# Sea trials vs prediction by numerical models—Uncertainties in the measurements and prediction of WASP performance



Citation for the original published paper (version of record):
Thies, F., Ringsberg, J. (2025). Sea trials vs prediction by numerical models—Uncertainties in the measurements and prediction
of WASP performance. Journal of Ocean Engineering and Science, 10(2): 239-245.
http://dx.doi.org/10.1016/j.joes.2024.05.001



(article starts on next page)

Journal of Ocean Engineering and Science 10 (2025) 239–245

Contents lists available at ScienceDirect

Journal of Ocean Engineering and Science

journal homepage: www.elsevier.com/locate/joes

# Sea trials vs prediction by numerical models—Uncertainties in the measurements and prediction of WASP performance

Fabian Thies, Jonas W. Ringsberg*

*Chalmers University of Technology, Department of Mechanics and Maritime Sciences, Division of Marine Technology, SE-412 96 Gothenburg, Sweden*

ARTICLE INFO

*Article history:*
Received 8 January 2024
Revised 14 March 2024
Accepted 13 May 2024
Available online 14 May 2024

*Keywords:*
Flettner rotor
Monte Carlo method
Performance prediction
Ship design
Uncertainty
Wind-assisted propulsion

ABSTRACT

Accurately predicting the power saving from wind-assisted ship propulsion is one of the most discussed topics in alternative and complementary propulsion methods. Aero- and hydrodynamic interactions between the sails and the ship increase the difficulty of modelling the propulsion contribution theoretically, but the sensibility of sail performance on the wind conditions increases the demands on measurement accuracy if the performance is to be measured in sea trials. This paper analyses and compares the uncertainties of sea trial tests and model predictions by means of parameter variation and Monte Carlo simulations. The results show that sea trials have an uncertainty of 23 %, well above 100 % of the measured savings, if performed using normal onboard equipment. Model uncertainties were found to be between 6 % and 17 % of the predicted savings.



## 1. Introduction

Wind-assisted propulsion is seen as one of the most promising technologies to radically reduce the emissions from shipping [1,2]. Contrary to alternative fuel solutions, wind-assisted propulsion (WASP) utilizes the energy of the wind, which is freely available at sea and thus does not require shore-based equipment or logistics and is seen as a cost-effective solution [2]. However, there are still barriers that hinder the large-scale application of WASP in shipping, with a lack of knowledge and proven performance being one of them [3]. While conventional propulsion systems only produce thrust, i.e., longitudinal forces, WASP systems also introduce large side forces which complicate the performance prediction of WASP systems, since drift and yaw balance and the associated resistances from rudder action and drifting, must be considered, which requires specially developed models [4]. In numerous studies, such models predicted high fuel savings from WASP systems on ships, e.g. in [5–8]. Some results from models were also validated using full scale measurements over a longer period and showed good agreement [9]. However, measurements of power savings from WASP during short period sea trials to predict the performance and validate the models in a controlled environment have not been established yet, even though sea trials methods for conventional ships are industry standard with well-developed methods [10]. Recently, an effort was made to establish recommended procedures for sea trials of WASP ships [11], and sea trials have been performed for five WASP ships [12–16]. These sea trial tests aim to improve the prediction accuracy of long term fuel savings by measuring the savings in certain conditions, validating and correcting the model predictions and applying the adjusted model to a wider range of conditions and the actual routes of the ships. Naturally, this procedure includes any effects and interactions between the ship and the sails in the predictions which might not be correctly captured by the prediction models. However, measurement uncertainties might significantly reduce the accuracy of the sea trial results. This paper presents a comparison of model prediction and sea trial results for two of the cases mentioned above (M/V Copenhagen and M/V Annika Braren, [12,16]) and evaluates the uncertainties of the measurements and model predictions by means of parameter variation studies and Monte Carlo simulations.

## 2. ShipCLEAN

ShipCLEAN is a generic ship energy performance prediction model developed to provide accurate prediction with very limited input parameters. During the development, the focus was put on generic applicability and accurate prediction of WASP performance. Generic applicability was achieved by relying on empirical, theoretical, and standard series methods. Accurate prediction of WASP performance was achieved by including 4 degrees-of-freedom and a model to predict the aerodynamic interaction of sails between each other and the interaction between sails and the hull. Further, ShipCLEAN includes methods for sail trim optimization. The model

* Corresponding author.
*E-mail address:* Jonas.Ringsberg@chalmers.se (J.W. Ringsberg).

https://doi.org/10.1016/j.joes.2024.05.001

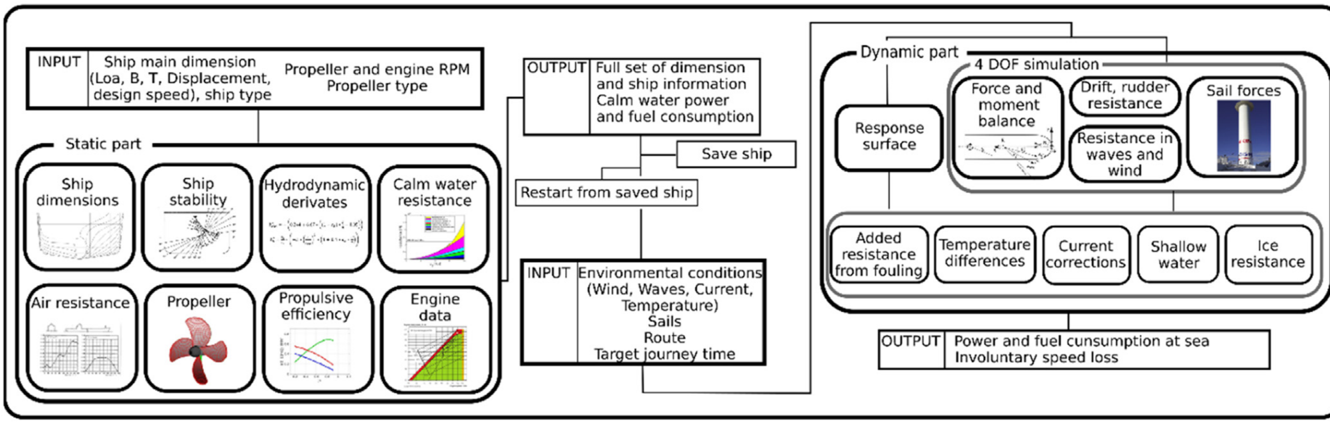


**Fig. 1.** Overview of the ShipCLEAN model.

and the underlying methods are described in detail in [8,17]. An overview of all parts of ShipCLEAN is shown in Fig. 1.

The ShipCLEAN model consists of two parts, a conventional 1 degree-of-freedom power prediction part (static part) and a 4 degrees-of-freedom solver (dynamic part) including the effects of drift, waves, wind, ice, fouling and wind-assisted propulsion to predict the performance of a ship in realistic operational conditions. In this study, the 4 degrees-of-freedom (dynamic part) and especially the wind-assisted propulsion module is used. As for the static part, the dynamic part was developed to be applicable with very limited information about the ship and thus is based on empirical and theoretical methods without using time expensive simulations, e.g., CFD.

The forces from the sails are estimated using lift and drag curves which are based on CFD, model tests and full scale force measurements (see [8,9]). If more than one sail is installed, the sail-sail interactions are modelled using a simplified Navier-Stokes equation, only respecting potential flow effects and predicting the influence of each sail on the wind angle and wind speed at the positions of the other sails. Ship-sail interaction is modelled using a wind speed curve over the height of the ship's deck [8] and a correction curve for the apparent wind angle due to deflection of the flow over the ship's deck [18]. Hydrodynamic side forces and added drag due to drifting are estimated using an adaption of the low-aspect-ratio wing theory and were found to be dominated by the cross flow drag [8]. Studies have shown that this approach gives a good representation of the hydrodynamic forces, even though a large variation of the added drag is expected due to differences in the hull forms of ships [19]. These effects are not modelled in ShipCLEAN, mainly due to the self-inflicted limitation of the available information about the ship. Rudder forces are estimated using common design equations [8]. With all forces and moments evaluated, an iterative 4 degrees-of-freedom solver finds the equilibrium by evaluating the drift, heel, added resistance and rudder angle of the ship to accurately predict the net thrust of the sails, i.e. the thrust of the sails deducted with the added resistance caused by the introduced side forces and yaw moments.

## 3. Sea trial procedure

The sea trials were performed as part of the Interreg WASP project (https://northsearegion.eu/wasp/). Due to differences in the instrumentation, the data acquisition differed for the ships in the WASP project, see Table 1. This study uses two ships from the Interreg WASP project, one RoPax ferry (M/V Copenhagen) and one general cargo vessel (M/V Annika Braren). While the sea trials of the RoPax ship were performed as standard trials in terms of double runs [16], the trials for the general cargo ship were performed as a series of single runs with different wind angles [12]. If double runs are used, the more accurate GPS (Global Positioning System) speed can be corrected for the current influence and thus used for the evaluation. In the case of single runs, the more uncertain speed through water measurements must be used. In both cases, similar runs at similar true wind angles (TWA), true wind speeds (TWS) and ship speeds ($v_S$) were performed with and without Flettner rotors (i.e. rotors at operational rpm or idling). Additionally, the general cargo vessel was not equipped with propeller torque meters, thus the propulsion power ($P_D$) is derived from manual readings of the fuel oil consumption (FOC) of the main engine. The sea trial results were corrected for speed differences during the test runs and normalized to a true wind speed (TWS) of 10 m/s. Detailed information about the correction methods is provided in [12,16].

## 4. Case studies

The particulars of the case study ships and the installed wind-assisted propulsion units are presented in Table 2. The sea trials were performed for both ships and are documented in [12,16]. The predicted and measured propulsion power savings ($\Delta P_D$) over the true wind angle (with 0° TWA defined as headwind) are presented in Fig. 2.

The model prediction and sea trial results agree very well for the RoPax ferry but show rather large differences for the general cargo vessel, especially in downwind conditions. Additionally, considerable differences appeared during several runs in the sea trials, as presented in Fig. 2. As discussed in Section 3, the data acquisition and trial procedure for the RoPax vessel was more accurate and closer to standard sea trial procedure. Thus, the results are assumed to be more certain, and the trial results and model prediction are very close to each other. Naturally, both the trial results and model prediction have their uncertainties for both cases. For the RoPax vessel, the difference between the model predictions and trial results are less than 5 % of the evaluated savings, which is less than what was found as model uncertainty in, e.g., [18]. Thus, this study focuses on the results of the general cargo vessel to explain the spread of the measurements and the difference between sea trials and ShipCLEAN and evaluate if the differences can be explained with the uncertainties or if there are obvious unknown errors.

To study the differences in more detail and to quantify the differences presented in Fig. 2, Table 3 presents the results and conditions for each run of the sea trial tests for the general cargo vessel, including the predicted savings from ShipCLEAN. For better comparability, all cases are corrected to a ship speed of 10 kn

**Table 1**
Summary of sea trials for two ships.

| | RoPax (M/V Copenhagen) | General cargo (M/V Annika Braren) |
|---|---|---|
| **Sea trial procedure** | Double runs (90°/90° TWA, 40°/140° TWA) | Single runs |
| **Speed measurement** | GPS (current corrected) | Speed log (speed through water) |
| **Wind measurement** | Ship's anemometer (automated log) | Ship's anemometer (automated log) |
| **Rotor power consumption** | Rotor log | Shaft generator (log files) |
| **Propulsion power** | Azimuth power and rpm (log) | Manual reading of fuel oil consumption |

**Table 2**
Main particulars of the case study vessels.

| | M/V Copenhagen | M/V Annika Braren |
|---|---|---|
| **Length over all (LOA) [m]** | 169.50 | 86.93 |
| **Beam (B) [m]** | 25.40 | 15.00 |
| **Draft (T) [m]** | 5.20 | 6.35 |
| **Displacement (Δ) [t]** | 11,870 | 6706 |
| **Speed ($v_S$) [kn] (design/operation)** | 18/16 | 12.5/10.5 |
| **Sail type** | Flettner rotor (1 pcs) | Rotor sail (1 pcs) |
| **Sail position** | Around midship | 81.4 m from AP |
| | 17.2 m from DWL | 6.6 m from DWL |
| **Sail size** | 5 × 30 m | 3 × 18 m |

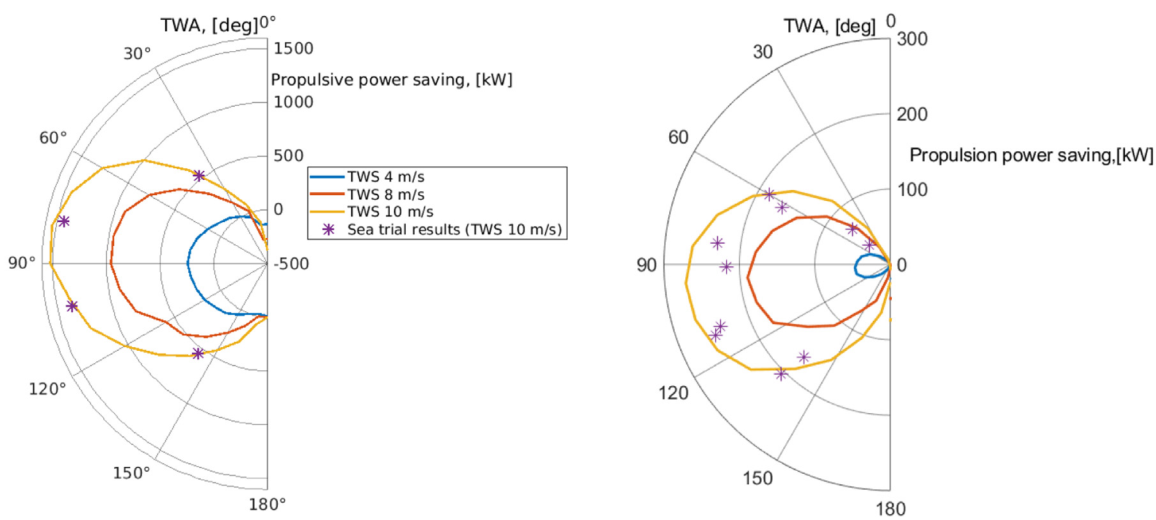


**Fig. 2.** Propulsion power savings according to model predictions and sea trials, RoPax ferry (left) and general cargo vessel (right). 0° TWA = headwind.

**Table 3**
Power savings and conditions for each run during sea trials.

| Run no. | TWS [m/s] | TWA [degrees] | ΔPd trial [kW] | ΔPd ShipCLEAN [kW] | Difference [kW] | Difference [%] |
|---|---|---|---|---|---|---|
| 3 | 8 | 135 | 131 | 114.1 | −16.9 | −14.8 |
| 6 | 9 | 112 | 202 | 211.1 | 9.1 | 4.3 |
| 9 | 10.1 | 62 | 166 | 203.4 | 37.4 | 18.4 |
| 13 | 8.6 | 47 | 51 | 97.5 | 46.5 | 47.7 |
| 16 | 8 | 83 | 150 | 185 | 35 | 18.9 |
| 4 | 7.8 | 137 | 101 | 101.1 | 0.1 | 0.1 |
| 7 | 8.8 | 110 | 186 | 206.2 | 20.2 | 9.8 |
| 10 | 9.7 | 60 | 174 | 185.6 | 11.6 | 6.3 |
| 14 | 8.4 | 47 | 27 | 91.4 | 64.4 | 70.5 |
| 17 | 7.4 | 91 | 120 | 164.5 | 44.5 | 27.1 |

The percentual differences between ShipCLEAN and the trial results are between −15 % (ShipCLEAN predicts lower savings) and +70 %, with the latter being for headwind/beating conditions (47° TWA). The absolute differences range between −16.9 kW and 64.4 kW.

## 5. Assessment of uncertainties

This section analyses the uncertainties in both, the sea trials and ShipCLEAN, to identify and quantify unknown error sources.

### 5.1. Uncertainties in the sea trial measurements

In the report of the sea trials with the general cargo vessel [12], an uncertainty assessment was presented, with the resulting standard deviations as shown in Table 4. The presented uncertainties include only the measurement uncertainties, taken from the variation of the time log of the data. However, according to [12] the fuel oil consumption was taken from manual readings of a display. Due to the way the sea trial results are evaluated, the power is

**Table 4**
Uncertainties during sea trials (according to [12]).

| Variable | Uncertainty (standard deviation) |
|---|---|
| Speed through water, STW | 0.1 kn |
| Fuel oil consumption, FOC | 10 % of the measured value |
| Apparent wind angle, AWA | 5 deg |
| Apparent wind speed, AWS | 0.5 m/s |

directly proportional to the fuel oil consumption, meaning that even the power has a 10 % uncertainty. With a power consumption of about 1000 kW (11 kn of ship speed), the uncertainty would be as high as the saving from the rotor itself.

To quantify the impact of these uncertainties on the results, several ShipCLEAN simulations are performed for each measurement point. As a first step, the minimum and maximum of each of the variables was used independently, to showcase the influence of the variation. In a second step, a Monte Carlo simulation for each measurement point was conducted, assuming a normal distribution for each variable.

*5.1.1. Parameter variation*

In a first step the input parameters wind angle, wind speed, and ship speed are varied to the maximum and minimum according to the uncertainties shown in Table 4, i.e. the parameters were set to plus and minus one standard deviation from the mean value. Table 5 and Table 6 present the results of the study for the case with sail and without sail, respectively. The uncertainty of the fuel oil reading linearly translates to the power savings and it is thus not considered in this part of the study but will be considered in Monte Carlo simulations in the next part.

As expected, the speed variation shows the largest impact on the power for both the case with and the case without sails. For the evaluation with sails, even the variation of the wind angle and speed can have large impact, depending on the wind angle. Especially in headwind (runs no. 9, 10, 13, 14) the differences due to the wind angle variation are huge, compared to the achieved savings.

*5.1.2. Monte Carlo simulations*

Given the uncertainties in the measurement values, Monte Carlo simulations were performed to estimate the standard deviation of the power savings from the sail. The simulations were performed using Matlab to generate random variables (all variables are assumed to follow a normal distribution) and the ShipCLEAN model to evaluate the standard deviation of the power savings due to the uncertain input conditions. Naturally, this procedure introduces some model uncertainties in the standard deviations; however, since the results are only comparative to the original values (i.e. only the standard deviations and not the mean values are of interest), the introduced uncertainties are expected to be small. The main source of uncertainty with this approach is the sail trim optimization. It is believed that the Flettner rotor was run at a constant rpm during the sea trials, while ShipCLEAN optimizes the rpm for each condition. However, for a single rotor ship, this is of relevance in headwind conditions.

As a first step, a simulation excluding the uncertainty of the fuel consumption reading was performed. Since the trials with and without sails are independent runs, the input values are also independent random variables. Thus, the simulations were performed using 6 parameters: ship speed, apparent wind angle and apparent wind speed for both cases (with and without sails). In total, 4000 variants were evaluated.

The results of the Monte Carlo simulations are presented in Table 7 and show a standard deviation between 43 kW and 65 kW for all trial runs. Compared to the measured savings of 27 kW to 202 kW, this must be considered huge. As discussed above, the main influences are the ship speed and the apparent wind angle.

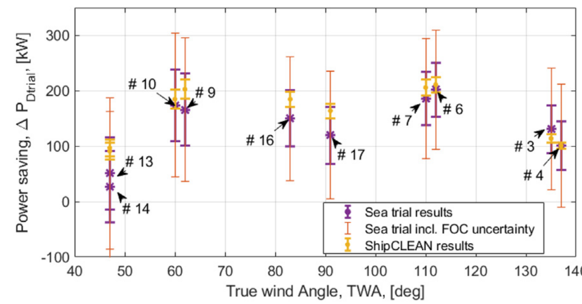


**Fig. 3.** Summary of the results of the sea trials, ShipCELAN predictions and Monte Carlo simulations.

As a second step, a similar simulation was performed, including two more parameters, the fuel oil consumption with and without sails. In total, 4000 variants were evaluated. The results are presented in Table 8.

As expected, the standard deviations of the savings are much larger, between 107 kW and 136 kW, which in many cases is larger than the measured savings. Naturally, the dominating influence is from the uncertainty in the fuel oil consumption (power) reading.

*5.2. Model uncertainties*

The model uncertainties in ShipCLEAN are studied and presented in [18]. The apparent wind angle deviation over the deck, the drag of the drifting hull, the center of the lateral force (CLR) and the lift coefficient of the sail were identified as the primarily important parameters and are used in this study. The values used in ShipCLEAN are defined as the mean values. The standard deviation of the added drag is derived from the results in [19] and assumed constant over the drift angle. The standard deviations of the remaining parameters are defined according to the discussion in [18]. The influence of the ship hull on the apparent wind over the deck is one of the biggest uncertainties. As described in [18], in ShipCLEAN it is modelled using a sinusoidal curve over the wind angle, with peaks of 8°, occurring at 45° and 135° apparent wind angle. The influence is assumed to decrease to 0° at 20 m above deck. The standard deviation of the lift coefficient of Flettner rotors is assumed to be 5 %, i.e., higher than the value derived in [18]. A higher uncertainty is mainly used since the rotor sail is from a different brand than those used in earlier studies using ShipCLEAN [9].

All variables are assumed to follow a normal distribution with standard deviations according to Table 9. As for the trial uncertainty evaluation, a Monte Carlo simulation using ShipCLEAN and 4000 variants was performed. The results are presented in Table 10.

The model uncertainty is higher for small wind angles, i.e. headwind. This is due to the more abrupt changes in thrust force at small angles and the higher influence of the added drag when drifting and the center of the lateral force. In downwind conditions, drift forces are small, and the drag of the rotors becomes more important, thus the uncertainties are reduced.

*5.3. Summary of uncertainties*

The results of the Monte Carlo simulations and the results of the sea trials and ShipCLEAN predictions are summarized in Fig. 3. The figure presents the measured/predicted values for each run together with the associated uncertainties. The plot is arranged over the true wind angle, to easier understand trends of the predicted

**Table 5**
Changes in propulsion power with sail due to input parameter variation.

| | | Power difference due to parameter variation [kW] | | | | | |
|---|---|---|---|---|---|---|---|
| | | Apparent wind angle | | Apparent wind speed | | Ship speed | |
| Run no. | TWA [degrees] | −5° | +5° | −0.5 m/s | +0.5 m/s | −0.1 kn | +0.1 kn |
| 3 | 135 | 7.5 | −6.1 | 23.3 | −19.9 | −40.4 | 42.8 |
| 6 | 112 | 23.1 | −21.5 | 22.9 | −27.0 | −38.7 | 41.1 |
| 9 | 62 | 52.9 | −49.0 | −0.7 | 2.3 | −40.2 | 42.7 |
| 13 | 47 | 56.3 | −48.9 | −0.6 | 5.2 | −42.5 | 45.0 |
| 16 | 83 | 33.2 | −29.6 | 18.9 | −12.7 | −39.6 | 42.1 |
| 4 | 137 | 4.7 | −3.5 | 23.5 | −22.3 | −40.8 | 43.3 |
| 7 | 110 | 23.1 | −21.0 | 23.0 | −26.9 | −39.0 | 41.4 |
| 10 | 60 | 54.8 | −48.7 | 2.5 | 1.4 | −41.0 | 43.5 |
| 14 | 47 | 53.5 | −51.0 | −0.9 | 1.4 | −42.1 | 44.9 |
| 17 | 91 | 34.1 | −33.4 | 15.1 | −12.1 | −40.3 | 43.0 |

**Table 6**
Changes in propulsion power without sail due to input parameter variation.

| | | Power difference due to parameter variation [kW] | | | | | |
|---|---|---|---|---|---|---|---|
| | | Apparent wind angle | | Apparent wind speed | | Ship speed | |
| Run no. | TWA [degrees] | −5° | +5° | −0.5 m/s | +0.5 m/s | −0.1 kn | +0.1 kn |
| 3 | 135 | 2.7 | −2.7 | 0.8 | −0.8 | −43.4 | 45.9 |
| 6 | 112 | 5.5 | −5.8 | −1.3 | 1.4 | −43.5 | 46.1 |
| 9 | 62 | 9.3 | −10.3 | −8.2 | 8.5 | −44.5 | 47.0 |
| 13 | 47 | 6.5 | −7.6 | −9.2 | 9.6 | −44.5 | 47.1 |
| 16 | 83 | 5.4 | −5.8 | −3.3 | 3.5 | −43.7 | 46.3 |
| 4 | 137 | 2.4 | −2.4 | 0.8 | −0.8 | −43.4 | 46.0 |
| 7 | 110 | 5.6 | −5.7 | −1.5 | 1.6 | −43.5 | 46.1 |
| 10 | 60 | 8.8 | −9.7 | −8.2 | 8.5 | −44.5 | 47.0 |
| 14 | 47 | 6.2 | −7.3 | −9.0 | 9.3 | −44.5 | 47.0 |
| 17 | 120 | 5.1 | −5.5 | −4.1 | 4.3 | −43.8 | 46.4 |

**Table 7**
Results of the Monte Carlo simulations, excluding the fuel oil consumption.

| Run no. | TWS [m/s] | TWA [degrees] | ΔPd Trial [kW] | ΔPd ShipCLEAN [kW] | Standard deviation [kW] | Standard deviation [%] |
|---|---|---|---|---|---|---|
| 3 | 8 | 135 | 131 | 114.1 | 43.2 | 32.8 |
| 6 | 9 | 112 | 202 | 211.1 | 48.7 | 23.8 |
| 9 | 10.1 | 62 | 166 | 203.4 | 65.0 | 39.2 |
| 13 | 8.6 | 47 | 51 | 97.5 | 65.2 | 127.5 |
| 16 | 8 | 83 | 150 | 185 | 50.7 | 33.3 |
| 4 | 7.8 | 137 | 101 | 101.1 | 43.4 | 42.6 |
| 7 | 8.8 | 110 | 186 | 206.2 | 48.5 | 25.8 |
| 10 | 9.7 | 60 | 174 | 185.6 | 64.3 | 36.8 |
| 14 | 8.4 | 47 | 27 | 91.4 | 64.5 | 237.0 |
| 17 | 7.4 | 91 | 120 | 164.5 | 51.3 | 42.5 |

**Table 8**
Results of the Monte Carlo simulations, including the fuel oil consumption.

| Run no. | TWS [m/s] | TWA [degrees] | ΔPd Trial [kW] | ΔPd ShipCLEAN [kW] | Standard deviation [kW] | Standard deviation [%] |
|---|---|---|---|---|---|---|
| 3 | 8 | 135 | 131 | 114.1 | 109.7 | 83.2 |
| 6 | 9 | 112 | 202 | 211.1 | 107.3 | 52.9 |
| 9 | 10.1 | 62 | 166 | 203.4 | 129.4 | 77.7 |
| 13 | 8.6 | 47 | 51 | 97.5 | 136.6 | 266.6 |
| 16 | 8 | 83 | 150 | 185 | 112.0 | 74.6 |
| 4 | 7.8 | 137 | 101 | 101.1 | 110.9 | 108.9 |
| 7 | 8.8 | 110 | 186 | 206.2 | 107.9 | 57.5 |
| 10 | 9.7 | 60 | 174 | 185.6 | 129.9 | 74.1 |
| 14 | 8.4 | 47 | 27 | 91.4 | 135.6 | 500.0 |
| 17 | 7.4 | 91 | 120 | 164.5 | 115.0 | 95.8 |

**Table 9**
Parameters and standard deviations for model uncertainty.

| Parameter | Standard deviation |
|---|---|
| AWA change over deck | 6° |
| cL of the sail | 5 % |
| CLR | 3 % of LOA |
| Added drag of the hull | 20 % |

**Table 10**
Results of the Monte Carlo simulations for the model uncertainty.

| Run no. | TWS [m/s] | TWA [degrees] | ΔPd Trial [kW] | ΔPd ShipCLEAN [kW] | Standard deviation [kW] | Standard deviation [%] |
|---|---|---|---|---|---|---|
| 3 | 8 | 135 | 131 | 114.1 | 7.2 | 6.3 |
| 6 | 9 | 112 | 202 | 211.1 | 14.1 | 6.7 |
| 9 | 10.1 | 62 | 166 | 203.4 | 17.7 | 8.7 |
| 13 | 8.6 | 47 | 51 | 97.5 | 15.3 | 15.8 |
| 16 | 8 | 83 | 150 | 185 | 14.1 | 7.6 |
| 4 | 7.8 | 137 | 101 | 101.1 | 6.3 | 6.2 |
| 7 | 8.8 | 110 | 186 | 206.2 | 14.0 | 6.8 |
| 10 | 9.7 | 60 | 174 | 185.6 | 17.4 | 9.4 |
| 14 | 8.4 | 47 | 27 | 91.4 | 15.1 | 16.6 |
| 17 | 7.4 | 91 | 120 | 164.5 | 13.3 | 8.1 |

values and uncertainties. It must be kept in mind that the true wind speed was slightly different for each run and that the values in the figure are not corrected for this. The uncertainties for the sea trials are divided into uncertainties with uncertain fuel oil consumption and without.

The results show that ShipCLEAN slightly overpredicts the savings for almost all trial runs but that the predicted values are within the 95 % confidence interval for all runs, even without the uncertainty of the fuel oil consumption reading. This shows that the difference between the model prediction and trial measurements does not necessarily have to be due to an error in the model or a measurement error but could be due to the uncertainties in the measurement and the model. For all measurement points, the model uncertainties are considerably smaller than the measurement uncertainties, even though the standard deviations of all parameters were assumed larger than what was seen during verification studies. This is mainly because the speed is certain in the model, and the sail area of the vessel is rather small. Thus, the most uncertain parameter, the hydrodynamic drag when drifting, plays a minor role since drift angles are small. Model and measurement uncertainties decrease with increasing true wind angle, which is mainly because of the decreased effect of the wind angle changes. In headwind conditions, a 5-degree change in wind angle might cause the sail not to deliver any thrust. In downwind conditions, the differences over small changes in wind angle are much smaller.

It must be noted that offset errors from the equipment installed onboard the vessels are not included in this study but could explain the overprediction by ShipCLEAN. Offset errors would mainly occur in the measurements of the ship speed, wind speed and wind direction, which could constantly show too high or low values due to wrong calibration. Further, anemometers are never free from obstruction onboard a ship, which could lead to offset errors only in some distinct wind angles. The rpm of the rotors was not included in the test report. Thus, the ShipCLEAN simulations are performed with the optimized rotor rpm, considering the wind angle, wind speed and drift resistance. ShipCLEAN also allows the rotor to reach its maximum rpm, which might not be the case. In the trial analysis, the propulsion power was estimated using the fuel oil consumption and a fixed specific fuel oil consumption, disregarding the different loading conditions of the engine. This could also introduce an error in the savings depending on the percentual difference to the propulsion power, which is not included in this study.

Naturally there could also be modelling errors that could not be detected in this study, mostly because the trial measurements show very high uncertainties. Model uncertainties are mainly found in the modelling of the hydrodynamic resistance of the drifting hull, which is less important in such a case with rather low sail load. Further, the influence of the hull on the wind angle is difficult to predict analytically/theoretically. However, this effect should mainly occur rather close to the deck. Given the rotor's height of 18 m plus a 2 m foundation above deck (the bottom of the rotor was at 9.63 m, the top at 27.63 m above the waterline at trial), a large part of the rotor should be unaffected by this, if not, a similar effect should be seen at the anemometer (24 m above waterline at trial, on top of the deckhouse), thus cancelling out this uncertainty.

## 6. Conclusions

This study compared the sea trial results and model prediction results of two ships with rotor sails. One case showed very good agreement between sea trial and prediction results, and one showed both a worse agreement between model and sea trial results and a large scatter of the sea trial results. Consequently, an uncertainty analysis of the second sea trial and the model prediction was performed.

The results showed that the uncertainty of the sea trial measurements had much higher uncertainty levels than the model prediction. The main contribution of the overall uncertainty of the sea trial measurements was identified as the speed, the wind angle, and the power measurements. In the model, the drag of the drifting hull and the lift coefficient of the sails were identified as the main contributors. With uncertainties of at least 23 % and up to well above 100 % of the measured fuel savings, it must be concluded that the sea trial results of the present case should not be used for verification or further prediction. The results show that high measurement accuracy is crucial to obtain trustworthy results during sea trials. In addition to the common sea trial procedure with double runs, propeller torque measurement and GPS speed measurements, even the wind angle and speed must be measured with high accuracy and well calibrated equipment. Preferably, the wind speeds should be measured at multiple places onboard, but even on stationary/independent equipment close to the ship, which could provide wind angle and speed readings without influences from the ship. This raises the bar for sea trials for WASP ships. Common practice for traditional sea trials is to perform the tests in regions and in times of low wind and low sea state, to minimize the environmental influences. However, WASP ships must be tested in reasonably high winds to measure a suitable saving, which requires accurate measurement.

Model uncertainties were evaluated to be between 6 % and 17 % of the evaluated savings, which aligns well with previous results. The areas of high uncertainty, especially the drag of the drifting hull, could easily be improved, and uncertainties could be reduced with the help of CFD computation.

With the results of this uncertainty study, it must be concluded that a component-wise validated prediction model is better suited to predict the power savings from WASP than sea trials performed with typical onboard equipment.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This study received funding from Chalmers University of Technology Foundation for the strategic research project "Hydro- and aerodynamics".

## References

[1] E.A. Bouman, E. Lindstad, A.I. Rialland, A.H. Strømman, Trans. Res. Part D Trans. Environ. 52 (2017) 408–421.
[2] Reduction of GHG emissions from ships: wind Propulsion Solutions, International Maritime Organization, 2020 MEPC 75/INF.26Available online: http://wind-ship.org/wp-content/uploads/2020/02/MEPC-75-INF.26-Wind-propulsion-solutionsComoros-1.pdf (accessed on 14 March 2024).
[3] I. Rojon, C. Dieperink, Energy Policy 67 (2014) 394–402.
[4] F. Tillig, J.W. Ringsberg, Ships Offshore Struct. 14 (2019) 112–120.
[5] T. Searcy, Mar. Policy 86 (2017) 164–172.
[6] M. Chica, R. Rivas Hermann, N. Lin, Technol. Forecast. Soc. Change (2023) 192.
[7] M. Traut, P. Gilbert, C. Walsh, A. Bows, A. Filippone, P. Stansby, R. Wood, Appl. Energy. 113 (2014) 362–372.
[8] F. Tillig, J.W. Ringsberg, Ocean Eng. (2020) 211, doi:10.1016/j.oceaneng.2020.107603.
[9] Viking Grace Rotor Sail Performance Analysis Results, Norsepower, Helsinki, Finland, 2019 Available: https://7c859085-dddb-4d30-8667-a689091113a8.filesusr.com/ugd/cea95e_a721091625ee452db73c9fb69804268e.pdf (accessed on 14 March 2024).
[10] ITTC. 2014, https://ittc.info/media/4208/75-04-01-011.pdf (accessed on 14 March 2024).
[11] S. Werner, J. Nisbet, A. Hörteborn, R Nielsen, International Conference on Wind Propulsion, 2021 15-16 September.
[12] Speed Trial and Route Analysis of M/V Annika Braren with Rotor Sail, SSPA AB, 2024 RE40201042-03-00-A, 2022 https://vb.northsearegion.eu/public/files/repository/20220707112458_RE40201042-03-00-A.pdf (accessed on 14 March).
[13] Speed Trial and Route Analysis of M/V Frisian Sea with Suction Wings, SSPA AB, 2024 RE40201042-02-00-A https://vb.northsearegion.eu/public/files/repository/20220728155051_RE40201042-02-00-A.pdf (accessed on 14 March).
[14] Speed Trial and Route Analysis of M/V Ankie with Suction Wings, SSPAAB, 2024 RE40201042-04-00-A https://vb.northsearegion.eu/public/files/repository/20230523105108_RE40201042-04Ankie.pdf (accessed on 14 March).
[15] Speed Trial and Route Analysis of M/V Tharsis with Wings, SSPA AB, 2024 RE40201042-05-00-A https://vb.northsearegion.eu/public/files/repository/20230505142244_RE40201042-05Tharsis.pdf (accessed on 14 March).
[16] Speed Trial and Route Analysis of M/V Copenhagen with Flettner Rotor, SSPAAB, 2024 RE40201042-01-00-A https://vb.northsearegion.eu/public/files/repository/20230505141934_RE40201042-01-revBCopenhagen.pdf (accessed on 14 March).
[17] F. Tillig, Simulation Model of a Ship's Energy Performance and Transportation Costs, Chalmers University of Technology, Gothenburg, Sweden, 2020 PhD Thesis, ISBN 978-91-7905-283-6.
[18] F. Thies, J.W. Ringsberg, HIPER 2022, Cortona, Italy, 29-31 August, 2022.
[19] H. Renzsch, F. Thies, 6th International Conference on Innovation in High Performance Sailing Yachts and Wind-Assisted Ships, 2023 23-31 May.