PERFORMANCE PREDICTION AND DESIGN OF WIND-ASSISTED PROPULSION SYSTEMS

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SUMMARY

Wind-assisted propulsion is seen as one of the main alternatives to potentially achieve large emission reductions in shipping. However, wind-assisted propulsion introduces new challenges in the design, retrofitting and performance prediction as well as the performance analysis. This paper presents and compares methods to predict the performance of wind-assisted propulsion, using the validated performance prediction model ShipCLEAN. Focus is put on evaluating the difference between 1 degree of freedom (1 DOF) and 4 DOF methods as well as the impact of aerodynamic interaction effects in between multiple sails. Practical design considerations and performance differences are discussed based on an example ship. The study includes a comparison of the performance of different sail types (Flettner rotors, Wing sails and Suction wings) under realistic operational conditions.

NOMENCLATURE

[Symbol]	[Definition] [(Unit)]
B	Beam (m)
DOF	Degree of freedom (-)
FP	Forward perpendicular (-)
L_{oa}	Length over all (m)
L_{pp}	Length between perpendiculars (m)
T	Draft (m)
TWA	True wind angle (deg)
TWS	True wind speed (kn, m/s)
$WASP$	Wind-assisted propulsion (-)
v_S	Ship speed (kn)
Δ	Displacement (t)

1. INTRODUCTION

Shipping today accounts for 90% of all freight transport. Forecasts of the world's transportation needs in 2050 show that it will double the current level. At the same time, shipping must become more energy-efficient and before 2050 reduce its contribution to emission of greenhouse gases to 50% of the level in 2008 (IMO, 2018). A first, and crucial step towards reducing the fuel consumption of ships is to be able to accurately predict the consumption of existing ships as well as the positive impact on the reduction of fuel consumption due to: (i) operational or retrofitting measures, (ii) design changes, and (iii) the installation of energy-saving devices such as sails. To achieve this, each part, and the interaction of all parts in a ship's energy system must be understood.

The ShipCLEAN simulation model presented by Tillig (2020) is developed as a coupled model including ship performance prediction and maritime transport logistics. Its capability and accuracy in ship performance predictions have been validated for commercial ships with and without Flettner rotors. It is used in the current study to compare methods to predict the performance of three sails, i.e., wind-assisted propulsion technologies, under realistic operational conditions: Flettner rotors, Wing sails, and Suction wings.

2. PERFORMANCE PREDICTION

With the increasing interest in wind-assisted propulsion, the need for accurate and versatile prediction models increases simultaneously. One basic question is the level of accuracy that is needed for a prediction of the fuel savings achieved by wind-assisted propulsion. In this section some important effects, hydrodynamically and aerodynamically, and their importance for an accurate performance prediction will be discussed.

2.1 DEGREES OF FREEDOM

For traditionally propelled ships, the typical performance prediction methods only include the resistance (including resistance from waves and wind) and the propulsive efficiency; hence they are 1 degree of freedom (1 DOF). Such an approach was also applied to wind-assisted ships, i.e., the sails would be treated as an additional propulsor creating pure thrust. However, since the sails create large side forces, more degrees of freedom must be considered, both to accurately predict the added resistance created from drifting and steering but also to model constraints for the sail forces, i.e., maximum rudder or heel angles. Thus, it is crucial to include at least 4 DOF: surge (thrust), drift (side force), yaw (side force), and heel (side force). The dynamical sinkage of the ship is only dependent on the ship's speed and will thus not change by the addition of wind propulsion unless the systems introduce a vertical force which is not the case for the wind propulsion systems discussed here.

As an example, one can estimate the necessary propeller thrust for a ferry, which is presented in more detail in Section 4.2. With a TWA of 60 deg, TWS of 20 kn, wave height of 1 m and a ship speed of 16 kn, the ship has an estimated total resistance (including added resistances) of 463.6 kN. The sail thrust of one 5×30 m Flettner rotor in this condition is estimated to be 55.3 kN, i.e., about 12% of the total required thrust. However, considering 4 DOF, a drift and rudder resistance of about 8.3 kN must be added, reducing the thrust reduction to about 10%. Additionally, the sail forces would be slightly reduced since the ship drifts with about 1.5 deg. The example shows the importance of considering 4 DOF, even for WASP ships with small sail areas. It gets even more important for ships with larger sail areas and for conditions closer to the wind, when sails often must be reefed for the ship to be able to hold course and maneuver (Tillig, 2020).

2.2 AERODYNAMIC INTERACTION

Sails on deck of a ship are interacting with each other and the deck or superstructure. Recently, numerous studies focused on the interaction effects of sails on a ship, e.g., Bordogna et al. (2020), Tillig and Ringsberg (2020). The results of these studies show that, in-between sails, potential flow interaction effects are predominant. Those effects are caused by the bound and tip/root vortices of the sails and cause a variation of local wind speed and direction in the flow field, i.e., each sail will experience a wind speed and direction different from the free flow speed and direction and different from the other sails. These induced speeds in a field of multiple sails cause a variation of the force centre of the combined force of all ships but no large losses. In general, the combined force acts more forward in a field of sails with modelled interaction than in the same field when interactions are disregarded. Thus, aerodynamical interactions are crucial to model to accurately predict the jaw moments and thus the necessary rudder angle and for reliable sail control, as discussed in the following section. The thrust forces from individual sails with and without interactions are compared in Figure 1.

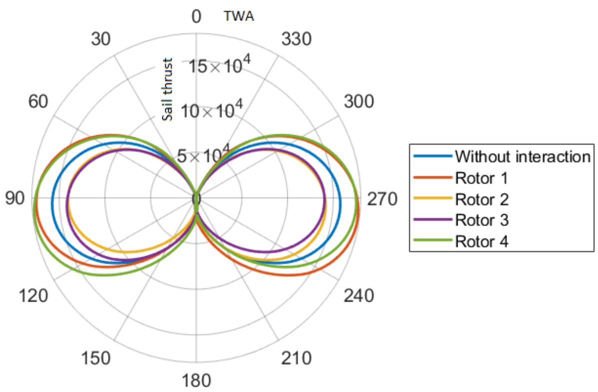

Figure 1: Effects of sail interaction (Tillig and Ringsberg, 2020).

2.3 SAIL CONTROL

In 1 DOF simulation model predictions, sails are often regarded to act in the trim delivering the maximum thrust. However, when 4 DOF are modelled, the sails shall be trimmed to find the best balance between thrust, drift, heel, and rudder angle as well as the associated added resistances. Further, constraints on the rudder and heel angle shall be kept and thus the sail might have to be de-powered (reefed).

Considering the complexity and the coupling between ship dynamics, sails, interaction effects, and the dependency of the rudder forces on the propeller thrust (and thus sail thrust/trim), sail trim becomes a classic optimization problem that is not analytically solvable. Further, especially in downwind conditions, it can be beneficial to inverse the aft sails (e.g., reverse the rotation of Flettner rotors), creating less thrust or even slightly negative thrust but acting as a rudder to counter the jaw forces of the more efficient forward sails. These effects only occur on ships with large sail areas or fully sail-powered ships. For more modest wind-assisted ships, the main benefit of sail trim optimization is found in the head wind range, as illustrated in Figure 2.

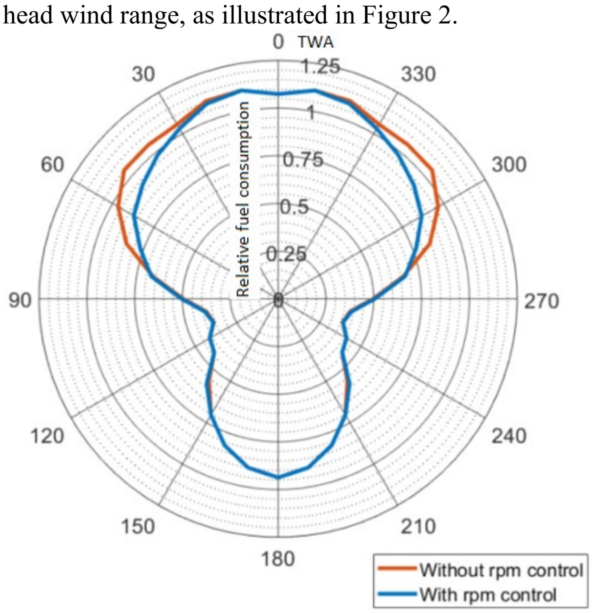

Figure 2: Fuel savings of 4 Flettner rotors on a RoRo ship, with and without optimized sail trim (Tillig and Ringsberg, 2020).

3. SHIPCLEAN

ShipCLEAN is a generic ship energy systems model, i.e., a ship performance prediction model that is modularized by means of the energy systems on board a ship. The structure and details of the model are extensively published and summarized in Tillig (2020). ShipCLEAN consists of two main parts. Firstly, a 1 DOF, generic power prediction model which provides power predictions for any cargo ship while requiring only the main parameters as input. Secondly, a 4 DOF part which includes environmental influences as well as methods for sails and aerodynamic interaction. The expected and achieved accuracy in predictions using this model is presented in Tillig et al. (2018) and Tillig (2020). In this study, both parts of ShipCLEAN are used.

4. DESIGN EXAMPLE

The example ship is a ferry with main dimensions according to Table 1. The ferry is equipped with one 5×30m Flettner rotor which is mounted midships, i.e., at $0.5 \times L_{pp}$ from the aft (AP), as illustrated in Figure 3 and three propellers, one center and two steerable Pods. However, for the studies in this work, the ship is assumed to have two conventional high lift rudders, since Pods would not create sufficient yaw moments when the main propulsion thrust is delivered from the sails.

L_{oa}	156.45 m
B	24.8 m
T	5.5 m
Δ	11996 t
Service speed, v_S	16 kn

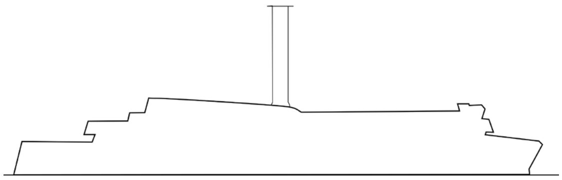

Figure 3: Sketch of the example ferry with one Flettner rotor.

The ferry operates on a route between Rostock (Germany) and Gedser (Denmark) with five daily departures in each direction. The open sea leg of the route is about 23 nm long with a course over ground of 165 deg (bound to Germany) and 345 deg (bound to Denmark). To accurately predict the long-term savings, a statistical approach using historical weather on the route is used, which is described in detail in Tillig and Ringsberg (2020). In short, this approach uses probability distribution functions of the wind speed and direction to estimate weights for the points evaluated in a polar diagram. In that way, the computational time can drastically be reduced while still maintaining a high level of accuracy of the prediction of fuel savings. Long term wind statistics (based on the years 2016 to 2018) on the route are summarized in a wind scatter plot in Figure 4. It is shown that there are two dominating true wind directions, between 190 and 210 deg (southwest) and between 10 and 30 deg (northeast).

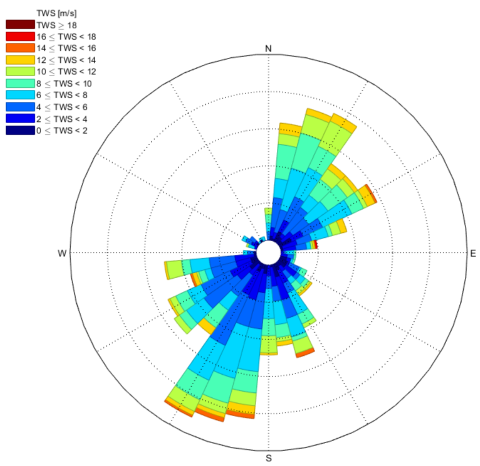

Figure 4: Wind scatter plot based on statistics from 2016 to 2018.

4.1 SAIL POSITION

The longitudinal position of the sail is crucial for the induced yaw moment. The further aft the sail is positioned, the higher the load on the rudder will be. A high rudder load is favourable since the lift to drag ratio of the rudder is much better than the ratio of the hull. However, large rudder angles must be avoided to keep manoeuvrability. Thus, a too far aft positioned sail might be de-powered most of the time. To evaluate the impact of the longitudinal position, the sail is moved from the forward perpendicular to the aft perpendicular in steps of $0.2\times L_{pp}$. The fuel savings are estimated using the statistical approach discussed above. Results are presented in Figure 5, which shows that a position slightly aft of the midship (50% L_{pp}) is most favourable.

4.2 SAIL AREA AND TYPE OF SAIL

To determine the best sail type and sail area for a ship, three main parameters must be considered: (i) the available space on deck, (ii) height restrictions and (iii) the return of investment, i.e., the achieved savings in comparison to the installation and running costs. In this study, different sail areas of two sail types, Flettner rotors and Suction wings, are compared by means of the

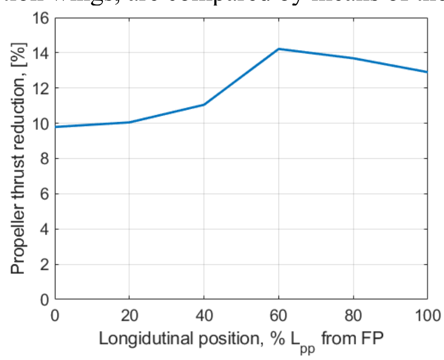

Figure 5: Influence of the longitudinal position on the power savings.

achieved savings. It is assumed that up to six Flettner rotors (5×30 m) and up to six Suction wings (5×30 m and 10×60 m) can be fitted on the ferry. Since installation and running costs are not available to the authors, only the achievable savings will be presented and discussed.

A first comparison of the Flettner rotor and the Suction wing can be done by means of the maximum lift coefficient. While Flettner rotors can achieve lift coefficients of up to 12, the maximum lift coefficient of the Suction wing is proven to be 5. On the other hand, the Suction wing has a higher lift to drag ratio of about 3.5 at the maximum lift point than the Flettner rotor, which has a lift to drag coefficient of about 3 at the highest lift and even at the typical working points. The difference in achievable lift coefficient is the reason for the choice of installed sail areas, where the maximum sail area for the Flettner rotors is predicted to be 6×150 m^2, i.e., 1000 m^2, while the maximum sail area for the Suction sails is 6×300 m^2, i.e., 1800 m^2.

Figure 6 compares propeller thrust reduction if the ship had been equipped with a different number of Flettner rotors or Suction wings. It is shown that the increase of the savings is not linear, especially for the Flettner rotor. While savings are almost similar for one 150 m^2 Flettner rotor and one 300 m^2 Suction wing, 1000 m^2 Flettner rotor (six units) give a saving of about 54%, while 1800 m^2 Suction wing give about 66%. This shows the effect of higher lift to drag ratios of the sail for high sail areas, which is rather unimportant for small sail areas.

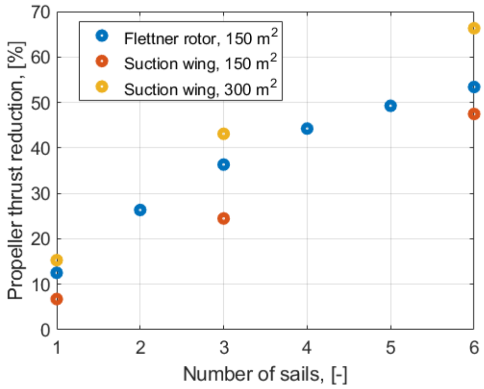

Figure 6: Achievable propeller thrust savings with different number of installed Flettner rotors and Suction wings.

5. CONCLUSIONS

Using a ferry ship as an example, this study discussed the necessity of considering 4 DOF and aerodynamic interaction for an accurate performance prediction for wind-assisted ships. By neglecting drift forces and yaw moments, the total resistance of the ship is under-predicted since added resistances from drift and the rudder are not included. Further, 1 DOF models cannot respect constraints on the rudder and heel angles. A 4 DOF model is also crucial to accurately model the optimal sail trim, considering the constraints and the optimal overall performance, which might involve de-powering the sails to reduce rudder and drift resistance.

In the example with a ferry operating on a short route in the Baltic Sea, it was shown how a statistical approach can be employed to accurately predict the long-term performance of WASP systems. The design of the WASP systems was discussed by varying the position and the size as well as type of the sail. Sails that were positioned optimally showed to achieve about 14% power savings, while those at the least optimal position only achieved 10% power savings. The sail size variation showed that the savings do not increase linearly with the sail size, mainly due to the rudder constraints and the increasing drift resistances.

In the comparison of Flettner rotors and Suction sails, it was shown that similar savings can be achieved with different sail types, given that the sail area is changes accordingly. However, the larger the sail area, the more important the lift to drag ratio. Thus, it must be assumed that the choice of sail type will be more important for fully wind-propelled ships. It was also presented that the savings do not increase linearly, mainly due to drift and rudder angles and maximum rudder angle constraints. Since this effect is more pronounced for the Flettner rotors, it can be concluded that the higher lift to drag ratio of the Suction wing is favourable at large sail areas while the large lift coefficients of the Flettner rotors are favourable for smaller sail areas. The results showcase the difficulty of comparing different sail types. Since the performance of the sails is always dependent on the sail area, it must be concluded that the most suitable parameter for comparison of different sail types would be the payback time. However, such comparison requires the availability of installation and running costs of the sail types.

6. ACKNOWLEDGEMENTS

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