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WIND ASSISTED SHIP DESIGN ANALYSIS AND OPERATIONAL CONSTRAINTS

R Eggers, and **G Gaillarde,** Maritime Research Institute Netherlands (MARIN), The Netherlands

SUMMARY

Wind assisted ship propulsion is a subject of research at MARIN anticipating and supporting a wider uptake in the shipping industry. This paper discusses the possible transformation of the industry and the existing and upcoming research methods to support successful projects. Studies to predict fuel/emission savings are quite common by now and should be on a path of standardisation. A description is given for three different methodologies that can be used depending on the development stage of a new project. Whereas studies are common in this field, there is certainly a need to define what modelling needs to be done. Research into operational constraints when in transit with a wind assisted ship is hardly done so far. The authors propose a few relevant topics that should be dealt with.

1. INTRODUCTION

Climate change has drastically changed the societal pressure and political decisions on energy supply. Possible new scenarios can be written today, as wind of changes are blowing in the energy supply and transport. While each of us likes to believe that sustainable solutions are the only future, it is our common responsibility in the maritime industry, to make it happen. Upcoming technical challenges are great, promises are high and the worst scenario would be to disappoint the maritime sector with solutions not delivering on their expectations. It is then of highest importance to prepare sufficient research investments and cooperate at development and implementation level to make it happen. Lessons can be learnt from the current development of wind turbine energy generation, a high-growth industry which goes from land-based to sea at this moment. They have reached in a record time a decrease in costs to make it a viable industry.

MARIN, as a knowledge contributor for maritime research and innovation, is ready to assist in reaching the necessary milestones for sustainable sea transport. Part of the current developments and upcoming challenges are presented hereafter.

2. BACKGROUND AND AMBITIONS

2.1 WIND AS AN ENERGY SOURCE

Wind is intermittent and velocities constantly change. It often isn't available when needed most. Above all, it requires significant investment to transform into energy without a short term return. Those are the strongest arguments to abandon any development on use of wind as energy resource.

Despite those constraints, engineering solutions are being developed to capture such energy, distribute it where needed and likely make it profitable.

Wind is set to be the backbone of the future power system, meeting almost 30% of Europe's power demand by 2030, according to the International Energy Agency IEA. There is no doubt that there is energy in the air. The challenge remains to capture it.

Going from land-based to sea-based will allow to capture even more wind. Offshore Wind Energy is growing strongly in many countries. An earlier study from 2015 (Mast, Rawlinson & Sixtenssion, 2015) predicted significant developments, as shown in Figure 1. The expected capacity in 2030 was 65 GW.

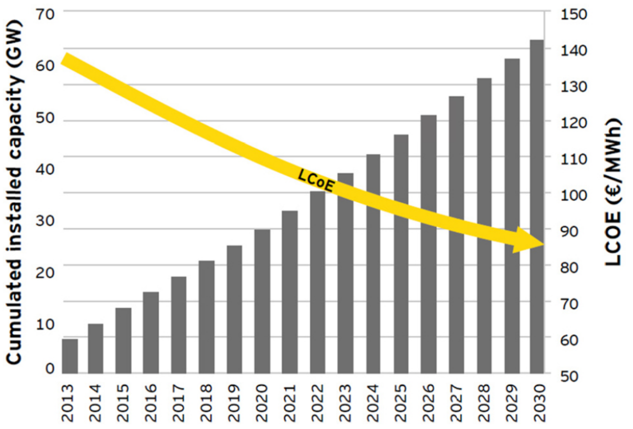

Figure 1: Cumulated Offshore Wind capacity

But things are changing fast, in particular thanks to the Paris agreement. It is expected today that offshore wind in the Netherlands could provide up to 50% of the total electric energy usage in 2030 (Tki Wind Op Zee, 2017).

At European level, offshore wind is expected to provide a total of 230 GigaWatt by the horizon 2030-2050, from which possibly 180 GW only in the North Sea. This is by far higher than the scenarios written in 2015.

2.2 WIND THRUST FOR SHPPING

Those remarks are far from the direct need in transport and shipping, but it shows that with a combined action of visionary governments, smart engineering and daring investors, a transition is possible in terms of energy supply. We see today concepts and products rising to transform wind into thrust onboard ships. Without doubting that the energy is available, the challenge is to develop designs and systems to capture such energy, without compromising the operations of the vessels.

A major contribution by wind as energy for sea transportation is also put forward by different studies, such as presented by SHELL in its strategic document: "2050: Fossil or sustainable" as shown in Figure 2. A study be CE Delft (Neilssen, et al, 2016) as commissioned by the European Commission also highlights the high potential of wind propulsion on ships (along with barriers that are to be overcome).

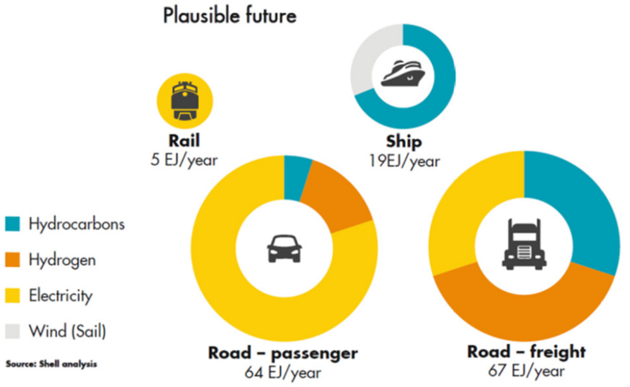

Figure 2: Possible energy supply per transport type *(source: SHELL analysis)*

Two approaches are going to prevail in the development of wind assistance:

- A refit market, where existing ship units will be equipped with standardised wings. They will probably not produce the most efficient solution in terms of wind propulsion but at least will be a low risk for the ship owners to "try" it. Lease options of portable systems or refit installations will appear.
- A new built market, where the ship design will include at concept level this mode of propulsion. At this moment, wind units are added to existing designs, but they will be much better integrated into the hull and superstructure when the ship is designed for it, also in terms of aerodynamics.

An additional development will certainly be on the supplier side. At this moment, one system is dominant on the market, but more research will likely introduce new systems and new players on the market.

3. METHODOLOGY TO EVALUATE WIND ENERGY PERFORMANCE IN SEA TRANSPORT

While the amount of prototypes to capture wind energy onboard ships is still limited, the feasibility studies to prove its potential have been numerous in the past years. All parties claim that today demonstrators must come to upscale those solutions.

No doubt about it, but we must also realise that demonstrators that will not meet the expectations will also jeopardise the development of this additional propulsion system. It is then of major importance to follow prescribed steps and make proper evaluation which is shared within the industry.

The steps that may be taken are herewith highlighted. These steps were followed in the INTERREG projects Wind Hybrid Coaster MariTIM (Maritim, 2016, Eggers, 2016) , SAIL (Schwarz-Röhr, 2015) and small research for the industry by MARIN. The example figures in this paper also come from these projects. It is further noted that MARIN is in the process to start a Joint Industry Project "WInd Ship Propulsion", "WiSP JIP" (MARIN), which, amongst others, intends to cover this topic.

3.1 WIND AVAILABILITY

The first stage to consider wind assisted ship propulsion may be at an owner owner/operator when no design is yet available, but only some intended routes or areas. Even without that design there are already relevant considerations. As wind assistance requires wind, a first analysis can be done on the wind speeds and angles over deck that may be expected. Hindcast weather databases can be sampled for the specific route. As shown in Figure 3 the results show the frequency of occurrence of wind angles and speeds. If the results show that the apparent wind on deck is only head wind, then it may be decided that the route is not suitable for wind assistance or the ship speed is too high. Assuming that this is not the case, the predominant wind angles and wind speeds already give a first indication which type of devices may be most suitable and which dimension may be appropriate. Some devices are better in stern quartering wind while other are more efficient in bow quartering wind.

3.2 STATISTICAL PERFORMANCE PREDICTION ON A GIVEN ROUTE

If the first stage was successful and some likely alternatives for the wind propulsion are available, then it is time for the second step: a statistical performance prediction. The same wind data as from stage 1 is used. However, at this point it is combined with the performance of the wind propulsion. The latter is obtained in a "PPP", Power Prediction Program (after the common acronym "VPP", Velocity Prediction program for sail boats. The prediction shows the power (or propeller thrust as in Figure 4) that is required to maintain a fixed ship speed for certain wind angles and velocities. By multiplying the required power with the wind probability for the same wind conditions, one arrives to the average (reduced) power required to maintain speed.

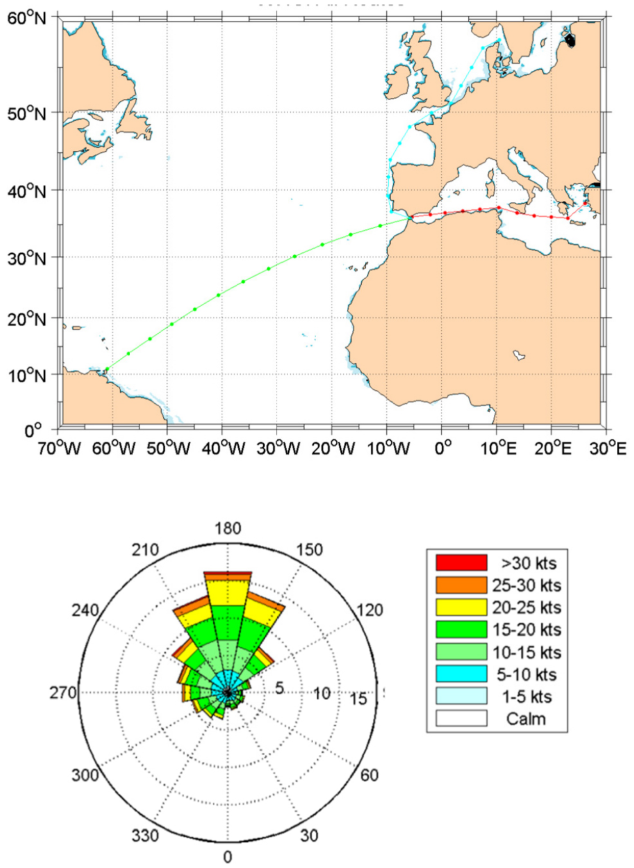

Figure 3: Evaluation of encountered wind conditions on a given route

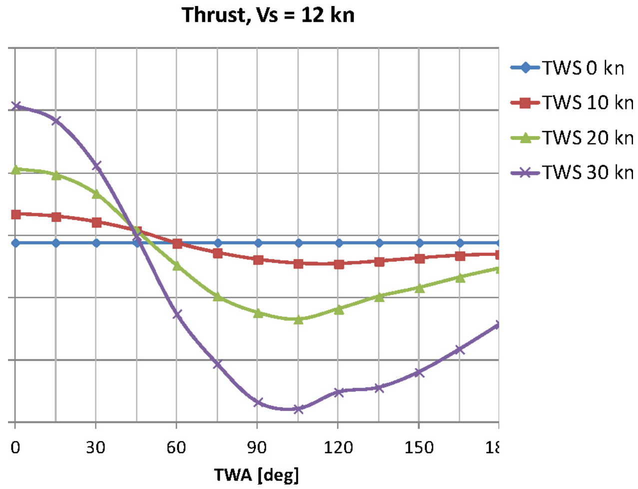

Figure 4: Required thrust as function of True Wind Angle (TWA) and True Wind Speed (TWS) for a fixed ship speed

EEDI implementation (IMO MEPC.1/Circ 815)

In its most simplest form this prediction could be based only on the wind propulsor. This is simple to obtain if wind coefficients are available (or generated) and only the settings (trim, rotor rotation rate, aspiration …) is optimized. This is actually the way in which one can already demonstrate the savings in CO_2 emissions within the EEDI framework in the form of reduction of the EEDI. IMO provided the required calculation method in MEPC.1/Circ.815. An intermediate step in this process also yields the (reduced) fuel consumption.

Even though Circ. 815 does not discuss it in detail, it is noted that accounting only for the thrust generated by the wind propulsion is rather simplistic. At the IMO level it helps to keep things simple, however based on work mainly in the Wind Hybrid Coaster and SAIL projects it is MARIN's opinion that the method is too simple to give realistic estimates to make investment decisions.

Notably the method lacks in the following areas:

- Wind thrust larger than the required propeller thrust may lead to a negative (!) EEDI
- No constraints are mentioned in the use of wind propulsors (e.g. keeping heel within a certain angle)
- An increased resistance of the hull and rudder due to the leeway and rudder angle that are required to counter the side force of the wind propulsion
- Changed (decreased) efficiency of the entire remaining propulsion train at lower loads
- Further it is not mentioned whether the interaction between devices and the superstructure should be accounted for or in general what should be the quality of the used wind propulsion forces and required power to run rotors or suction wings

At least these aspects should be considered when preparing a prediction for wind propulsion. The exact impact and relevance of each item is discussed in some publications and presentations e.g. by Leslie-Miller (2017). However, this field certainly needs further research. One effort in this respect is the "WiSP JIP" as mentioned earlier.

Design variant and balancing aero and hydro forces

This is also the time to experiment with alternatives in wind propulsion, hull form and appendages. Aside from just performance, a related topic to be addressed is the steering balance. Most modern ships, when sailing at a leeway angle have the centre of effort of the side force somewhere near or even in front of the bow. The latter can occur due to an opposing force near the aft of the ship ("Munk Moment"). However, the centre of effort on the aerodynamic forces will be positioned somewhere within the length of the vessel, more likely closer to midship. So most probably there is a difference between these locations, which means that the rudder is required to obtain yaw balance. It must be ascertained that in order to keep balance the rudder will not need to go to excessive angles as that would decrease the overall steering ability. Furthermore, the distribution of side force over hull and rudder can be optimised (by positioning the wind propulsion and by using appendages on the hull). In short, the rudder is likely to be more efficient for small side forces as with it good aspect ratio and shape it is typically an efficient lift producer. However, at larger side forces, the rudder area simply becomes too small. Lift coefficients become too large and the rudder may be operating near stall. At that point the hull will be the more efficient side force producer.

3.5 FINAL VERIFICATION IN VOYAGE SIMULATIONS

Stage three, voyages simulations, would be the last step in the process. This step is intended to verify the performance with the best modelling available. Compared to typical predictions this step may be particularly important for wind assistance because demonstrating the performance in trials or actual service is more difficult than simply the speed/power performance in calm water. It will be hard in trials/service as it depends on some many independent variables and measurements always come with other disturbances (e.g. added wave resistance that will be inevitable with some wind).

The voyage simulations should also be conducted using hindcast data for wind. This time the waves and current are also added and simulations are done without reducing the data to statistics. At this point the data is used as available from weather models, i.e. dependent on time and location.

In order to reduce statistical uncertainty, simulations should be done over a relatively long duration (e.g. 5 years) and with many individual trips (e.g. one departure per week) being conducted within that duration. If this would not be done a few lucky (or unlucky) trips could dominate the results.

Modelling of propulsion train and energy flows

Voyage simulations are also a good tool to model and then check the usage of the propulsion train. As mentioned earlier, reduction of efficiency of the propulsion train at lower loads can be checked. E.g. this can be used to decide whether a diesel-direct or more advanced installation is required. Figure 5 shows the operational conditions encountered in a schematic engine envelope of a diesel direct installation with Controllable Pitch Propeller and Combinator. This particular example shows that loads can indeed be very low.

Sankey diagrams as in Figure 6 can be very useful to understand the relevance of the wind propulsion contribution and also the changes in efficiency. The example here is for a modest wind propulsion installation with Flettner rotors. Amongst other it shows here that the average leeway induced resistance for such installations can be modest when compared to the total (even if this resistance component may be very large at specific sailing conditions).

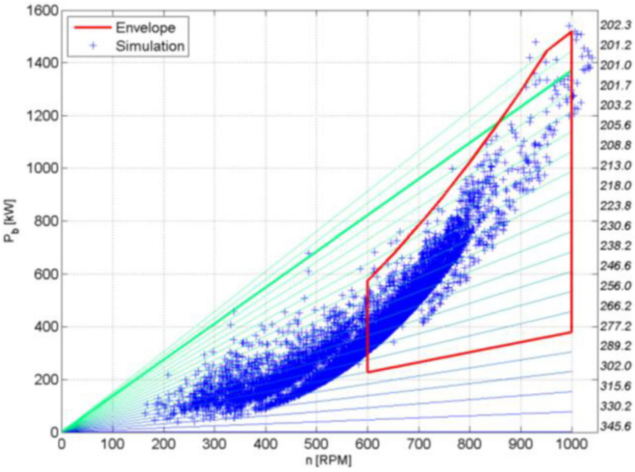

Figure 5: Engine diagram on a given route

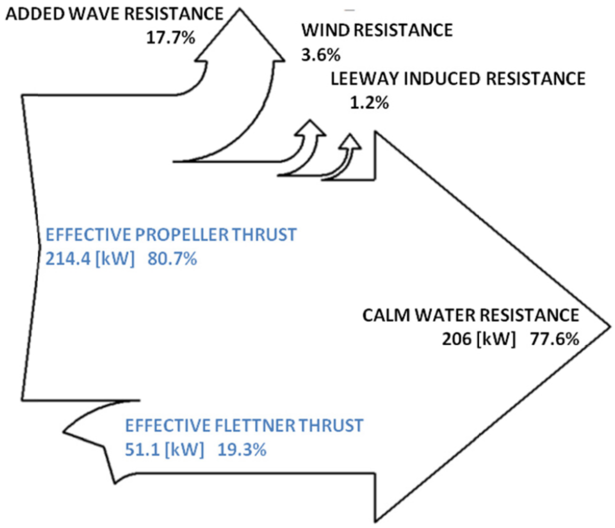

Figure 6: Average power balance at the level of thrust in service conditions

Route and speed changes and optimisation

Different than the statistical performance prediction, the voyage simulations can account for changes relative to a fixed route and speed which naturally occur due to voluntary speed loss/course changes (good seamanship and route optimisation) and involuntary speed loss (added resistance in waves). This includes sailing faster when the wind propulsion provides the majority of propulsion, which solves the problem that occurs for such in a condition in a PPP.

Thus, the merits of optimising the route and speeds for each individual trip can be demonstrated. Previous projects showed that the merits can vary greatly from route to route and from ship to ship. Previous projects at MARIN showed that re-routing was particularly interesting with variable winds from unfavourable directions for a ship with a large fraction of propulsion delivered by the wind, but not much in other cases.

Doing actual voyage simulations also allows to study the trade-off between average fuel/emissions savings and probability to arrive in time. Whereas it is perfectly possible to maintain an accurate schedule with wind assisted propulsion, the savings can be larger if some flexibility is allowed.

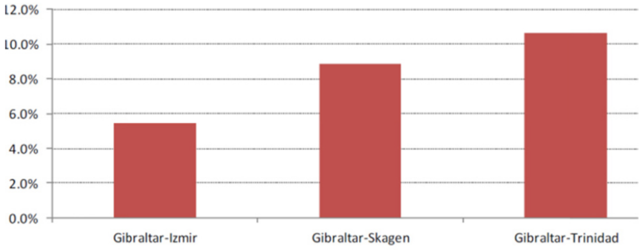

Figure 7: Fuel saving on several routes

4. CURRENT RESEARCH DEVELOPMENTS

As already mentioned previously, basic studies to determine performance for vessels with wind assisted propulsion have been numerous. However, there are many topics where further research is desired. Topics that will be addressed in the short term at MARIN are highlighted here.

4.1 DESIGN EXPLORATION

Whereas the performance of wind assisted vessels has been shown on a case by case basis, little systematic knowledge has been published about matching a wind propulsion device with a vessel (or vice versa). It is the combination of both that determines the performance. Optimisation algorithms could of course handle this as a black box. However, there are some specific tradeoffs that can be identified. Understanding these will greatly help the specification and design of ships with wind assisted ship propulsion. The following tradeoffs are under consideration:

- Wide versus deep hulls: At the same displacement a wide (shallow) hull will have a large roll stability, allowing it to be equipped with more wind propulsion capacity for the same maximum heel angle. At the same time a wide shallow hull will have a large leeway induced resistance and quite possibly also parasitic resistance. Thus, what is the “optimum” beam-to-draught ratio?
- Positioning wind propulsors (relatively) forward or aft: as mentioned earlier, the distribution of side force over hull and rudder determines the efficiency to generate side force and the steering balance.

As part of this research, efficiency of propellers in an oblique inflow condition requires revisiting past research by e.g. Gutsche (1975) with newer tools.

This research builds on a database of RANSE force calculations for a systematic series of hulls as conducted in a collaboration with Delft University of Technology, Dykstra Naval Architects and Damen Shipyards. Some of the parent hulls are shown in Figure 8.

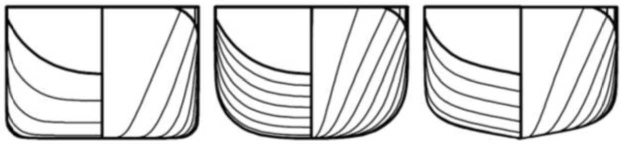

Figure 8: Example of hull form variation as already published by Van der Kolk *et al* (2017)

4.2 POSSIBLE OPERATIONAL ISSUES WHILE IN TRANSIT

A number of operational constraints for wind assisted ships while in transit have not yet received much consideration in general research and will also be part of further research at MARIN.

- The possibility to keep course in stern quartering wind and seas. Stern quartering seas, especially with wave lengths similar to the ship length and travelling at approximately the same velocity, are demanding for course keeping. When the wind is from the same direction then this is also very favourable for the wind propulsion, meaning that possibly there is hardly or no propeller thrust required. This means that the flow speed over the rudder(s) will be relatively low at a time when the highest rudder forces are required. Whether and when this really presents a problem and if it should be accounted for also in the speed-power prediction is to be investigated.
- Related to the previous item is the possibility to make manoeuvres, including avoidance of other ships. This relates directly to IMO resolution MSC 137(76) which a minimum performance in zig-zag and turning circle manoeuvres. The resolution does not state whether the performance needs to be met also with active wind propulsion. However, DNV-GL now has a draft procedure for certification of Flettner Rotors onboard vessels. There they require that the IMO rules for manoeuvring should also be complied with by ships with active wind propulsion. Thus, this should then be accounted for in the design stage.
- Finally, wind assistance will induce a heel angle if it cannot be compensated (e.g. by ballast water or roll stabilisation fins). The first question is: what is an acceptable heel angle? This will likely be different per ship type and may relate to cargo, crew and passengers. At the moment it is noted that various publications use no threshold at all while others do pick a number. If a threshold is used it tends to be 10 degrees. However, none of the studies known to the authors provided a firm basis for the selection of the

threshold value although for some ships it can really limit the achievable savings. Further, sails are known to increase roll damping. This means that aside from an increase of the (steady) heel angle, the (dynamic) roll angle due to waves may in fact decrease. An investigation of this issue and its impact on performance is to be done.

4.3 RESEARCH METHODS FOR OPERATIONAL ISSUES

The operational issues as described in the previous section may be assessed using time domain simulations. However, the required input is very detailed as it involves a lot of physics (restoring forces, damping, added mass effects) and control and this all needs to be covered in empirical models or databases. MARIN intends to not only do simulations, but to conduct "validation" scale model experiments which can then be used to compare against the simulations. The comparison will show what the way forward should be.

An example of the experimental set-up that could be used for wind assisted vessels was already applied for a few projects. Such a set-up was developed within the background research program of MARIN and was published for the first time in 2007 by Gaillarde and De Ridder *et al* (2007). Recently an improved version of this set-up was used for the AkzoNobel team in the 2017-2018 Volvo Ocean Race. In this effort a scale model of the yacht was equipped with a rig to allow a connection in the aerodynamic centre of effort. Lines were connected between this point and two individual actively controlled winches. A third winch was connected with a point on the bow to apply a small viscous model scale correction.

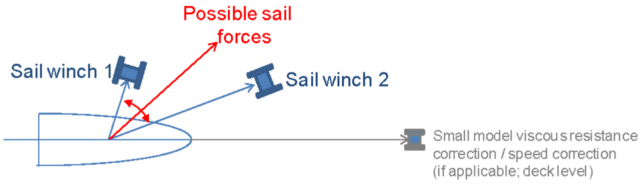

Figure 9: Top view of winch system to apply wind loads

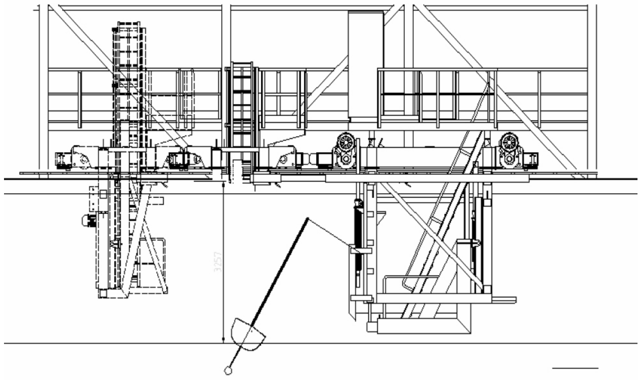

Figure 10: Front view of scale model connected to the winches on the carriage

The sail force winches were controlled to apply a continuously updated wind force. Using two winches allowed to vary the direction of the force vector between the two winches. For each test a true wind speed and wind angle relative to the longitudinal axis in the basin was defined. At each time instant, the apparent wind speed and angle were determined while accounting for the heading, leeway and speed. Based on the apparent wind angle and speed and the yacht heel and chosen sail trim settings, the force was looked up in the wind force database and applied by the winches. In addition an estimate of the aerodynamic roll damping was applied. This process was ran at each measurement time step. As far as known to the authors this set-up is unique in the world.

Figure 11: Picture of the VO65 model free running in bow quartering waves

7. CONCLUSIONS

As summarised from prior research and publications it is judged that using wind energy for ship propulsion has high potential, but both background research and applied research in projects is necessary for a bigger and successful uptake in the shipbuilding and shipping industry.

Based on MARIN experience in past projects, predictions on the performance of wind assistance ship propulsion can be done in three stages with increasing complexity and completeness:

- Stage 1: Wind availability on a route, looking at both the apparent wind angle and speed over deck as function of sailing speed
- Stage 2: A Power Performance Program (for a fixed speed) multiplied with the wind probabilities on a route. This is similar to the approach in EEDI MEPC.1/Circ.815, although the requirements in that approach are very flexible.
- Stage 3: Time accurate voyage simulations on a route. The intention in this last step is to deliver the best prediction possible, also accounting for

voluntary (re-routing and seamanship) and involuntary speed and course changes.

Whereas case studies have followed this path before, there are still open points with regard to the modelling.
Aside from pure speed-power performance, the open topics for research also concern possible operational constraints in transit.

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9. AUTHORS BIOGRAPHY

Rogier Eggers holds the position of Senior Project Manager and knowledge co-ordinator on Ships Manoeuvring at the Maritime Research Institute Netherlands. He started his career in 2008 at MARIN focusing on ship manoeuvring. Over the years he also covered seakeeping aspects. Finally, since about 5 years he is the main leader of background and applied research on wind assisted vessels at MARIN.

Guilhem Gaillarde is currently head of the Ships department at the Maritime Research Institute Netherlands. After graduating in marine engineering and naval architecture, he started his hydrodynamic career in 1998 at MARIN as Seakeeping project manager and evolved in multidisciplinary projects covering also powering and manoeuvring fields. He initiated the Natural Propulsion seminar in 2012 and is actually chairman of the Blue Forum which aims at initiating projects and discussing technical progress for sustainable marine activities and innovation. He is also a member of the RINA and of the SNAME.