SPEED TRIAL VERIFICATION FOR A WIND ASSISTED SHIP

S Werner, **J Nisbet, A Hörteborn,** SSPA Sweden AB, Sweden
R Nielsen, Scandlines, Denmark

SUMMARY

As the number of wind assistance installations in commercial shipping grows and the industry matures, the need for full-scale verification of the performance increases. Standard procedures or guidelines for conducting such full-scale trials of are still lacking. One strategy is proposed and discussed here. The method is demonstrated using a speed trial conducted with Scandlines' hybrid ferry Copenhagen equipped with a rotor sail. The trial result is extrapolated to yearly power saving using a statistical route analysis. With this approach, the result can be derived at a feasible cost, within a limited time frame and using commercially available tools and established procedures.

NOMENCLATURE

ρ_{air}	Density of air (kg/m^3)
AWA	Apparent Wind Angle (°)
AWS	Apparent Wind Speed (m/s)
C_L	Lift and drag coefficient (-)
C_D	Drag coefficient (-)
$C_{D\ rotor}$	Drag coefficient of rotor (-)
COG	Course over ground
CFD	Computational Fluid Dynamics
D	Rotor diameter (m)
DOF	Degrees of freedom
EEDI	Energy Efficiency Design Index
H	Rotor height (m)
ITTC	International Towing Tank Conference
Ps	Shaft power (kW)
Pd	Delivered power (kW)
STW	Speed through water (knots)
SOG	Speed over ground (knots)
TWA	True Wind Angle (°)
TWS	True Wind Speed (m/s)
TWS_{10m}	True Wind Speed at 10 m above sea (m/s)
VPP	Velocity prediction program
V_{ref}	Nominal ship's speed (knots)

1. INTRODUCTION

Following IMO's request to reduce green-house gas emissions from shipping [1], wind propulsion has emerged as a feasible solution. The number of cargo vessels equipped with wind assistance technology is still low but rapidly increasing. Flettner rotors are so far the most common type, with several manufacturers active on the market, but there are also other types like rigid wings, soft sails and suction wings.

The emission reduction that a wind assistance technology can offer is typically predicted at design stage using numerical or experimental tools. After installation onboard a vessel, there is for several reasons a need to verify the performance in full-scale. The ship owner may request confirmation of the expected savings. The manufacturers and designers need validation data in order to improve the design and prediction methods for future installations. The shipping community needs confirmed performance indicators to be able to compare different technologies and for fact-based investment decisions. The lack of verifiable data on the fuel savings potential is reported to be one of the key barriers for market uptake of wind assistance technology [2]. Last but not the least, authorities request trustworthy verification of energy reduction for legal indicators such as EEDI [3], and other voluntary notifications of sustainable shipping.

Apart from confirmation of the emission reductions, post-installation testing can include other aspects like safety, manoeuvrability, stability, noise and working conditions. This paper focus entirely on power consumption, which is directly linked to green-house gas emissions. The other aspects will be addressed in future work. The scope is limited to wind assistance, i.e. installations that can reduce a vessels fuel consumption when activated, and when de-activated lets the ship function as a conventional vessel.

Since the wind propulsion industry is fairly new, at least on a larger commercial scale, the community has not converged towards a standard procedure for conducting full scale verification tests. As the industry matures and the number of manufacturers and installations increases, the need for standardised methods for full scale verification grows. The present work aims to contribute to the development and harmonisation of methods for full-scale verification of wind assistance vessels. A methodology is proposed, discussed, and demonstrated for the ferry m/v Copenhagen equipped with a rotor sail shown in Figure 1.

Figure 1. m/v Copenhagen with a Norsepower rotor.

© 2021: The Royal Institution of Naval Architects

The work is a part of EU Interreg project WASP, running from 2019 to 2023. Further demonstrations for four other vessels are planned within the WASP project. While the primary aim of these five verification campaigns is to confirm the energy saving of the wind propulsion installations, they will also generate experiences and knowledge on the testing methodology and identify advantages and pitfalls of various methods and strategies.

The full-scale verification tests for wind assisted ships that have been published in recent literature can be divided in two different strategies:

- Long-term monitoring. The fuel consumption is logged using the ship's performance monitoring system and periods with and without the wind assistance are compared. This method was used to evaluate two different rotor sail installations: Viking Grace and Maersk Pelican [4].
- Short trials. Dedicated tests over less than a few hours and comparison of speed or power with the device turn on and off. This method is reported briefly for E-Ship 1 [5] and Fehn Pollux [6].

The present study employs the short trial strategy and seeks to re-use as much as possible from the existing and well recognised standards for speed-trials (ISO [7], ITTC [8]), and just modify them where it is needed to fit the purpose.

2. CASE

The RoPax ferry m/v Copenhagen (L=156.45m, B=24.6m, IMO 9587867) operates the route Gedser-Rostock. It is equipped with a 5m x 30m Norsepower rotor sail with end plate. (See ref [4] for a description of the rotor technology.) The rotor is positioned longitudinally around mid-ship, 17.2 m above design water line. The rotation speed of the rotor is set automatically by its control system, based on the measured apparent wind speed. The anemometer is positioned in the top of the signal mast over the bridge. The vessel is driven by two Azimut thrusters and a centre propeller with controllable pitch.

3. CONDUCTION OF SPEED TRIAL

3.1 SETTINGS

On March 6-7, 2021, a speed trial was performed with m/v Copenhagen with the purpose of evaluating the performance of the rotor. The Trial Team present onboard included Ship Master Captain Alan Bach, Scandlines' Naval Architect Rasmus Nielsen, and Sofia Werner, SSPA Sweden AB. The trial was planned and conducted by the Trial Team in cooperation.

The trial was conducted off Gedser in an area of sea water depth 24-25m (Figure 2.). The trial was conducted at night and therefore no visual observations of the wave height could be made. An external weather source (fcoo.dk) reported a wave height of 1 m from west. There is unsignificant tidal current in the area but a constant current from northwest was reported by the external weather provider. The true wind measured with the ship's sensors was 8-9 m/s.

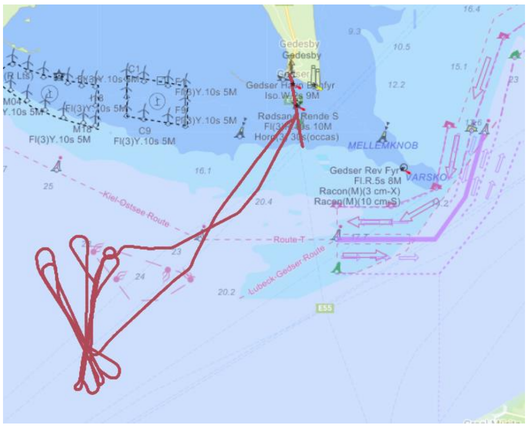

Figure 2. Trial area off Gedser

3.2 DATA ACQUISITION

The speed over ground and track were recorded from the DGPS every 5 seconds. The Azimut power and rpm were recorded every 5 seconds from the electric engine power output. Speed through water from the ship's doppler log, heading from the gyro and the rotor rate of revolution were recorded every 60 seconds. The relative wind speed and direction was measured using the ships anemometer at the mast top with a frequency of 60 seconds. The rotor power consumption was recorded from the electric engine every 30 seconds.

3.3 SPEED TRIAL PROCEDURE

The trial was conducted according to the principles in ISO 15016 / ITTC 7.5-04-01-01.1. The trial program included four double runs according to the plan in Table 1. Each run was 10 minutes long. Constant heading was kept during the runs using the ship's autopilot. The ship's thrusters were set to constant shaft rate. The centre propeller was not engaged during the trial. The rpm of the rotor was set automatically by the rotors control system.

After having reached the trial area, the global wind direction was identified by turning the ship through the wind while reading the anemometer. The direction of the first run was determined to be around 90 degrees off the global wind direction. The first double run was performed without the rotor spinning, directly followed by a double run in the same direction with the rotor turned on. This was then repeated aiming for a true wind direction of 40/-140 degrees. The tracks are shown in Figure 3, where the circles mark the start of a run.

© 2021: The Royal Institution of Naval Architects

Run	True Wind Angle	Rotor
1	90° port	Off
2	90° s.b.	Off
3	90° port	On
4	90° s.b.	On
5	40° port	Off
6	140° s.b.	Off
7	40° port	On
8	140° s.b.	On

Table 1. Planned trial program. True wind angles relative to ship bow.

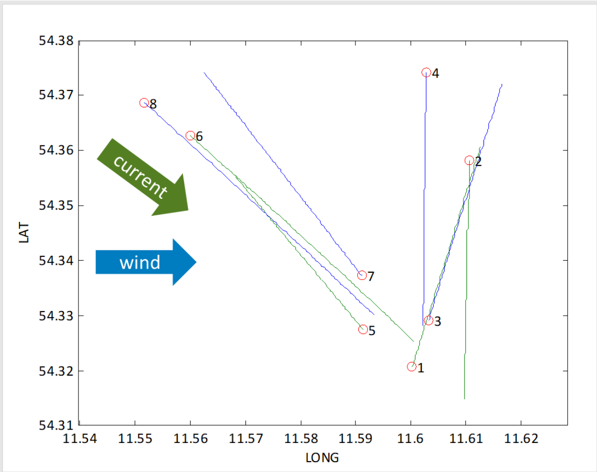

Figure r. Tracks of trial runs. Circles mark the start of each run.

4. SPEED TRIAL ANALYSIS

4.1 CURRENT

One of the key outputs from a speed trial is of course the ship's speed through water (STW). However, speed logs are in general too inaccurate [9, 10]. Measuring the speed over ground (SOG), historically by using land marks and accurate timing, and nowadays using GPS, is much more accurate. The problem is that the SOG readings are affected by current. In the standard ISO/ITTC speed trial procedure [7,8], current is eliminated using double runs, .i.e. two runs in reciprocal direction with the same engine power setting. The correction method, either the so-called Means of Means or the Iterative method (see [11] for further details) effectively compensate for the current, under the condition that the engine power is constant over the two runs, and that the effect of wind and waves can be estimated and subtracted. For the present case, the first condition cannot be fulfilled for other wind directions than exactly +-90 degrees from the bow. For all other wind directions, there is an additional, unknown, propulsive power that is different between the two runs.

The solution applied in this case is to use the ship's log directly, and therefore avoid the need to correct for current. A bias error on the speed log of 0.1 knots was estimated by comparing with the GPS and assuming a slowly changing current, and this was extracted from all runs. However, since the aim of the current trial is to compare the runs with and without rotor, a small bias error in the speed log readings will have no influence on the result.

4.2 DRIFT

According to the standard ISO/ITTC procedures, no correction is applied for drift or rudder angle. It is anyway interesting to examine whether the rotor contributed to any considerable drift. The drift, derived as the difference between the course over ground (COG) and heading, was compared between the runs with and without rotor. The derived drift was between 2 and 5 degrees, but there was no difference between the runs with and without rotor except for the run at true wind angle 40 degrees. The side force from the running rotor then increases the drift angle by 2 degrees. This small increase does not contribute to any measurable increased resistance.

4.3 WIND

The true wind during the trial is derived from the apparent wind measured using the ship's anemometer and the ship's speed. As can be seen from the black lines in Figure 5, the derived true wind appears to change magnitude depending on the ship direction. This is of course unreasonable, and the reason for this is the disturbance of the hull superstructure. As this is a common phenomenon, the standard ISO/ITTC procedures include a strategy for dealing with this error source. The method is denoted "wind averaging" and prescribes that the derived true wind from an up-run and its corresponding down-run are averaged.

The red curve in Figure 4 marks the true wind after averaging between double runs. This corresponds to a true wind speed between 8 and 10 m/s at reference hight 10m above sea level, from V-NV direction. This fits with the externally reported weather.

Table 2 lists the derived true wind after averaging and correcting to 10m height according to ISO standard, as well as the apparent wind computed back based on the averaged true wind and the ship's heading and speed. These are the wind properties that are used in the speed trial analysis.

4.4 WATER TEMPERATURE, DISPLACEMENT AND SUPERSTRUCTURE RESISTANCE

The measured power for each single run is corrected for the resistance of the superstructure based on ISO/ITTC standard procedure. The wind resistance coefficient is the "Ferry/Cruise ship" from the ITTC procedures. Correction for water temperature and a correction of displacement to baseline displacement are done according to the same procedures.

© 2021: The Royal Institution of Naval Architects

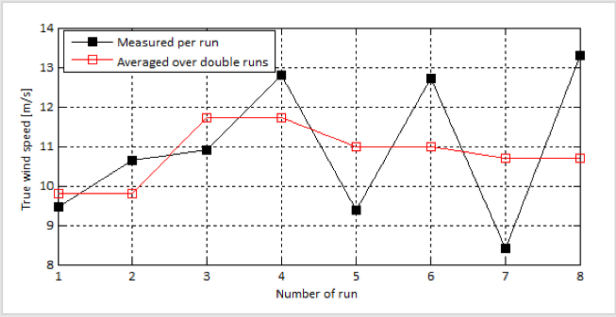

Figure 4. True wind speed, at height of anemometer. The black squares are 10 minutes average of the single runs. The red squares mark the averages between double runs (1&2, 3&4 etc).

Run No		TWS (m/s)		TWA (deg)	
No rotor	with rotor	No rotor	with rotor	No rotor	with rotor
1	3	8.1	9.7	88	78
2	4	8.1	9.7	92	102
5	7	9.1	8.9	41	38
6	8	9.1	8.9	139	142

Run No		AWS (m/s)		AWA (deg)	
No rotor	with rotor	No rotor	with rotor	No rotor	with rotor
1	3	12.6	15.7	51	47
2	4	12.6	13.1	51	61
5	7	17.3	17.4	25	22
6	8	7.3	6.6	90	90

Table 2. Derived wind after averaging over double runs. True wind is corrected to reference level 10 m above sea.

4.5 IDLING ROTOR RESISTANCE

Since the purpose of the exercise is to derive the effect of the rotor compared to the ship without any rotor, the resistance of the idling rotor during the trial must be subtracted from the runs when the rotor was not used. The rotor resistance is estimated as:

$$R_{rotor} = C_{\mathrm{D\,rotor}} \frac{1}{2} \rho_{air} \cdot H \cdot D \cdot AWS_x{}^2 \quad (1)$$

The resistance coefficient of the idling rotor, $C_{\mathrm{D\,rotor}}$, is estimated to be 0.5 [12]. AWS_x is the apparent wind speed in the ships longitudinal direction at the height of the rotor.

4.6 POWER CORRECTION

The correction of propulsive efficiency due to the added resistance corrections and idling rotor resistance is derived according to the ISO/ITTC standard using the Direct Power Method, see [7,8] for details.

5. SPEED TRIAL RESULTS

Due to the fluctuating wind, drift and current, the wind direction relative to the ship came out differently from the original plan. The resulting range and distribution of wind angles cover well the operational range of the rotor, though.

To extract the effect of the rotor, the single runs with and without rotor at the same wind conditions are compared. Table 3 and Figure 5 present a comparison of the speed and corrected power between the runs with and without rotor. These results reflect that there are several effects of the rotor:

- Increase of speed due to the additional thrust.
- Reduction of power due to off-loading the propellers. Since engine shaft rate is the same for all runs and forward speed is increased due to the rotor, the advance ratio is increased and with that also the propeller efficiency.
- Changed rudder angles and drift due to side force. These effects are included in the speed and power figures but have not been quantified separately.

Run No		TWA	Δ STW	Δ Ps
No rotor	with rotor	(deg)	(knots)	(%)
1	3	79	1.15	-8.0%
2	4	101	1.20	-4.1%
5	7	38	0.58	-0.0%
6	8	142	0.31	-3.2%

Table 3 Difference of speed and corrected power between speed trial runs with and without rotor.

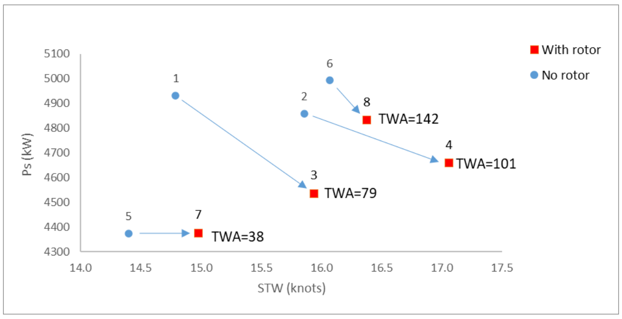

Figure 5. Speed and corrected power from trial

6. GENERALISED ROTOR PERFORMANCE

The result of the speed trial in the previous chapter showed that the rotor contributed to an increased speed as well as a power reduction. In this section, the speed trial result is normalised to derive a power reduction for a given ship speed and reference wind speed. Two alternative methods for the normalisation are used.

6.1 DIRECT NORMALISATION METHOD TO NOMINAL SPEED

To derive a power difference at nominal speed V_{ref}, the power figures from the speed trial analysis is interpolated to V_{ref}, using the shape of the ship's baseline speed-power

 © 2021: The Royal Institution of Naval Architects

curve. For the actual vessel, baseline curves have previously been derived by the Ship owner based on speed trials. The interpolation is done by fitting a 3rd order polynomial to the baseline curve and shift it vertically, as Figure 8 indicates.

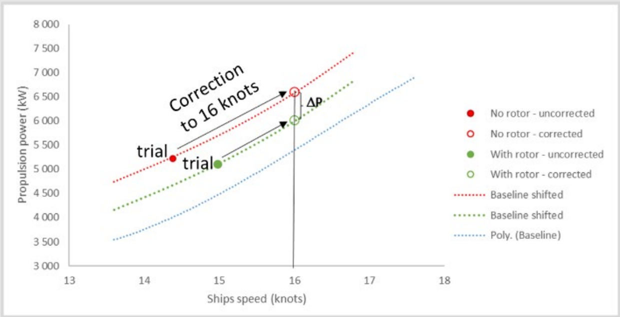

Figure 6. Example of how speed trial result is extrapolated to nominal speed using the shape of the ship's speed-power curve.

The derived power difference is corrected to a nominal wind speed using:

$$\Delta P_{TWS_{ref}} = \Delta P \cdot \frac{TWS_{ref}^{2}}{TWS^{2}} \quad (2)$$

where TWS_{ref} is the reference wind speed and TWS is the true wind speed at the sea trial, at the same height. The reference speed is according to standard praxis given for a hight of 10 m above the sea. The wind variation over height is computed according to ISO 15016 using exponent 1/7. As shown in Figure 7, if the reference speed is 10m/s at 10m hight above sea, the wind is between 10.8 and 12.5 m/s over the rotor. TWS_{ref} is the wind speed at the mid-span of the rotor, which is 11.8m/s in this case.

The resulting power savings are given in Table 4. The "net" numbers at the right-hand side of the table includes the power consumption from spinning the rotor.

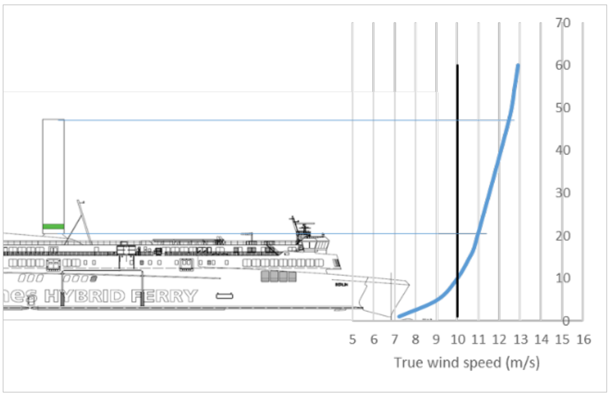

Figure 7. Wind profile according to ISO/ITTC [7,8]. (Note that the rotor end plate is missing in the drawing.)

The direct normalisation method includes several simplifications. The translation of a speed increase to a power decrease by shifting the power curves does not fully account for the changed propulsive efficiency. A second simplification is that the changed apparent wind due to a changed ship speed is not included. Therefore, a more advanced method is proposed in the next section.

TWA	ΔPd Gross	ΔPd Net
deg	%	%
78	27	25
102	25	24
38	10	8
142	10	9

Table 4. Direct normalisation method results: Power reduction derived from speed trial and normalized to ship's speed 16 knots and TWS_{10m} 10 m/s. "Gross" means without considering power consumption from rotor, "Net" means with.

6.2 GENERAL PERFORMANCE MODEL

In order to extrapolate the trial results to any arbitrary speed and wind condition, a ship simulation program is used. The program is part of SSPA's inhouse simulation code SEAMAN. The part that is used here is a static 4DOF VPP including propeller and power models. The process includes the following steps:

The starting point is generic lift and drag curves for a rotor of the actual aspect ratio derived using full scale CFD simulations [13]. The aim is to tune the generic rotor curves to the measured speed trial results. To do that, the *rotor thrust force* needs to be extracted from the speed trial results. For that purpose, a ship simulation program is used, which can model the relation between speed, resistance, power and the change in propeller efficiency due to changed speed or propeller load. The model is here based on resistance and propulsion characteristics derived from earlier model test and the result is tuned against the ship's calm water speed-power curve at the actual loading condition, without rotor.

With the help of this speed-power model, it is possible to derive the difference in longitudinal force that match the speed and power differences observed in the sea trial, while considering the effect of changed propulsive efficiency. This difference is assumed to be the rotor thrust force.

The derived rotor thrust forces is non-dimensionalised using the apparent wind speed and air density and compared with the generic rotor values from CFD. For this case, the difference increases quadratically with the apparent wind angle, such that the generic model overpredicts the performance at the larger wind angles. This is in line with what has been observed at SSPA in numerical studies of similar ships. The authors believe that the reason is the effect of the ship superstructure on the incoming flow. In the CFD simulations for the generic case, the rotor is placed on a symmetry plane, i.e without any ship hull. The performance of a Flettner rotor standing on a ship hull has been reported to be quite different from that of a rotor standing on a symmetry plane or on a floor in a wind tunnel. CFD studies by Garneaux [14] showed both increased and decreased performance depending on the wind angle. Vahs [6] reported an increased performance compared to the ideal case for a rotor positioned in the bow of a coaster measured in full-scale. Jones [15] on the other hand, observed decreased performance when placing rotors on tanker ship hull. The discrepancy between the generic rotor and the measured performance can also be due to errors in the CFD simulations. This topic will be addressed further in future work.

The rotor model thrust coefficient is now tuned using the second order polynomial derived from the described comparison. The same correction is applied to the side force, assuming that the ideal rotor C_L/C_D is preserved. This is an assumption, but since side forces is not measured at the speed trial, it is the best possible approach. However, the magnitude of the side force has only a marginal effect on the power gain for the current case.

The force from the rotor can now be derived for any wind condition using the tuned thrust coefficient, air density and the wind speed at the mid-span of the rotor.

When the rotor thrust is negative, it is assumed that the rotor is turned off. In head wind, the rotor will give an added resistance according to equation (1).

The drift and rudder forces are introduced in the ship simulation tool in terms of manoeuvring coefficients based on the bis system model due to Norrbin [16]. In the present case, the manoeuvring coefficients are extracted from SSPA's database of manoeuvring model tests. Added resistance in waves are derived using spectral superposition of response amplitude operators (RAO) (found from model tests in regular waves from SSPA database) and wave spectrum (ITTC) to find mean added resistance in an irregular sea state.

The power saving due to the rotor can now be extracted at any ship's speed and wind condition by executing the ship simulation with the rotor model turn either on or off. Figure 8 show the result at ship's speed 16 knots and TWS_{10}=10m/s, together with the results from the more simplified direct normalisation described in earlier. The two methods coincide within the uncertainty level, which indicates that the simplified method is acceptable. However, this needs to be studied further with other test cases.

Figure 9 presents the power savings at a number of wind conditions. The ship's speed is fixed to 16 knots and density of air is 1.24 kg/m3. The rotational speed of the rotor is dependent on the wind speed and direction according to tabular values provided by Norsepower. The power required to operate the rotor is dependent on the rotational speed and based on information from Norsepower.

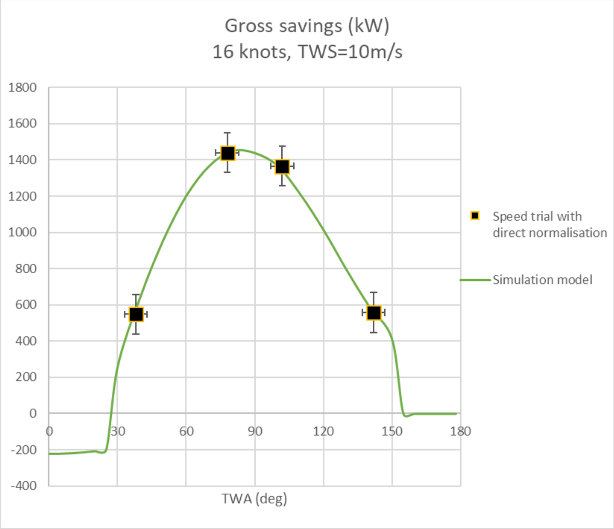

Figure 8. Gross Power saving derived from speed trial with direct normalisation and with ship simulation model tuned with thrust coefficient from speed trial. Error bars as described in section 8.1.

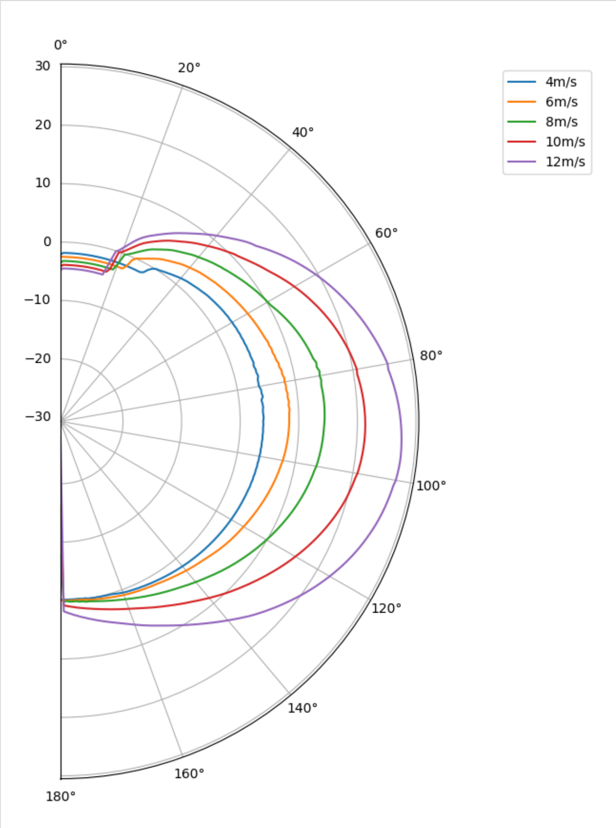

Figure 9. Power saving (%) including the power consumption from spinning the rotor for a variation of true wind speeds and angles. Derived using simulation model tuned to full-scale trials.

© 2021: The Royal Institution of Naval Architects

7. YEARLY FUEL SAVING

The final step in the analysis is to estimate the early fuel saving. This is done using a route analysis compassing the following parts:

- The ship and rotor model described in the previous section.
- Weather statistics on the route
- A Monte-Carlo based route simulation

7.1 SETTINGS

The route analysis is carried out for the following conditions:

- Fixed speed 16 knots (the ship's service speed)
- Design loading condition
- Air density 1.24 kg/m^3
- Route Gedser and Rostock and back (Figure 10).

Limitations:

- The main engine is assumed to always deliver enough power and torque to reach the intended speed, i.e. no involuntary speed reductions.
- Voluntary speed reductions are not accounted for.
- Hull fouling is not accounted for.

Figure 12. The route Gedser – Rostock

7.2 WIND STATISTICS

Statistical wind distribution for the area is obtained from the Global Wind Atlas [17]. The Global Wind Atlas use the reanalysis ERA5 statistics and apply both mesosacale and microscale modelling in order to get a 250x250m grid of local wind climate. In this case is the weather statistics gathered from a polygon with lower left (11.95175 54.20985) and upper right (12.06024 54.51391) at 10m with a 0.0 reference roughness length.

As a complement, the wind statistics from EEDI Global Weather matrix [2] is also included. It represents the wind on the mayor world-wide trade routes. This wind statistic is not representative for the current ferry route, but it is included here to give a general, route-independent performance evaluation. The comparison of the wind speed distribution in Figure 11 shows that Global Wind Atlas predicts higher wind speeds for the actual sea area than the EEDI global weather matrix.

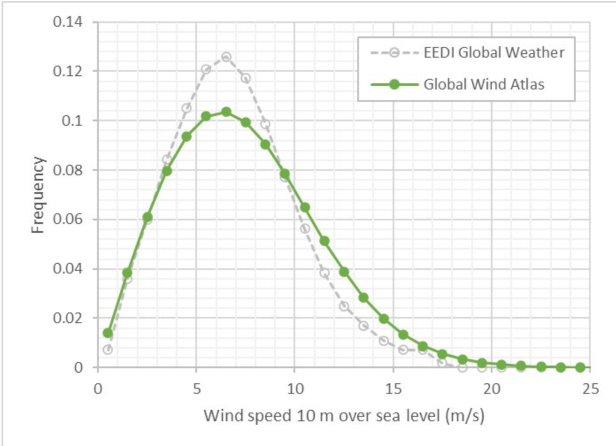

Figure 13. Wind speed distribution from Global Wind Atlas for the actual area, and the EEDI Global Weather matrix [2].

7.3 ROUTE SIMULATION TECHNIQUE

Route simulations are carried out by performing statistical simulations of Monte Carlo type over different combinations of environmental conditions along the route to estimate statistical properties of route energy requirement.

The route between Gedser and Rostock is divided into five legs. For each leg on the route, a discrete joint weather distribution (True wind speeds and True wind angles) is defined. Each leg is treated independently, and leg-wise distributions are assumed to be uncorrelated.

A Monte Carlo simulation is then performed according to the following steps:

1. For each iteration in the Monte Carlo simulation
   a. For each leg on the route
      i. Find the average azimuth and distance that the ship will travel on this leg
      ii. Draw a sample weather condition from the discrete, joint weather distribution. The sample is randomly chosen based on its probability of occurrence, i.e. a weather condition with 2% probability of occurring has a 2% probability of being sampled.
      iii. Evaluate ship performance for this specific weather condition using the performance polar curves from the VPP, linearly interpolating where necessary.
   b. Aggregate the results for the entire route based on the sub-results from each leg.

2. Combine the aggregate route results from all iterations into a single cumulative performance distribution

7.4 ROUTE SIMULATION RESULTS

As the vessel will experience different weather over a period in time (introduced by the Monte Carlo simulations) the power requirement will be different from one journey to another. Figure 12 gives the probability distribution of power for the two cases with and without the rotor employed. It can be noted that for a majority of the trips, the difference is small. The case *with* rotor has, naturally, a larger spread in power demand. The difference is largest at the lower power range (to the left in the figure), which probably convers the days of strong beam wind. This condition is optimal for the rotor, but also not very harmful for the case without rotor. The higher power range (to the right in the figure) covers the days of strong head wind, when both cases struggle.

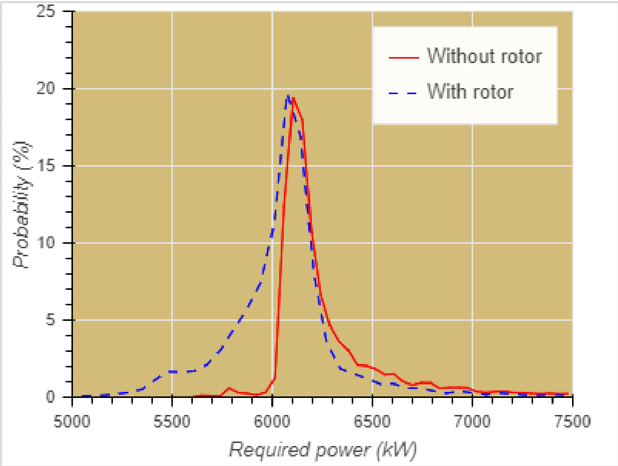

Figure 12. Probability density function for required power on the route to keep 16 knots ship's speed, with and without rotor sail.

Averaged over a long period, the difference in power requirement corresponds to a 3.9% reduction in power, including the power requirement of spinning the rotor. Since the fuel consumption is proportional to the power requirement within the limited design range of shaft rates, the same percentage saving is valid for the expected fuel saving. The corresponding value when using the EEDI Global Weather Matrix as the weather source is 2.0 %.

Weather source	Yearly Power Saving
Global Wind Atlas	3.9%
EEDI Global Weather matrix	2.0%

Table 5. Expected averaged power saving based on different weather sources.

8. UNCERTAINTY ASSESSMENT

8.1 SPEED TRIAL UNCERTAINTY ASSESSMENT

The bias uncertainty of speed trials is stated in the ISO/ITTC [7,8] standard to be 2%. In the present work, the purpose is to derive a power difference, and then the bias error can be assumed to cancel out. The exception is the wind; a bias error of the anemometer will strike differently on the run with rotor compared to the run without rotor.

The precision error of speed trials in general is estimated by Werner [18] and Insel [19] using series of sister ships to be around 7-8%. However, most of this uncertainty is probably due physical differences between sister ships, and trials conducted at different occasions. The precision uncertainty for the current comparative test is probably smaller, but there are no published results to lean on.

Here follows an estimate of the uncertainty of the derived power difference, following ITTC 7.5-02-01-01 (Type A). The authors do not claim it to be a complete uncertainty assessment, but an indication of the magnitude of the larger error sources.

The largest source of uncertainty is the standard deviation of the speed log (see Table 4), which was retrieved at low frequency (1 min). However, comparing with a prediction based on GPS speed shows that the uncertainty is probably less than the standard deviation indicates.

The anemometer also affects the evaluation uncertainty. The fluctuation of the natural wind is high and therefore, higher frequency logging would have been preferred. There is also some disturbance caused by the hull, which is more problematic as it is very difficult to assess. It is difficult to measure the "true" apparent wind hitting the rotor, since all possible locations to place an anemometer is disturbed by the hull or the rotor. On this ship, the anemometer has been corrected using lidar measurements, but the hull disturbance is anyway significant, which the oscillating behaviour of the calculated true wind in Figure 5 indicates.

The experimental design employed in this work implies that single runs with and without rotor *at the same wind conditions* are compared. Possible differences in wind condition between runs that are compared could disturb the comparison. Figure 13a-b show the wind conditions of the runs with and without rotor that are paired for the comparison. It is seen that the conditions are reasonably close within the pairs. Between run 1 and 3 the wind speed increased, which means higher hull windage drag. However, the superstructure resistance is compensated for by a correction of the power (see section 4.4). The air resistance coefficient is taken from the ITTC library and is not ship specific, which could introduce an error in the comparison. The possible error from this approximation is

 © 2021: The Royal Institution of Naval Architects

Variable	Comment, source of uncertainty	Uncertainty of variable (Type A)	Uncertainty of power saving
Heading	Standard deviation of time signal	1 deg	insignificant
STW	Standard deviation of time signal	0.25 kts	240 kW
STW	Comparing with analysis based on SOG	0.1 kts	130 kW
power	Standard deviation of time signal		90 kW
AWA	Standard deviation of time signal Disturbance of hull	5 deg	Secondary effects: hull air resistance, regression of thrust function in Method 2
AWS	Standard deviation of time signal Disturbance of hull Atmospheric boundary layer difference from 1/7 power law	1 m/s	150 kW (on the normalisation to given wind speed)
	Assumptions in the normalisation method. Assessed by varying the input.		50 kW

Table 6. Speed trial uncertainty assessment

conservatively estimated to 10% of the air resistance. However, the wind resistance correction is just up to 3% of the total resistance for run 1-3. This means that the possible error on the power difference is around 0.3%.

Figure 13a. Apparent wind speed for pairs of runs with and without rotor.

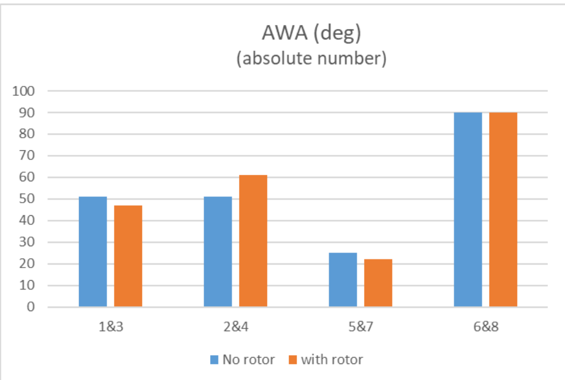

Figure 13b. Apparent wind angle for pairs of runs with and without rotor.

To reduce the uncertainty for coming trials, it is recommended to:

- Use high frequency automatic data collection of speed log
- Use high frequency automatic data collection of anemometer
- Try to correct anemometer for hull disturbance using Lidar or CFD simulations
-

8.2 GENERALISED SHIP MODEL UNCERTAINTY

Simulation models always include assumptions and simplification and cannot mimic the behaviour of complex ship system exactly. This introduces errors in the simulation results.

The comparison between the two normalisation methods in Figure 8 shows that they agree well. The first method is simple and transparent and does not require any speed-power prediction program as the second method does. Therefore, it can be a useful method in praxis.

Both methods rely on assumptions and model test data related to the propulsion factors. The possible uncertainty that this causes could be reduced if the trials were conducted not at constant shaft rate, but instead aiming for similar speed between the runs with and without rotor. This test design will be investigated in future trials.

For the complete generalised model, the manoeuvring coefficients are estimated based on experience and the Azimut thrusters have been modelled as conventional propellers and rudders, since there was no model test of CFD analysis done to extract the manoeuvring coefficient for the actual vessel. This is believed to have insignificant effect on the fuel saving results as the drift was found to be small even for the high wind speeds at the speed trial.

The process of tuning the simulation model to the trial tests is believed to result in an accurate ship model for true wind angles between 35 and 145 degrees from the bow. The resistance that the rotor is assumed to generate in head wind is based on an empirical assumption of resistance of a cylinder. The uncertainty associated with this assumption, in particular the influence of the hull, should be investigated further using numerical tools.

8.3 ROUTE SIMULATION UNCERTAINTY

The weather statistics probably contributes to high uncertainty in the route simulation. The weather provider does not state any uncertainty levels for the data, though. Wind measurements are currently assembled onboard the ship, and this will complement the study later.

The largest uncertainty relates to the actual operation of the vessel and rotor. The annual power saving derived with the route analysis assumes that the rotor is used all the time when the wind conditions allows, i.e. no down-time due to maintenance etc. It is also assumed that the speed is kept constant, i.e. that the crew chose to adjust the engine power to keep the fixed speed when the rotor is in operation, rather than running at a fixed power and "save" time to port. If the latter happens, no fuel saving will be made.

9. METHODOLOGY DISCUSSION

9.1 ASSESSMENT STRATEGY – LONG TERM MONITORING OR SHORT TRIAL

Full-scale verification campaigns for wind assisted ships in recent publications can be divided into two different strategies: Long-term monitoring and Short trials. The selection of strategy does not need to be exclusive; combinations are of course possible. For the present work it was decided to lay the focus on the short trial strategy, and possibly compliment with the long-term monitoring later on. Here follows a short discussion on the reasoning behind this decision.

In the Long-term monitoring strategy, the fuel consumption is logged using the ships performance monitoring system and periods with and without the wind assistance are compared. The advantage of this strategy is that all unpredictable operational aspects are covered: unexpected down-time of wind propulsion device, crew skill in operation, actual experienced environmental conditions. The disadvantages are:

- The uncertainty and scatter of in-service logging data is in general very high. Very long time periods are needed in order to get reliable trends. This means that within the course of the test period with and without the wind assistance technology (e.g. before and after installation), the fuel consumption may be affected by other factors, for example hull fouling, docking, hull cleaning, engine maintenance. There is a risk that this influences on the conclusions.
- The issue above can be avoided by instead deliberately in-activate the wind assistance device for test periods between periods of active use. In that case the ship operator misses out a large potion of potential fuel saving!
- For ships that do not operate on a fixed and regular trade, the logging periods with and without wind assistance will never be similar. Loading condition, wind, waves, current, temperature and so on may heavily disturb the comparison even when to corrected for.
- When post-processing the large amount of data, different filtering and correcting settings may lead to different results, giving ambiguous conclusions.
- The result is valid for the particular trade, and the particular time only. Hence it is difficult to derive general performance indicators that can be compared with other wind assistance installations. This may be irrelevant for the individual ship owner but is a drawback for the shipping community and the further development and uptake of wind propulsion.

The Short trial strategy overcomes the issues above by performing the comparison in unchanged ship and environmental condition. The main advantage is that it safely provides transparent results and general performance indicators that are valid for any route and weather condition. The drawback is instead that the test results is limited to a few conditions. Route simulations and weather statics need to be used to derive an expected fuel saving. Unexpected issues in the operation will not be accounted for. Therefore, this kind of evaluation should be accompanied with long-term monitoring and independent evaluation of the actual operationality.

9.2 SPEED TRIAL METHODOLOGY

The proposed method seeks to follow the standard speed trial procedures as much as possible. The standard procedures prescribe the use of reciprocal double runs as a mean to correct for current so that the ship's speed can be measured using a GPS instead of the ship's log, which is usually inaccurate. The standard correction methods cannot be applied in case of wind propulsion, unless the wind angle is +-90 degrees from the bow.

The here proposed method suggests using the speed log for the ships speed and thereby avoid the need for current correction. Since the objective is to derive a difference between two conditions, with and without wind power device, a bias error of the log will cancel out. Precision error of the log will affect the uncertainty of the evaluation, though. However, the authors believe that it is better to accept this uncertainty, than not to measure at all. The alternative solution to evaluate the wind propulsion device at 90 degrees only is in the authors opinion worse. The hull influences the inflow differently at different wind angles, and the performance can be both higher and lower at other wind angles. Moreover, the performance at for example quarterly wind is in many cases what makes a large difference between different wind propulsion technologies on the market. For those reasons, it is highly

 © 2021: The Royal Institution of Naval Architects

important to evaluate the wind propulsion technologies at other wind angles than 90 degrees.

By using the speed log, there is no need for double runs for the current correction. However, the double runs approach has the advantage that the disturbance of the hull to the wind anemometer can be checked and corrected for using the wind average method prescribed in the ISO/ITTC standards. Moreover, with double runs, the trial area can be kept to a smaller geographical area which means that wind, waves and water depth is more likely to be similar between the runs.

In the trial test presented in the present work, the rotor was alternative turn on and off for every double run. The gain of the rotor was derived by comparing two single runs with equal heading, with and without rotor. This approach will fail if the weather change during the trial so that the two runs are not comparable. For that reason, it could be a feasible approach to turn the wind propulsion on and off during each single run. This requires a larger undisturbed trial area. The approach will be tested by the authors in coming trials.

10. CONCLUSION

Wind assistance technology is one way to reduce the fuel consumption and green-house gas emissions from shipping. A key barrier for market uptake of wind assistance technology is the lack of verifiable data on the fuel savings potential [3]. So far there is no agreed standard for full scale verification of wind assistance technology of commercial vessels. In this work, a methodology based on short, dedicated trial is proposed. The trial is complemented with a route simulation and weather statistics to estimate the yearly fuel saving.

The methodology is demonstrated for the RoPAX ferry Copenhagen equipped with a Flettner rotor. A speed trial was conducted on the waters off Gedser in March 2021. The standard ISO/ITTC speed trial procedures were followed to as large extent as possible. In contrast to the normal procedures, the speed was measured using the ship's log and therefore no current correction was needed. The effect of the rotor was extracted by comparing single runs with and without rotor for the same wind condition.

Two methods to normalise the speed trial results are proposed. The first method uses the shape of the ships's speed power curve to extrapolate to nominal condition. This method involves several simplifications including the effect on propulsive efficiency due to changed propeller load. The second method is more complex and makes use of a ship simulation model. The difference between the results of the two methods are well within the estimated uncertainty margin.

It is demonstrated how a route simulation tool using hind-cast weather statistic can be used to extrapolate the trial result to yearly fuel saving for a specific route. The result for the specific case show that an average power saving of 4 % is possible. Continuous logging of wind speed on the route, the ship's fuel consumption and operability of the rotor for at least one year will complement this number and will be presented in future publications.

The mayor uncertainties include the disturbance of hull to the wind measurement onboard the vessel. This may disturb the relation between the trial result, which is based on the on-board measurements, and the route analysis that scale up the result to yearly fuel savings, which is based on the natural undisturbed wind on the ocean. Furthermore, the wind statistics introduce large uncertainties in the process. The largest uncertainty is probably the way the wind assistance technology will be handled and operated in reality. If the device will be in-active due to maintenance, failure, safety or other issues, then the power saving will off course be less. The same applies if crew choose to use the additional thrust from the wind to increase the ship's speed instead of reducing the power.

The proposed methodology is shown to be a feasible way to perform full scale verification for commercial vessels. With this approach a trustworthy result can be derived at a feasible cost, within a limited time frame, and using transparent, commercially available tools and established procedures.

The process will be refined further and applied to four other ships with wind assistance technologies. Among the issues that will be investigated is to keep the speed fixed over the runs instead of fixing the power, and to turn off and on the wind propulsion device within each run instead of between double runs.

11. ACKNOWLEDGEMENTS

The work is funded by EU Interreg North Sea Region.

12. REFERENCES

[1] International Maritime Organization, "Strategic plan for the organization for the six-year period 2018 to 2023," IMO International Maritime Organization, 2017.

[2] Rehmatulla, N., Calleya, J., Smith, T., "The implementation of technical energy efficiency and CO2 emission reduction measures in shipping", *Ocean Engineering*, Volume 139, pp 184-197, 2017

[3] MEPC.1/Circ.815 - 2013 Guidance on treatment of innovative energy efficiency technologies for calculation and verification of the attained EED (MEPC.1/Circ.815 (IMO, 2013)

[4] Paakkari, V., Hurford,. A., Craddock, C., "Rotor sail GHG reduction potential, modelling and sea trial validation" *Proceedings of 5th International Conference on Innovation in High Performance*

[5] *Sailing Yachts and Sail-Assisted Ship Propulsion,* Gothenburg, Sweden, June 2020

[6] Comer, B., Chen,.C., Stolz,.D., Rutherford, D., "Rotors and bubbles: Route-based assessment f innovative technologies to reduce ship fuel consumption and emissions" Working paper 2019-11, *The international council on lean transportation*, 2019

[7] Vahs, M., "Retrofitting of flettner rotors – results from sea trials of the general cargo ship "Fehn Pollux" *in Proceedings of the International Conference on Wind Propulsion*, 15th -16th October 2019, London, UK

[8] ISO 15016:2015 (2015), *Ships and marine technology – Guidelines for the assessment of speed and power performance by analysis of speed trial data*

[9] ITTC (2017b), Recommended Procedure 7.5-04-01-01, *Preparation, Conduct and Analysis of Speed/Power Trials*

[10] Øksnes, Ø., Dalheim, Steen, S., "Uncertainty in the real-time estimation of ship speed through water", *Ocean Engineering,* Volume 235, 2021

[11] Specialist Committee on Performance of Ships in Service, *Final report and recommendation to the 27th ITTC*, 27th International Towing Tank Conference 2014

[12] Strasser, G., Takagi, K., Werner, S., Hollenbach, U., "A verification of the ITTC/ISO speed/power trials analysis", Journal of Marine Science and Technology, 2015

[13] Kramer et.al, "Drift Forces –Wingsails vs Flettner Rotors", *High-Performance Marine Vehicles*, 2016

[14] Li, D.-Q., Leer-Andersen, M., & Allenström, B., "Performance and vortex formation of Flettner Rotors at high Reynolds numbers". *29th Synopsium on Naval Hydrodynamics.* Gothenburg. 2012

[15] Garenaux, M., Schot, J., Eggers,. R., "Numerical Analysis of Flettner Rotors Performances on the MARIN Hybrid Transition Coaster" *in the Proceedings of 12th Symposium on High-Performance Marine Vehicles, 2020*

[16] Jones, L., Prince, M., Hudson, D., Cocks, J., Predicted Fuel-Savings For A Flettner Rotor Assisted Tanker Using Computational Fluid Dynamics, In the Proceedings of RINA Wind Propulsion, 15th -16th October 2019, London, UK

[17] Norrbin, N. H. "Theory and Observations on the Use of a Mathematical Model for Ship Manoeuvring in Deep and Confined Waters", *Proc Eighth Symposium on Naval Hydrodynamics*, Pasadena 1970

[18] https://globalwindatlas.info/

[19] Werner, S., "Uncertainty of Speed Trials", in the *Proceedings of HullPIC*, 2020

[20] Insel, M., "Uncertainty in the analysis of speed and powering trials", *Ocean Engineering* 35, 2008

9. AUTHORS BIOGRAPHY

Sofia Werner is responsible for method development within fluid dynamics at SSPA. Her previous experience includes towing tank testing and ship design using CFD. 2011-2017 she was a member of the ITTC committee that developed the Recommended Procedures for Speed Trial. She is currently Chairman of the ITTC Specialist Committee for Wind Powered Ships.

Axel Hörteborn holds the current position of Specialist at SSPA Sweden AB. He is responsible for ship simulations, AIS data and Monte Carlo simulations analysis. His previous experience includes risk assessments of large-scale Monte Carlo inspired ship simulations, simulation of sailing ship.

Jonny Nisbet holds the current position of Senior Specialist at SSPA Sweden AB. His previous experience includes manoeuvring and seakeeping model testing, as well as simulation and CFD.

Rasmus Nielsen, Naval Architect in Scandlines. Educated Master Mariner and Naval Architect. Has been working 3 years as nautical officer, and one year at a consulting company before joining Scandlines in 2003. Working with projects in Scandlines, business case development and project management.

 © 2021: The Royal Institution of Naval Architects