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Report.

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Speed trial and route analysis of m/v Copenhagen with Flettner rotor

Wind Assisted Ship Propulsion

Interreg North Sea Region WASP
European Regional Development Fund

EUROPEAN UNION

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Speed trial and route analysis of m/v Copenhagen with Flettner rotor

A speed trial was performed with m/v Copenhagen in March 2021. The purpose of the test was to verify the power saving of the Flettner rotor. This report describes the tests conditions, measurements, analysis, and results. The trial test result is extrapolated to annual fuel reduction using voyage analysis and statistical weather distribution.
The work is a part of the Interreg North Sea Region project WASP - Wind Assisted Ship Propulsion.

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Revision History

Rev.	Publish Date	Description of changes	Signature
B	2023-05-01	Updated power saving figures reflecting new methodology and updated weather statistics	SW

Summary and recommendations

A speed trial was performed with m/v Copenhagen in March 2021. The purpose of the trial was to verify the power saving of the Flettner rotor.

The speed trial result is scaled up to annual fuel reduction using a ship simulation model correlated to the actual speed trial measurements, a voyage prediction tool and statistical weather distribution.

It is estimated that the ideal power reduction due to the Flettner rotor is around 375 kw or around 7%, when considering only the sea legs and with 100% operability.

There are several error sources that influence the uncertainty of this estimate. The largest uncertainty relates to the actual operation of the vessel and rotor. It is here assumed that the rotor is used all the time when the wind conditions allow, i.e. no down-time due to maintenance etc. It is also assumed that the speed is kept constant, i.e., that the crew 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.

After a longer period of operation, this report may be updated based on weather statistics and other operational data.

There is no standard procedure for the analysis of speed trials for wind powered ships. A methodology is suggested in this report, which follows the existing ISO 15016 as close as possible. The approach is shown to be feasible, however, some improvements can be done. For coming trials, it is suggested not the keep shaft rate constant between the speed runs but instead aim for similar ship's speed between the runs with and without wind power system.

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Appendix 1

Symbols and abbreviations

ξ_p	Load variation factor, for power correction according to ITTC (2017)	-
AWS	Apparent wind speed	m/s
AWA	Apparent wind angle	deg
AWS_x	Apparen wind speed in ship longitudinal direction	m/s
AP	Aft perpendicular	
A_T	Transversal wind area	m^2
B	Beam of hull	m
BL	Baseline	
CL	Center line	
D	Rotor diameter	m
FP	Fore perpendicular	
FS	Full scale	
GWA	Global wind angle	deg
H	Rotor height	m
IMO	International Maritime Organization	
ITTC	International Towing Tank Conference	
T	Draught	m
T_F	Draught at fore perpendicular	m
TWA	True wind angle	deg
TWS	True wind speed	m/s
V	Volume displacement	M3
V_s	Ship speed	knots
SOG	Speed over ground	knots
COG	Course over ground	deg
STW	Speed through water	knots

1 Introduction

Scandlines installed a Flettner rotor from Norsepower on the ferry m/v Copenhagen in 2020. On March 6, 2021, a speed trial was performed with the purpose of evaluating the performance of the rotor.

The Trial Team present onboard included Ship Master 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 speed trial result is scaled up to predicted annual fuel reduction using a route analysis and statistical weather data. All data processing, analysis and route evaluation is carried out independently by SSPA.

This work is a part of Work Package 5 in the Interreg North Sea Region project WASP. The scope of Work Package 5 is to demonstrate the performance of Wind Propulsion Technologies on five vessels. m/v Copenhagen is the first out of these five to be tested.

Figure A. m/v Copenhagen (169.5m x 25.4m) with a 5x30m Flettner rotor.

2 Speed trial data

2.1 Conventions and definitions

The following coordinate systems are used in this report:

- Used when referring to locations or distances on the ship:
    - Body-fixed, Cartesian, right-handed system “XYZ” with the origin in intersection of AP, CL and BL.
    - X-axis positive forward
    - Y-axis positive to port
    - Z-axis positive upwards

The following definitions of directions and angles are used in this report.

- Course: direction of the path the model is travelling (basin fix)
    - Course=0° means model travelling in positive basin x direction
    - Course=90° means model travelling in positive basin y direction
- Heading: direction in which the model bow is pointing at a certain moment (basin fix)
    - Heading=0° means model bow in positive basin x direction
    - Heading=90° means model bow in positive basin y direction
- Leeway angle: angle between the centerline of the ship and the course direction
    - Leeway angle=0°: model centerline in line with course direction
    - Leeway angle=90°: model centerline off from course direction, to port
- Global wind angle (GWA): defined in the basin-fix coordinate system
    - GWA=0° means wind coming from positive basin x
    - GWA=90° means wind coming from positive basin y
- True wind angle (TWA): the angle between the wind direction and the course of the model
    - TWA=0° means head wind
    - TWA=90° means beam wind (port side)

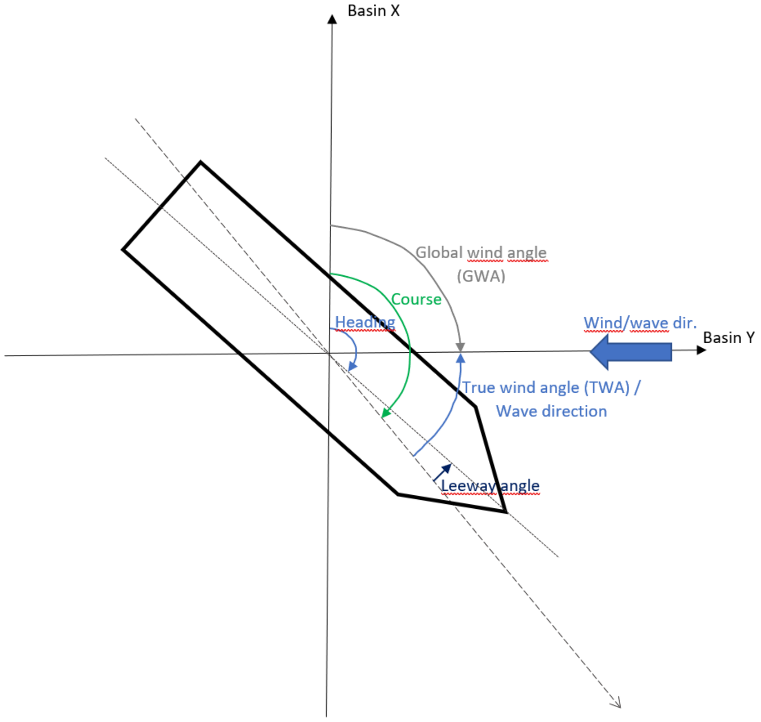


Figure B Definitions of directions and angles

2.2 Ship

The RoPax ferry m/v Copenhagen (IMO 9587867) operates the route Gedser-Rostock. It is equipped with a 5 x 30 m Flettner rotor with end plate. The rotor is positioned longitudinally around mid-ship, 17.2 m above water at design draft.

The ship data used for the sea trial analysis is listed in Table 1.

Table 1. Ship data

Name	Symbol	Magnitude	Comment
Length over all	Loa	169.5 m	
Beam over all	B	25.4 m	
Load variation factor for power	ξ_P	-0.126	Based on virtual load variation test using model test propeller data from HSVA (HSVA 2011), (Figure 7 Appendix 1)
Hight of anemometer	h	37 m	
Transversal wind area	A_T	500 m^2	From model test report (HSVA 2011)

The ship loading condition during trial is given in Table 2

Table 2. Ship loading condition during trial

Name	Symbol	Magnitude	Comment
Draft forward	Tf	5.2 m	
Draft aft	Ta	5.25 m	
Displacement	Δ	11581 m^3	

2.3 Trial location and environmental conditions

The trial was conducted off Gedser in an area of sea water depth 24-25m (Figure C.). Environmental conditions are given in Table 3.

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:

- wave height 1 m from west
- current 0.8 knots from north west

Table 3. Environmental conditions

Name	Symbol	Magnitude	Comment
Temperature sea water	t_{sw}	3°	
Density sea water	ρ_{sw}	1012 kg/m^3	Derived from temperature
Temperature air	t_a	3°	
Air pressure	p	1013 mbar	Was not measured
Density air	ρ_a	1.28 kg/m^3	Derived from temperature

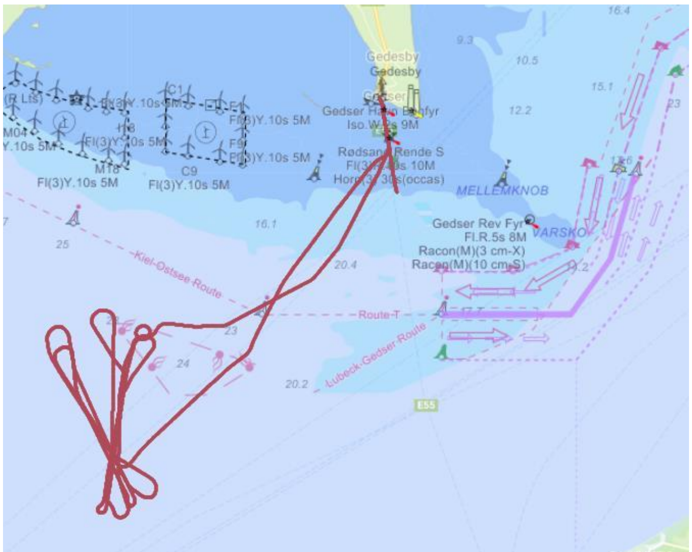


Figure C. Trial area off Gedser

2.4 Data acquisition

All recorded data is listed in Appendix 1, Figure 1-5.

Data acquisition was performed using the systems given in Table 4

Table 4. Data acquisition sources

Variable	System	Frequency
GPS speed Azimut power & rpm Track	IMAC	5 sec
STW (Logg) Heading (gyro) Rotor rpm	Manual reading of displays on the bridge during trial runs	1 min
Relative wind at mast top	Ships Anemometer	1 min
Rotor power consumption	Rotor log	30 sec

The data was submitted in the following data files:

Table 5 Measurement data files

System	Datafiles
IMAC	CPH_Export20210307.csv CPH_Export20210307_2.csv
Wind	Rotor Sail speed test wind data 2021-03-06 2030 UTC.csv
Rotor consumption	Copenhagen Rotor Sail cum propulsion data 2021-03-06 2030 UTC.csv

2.5 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 6. Each run was 10 minutes long. (However, some of the runs had to be cut in the post-processing, to exclude parts of the runs when the speed was not constant.) Constant heading was kept during the runs using the ships autopilot.

The ship's thrusters were set to constant shaft rate. The centre propeller was not engaged during the trial, because it was not possible to keep the propeller pitch fixed, and this was judged to make the analysis harder.

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 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 D, where the circles mark the start of a run.

The rpm of the rotor was set automatically by the rotors control system.

Table 6. Trial program as planned (note that actual wind angle deviated somewhat from the planned)

Run	TWA	Rotor
1	90	
2	90	
3	90	x
4	90	x
5	40	
6	140	
7	40	x
8	140	x

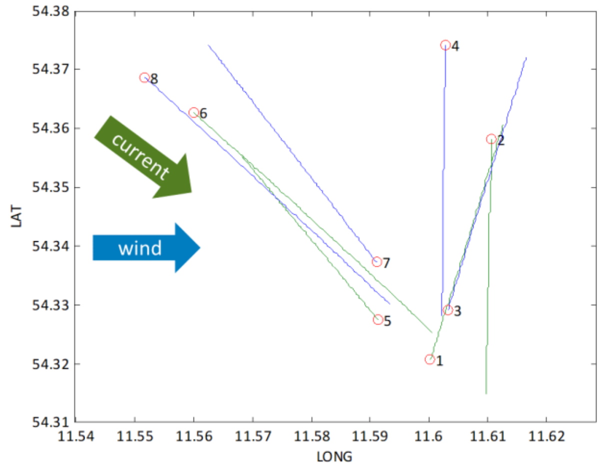


Figure D. Tracks of trial runs. Circles mark the start of each run.

3 Trial analysis and results

3.1 Current

In standard speed trial analysis, the ship's speed over ground (SOG) is measured with the GPS and corrected to speed through water (STW) using the double runs. The GPS is generally regarded as far more accurate than the speed log. As discussed further below in Section 6.1, this procedure is not possible to follow in the current trial, due to the presence of wind propulsion. Instead, the speed is measured with the ship's log. There is therefore no 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.

3.2 Drift

According to the standard procedures, no correction is applied for drift or rudder angle. It is anyway interesting to check whether the rotor contributed to any considerable drift. Figure E show the difference between the course over ground (COG) and heading i.e., drift. The drift can be from wind, waves, current and rotor. The only difference in drift due to rotor that can be detected is for the case of TWA~40 degrees (run 5&7). The rotor then increases the drift angle by 2 degrees. This small increase does not contribute to any measurable increased resistance.

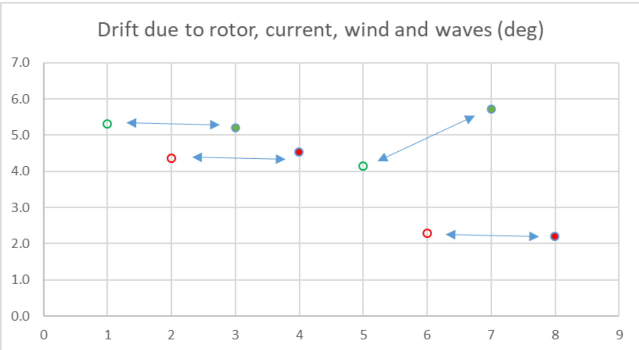


Figure E. Drift (COG-heading). Filled circles are runs with rotor. Green marks up-runs, red down-runs.

3.3 Wind

The true wind during the trial is derived from the apparent wind measured with the ship's anemometer and the ships speed. As can be seen from the black lines in Figure F and Figure G, the derived true wind appears to change magnitude and direction 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 well-known phenomenon, the standard procedures include a strategy for dealing with this error source. It is denoted "wind averaging" and prescribes that the derived true wind from an up-run and it corresponding down-run are average.

The red curve in Figure F and Figure G 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 7 lists the derived true wind after averaging and correcting to 10m height according to ISO standard, as well as the apparent wind computed based on the averaged true wind and the ships heading and speed. These are the wind properties that are used in the speed trial analysis.

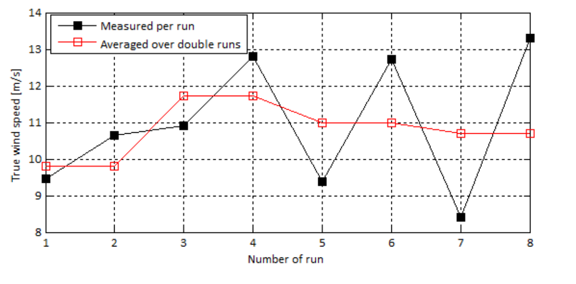


Figure F. True wind speed, at height of anemometer

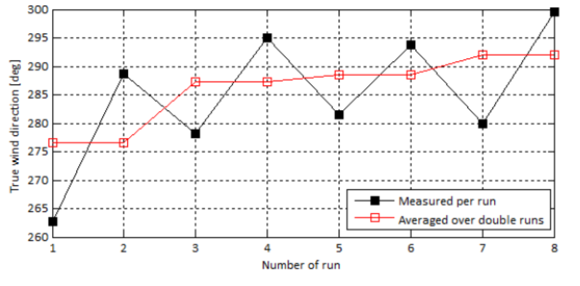


Figure G. Global wind direction, at height of anemometer

Table 7. Derived wind after averaging over double runs. True wind is corrected to reference level 10 m above sea.

Run No		TWS (m/s)		TWA (deg)		AWS (m/s)		AWA (deg)	
No rotor	with rotor	No rotor	with rotor	No rotor	with rotor	No rotor	with rotor	No rotor	with rotor
1	3	8.1	9.7	88	78	12.6	15.7	51	47
2	4	8.1	9.7	92	102	12.6	13.1	51	61
5	7	9.1	8.9	41	38	17.3	17.4	25	22
6	8	9.1	8.9	139	142	7.3	6.6	90	90

3.4 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 procedures.

3.5 Idling rotor drag

Since the purpose 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:

$$R_{rotor} = C_d \frac{1}{2} \rho_{air} \cdot H \cdot D \cdot {AWS_x}^2 \tag{3}$$

The resistance coefficient of the idling rotor, C_d, is estimated to be 0.5 (Kramer, 2016). AWS_x is the apparent wind speed in the ships longitudinal direction at the hight of the rotor.

Figure 6 in the Appendix list the resistance components that are subtracted from the measurements, including the idling rotor drag. The rotor drag can appears to be large in comparison to the superstructure resistance, but then it should be noticed that the superstructure drag does not include the wind speed from the ships forward motion, as per ISO standard, whereas this component is included in the rotor drag.

3.6 Power correction

The correction of propulsive efficiency due to the added resistance corrections and idling rotor resistance is derived using the Direct Power Method according to the ISO standard using the assumed load variation factor stated in Table 1. (See the ISO 15016 standard for a detailed description of the Direct Power Method)

The corrected power is listed in Appendix 1, Figure 3.

3.7 Rotor evaluation

The principle of the rotor evaluation is to compare single runs *with and without* rotor at the *same wind conditions*. Section 6.2 discusses whether this approach is reasonable. Table 8 and Figure H gives a comparison of the speed and corrected power between the runs with and without rotor. There are three main effects of the rotor:

1. Increased speed due to the additional thrust.
2. 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.
3. Changed rudder angles and drift. These effects are included in the speed and power figures but have not been quantified separately.

These are the direct results from the trial. In Chapter 4, the result is normalised to give representative power savings for a given speed.

Table 8. Speed and corrected power from speed trial.

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

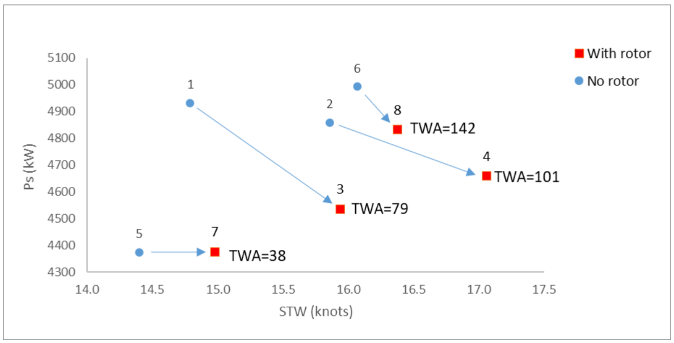


Figure H. Speed and corrected power from trial

4 Rotor performance analysis

The result of the speed trial in the previous chapter showed an increased speed as well as a power reduction. In this chapter, 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, and the differences are discussed in Chapter 5.

4.1 Reference wind speed

Due to the atmospheric boundary layer, the wind velocity increase with height. The reference speed is according to standard praxis given for 10 m over the sea. The wind variation over height is computed according to ISO 15016 using exponent 1/7. As shown in Figure I, 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. In the following sections, the wind speed acting on the rotor, $\mathrm{TWS_{ref}}$, is the wind speed at the mid-span of the rotor, which is 11.8m/s for 10m/s at 10m height.

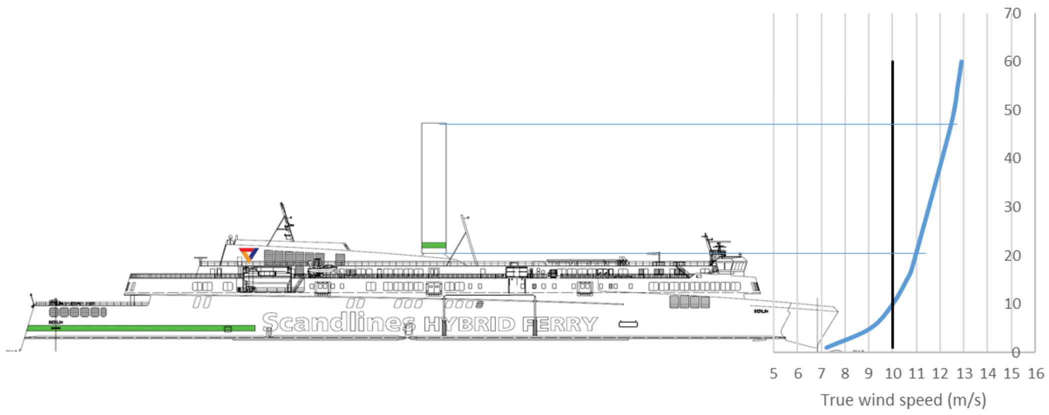


Figure I. Wind profile

4.2 Normalisation method 1

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 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 J indicates.

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

$$\Delta \mathrm{P_{TWS_{ref}}} = \Delta \mathrm{P} \cdot \frac{\mathrm{TWS_{ref}}^2}{\mathrm{TWS}^2} \tag{4}$$

Where $\mathrm{TWS_{ref}}$ is the reference wind speed and TWS is the true wind speed at the sea trial, at the same height.

The resulting power savings are given in Table 9. Including the power consumption from spinning the rotor results in the "net" numbers at the right hand side of the table.

This method includes several simplifications, which will be discussed further in Chapter 5.

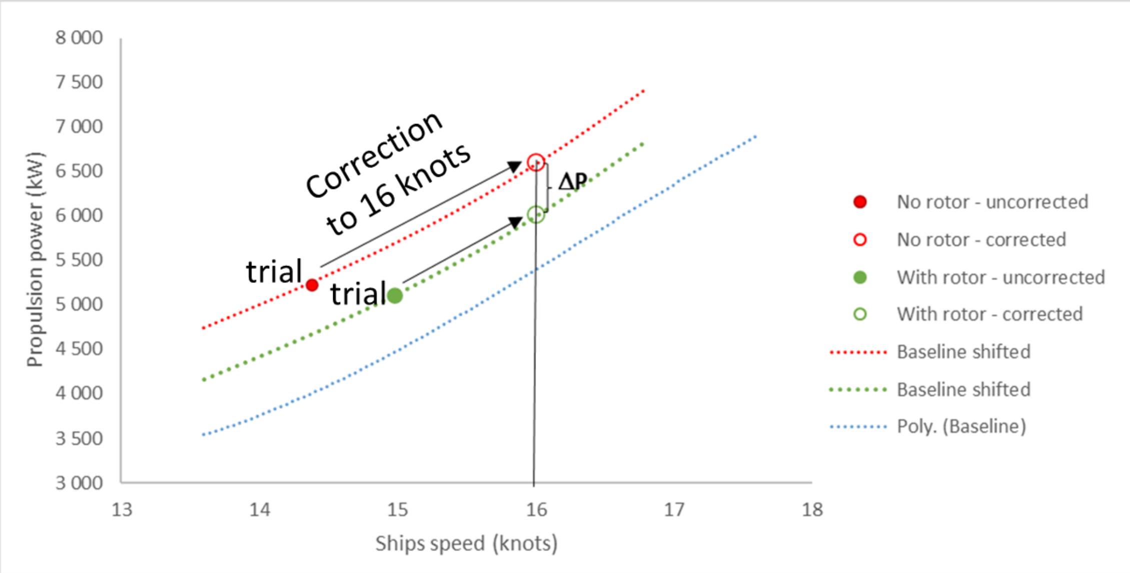


Figure J. Example of how speed trial result is extrapolated to nominal speed using the shape of the Baseline curve.

Table 9. Method 1: Power reduction derived from speed trial and normalized to reference ship's speed and wind. "Gross" means without considering power consumption from rotor, "Net" means with.

	At ship's speed 16 knots and speed trial wind condition		At ship's speed 16 knots and TWS_{10m} 10 m/s			
TWA	**ΔPd Gross**	**ΔPd Gross**	**ΔPd Gross**	**ΔPd Gross**	**ΔPd Net**	**ΔPd Net**
deg	kW	%	kW	%	kW	%
78	1419	24	1440	27	1341	25
102	1346	27	1366	25	1267	24
38	451	8	548	10	449	8
142	458	9	557	10	458	9

4.3 Normalisation method 2

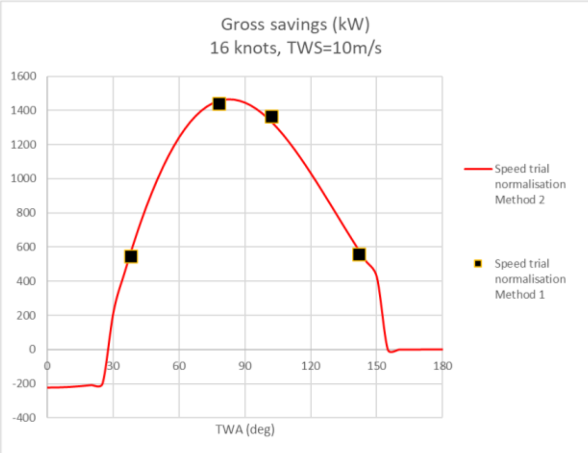
In Method 1, the translation of a speed increase to a power decrease is done by shifting the power curves. However, this does not fully account for the changed propulsive efficiency. A second simplification in Method 1 is that the changed apparent wind due to a changed ship speed is not included. In order to check the influence of these effects, a second normalisation method is introduced. It makes use of a 1DOF speed-power prediction program, which can model the relation between speed, power and the change in propeller efficiency due to changed speed or propeller load. The propeller characteristics of the ship's propeller as given in the model test report (HSVA 2011) is used as input. The process follows the present steps:

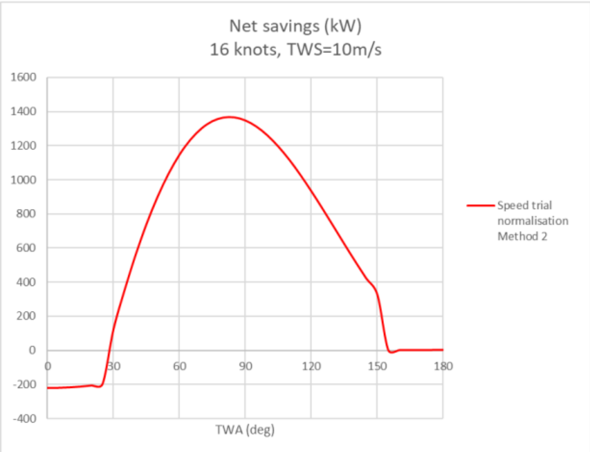
1. Ensure that the output of the speed-power prediction program is equal to the Baseline curve (the ship's calm water speed-power curve at the actual loading condition, without rotor)
2. As described earlier, each run from the speed trial is corrected for wind, temperature. Anyhow, there is some deviation between the measured points and the Baseline curve. The remaining part can be wave resistance, fouling, or something else. This remaining part, now denoted "added resistance", is derived for each single run *without* rotor by adjusting the resistance in the speed-power prediction program until the output speed, and power is equal to the speed and corrected power from the trial evaluation.

3. It is now assumed that this “added resistance” is the equal for the run *with* rotor as for the corresponding run *without,* for the run-pairs with same heading.
4. The speed-power program is used again to find the resistance (i.e. the total force in the ships longitudinal direction) that match the speed and corrected power for the runs *with* rotor. The difference in longitudinal force between the run with and without rotor, when the “added resistance” is subtracted from both, that is the rotor thrust, *T*.
5. The thrust coefficient is derived by

$$C_t = \frac{T}{\frac{1}{2}\rho_a \cdot H \cdot D \cdot AWS^2} \qquad (5)$$

6. Ct is regressed against AWA using a second order polynomial. The result is shown in Appendix 1, Figure 8
7. For the nominal condition (ship’s speed 16 knots, TWS_{10m}=10m/s, air temperature 15 deg), the apparent wind is computed for a range of wind directions, and the rotor thrust *T* is computed using the C_t-polynomial.
8. 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 (3).
9. The speed power prediction program is executed both with and without the rotor thrust (entered as a reduction of resistance) and at the nominal speed. The difference in the resulting power is denoted Gross Power Saving. This represents the hydrodynamic power saving.
10. The rotor power consumption, stated by the rotor provider to be 99kW at full rate of rotation, is subtracted from the Gross Power Saving to give the Net Power Saving. It is assumed that this number include transmission efficiency.
11. Finally, the net saving is compared to the calm water baseline curve to give the percentage power gain.





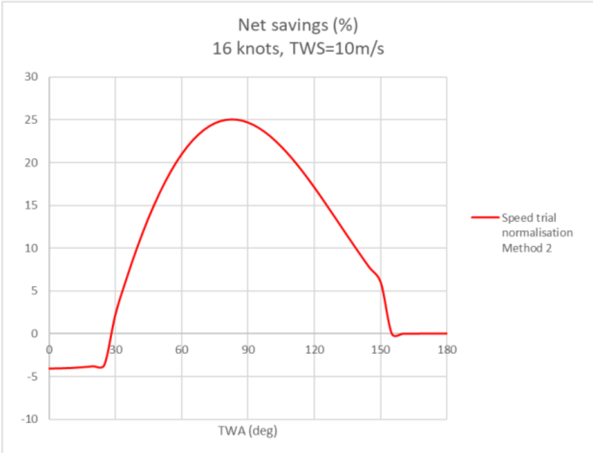


Figure K. Power savings derived with normalization method 1 and 2 at nominal conditions. Reference speed 10m/s at 10m above sea, corresponds to 12 m/s at the mid-span of the rotor.

4.4 Rotor performance

Using the normalisation method 2 described above, it is possible to predict the power saving at arbitrary wind speeds and directions.

4.5 Discussion of rotor performance

The performance of a Flettner rotor is often presented as lift over spin ratio, derived either by CFD or wind tunnel test. Figure L shows the lift curves for a rotor of the actual aspect ratio derived with full scale CFD simulations (Li, 2011). The CFD methodology has earlier been compared to wind tunnel measurement with satisfactory agreement.

The CFD simulations models the rotor standing on a symmetry plane, i.e without any ship hull. From earlier experience of similar projects, the performance if a Flettner rotor standing on a ship hull is quite difference from that of a rotor standing on a symmetry plane or on a floor in a wind tunnel. This has also been described in recent literature. Vahs (2019) reports an increased performance compared to the ideal case for a rotor positioned in the bow of a coaster. Jones (2019) on the other hand, observed decreased performance when placing rotors on tanker ship hull. Jones observed a that the reduction was worst at beam wind and less for the smaller apparent wind angles. This is in line what SSPA has experience in a number of commercial projects.

There are several phenomena that cause this difference. The most dominating is that the presence of the hull both change the flow direction and magnitude at a significant height over the deck. From our experience, the effect is more severe in following wind to beam wind, and reduces for the wind directions closer to bow. At closed haul (forward quarter), the flow disturbance can even be beneficial for the rotor performance, compared to the free stream. The flow is accelerated and bent so that the effective angle of attach is increased.

Another part of the hull-rotor interaction is the effect of the rotor onto the hull. CFD simulations reveals that the rotor changes the flow and the pressure distribution onto the hull, which creates a difference in the hull resistance.

The hull-rotor effects are highly dependent on the hull form and difficult to generalise. They can be studied with CFD simulations of the complete hull and rotor system. However, such simulations are rather time consuming and requires complex meshing. The present speed trial results offers another chance to study the hull effect.

Th red squares in Figure L shows the lift coefficient derived from the present speed trial results. To derive the lift force, both thrust and side force is required, but the latter is not possible to determine from the speed trial. To get around this problem, the Cl/Cd relation is taken from the CFD case. This is obviously a simplification and therefore, the lift curve in Figure L should be used as an interesting illustration only.

The number above the red squares gives the apparent wind angle. For the wind directions closer head wind (22 and 47), the derived rotor lift is close to the ideal case. As the wind direction approaches beam wind, the performance decreases compared to the ideal case. This is hence in line with the reported observations mentioned above. Figure M compares the rotor force in the ship's longitudinal direction, i.e. driving forces. This illustrates clearly the increasing negative effect of the hull compared to the ideal rotor, and that the effect seams to peak around beam wind (apparent wind angle 90 degrees).

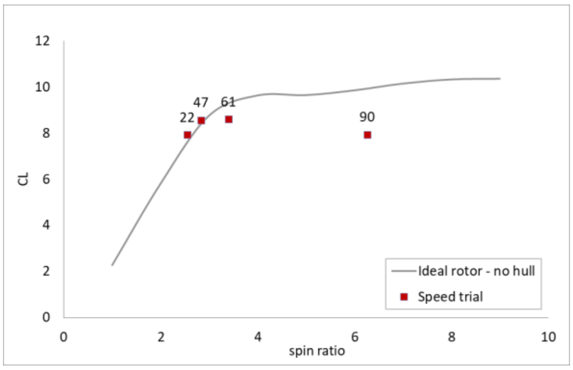


Figure L. Estimated Cf (lift). Numbers above the speed trial points gives the apparent wind angle.

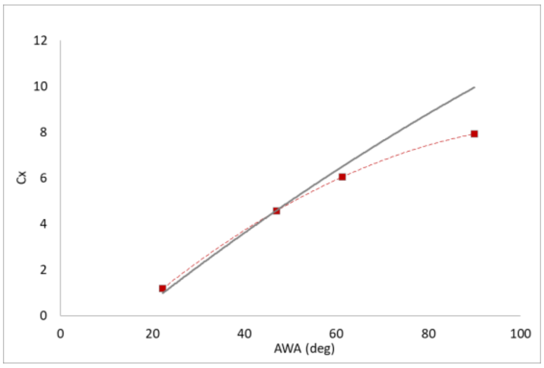


Figure M. Estimated Cx (force in the ship's longitudinal direction).

5 Yearly fuel saving

5.1 Route analysis method

The following sections describe the methodology applied to estimate the power saving due to the rotor for the given route.

In short, the procedure is outlined as follows:

- Preparation of digital models of the ship, propeller and rotor.
- Predict the required power to reach the intended speed for a matrix of environmental conditions, using a in-house Velocity Power Prediction (VPP) program. The VPP model is presented in section 5.2.
- Assembly statistics of the possible environmental conditions that the vessel may encounter along the route over time.
- Route simulations by performing a statistical analysis using Monte Carlo technique simulations over combinations of environmental conditions along the route to estimate statistical properties of route energy requirement.

Limitations and assumptions

The methodology entails the following limitations and assumptions:

- 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.

5.2 Power prediction model

For each unique environmental condition encountered by the vessel it is necessary to predict the power requirement to reach the intended speed. Essentially, a quasi-static force equilibrium is to be found at the intended speed where propulsive and rudder forces are in equilibrium with hydrodynamic and aerodynamic forces. This equilibrium equation is set up in 4 DOF (Degrees of Freedom) including surge, sway, roll and yaw as follows:

$$[Fx, Fy, Mx, Mz] = f(n, \delta, \varphi, \psi)$$

Where $[Fx, Fy, Mx, Mz]$ are total force and moment residuals on the vessel in surge, sway, roll, and yaw respectively, n is the propeller rpm, δ is the rudder angle, φ is the heel angle and ψ is the leeway angle. The problem is a multi-dimensional root-finding problem and is solved iteratively, ultimately finding the required input parameters to generate a zero vector as output.

The function f consists of a set of force calculation routines, each one responsible for calculating a subset of the total force acting on the vessel given the current input parameters. The following force calculation routines has been used in this project:

- **Calm water resistance**

Calm water resistance is calculated using an assumed total efficiency η_D with data based on model test power predictions (HSVA 2011).

- **Added resistance in waves**

Spectral superposition of R_{AW} (found from model tests in regular waves from SSPA database) and wave spectrum (ITTC) to find mean added resistance in an irregular sea state.

- **Manoeuvring and rudder forces**

Manoeuvring forces based on bis system model in Norrbin (1970). The forces on the hull and rudder due to drift and rudder angles are introduced in the ship simulation tool in terms of manoeuvring coefficients. The manoeuvring coefficients used is extracted from SSPAs database of manoeuvring model tests.

- **Hydrostatic forces**

Righting heeling moment. Based on hydrostatic data for the specific loading condition.

- **Propulsive forces**

Thrust and induced lateral force from propeller calculated by interpolation in $K_T(J)$ an $K_Q(J)$ curves from model tests (HSVA 2011):

  - Advance ratio J = V/nD
  - Thrust T = $\rho D^4 K_T n^2$
  - Torque Q = $\rho D^5 K_Q n^2$

where n = propeller rate (rps)
D = propeller diameter (m)
ρ = density of water (kg/m^3)

- **Superstructure aerodynamic forces**
  Wind tunnel coefficients for similar vessel from SSPA database.

- **Generic rotor sail model**

A quasi-static force model of a generic rotor sail is used for the route simulations in this report

- Apparent wind is calculated, including effects from the Atmospheric Boundary Layer (ABL) in accordance with ITTC recommended profile (ITTC 1984).
- Rotor force coefficients are derived as detailed in Section 5.3.
- Force contribution in vessel coordinate system is calculated based on apparent wind, aerodynamic coefficients and geometry

5.3 Rotor model

The rotor model is derived with the following process:

The starting point is lift and drag curves for a rotor of the actual aspect ratio derived using full scale CFD simulations (Li, 2011). In these CFD simulations, the rotor is standing on a symmetry plane, i.e without any ship hull. As described above, the hull influences the rotor performance in varying degree depending on wind direction. Therefore, the ideal rotor model needs to be tuned to the measured speed trial results. This is done by multiplying the force coefficient C_x of the ideal rotor with a correction factor *c*, which is a function of apparent wind direction.

The correction function derived as a second order polynomial curve fit which coefficients are found by minimizing the difference between the tuned rotor thrust force and the thrust force from the regression of the speed trial results (se section 4.3). Figure N shows the result of the optimization.

The same correction is applied to the side force, assuming that the ideal rotor Cl/Cd is preserved. This is an assumption, but since side forces is not measured at the speed trial, it is the best possible assumption. However, the magnitude of the side force has only a marginal effect on the power gain for the current case.

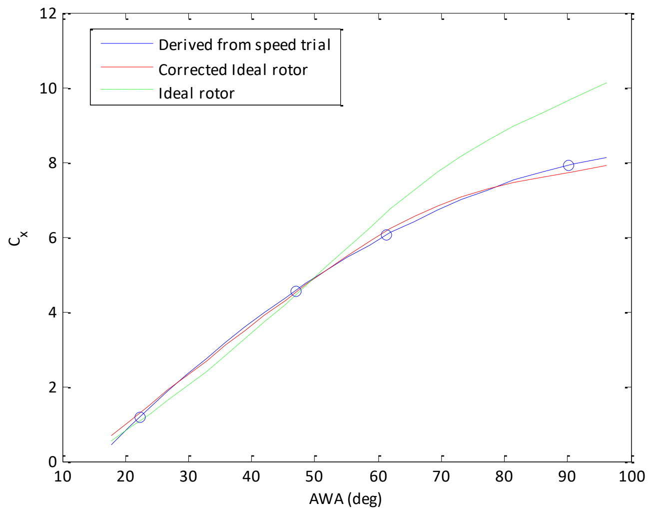


Figure N. Derivation of tuned rotor sail model

5.4 Operational conditions for route simulation from Gedser to Rostock

The route analysis is carried out for the following conditions:

- Fixed speed 16 knots, which is the ship's service speed
- Loading condition T=5.3 m.
- Density air 1.24 kg/m^3
- The route between Gedser and Rostock is divided into five legs (Figure O). 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.
- Statistical wind distribution for the area is obtained from the Copernicus Climate Data Store (https://cds.climate.copernicus.eu).
- The rotational speed of the rotor is set based on interpolation in tabular values provided by Norsepower.
- The power required to operate the rotor is calculated based on information from Norsepower.

Figure O The route between Gedser-Rostock

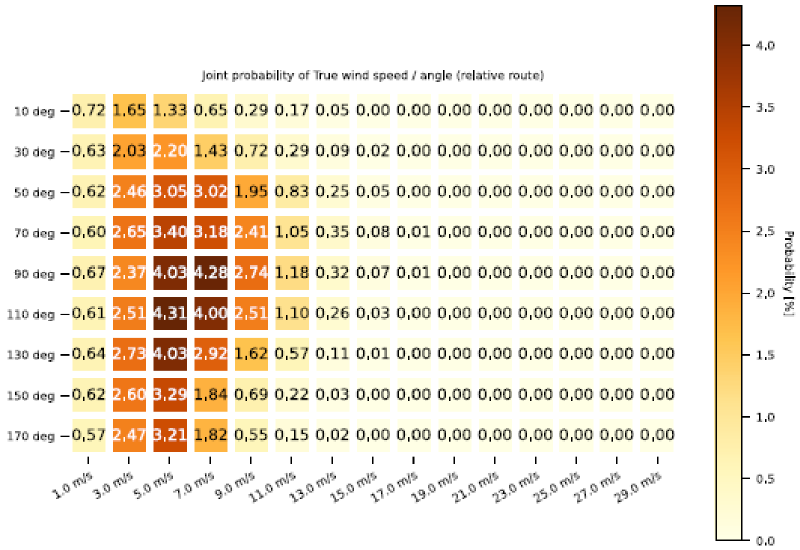


Figure P The probability of true wind speed between Gedser and Rostock.

5.5 Results

5.5.1 Validation of the ship and rotor sail model in the VPP simulations

The following steps (similar to the steps in section 4.3) are performed to validate the ship and rotor model in the VPP simulations:

1. The speed-power prediction in the VPP simulations is compared to the Baseline curve (the ship's calm water speed-power curve at the actual loading condition, without rotor, earlier derived by Scandlines based on full scale trials)
2. For the nominal condition (ship's speed 16 knots, TWS10m=10m/s, air temperature 15 deg), the apparent wind is computed for a range of wind directions, and the rotor thrust T is using the rotor sail model in the digital VPP simulation model.
3. 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 (3).

4. The speed power predictions are executed both with and without the rotor thrust at the nominal speed. The difference in the resulting power is denoted Gross Power Saving. This represents the hydrodynamic power saving.

Figure Q shows the rotor thrust derived with normalization method 2 and route simulation model at nominal conditions.

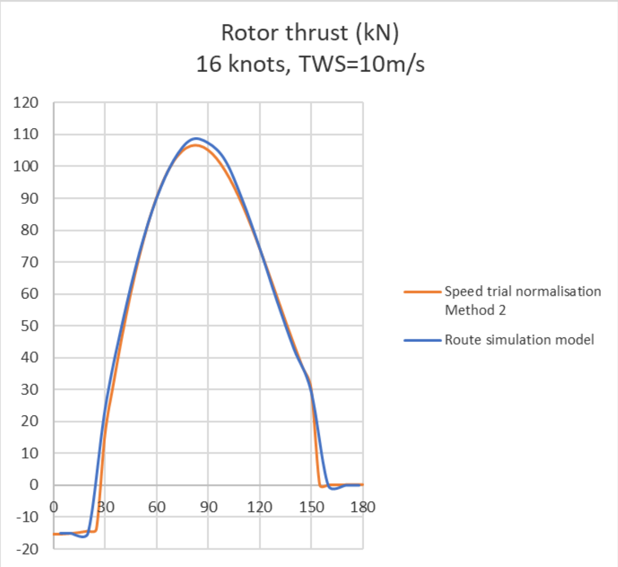


Figure Q Rotor thrust derived with normalization method 2 and route simulation model at nominal conditions.

Figure R shows the gross savings (without considering the energy consumption of the rotor) with normalization method 1 and 2 and route simulation model at nominal conditions. This shows that the digital model for the route analysis is well fitted to the sea trial results.

Figure R Gross savings with normalization method 1 and 2 and route simulation model at nominal conditions.

Figure S shows the net power savings a various wind speeds including the power consumption from spinning the rotor for a variation of true wind speeds and angles.

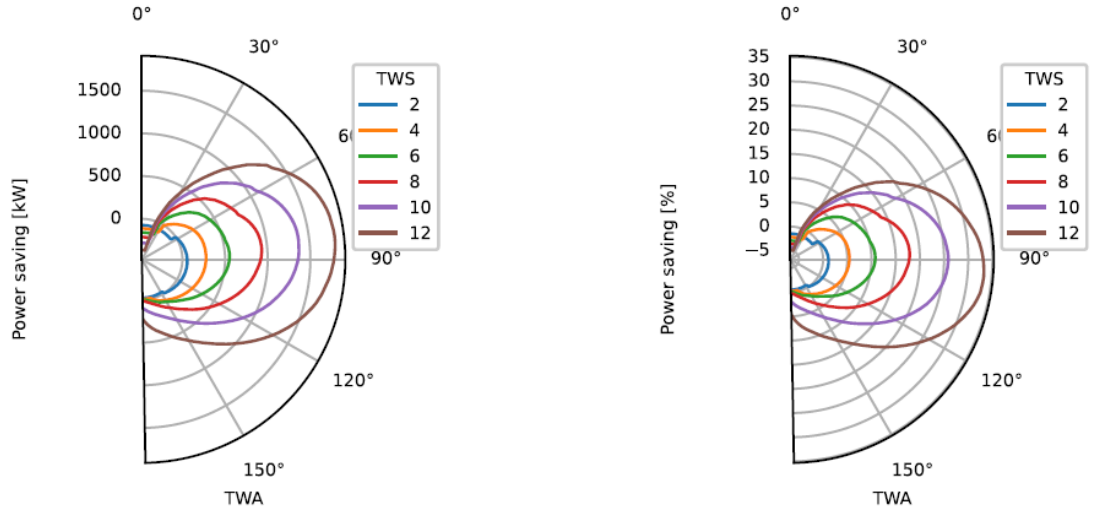


Figure S. Net power saving at various wind speeds.

5.5.2 Power saving on the route

It is estimated that the ideal power reduction due to the Flettner rotor is around 375 kw including the power requirement of spinning the rotor. This corresponds to around 7%, when considering only the sea legs and with 100% operability.

6 Discussion on evaluation methodology

6.1 The use of double runs in the speed trial

Normally, the main objective of a speed trial is to measure the ship's speed through water (STW). It is a well-known fact that many ship speed logs are inaccurate. For that reason, standard speed trial procedures require that the ship's speed is measured using a GPS. The speed from a GPS is however the speed over ground (SOG), and not speed through water. In areas with tidal or ocean current, difference is substantial. As a mean to correct for the current, standard speed trials are always conducted by measuring the speed over ground during two runs with reciprocal headings, so called double runs. The current is corrected for by the so called "Means of means" method or the "Iterative method".

A condition for this to work is that the power is same for both runs and that the added resistance due to wind and waves can be estimated and corrected for. In the current trial, the Flettner rotor contributes with an additional, unknown, force which magnitude is different between the runs, except for when the wind direction is parallel to the run direction (beam wind).

A solution could be to limit the trial to beam wind cases only. However, it is very important to be able to verify the performance at other wind directions than beam wind. The performance at for example quarterly wind may be the advantage of one technology compared to others. It is the authors opinion that it is better to verify the performance at other wind directions than beam wind to a lower accuracy than for normal speed trials, than not to verify it at all.

Hence, the procedure to conduct double runs is still valuable, but used in a different way as prescribed in the standard procedures. Another advantage of the double run approach is that it limits the spatial extension of trial area, compared to running a series of runs with the same heading. The advantage is that the spatial variation of environmental conditions and water depth is limited.

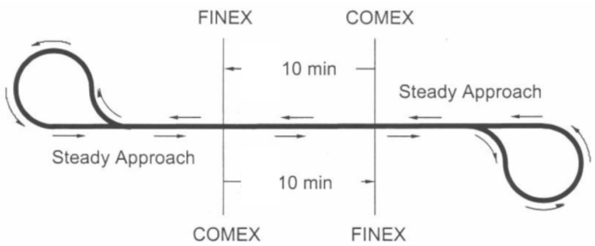


Figure T. Trial trajectory of one double run (ITTC 2017)

6.2 Rotor evaluation based on single runs

The testing principle employed in this project is that single runs *with and without* rotor at the *same wind conditions* are compared. The following list discusses the issues that could disturb the comparison:

- Difference in wind condition for runs that are compared. Figure U and Figure V shows 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 3.4). 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 conservatively estimated to 10% of the air resistance. However, as can be seen in Appendix 1

Figure 6, 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%.

- The waves during the trial caused no ship motions and their contribution to the resistance were assumed small. The wave resistance is assumed to be similar enough between the runs with the same heading.

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

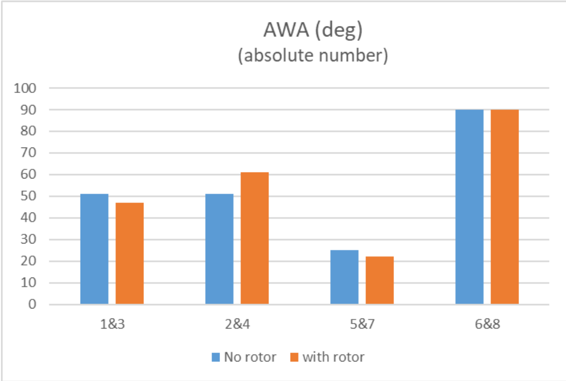


Figure V. Apparent wind angle for pairs of runs with and without rotor.

6.3 Normalization methods

The normalization method 1 is approximate in the following aspects:

1) The propulsive efficiency is not necessarily the same when moving along the power curve (as we do in this correction method) as when effectively reducing the resistance at the same speed (as when adding a rotor at the same speed)
2) Correcting to another ship speed and true wind speed also means that the apparent wind speed and angle is different.

Method 2 also requires assumptions and simplifications:

1) The added resistance due to wind and waves is assumed to be same for the two runs with and without rotor at the same heading, even though the speed is different. This is probably correct of most of the added resistance is wind drag and the true wind is strong. Assuming that the added resistance increases with speed or speed squared only change the prediction marginally, however.
2) The propeller efficiency calculation models only the wing thruster, as that is what was used during the trial. The changed propulsive efficiency of the center propeller is not modelled.

A comparison between the two normalisation methods were presented in Figure K. It shows that they agree well. Method 1 is simple and transparent and does not require any speed-power prediction program as Method 2 does. Therefore, it can be a useful method in praxis.

However, both methods rely on assumptions and model test data. 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.

6.4 Speed trial uncertainty assessment

The bias uncertainty of a speed trial is stated in the ISO 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 (2020) and Insel (2008) to be around 7-8%. However, most of is this uncertainty relates to the fact that there are different sister ships tested, and trials conducted at different occasions.

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 rather an indication of the magnitude of the larger error sources.

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

The largest source of uncertainty is the standard deviation of the log, which was retrieved at too 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. One part is related to fluctuation of the natural wind and therefore, high frequency logging is required. The other part is the disturbance of the hull, which is more problematic as it is very difficult to assess. It is hard to measure the “true” apparent wind hitting the rotor sail, as 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, as Figure F indicates.

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
- Perform the runs at constant (close as possible) speed between the runs instead of constant shaft rate

The analysis leads to the 95% uncertainty interval indicated in Figure W.

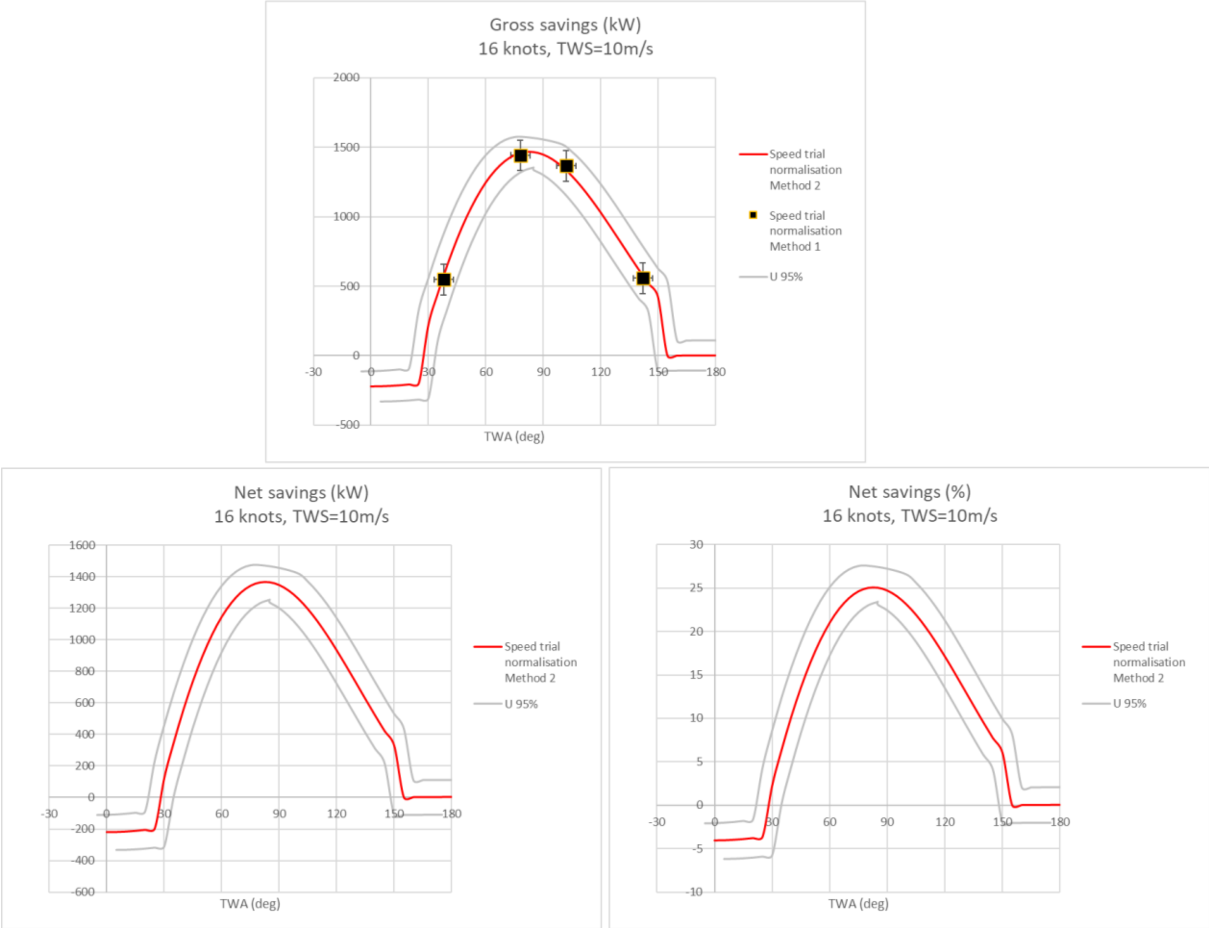


Figure W. Speed trial evaluation with estimated 95% uncertainty interval

6.5 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.

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.

6.6 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.

After a longer period of operation, this report may be updated based on weather statistics and other operational data.

7 Conclusions

A speed trial was performed on m/v Copenhagen in March 2021 with the purpose of verifying the power saving of the Flettner rotor.

The standard ISO/ITTC speed trial procedures were followed to as large extent as possible. In contrast to 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 ship'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.

The speed trial result is scaled up to annual fuel reduction using a ship simulation model correlated to the actual speed trial measurements, a voyage prediction tool and statistical weather distribution.

It is estimated that the power reduction due to the Flettner rotor is around 7%, considering only the propulsion power and assuming no idling due to maintenance etc.

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 trial methodology is shown to be a feasible way to perform full scale verification for commercial vessels with wind assistance. 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.

7.1 Recommendations

It is recommended to log the wind speed on the route, the ship's fuel consumption and operability of the rotor for at least one year to complement this study.

8 References

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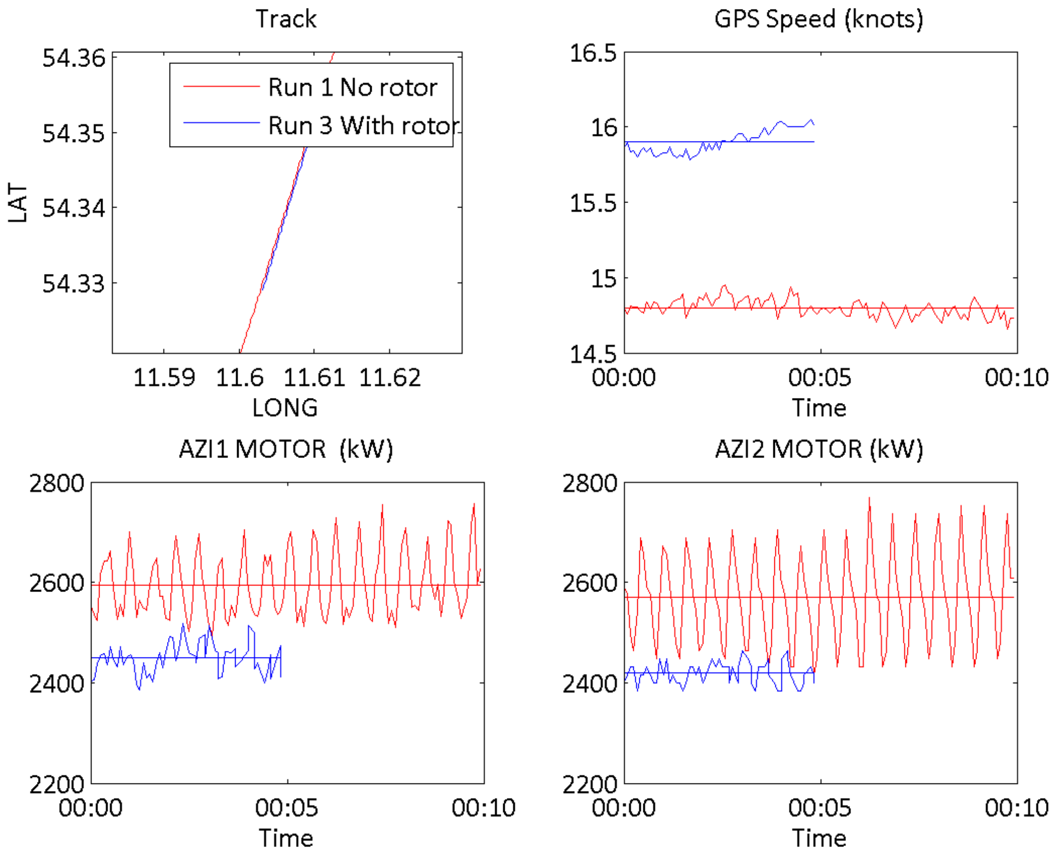
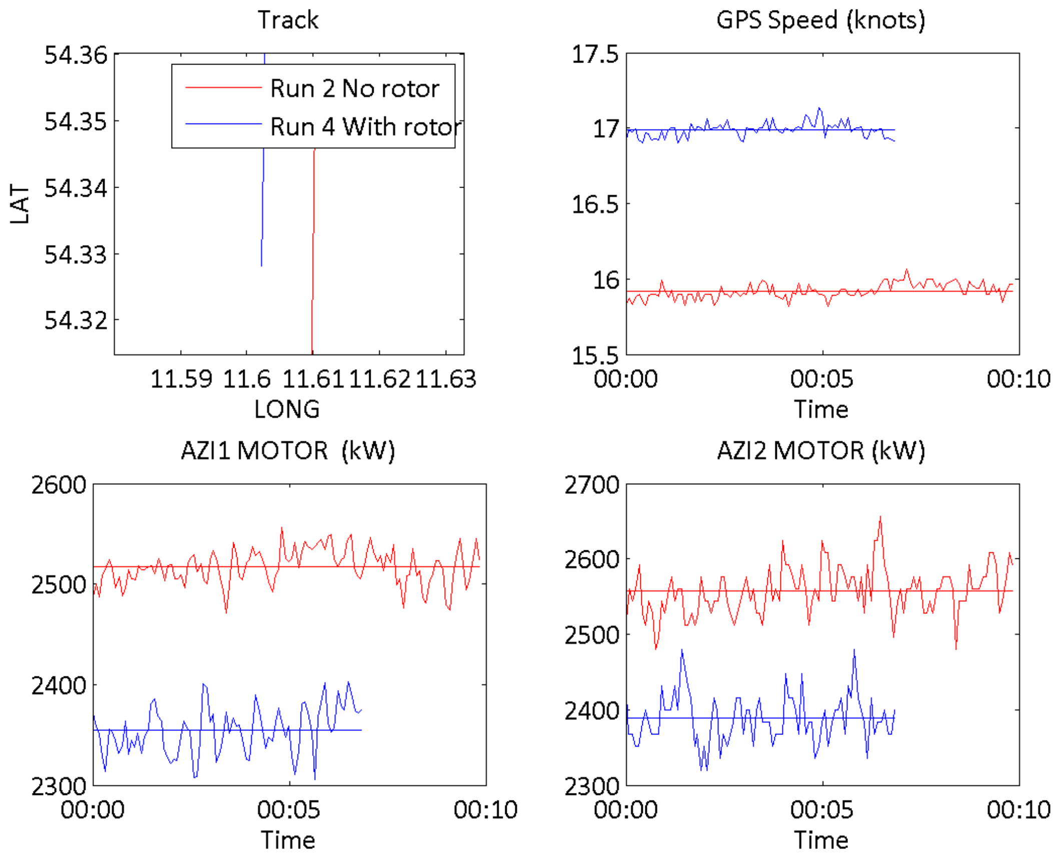
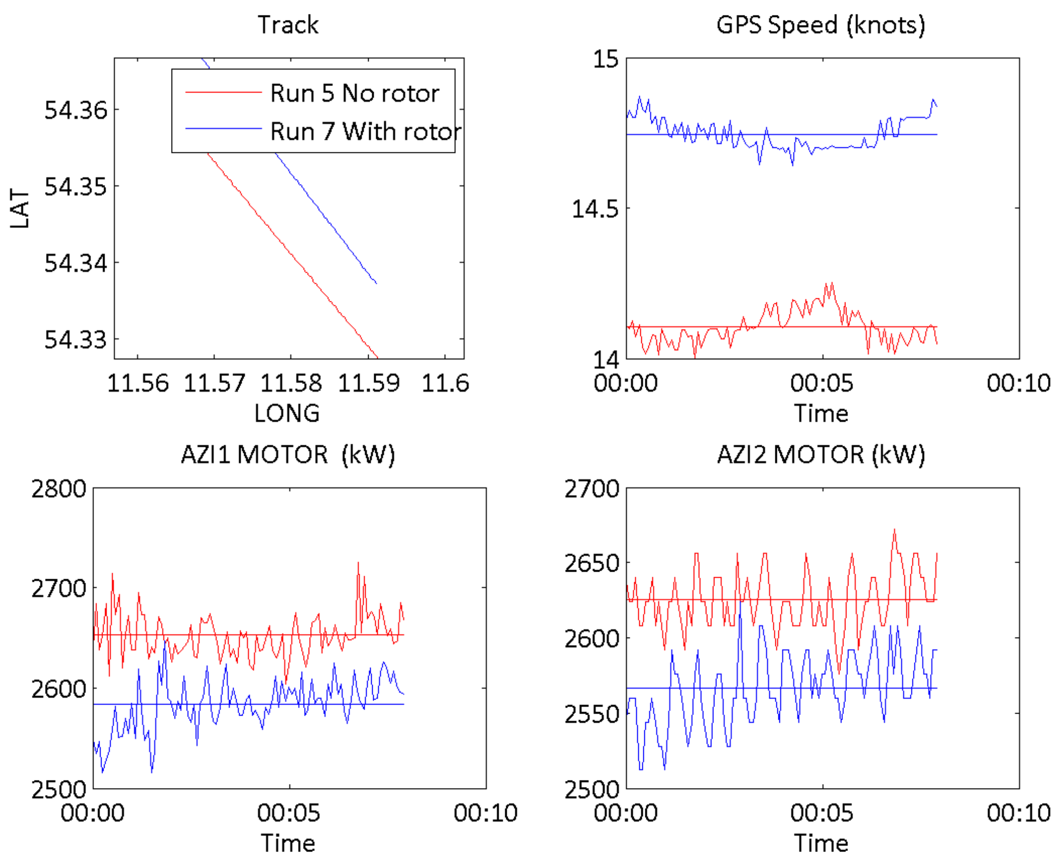
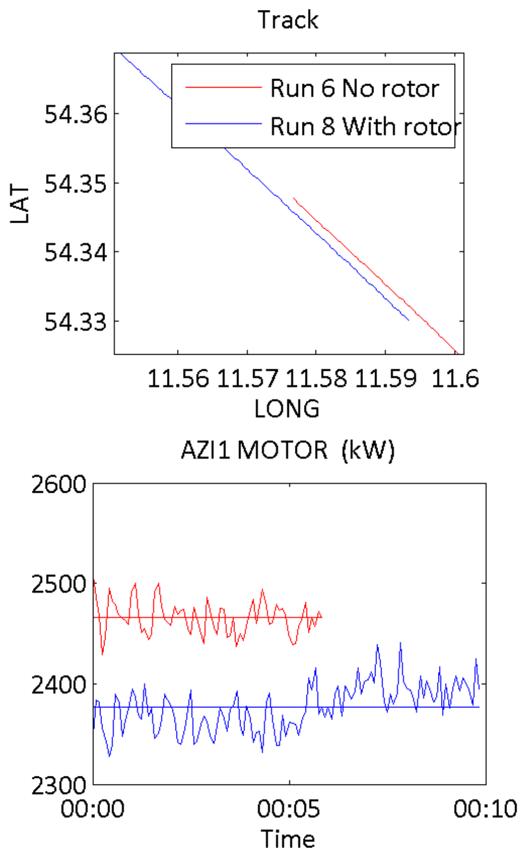
			IMAC			
run	Start	Rotor	SOG knots	COG deg	power kW	shaft rate rpm
1	21:22:00		14.80	10	5165	200
2	22:00:00		15.92	181	5074	200
3	22:35:00	x	15.90	10	4868	201
4	23:16:00	x	16.99	181	4743	201
5	23:51:00		14.10	334	5278	200
6	00:24:00		16.32	148	4964	201
7	01:02:00	x	14.75	336	5150	200
8	01:37:00	x	16.72	148	4790	201

	Manual reading			Anemometer		Rotor Instrument
run	Logg knots	Heading deg	rotor rotation rpm	AWA deg	AWS m/s	rotor consumption kW
1	14.88	5		301	10.8	0.2
2	15.95	185		61	11.8	0.2
3	16.03	5	170	309	14.0	92.6
4	17.15	185	170	70	12.8	92.0
5	14.49	330		333	15.3	0.2
6	16.16	150		105	7.8	0.2
7	15.08	330	170	334	14.6	94.1
8	16.47	150	158	114	7.4	78.9


Track
54.36
54.35
54.34
54.33
LAT
11.59
11.6
11.61
11.62
LONG
Run 1 No rotor
Run 3 With rotor
GPS Speed (knots)
16.5
16
15.5
15
14.5
00:00
00:05
00:10
Time
AZI1 MOTOR (kW)
2800
2600
2400
2200
00:00
00:05
00:10
Time
AZI2 MOTOR (kW)
2800
2600
2400
2200
00:00
00:05
00:10
Time


Track
Run 2 No rotor
Run 4 With rotor
LAT
LONG
54.36
54.35
54.34
54.33
54.32
11.59 11.6 11.61 11.62 11.63
GPS Speed (knots)
17.5
17
16.5
16
15.5
00:00 00:05 00:10
Time
AZI1 MOTOR (kW)
2600
2500
2400
2300
00:00 00:05 00:10
Time
AZI2 MOTOR (kW)
2700
2600
2500
2400
2300
00:00 00:05 00:10
Time

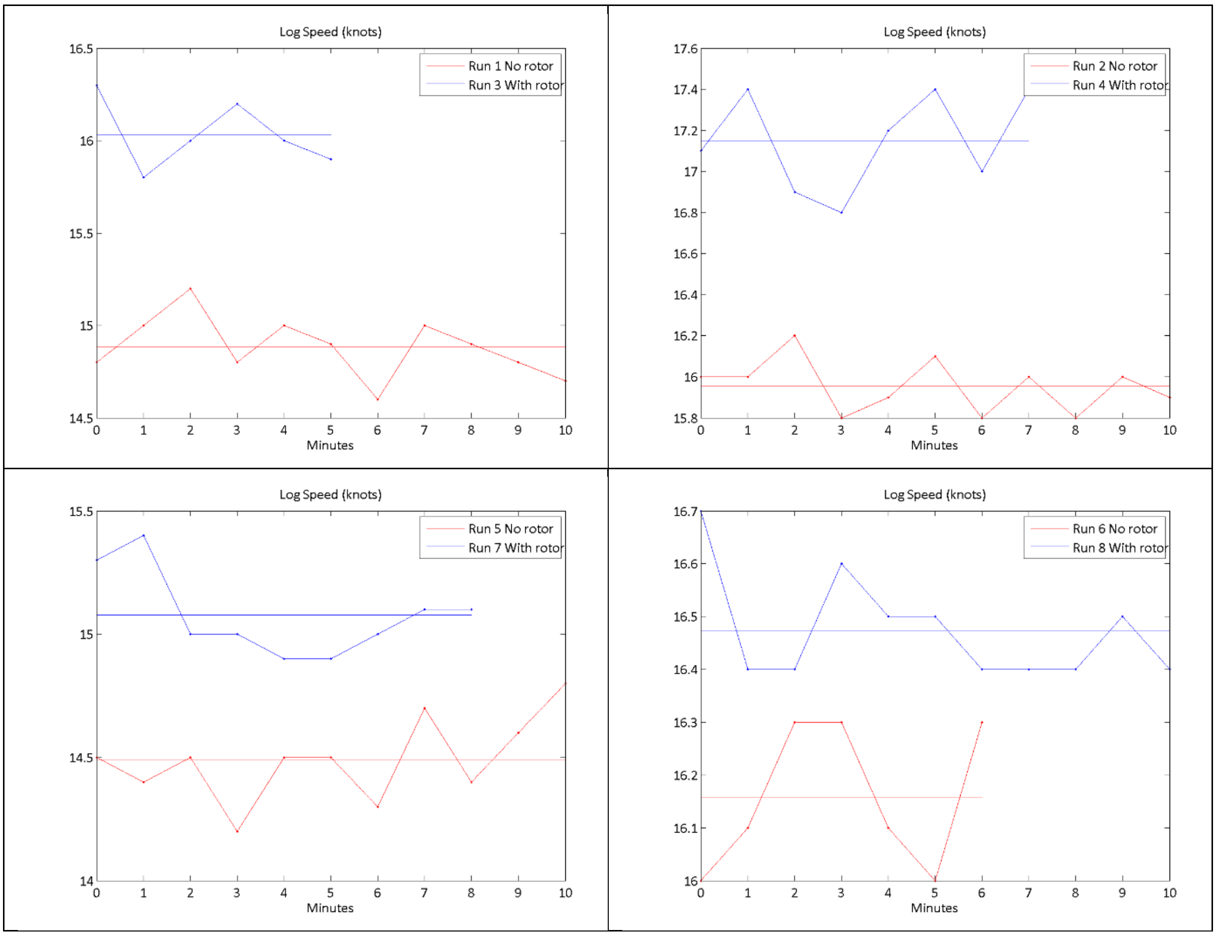

Track
Run 5 No rotor
Run 7 With rotor
LAT
54.36
54.35
54.34
54.33
11.56 11.57 11.58 11.59 11.6
LONG
GPS Speed (knots)
15
14.5
14
00:00 00:05 00:10
Time
AZI1 MOTOR (kW)
2800
2700
2600
2500
00:00 00:05 00:10
Time
AZI2 MOTOR (kW)
2700
2650
2600
2550
2500
00:00 00:05 00:10
Time

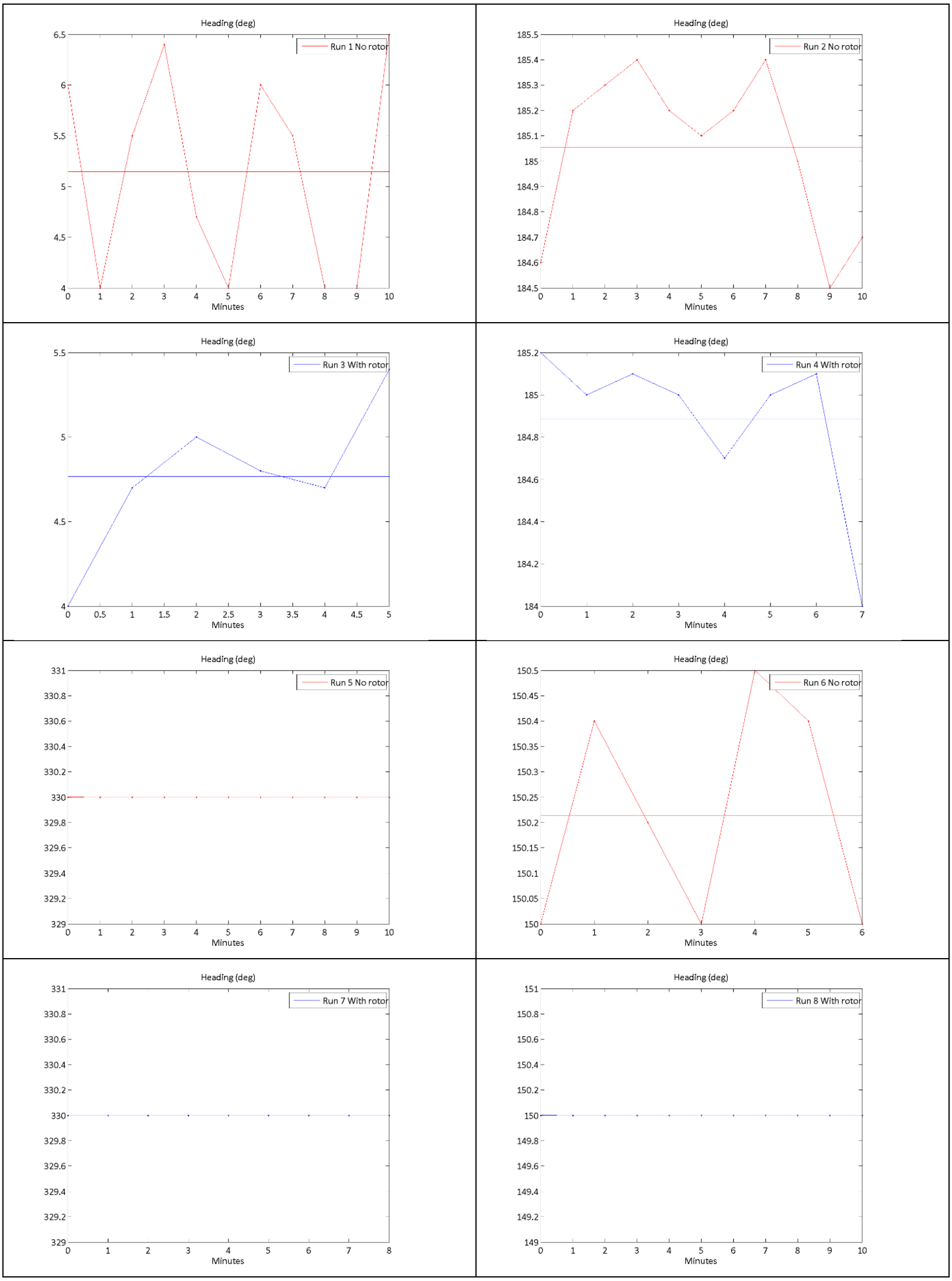

Track
Run 6 No rotor
Run 8 With rotor
LAT
54.36
54.35
54.34
54.33
11.56 11.57 11.58 11.59 11.6
LONG
GPS Speed (knots)
17
16.5
16
00:00
00:05
00:10
Time
AZI1 MOTOR (kW)
2600
2500
2400
2300
00:00
00:05
00:10
Time
AZI2 MOTOR (kW)
2600
2500
2400
2300
00:00
00:05
00:10
Time

Manual readings – speed through water

Appendix: 1

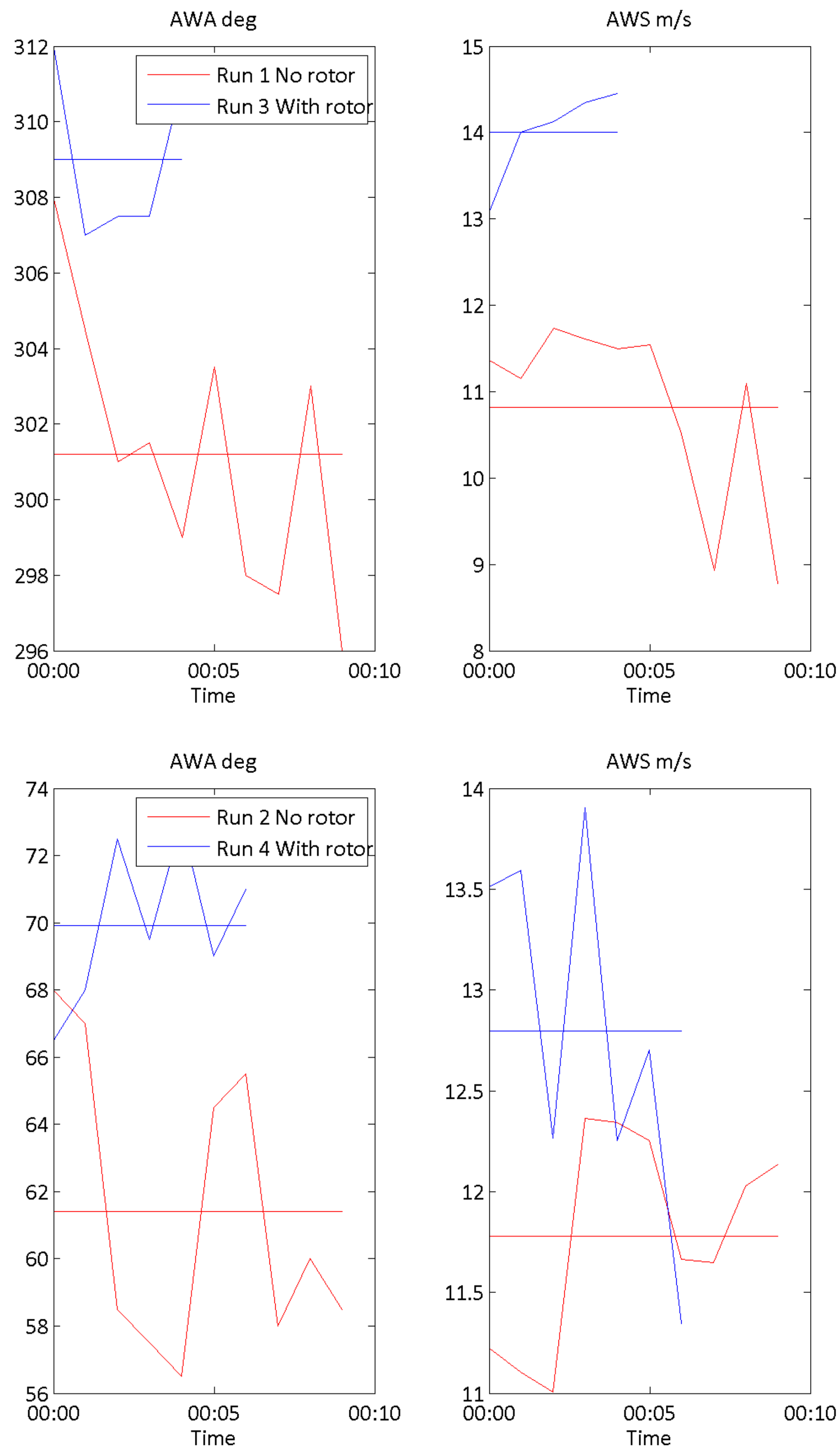
Figure: 3




Heading (deg)
Run 1 No rotor
Minutes
Heading (deg)
Run 2 No rotor
Minutes
Heading (deg)
Run 3 With rotor
Minutes
Heading (deg)
Run 4 With rotor
Minutes
Heading (deg)
Run 5 No rotor
Minutes
Heading (deg)
Run 6 No rotor
Minutes
Heading (deg)
Run 7 With rotor
Minutes
Heading (deg)
Run 8 With rotor
Minutes

Appendix: 1

Figure: 5a



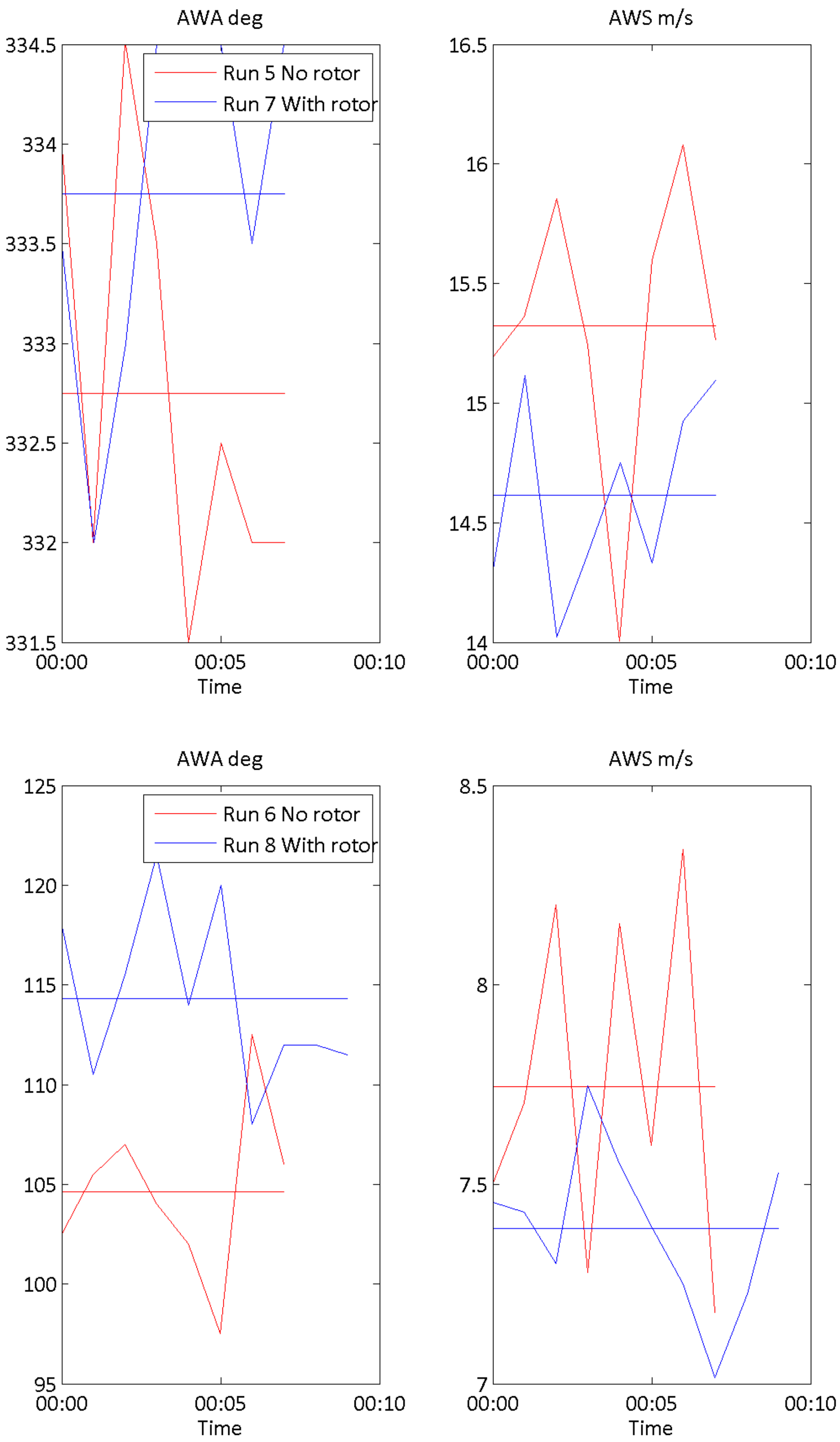

AWA deg
334.5
334
333.5
333
332.5
332
331.5
Run 5 No rotor
Run 7 With rotor
00:00
00:05
00:10
Time
AWS m/s
16.5
16
15.5
15
14.5
14
00:00
00:05
00:10
Time
AWA deg
125
120
115
110
105
100
95
Run 6 No rotor
Run 8 With rotor
00:00
00:05
00:10
Time
AWS m/s
8.5
8
7.5
7
00:00
00:05
00:10
Time

Figure: 6a

Ship particulars		**Propulsion particulars**	
SSPA hull no.	CPH	SSPA propeller no.	x
Length L_{PP} [m]	156.45	Number of propellers	3
Length L_{WL} [m]	156.00	Number of blades (each)	
Beam B [m]	24.80	Propeller diameter [m]	
Cb [-]	0.585	Pitch ratio [-]	
C_p [-]	1.00	C_n [-]	1.000
ESD	no	MCR [kW]	14400

Loading condition	**Baseline**	**Sea trial**	**Warnings**
Displacement [metric tonnes]	12186	11581	Dev. of displacement: 4.97% > 2%
Draft at aft perpendicular (T_A) [m]	5.30	5.25	
Draft at forward perpendicular (T_F) [m]	5.30	5.20	
Transverse projected area‡ (A_T) [m²]	500	500	

Nomenclature of environmental parameters					
GWA	Global wind angle	$H_{W1/3}$	Significant height of local wind driven waves	h	Water depth
AWA	Aparent wind angle	θ_{WT}	True wave direction	ρ_{air}	Density of air
AWS	Aparent wind speed	θ_{SR}	Relative swell direction	ν_{water}	Kinematic viscosity of sea water
TWS	True wind speed	θ_{ST}	True swell direction	ρ_{water}	Density of sea water
TWA	True wind angle	$H_{S1/3}$	Significant height of local swell	T_{water}	Water temperature
T_{Wm}	Mean wave period	T_{Sm}	Swell period	T_{air}	Air temperature
		θ_{WR}	Relative wave direction		
Remarks: Relative directions are defined clockwise from bow. All wave and wind directions are defined as the direction the waves or wind come from. 0º=from the bow.					

Figure: 6b

Environment			
Air temperature [deg C]	3.0	Water temperature [deg C]	3
Air density [kg/m^3]	1.279	Water density [kg/m^3]	1012
Water depth [m]	1000		

Onboard measurements					
Run	Time	Heading [deg]	V_S (SOG) [knots]	Shaft rate [1/min]	P_d [kW]
1	00:22:00	5	14.79	200.3	5113
2	01:00:00	185	15.86	200.5	5024
3	01:34:59	5	15.94	201.0	4819
4	02:15:59	185	17.06	201.1	4696
5	02:51:00	330	14.40	200.2	5225
6	03:24:00	150	16.07	200.8	4915
7	04:02:00	330	14.98	200.5	5099
8	04:36:59	150	16.38	201.0	4742

Measured or observed wave data						
Run no.	$H_{W1/3}$ [m]	T_{Wm} [s]	θ_{WR} [°]	$H_{S1/3}$ [m]	T_{Sm} [s]	θ_{SR} [°]
1	0.0	-	-	0.0	-	-
2	0.0	-	-	0.0	-	-
3	0.0	-	-	0.0	-	-
4	0.0	-	-	0.0	-	-
5	0.0	-	-	0.0	-	-
6	0.0	-	-	0.0	-	-
7	0.0	-	-	0.0	-	-
8	0.0	-	-	0.0	-	-
Remarks: If wave or swell directions are missing, the program will use the true wind directions and ship headings to calculate the relative wave direction.						

Figure: 6c

Wind at the height of anemomenter					
Run no.	AWS [m/s]	AWA [deg]	TWS [m/s]	TWA [deg]	GWA [deg]
1	10.82	-59	9.47	-102	263
2	11.78	61	10.64	104	289
3	14.00	-51	10.90	-87	278
4	12.80	70	12.79	110	295
5	15.32	-27	9.37	-48	282
6	7.79	105	12.73	144	294
7	14.61	-26	8.42	-50	280
8	7.39	114	13.30	150	300

Wind at the height of anemomenter - averaged over double runs					
Run no.	AWS [m/s]	AWA [deg]	TWS [m/s]	TWA [deg]	GWA [deg]
1	12.57	-51	9.80	-88	277
2	12.59	51	9.80	92	277
3	15.67	-47	11.72	-78	287
4	13.06	61	11.72	102	287
5	17.25	-25	10.99	-41	289
6	7.27	90	10.99	139	289
7	17.44	-22	10.71	-38	292
8	6.60	90	10.71	142	292

Wind at reference height					
Run no.	AWS [m/s]	AWA [deg]	TWS [m/s]	TWA [deg]	GWA [deg]
1	11.28	-46	8.13	-88	277
2	11.37	46	8.13	92	277
3	13.99	-43	9.72	-78	287
4	11.63	55	9.72	102	287
5	15.47	-23	9.12	-41	289
6	6.20	77	9.12	139	289
7	15.69	-20	8.88	-38	292
8	5.66	75	8.88	142	292

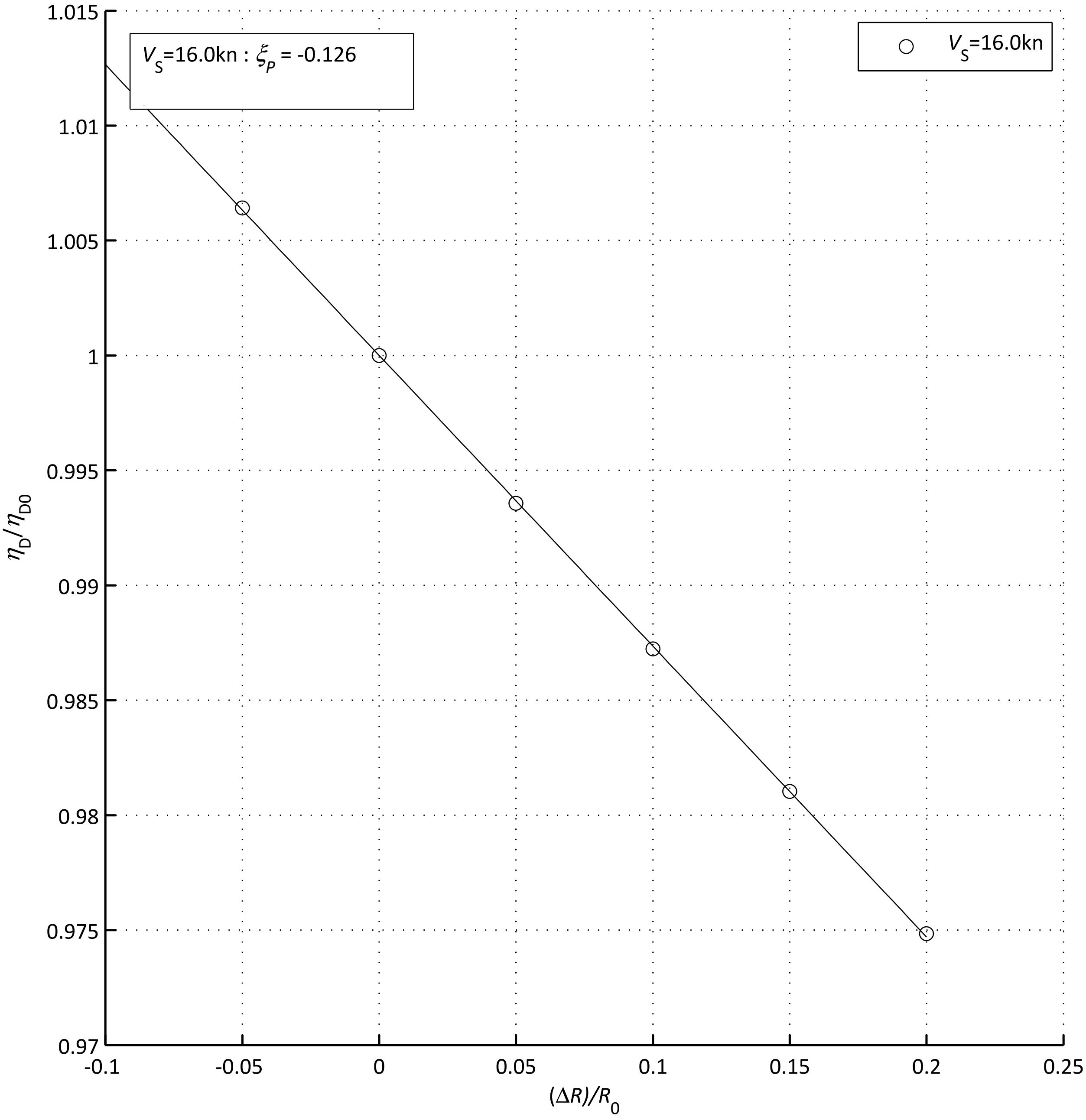
Figure: 6d

Corrections						
Run no.	Wind [kN]	Waves [kN]	Depth [knots]	Temp/Dens [kN]	Idling WPU [kN]	Current [knots]
1	1.1	0.0	0.00	-0.0	3.0	-0.5
2	-0.2	0.0	0.00	0.2	3.0	-0.5
3	11.3	0.0	0.00	0.2	0.0	-0.6
4	-6.1	0.0	0.00	0.4	0.0	-0.6
5	42.6	0.0	0.00	-0.1	11.7	0.8
6	-15.7	0.0	0.00	0.2	0.0	-0.8
7	43.7	0.0	0.00	0.0	0.0	0.7
8	-15.9	0.0	0.00	0.3	0.0	-0.7

Corrections in percent of total resistance							
Run no.	Wind [%]	Waves [%]	Depth [%]	Temp/dens [%]	Idling WPU [%]	Displ. [%]	Eff. [%]
1	0.3	0.0	0.0	-0.0	0.7	-2.5	0.3
2	-0.1	0.0	0.0	0.0	0.7	-2.5	0.3
3	3.3	0.0	0.0	0.0	0.0	-2.5	0.3
4	-1.7	0.0	0.0	0.1	0.0	-2.5	0.3
5	11.7	0.0	0.0	-0.0	3.2	-2.5	0.3
6	-3.8	0.0	0.0	0.0	0.0	-2.5	0.3
7	12.4	0.0	0.0	0.0	0.0	-2.5	0.3
8	-4.1	0.0	0.0	0.1	0.0	-2.5	0.3

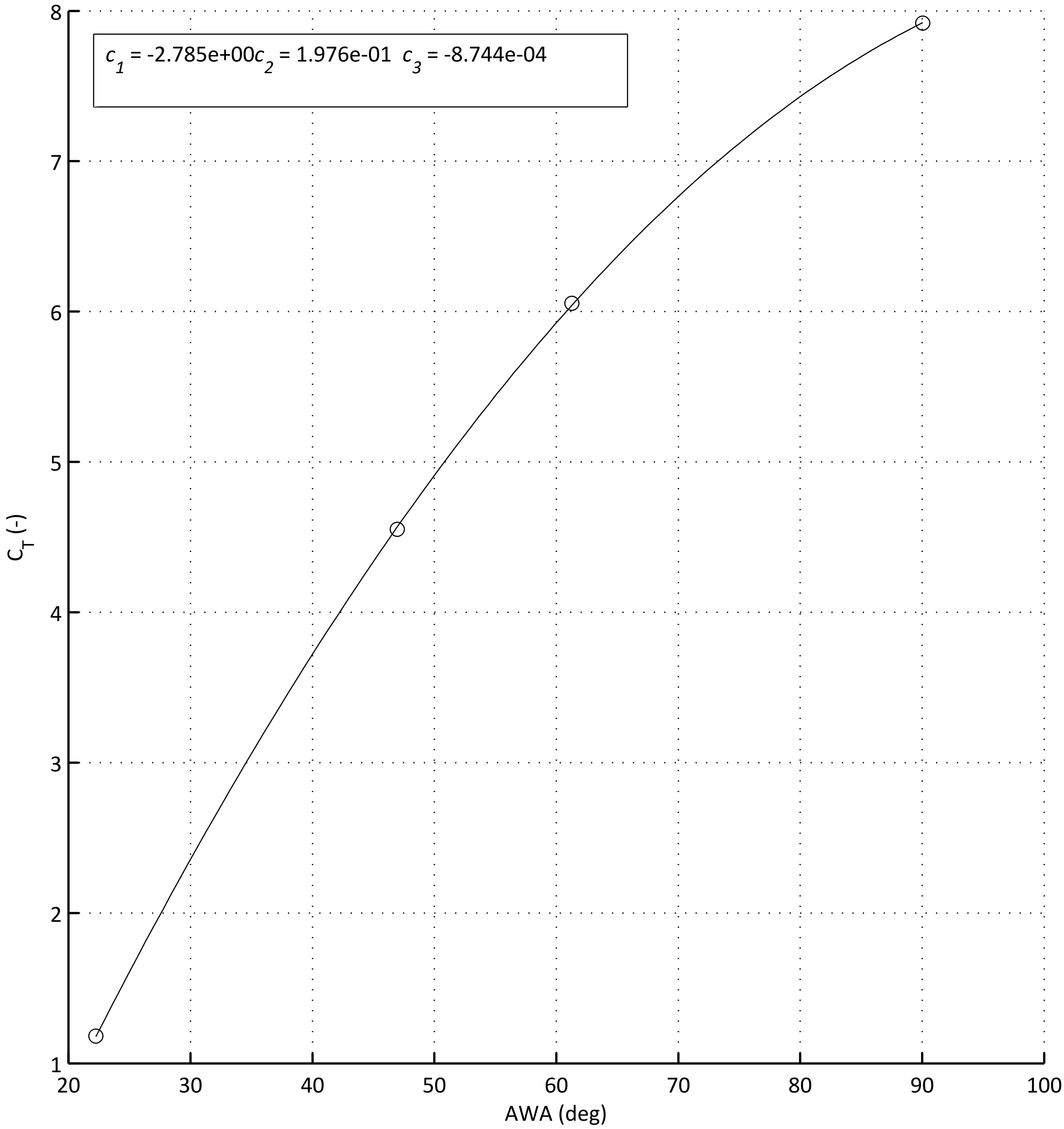
Corrected power	
Run no.	Pdt (ST) [kW]
1	4932
2	4859
3	4535
4	4658
5	4374
6	4993
7	4375
8	4832

Figure: 7



Test series	Virtual load variation	Description		
Ship model	mv Copenhagen	Description		
Loading condition	Design	Length L_{PP}	1.00	m
Propeller model	$HSVA_W$P88-10	Draft fore FP T_F	5.20	m
Scale factor α	1.000	Draft aft AP T_A	5.20	m
Displacement ∇	11581 m^3			

Figure: 8



Test series	Speed trial	Description		
Ship model	m/v Copenhagen	Description		
Loading condition	Design	Length L_{PP}	156.45	m
Propeller model	$HSVA_W$P88-10	Draft fore FP T_F	5.2	m
Scale factor α	1.000	Draft aft AP T_A	5.25	m
Displacement ∇	11581 m^3			