynamics Laboratory (MDL) coordinate system.

Numerical methodology

The numerical methodology has been developed to optimise the Virtual Captive Test (VCT) capacities. Its robustness has already been described by (Marimon Giovannetti, et al., 2021).
The results from the VCT, in the purpose of this study, are used for input to VPP simulations as well as time domain manoeuvring simulation to compare to the MDL results. For the VPP to solve the equilibrium equations, the hydrodynamic forces and moments acting on the underwater surface of the hull and appendages are solved for an extended test matrix that simulates a large number of inflow conditions and different scales by the ship hydrodynamics SHIPFLOW solver.
This research not only focuses on the creation of a VCT and the possibility of using the CFD results as a base for a consistent VPP and manoeuvring simulations, but focus has also been applied to assess the influence of scaling effects, choosing a large range of scales and powering methods to be able to describe the flow phenomena happening to the ship or model.
The numerically investigated conditions only cover Froude Number (Fn) of 0.137 and a specific Reynolds number (*Re*) range for the rudders from $1.31x10^5$ and $3.96x10^7$. This range spans from a laminar to turbulent region for what concerns the flow around the rudders. For the purpose of this research only the underwater components of forces and moments of the ship are considered from the RANS simulations with a condition of symmetry plane at the free-surface. However, the free-surface and the corresponding effects are simulated with a three-dimensional potential-flow Rankine-source panel method, when analysing the resistance of the ship, and the total ship resistance is compared to the measured one.

Within SHIPFLOW the Finite Volume Method (FVM) discretisation solver XCHAP has been selected to solve the RANS partial differential equations. With the FVM the flow domain is discretised by a collection of grids. In SHIPFLOW, the grids are only structured, therefore arranged in a regular pattern. The current research solves a hull completed with appendages, therefore overlapping grids are present. The fluid domain and the underwater part of the hull are represented by a H-O structured grid topology. The appendages, such as the rudders, are represented by a O-O grid topology. In the overlapping grid, the appendages are treated as separate blocks of component grids. The component grids are fitted to the body and then stretched outwards toward the fluid domain, keeping the specified y+ value. The target y+ value for every simulation is specified as 0.5, fully resolving the boundary layer around the hull and appendages, key aspect for the scaling effects simulations. An example of overlapping grids can be seen in Figure 5.
The SST k-ω turbulence model is used in the simulations.
All the simulations are performed with a mesh of approximately 20-25 million cells performed on a Linux Intel(R) Xeon(R) Gold 6142 CPU @ 2.60HHz (32 CPUs), 192 GB RAM. Using 32 cores and depending on the inflow direction the simulations take approximately 7-15 hours for a fully converged solution.

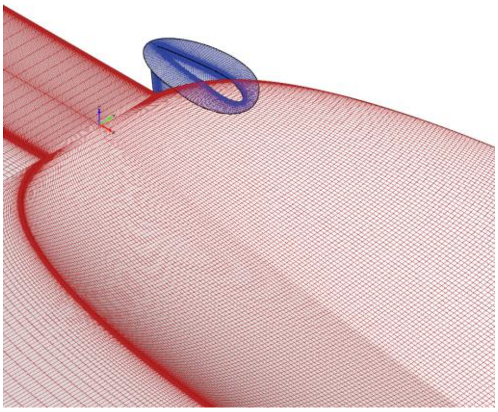

Figure 5: Example of overlapping grid between hull (H-O topology in red) and rudder (O-O topology in blue).

Assessment of scaling in CFD

The current research investigates the effects acting on a wind powered ship sailing at leeway and with set rudder angle.
The total force on such a vessel can be written as:

$$C_T = C_F + C_V + C_W + C_\lambda + C_\delta$$

Where C_λ is the additional force associated with leeway and C_δ is the additional force associated with rudder angle. These components will show some dependency on both Reynolds number and Froude number (Bradbury, 1985).
If the flow separation position changes with Reynolds number this component can be expected to show a Reynolds number scale effect: this is likely to be small over a range of Re if, either the flow separation patterns can be shown to be virtually unchanged over this range, or the flow separation positions can be contrived to remain unchanged over this range (Bradbury, 1985).
These components can also be expected to show a Froude number dependency, as there will be asymmetric pressure forces associated with the asymmetric surface wave pattern. However, from towing tank tests it was concluded that the effect of wave making resistance is not influenced by leeway angle for Froude numbers up to 0.2 and leeway angles up to 15 deg (Bradbury, 1985).
The CFD results presented herein only measure the non-wave making part of the forces associated with the underwater body for both leeway and rudder angle at Froude number of 0.137.
From Figure 6 it is possible to see how the lift produced by the rudders in a Virtual Captive Tests (VCT) are affected both by rudder and leeway angle. Even at zero leeway angle however, the geometry of the aft body and the upwash from the flow over the rudders, shows that the rudders will be generating different side forces for the same set rudder angle. The complexity of the flow around the aft body therefore shows the importance of capturing the correct flow behaviour.

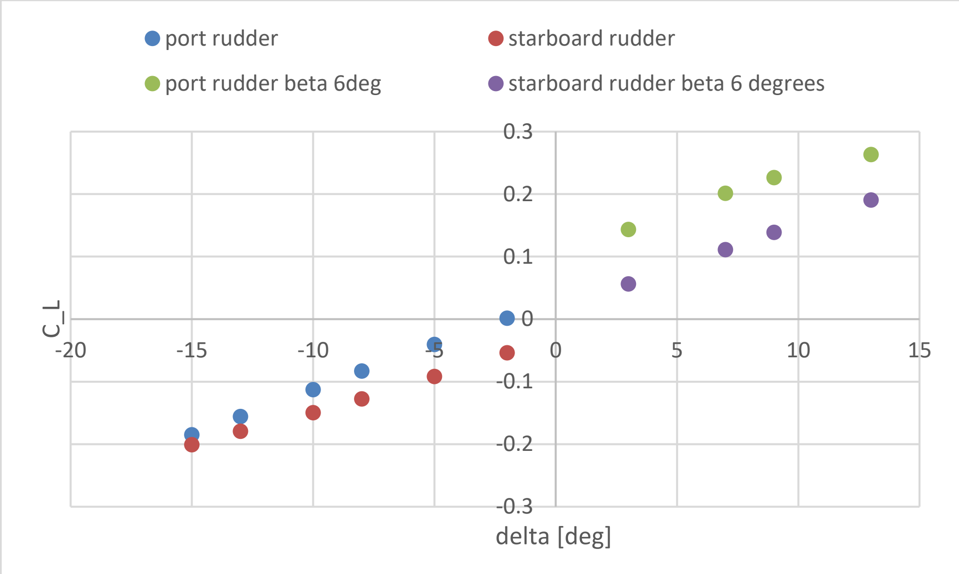

Figure 6: Lift coefficient produced by each of the two rudders over rudder angle (δ) for a leeway (β) of zero and six degrees for MDL scale – scale factor 41.2.

When analysing Figure 7 the first scaling effects are evident in the lift coefficient. The only parameter changed during the CFD simulations, as discussed in the above sections, is the scaling factor, so the flow behaviour and the boundary layer growth are responsible for the change in lift coefficient.

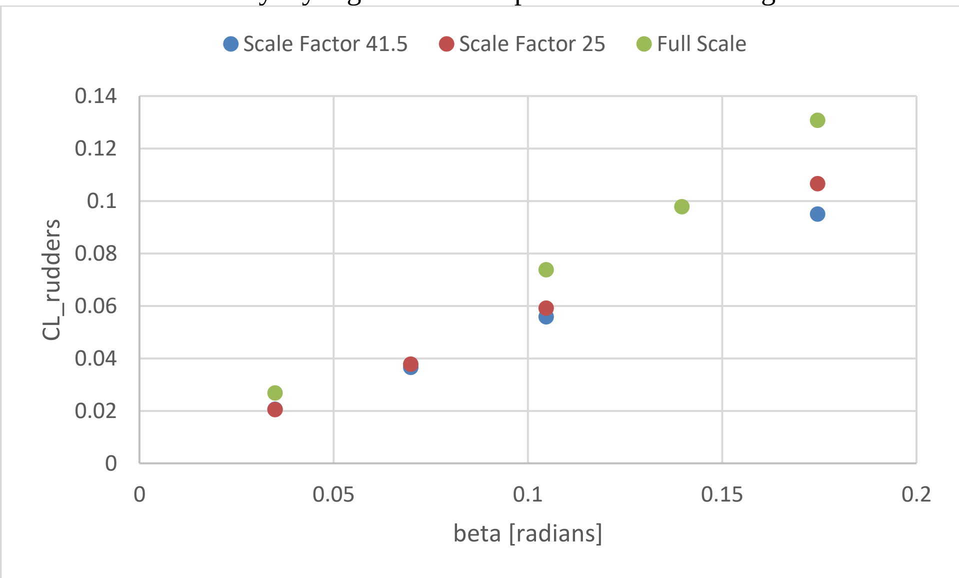

Figure 7: Lift coefficient produced by the two rudders over leeway angle for different scales, MDL scale (scale factor 41.2), towing tank scale (scale factor 25) and full scale.

This can be explained investigating the velocity profiles (Figure 8) and the skin friction coefficient (Figure 9) and relating it to the Reynolds number difference between the full scale and the smallest scale tested (scale factor of 45), see Figure 10.
Analysing those figures, it is possible to see that the boundary layer changes with the different flow regimes, holding a y+ target of 0.5.

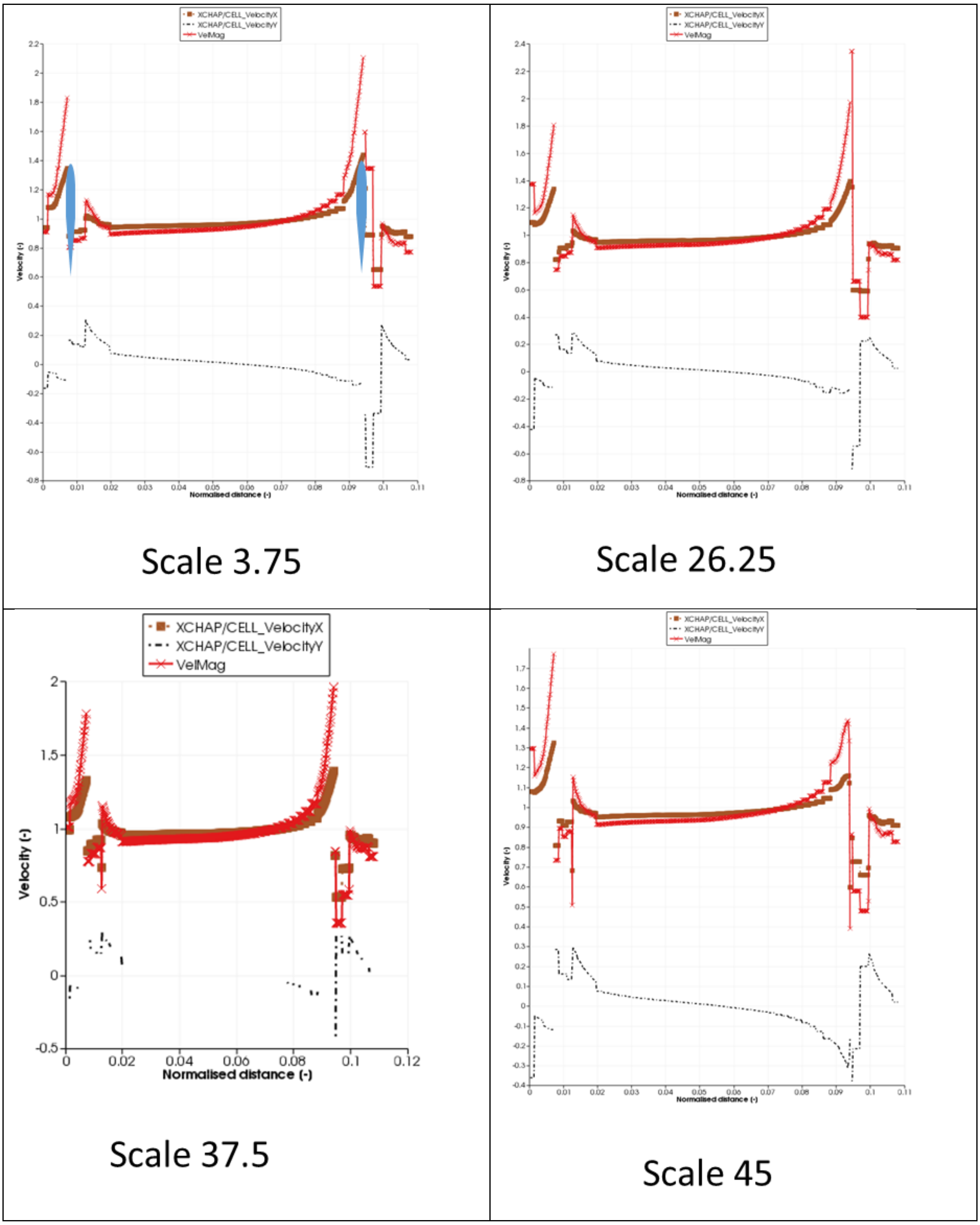

Figure 8: Velocity in x, y and magnitude profile for a line spanning the CFD domain in the y-direction for different scale factors. The location of the rudders can be seen in the picture representing Scale 3.75.

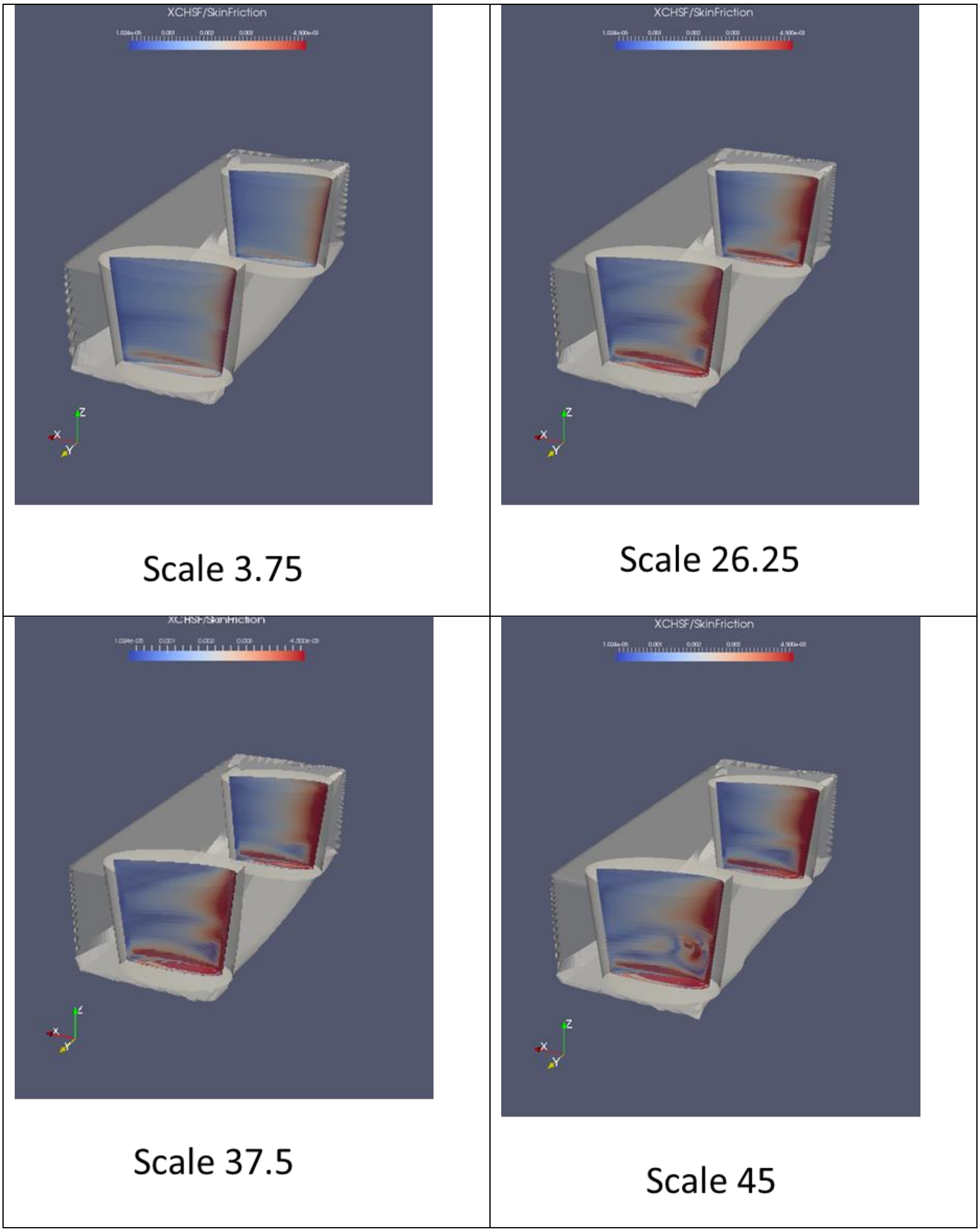

Figure 9: Skin friction coefficient for different scale factors. Starboard rudder on bottom of the pictures and port rudder on top.

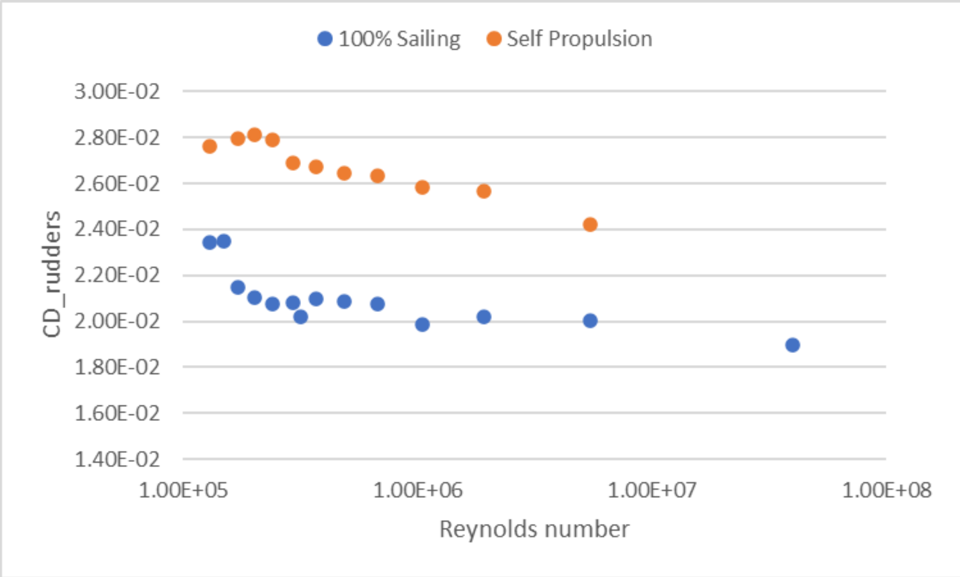

Figure 10: Drag coefficient for the rudders over Reynolds number from scaling factor of 45 to full scale for self-propulsion and 100% sailing conditions.

As opposed to a conventional ship, the rudders of the wind powered ship are not affected by the accelerated flow from the propellers, when fully sailing. As the propeller race effectively, both increase the flow velocity locally and change the turbulence and flow direction, it is interesting to study how absence of the propellers influences on the scale effects. Therefore, a range of simulations in self-propulsion modes were performed, as seen in Figure 11. Investigating the lift coefficient, the self-propulsion cases seem to become closer to the full-scale values at larger scale factors. Another interesting observation is that the scale effects are not linear with rudder angles, it is possible indeed to see how the two trendlines fitted to the full-scale and MDL scale results diverge for the larger rudder angles.

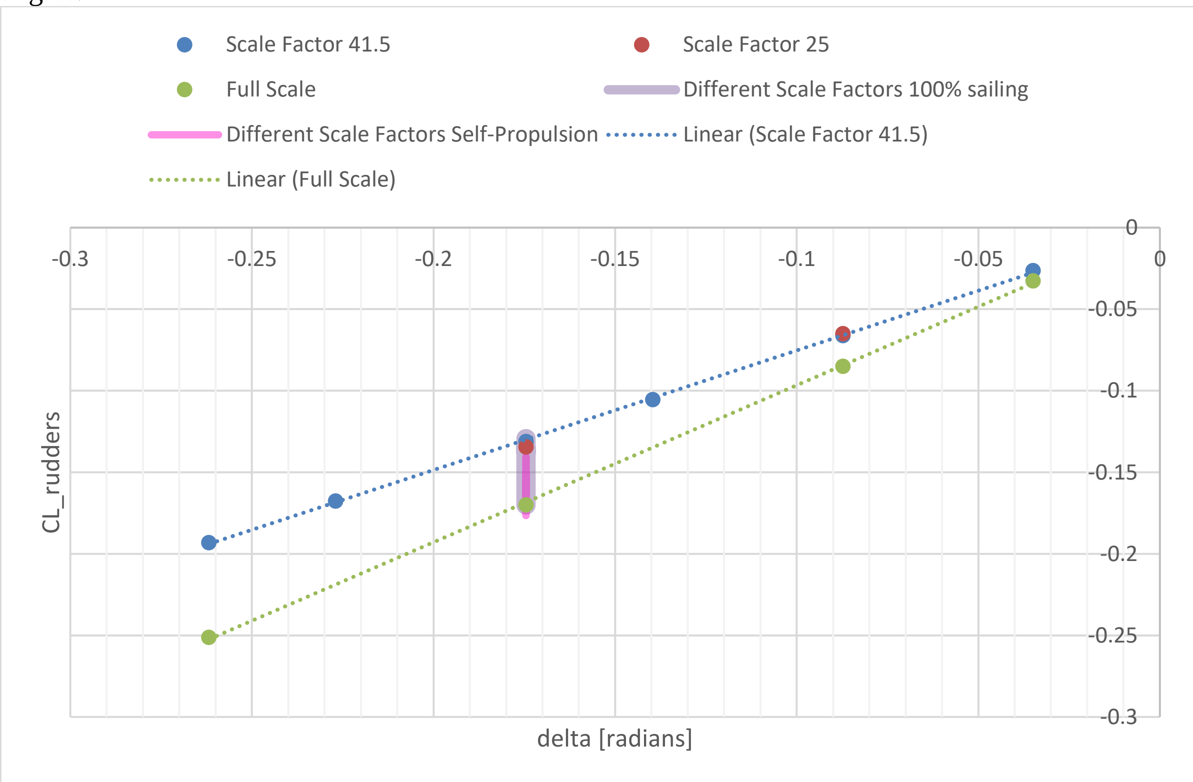

Figure 11: Lift coefficient over rudder angle for different scale factors for both "100% sailing conditions" and self-propulsion modes.

The benefits observed in the lift coefficient-only scenario, where the self-propulsion seems to improve the results for small-scale rudders, are not however transferrable to the lift to drag ratio (or drag coefficient), see Figure 12. Indeed, the change of the boundary layer and skin friction given by the self-propulsion mode entails a larger drag (as identified in Figure 10).

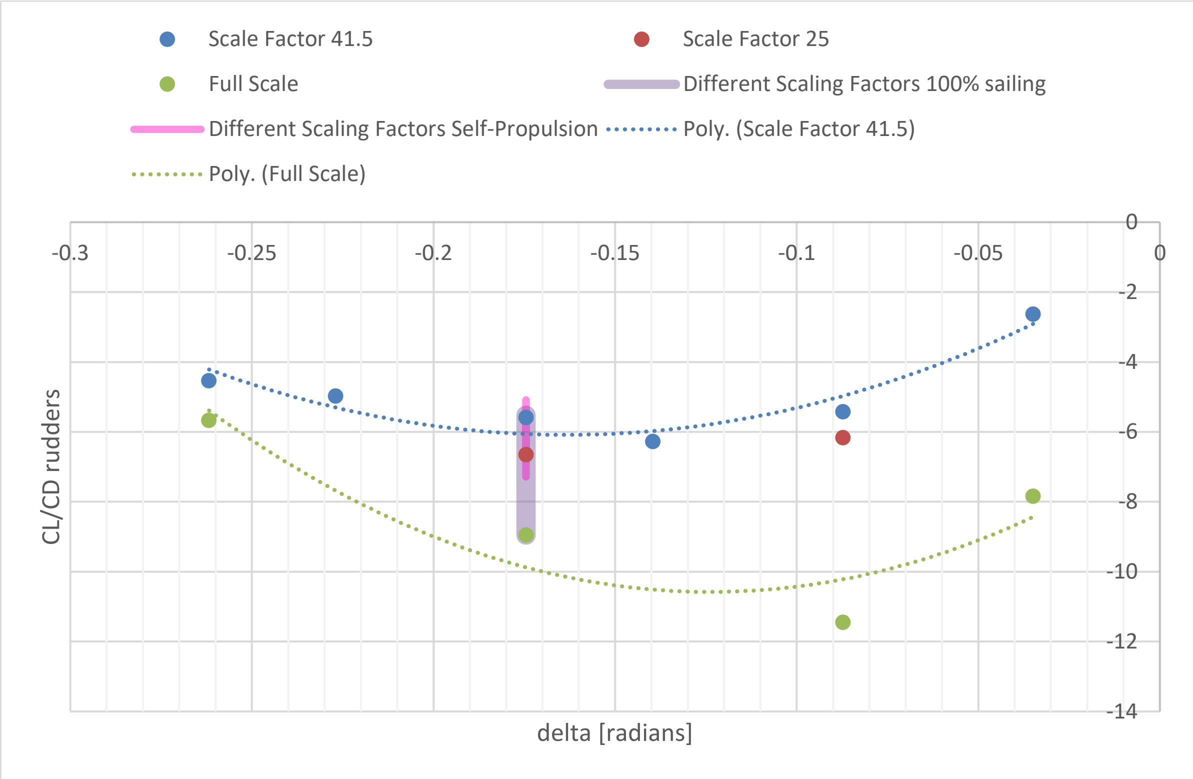

Figure 12: Lift to drag coefficient ratio over rudder angles for different scaling and propulsion systems.

Figure 13 finally shows a comparison of the quasi-static VPP rudder angles with inputs from the CFD based VCT in full and model scales. Whilst the polar for speeds and leeway angles compare well, the rudder polar shows the importance of understanding Reynolds scaling for lifting surfaces.

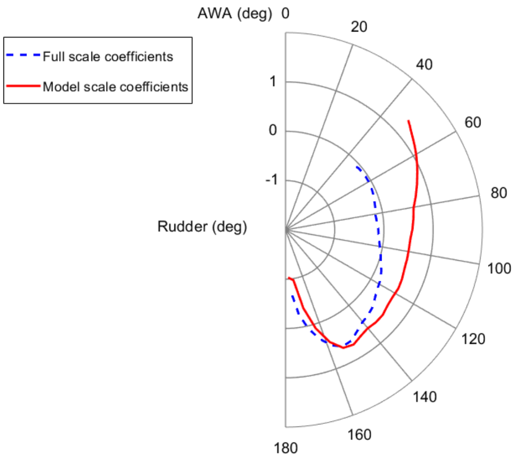

Figure 13: VPP rudder angle polar for full-scale and model scale (scale factor 41.5) hydrodynamic derivatives coefficients.

The art of model testing

The sections above illustrated the presence of scale effect on the rudder forces. In manoeuvring model tests, these effects may lead to unreasonable behaviour such as poor steering ability and large rudder angles. Several approaches to handle this problem was described earlier in the Introduction. In this section, one of the suggested approaches; to change the aerodynamic forces and moments, is discussed and tested in the manoeuvre and seakeeping basin.

As described earlier, the wings are replaced by two fans that provide thrust and side-force. Due to the scale effects, the forces that the fans should generate cannot be determined by scaling down the wing aerodynamic forces directly. Instead, the following methodology is used:

1. The fan thrust force, F_{XM} , is scaled so that the target model speed is achieved.

2. The fan side force, F_{YM}, is then scaled using the same scale factor as F_{XM} times an additional scale factor, such that the rudder performance as in full-scale.

In order to determine a suitable scale factor for F_{YM}, the expected full-scale performance is firstly simulated using a VPP based on hydrodynamic derivatives from *full-scale* CFD and an aerodynamic model of the wing sails. The same is repeated but using *model scale* hydrodynamic derivatives for the VPP input. The results in Figure 14 shows the effect of rudder angle as a response to sail Fx/Fy, virtually a variation of wind conditions. The black line represents the full-scale performance, derived with the VPP based on full-scale hydrodynamics. The red curve shows the VPP-results based on model scale hydrodynamics, when F_{YM} is scaled with the same factor as F_{XM}, which leads to excessive rudder angles. By applying other scaling factors to the F_{YM}, the rudder angles are approaching the full-scale predictions, and scale factor 0.5 gives the closest agreement.

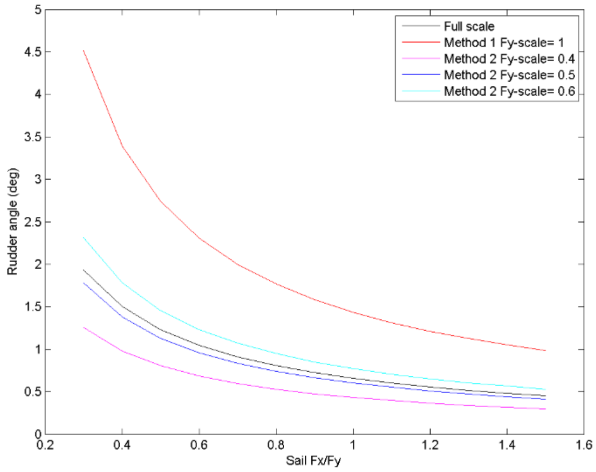

Figure 14: Rudder angle over fan forces for different Fy scaling factors. Computed with VPP.

The methodology is now demonstrated using model test for one selected wind condition. At full-scale the rudder angle was predicted to be 2 degrees and at model scale the VPP prediction resulted in a rudder angle of 4.5 degrees (Figure 15). The fans forces in the model test were set as described above and the rudders adjusted automatically using an auto-pilot to achieve a steady course, i.e. close to static conditions. If no additional scaling of the F_{YM}, was applied, model rudder angles of 6.5 degrees gave a steady course, i.e much larger than the one predicted for a full scale (Test A in Figure 15). By applying the additional scale factor 0.5 of the F_{YM}, the resulting rudder angles where much closer to the full-scale predictions (Test B in Figure 15). The yaw moment can be scaled in a similar approach.
The results show that it is possible to overcome or reduce scale effects related to rudder forces by adjusting the scaling of the aerodynamic forces.However, more research is required to confirm the strategy in various conditions.

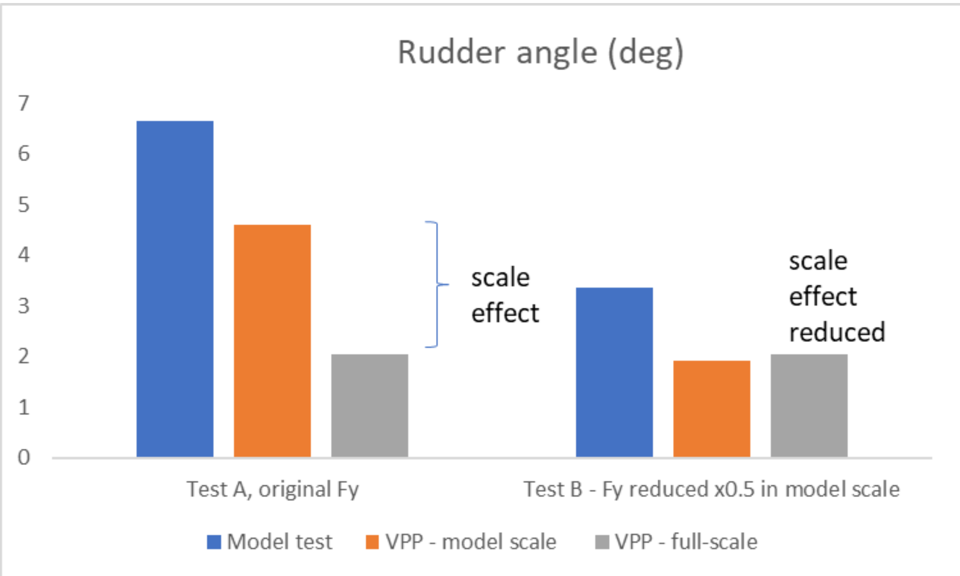

Figure 15: Rudder angle in degrees and the effect of reducing the model scale Fy.

The art of model testing lies in understanding where the differences may arise and how to tackle the changes needed to be able to correctly predict what will happen in full-scale. Learning from physical model-scale testing with the aid from CFD simulations can show how those techniques can coexist and gain from each other to ultimately better understand the behaviour of real seagoing vessels.

Conclusions

The paper describes the problems arising with lifting surfaces when using Froude scaling during manoeuvring and seakeeping model test of wind propelled ships. A range of CFD simulations was conducted specifically to assess the Reynolds scaling effects on a fully appended ship at different scale factors. The effects on boundary layer growth and skin friction coefficient are presented and the resulting lift and drag coefficients are compared.

Assessing a wind powered ship exaggerates those differences as the flow over the rudders is no longer accelerated by the propellers. However, it was shown that, whilst the lift coefficient gains accuracy with operational propellers, the lift to drag ratio or the drag coefficient is actually further away from the full-scale ship.

The complex flow that results from bending around the hull and in the vicinity of the shafts and brackets, including the upwash from the rudders, leads to a large number of variables that need to be understood.

Using CFD to study the rudder scale effects and using CFD based VPP simulations to improve a model testing technique was shown to be a fruitful way to combine CFD and EFD methods. The numerical simulations revealed how the aerodynamic side force in the model tests could be scaled in order to achieve a full-scale like manoeuvring behaviour. The findings will be important for the assessment of safety and performance of wind powered ships in the new era of zero-emission shipping.

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