Parametric study of the influence of the wind assisted propulsion on ships

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Abstract

Environmental concern and increasingly strict regulations push the marine industry towards adopting greener technologies to increase energy efficiency and reduce ship fuel consumption. Several measures have been identified, or even applied, with the potential to achieve substantial fuel consumption and emission reductions, like slow-steaming, bio-fuels, and alternative propulsion technologies. Slow steaming has been already analysed to a great extent, whereas biofuels have raised concerns about environmental impact and availability. Among alternative propulsion technologies, a resurgence in wind-assisted propulsion is observed in recent years, primarily due to its high potential for fuel consumption and emission reduction. Wind power is currently being developed through both conventional sails and modern alternatives. These include Flettner rotors, kites or spinnakers, soft sails, wing sails and wind turbines. In particular, Flettner rotors are rotating cylinders generating lift when immersed in a fluid stream. This paper presents a ship propulsion model study, able to account for the thrust force produced by the rotor accounting for different vessel speed and weather scenario. This paper aims to assess the improvement of the ship's energy efficiency and optimise the ship operating conditions in terms of daily performance. The result clearly shows the potential reduction achieved in the propeller delivered power given using the rotor as an auxiliary propulsion device.

Keywords: Energy efficiency, Ship propulsion, Wind-assisted propulsion, Flettner rotor.

1 INTRODUCTION

According to recent estimates, global shipping emits about 1 billion tonnes of carbon dioxide (CO_2) annually, equivalent to over 3% of the global anthropogenic CO_2 emissions. These figures are expected to increase significantly in the future despite market-driven and regulatory efficiency improvements, just due to the sector's growth. Therefore, measures that can substantially reduce the CO_2 emissions of the shipping sector will have a crucial role in the future.

Several measures have been identified, or even applied, with the potential to achieve substantial emission reductions, like slow-steaming, bio-fuels, and alternative propulsion technologies. Slow steaming has been already analysed to a great extent, whereas biofuels have raised concerns about environmental impact and availability. A resurgence in wind-assisted propulsion is observed among alternative propulsion technologies in recent years, primarily due to its high potential for fuel consumption and emission reduction.

Wind power is currently being developed through both conventional sails and modern alternatives. These include Flettner rotors, kites or spinnakers, soft sails, wing sails and wind turbines [1]. The compatibility of different designs varies between ship classes due to potential interference with cargo handling [2]. However, it is known that any current design alone cannot provide the typical ships propulsive power demand, but high wind speeds typically encountered in high seas can allow for significant fuel savings whilst maintaining full speed [3]. Furthermore, research has shown that wind propulsion is most effective at slower speeds (e.g. less than 16 knots) and on smaller ships (3000 - 10,000 tonnes) [4], which account for one-fifth of global cargo ships.

Among all renewable energy sources, wind is the most abundantly available for ships; thus, it is worth investing in research and technologies that harness wind energy for ship propulsion. One promising technology is the Flettner rotor, a rotating cylinder generating lift when immersed in a fluid stream, thanks to the Magnus effect. Flettner rotors are named after the German engineer Anton Flettner, who, in the 1920s, began studying how to improve ship propulsion by returning to the wind as a source of energy and came out with the idea of a rotating cylinder to harness the wind to propel a ship. The Magnus effect is the physical principle upon which his invention is based: a cylinder revolving in a fluid stream (the wind) generates lift thanks to the increase of air pressure on one side and suction on the other. Flettner experimented with his invention in 1924 on the sailing ship Buckau. Unfortunately, his invention did not succeed in his lifetime and ended up in oblivion: the system was not economical as the energy needed to drive the rotating cylinder was superior to the gain in propulsion.

Today we are starting to rediscover this invention, which becomes more efficient thanks to technological advancement. Flettner rotors are nowadays considered a potential application to achieve additional fuel-saving in modern propulsive plants.

In Seddiek et al. [5], the authors highlight the applicability of harnessing wind power for ships. The authors considered a bulk carrier operating between Damietta port in Egypt and Dunkirk port in France as a case study. The results showed the strong influence of the interaction between ship course and wind speed and direction on the net output power of Flettner rotors. Economically, the results reveal that the use of Flettner rotors will contribute to considerable savings, up to 22% of the annual ship's fuel consumption. The pay-back period of the proposed concept will be six years with a significant value of Levelized cost of energy.

A very similar fuel consumption reduction is shown in [6], where a conventional propulsion system integrated by Flettner rotors is investigated. The results show up to 20% savings in annual fuel consumption and a similar reduction in pollutant emissions.

In [7], a four degrees of freedom ship performance prediction model is used to compare different wind-assisted ship propulsion technologies: the Flettner rotor, a wingsail and the DynaRig concept. An Aframax Oil Tanker on a route between Gabon and Canada is used in a case study to compare the three technologies using actual information for the voyage. The fuel savings were calculated, and they varied between 5.6% and 8.9%; the Flettner rotor showed the most significant fuel savings.

In [2], numerical models of Flettner rotor and towing kite are linked with wind data of five shipping routes to compute the thrust as a function of the wind. The average wind power contribution is obtained for a single rotor (and kite), and the study provides a range of 2-24% fuel savings for a single rotor, concordant with [5,6].

In [8], the power developed/consumed by the Flettner rotor on a ship is calculated, for different values of wind speed and ship speed, using four different empirical relations for the friction coefficient. Results showed that the values of the power generated by the Flettner rotor using these four different formulae didn't have a significant difference. The rotor maximum contribution to the propulsive power is when the wind direction is 90°.

In [9], the influence on the stability of a container ship of four Flettner rotors is presented. The forces which influence the Flettner rotors and how they impact the ship stability are shown. The results show only moderate or insignificant influence on ship stability characteristics.

The study reported in [10] addresses the influence of Flettner rotors on the roll motion of ships and the effects of roll motion on the performance of Flettner rotors in beam waves. The analyses are performed with 0°, 20°, 40° and 60° heel angles to obtain the heeling moment function and driving force function with respect to heeling angle. The results show that the lift power performance of Flettner Rotors decreased with increasing heeling angle. After adding the Flettner Rotor contribution to heeling moment function, the authors reported that Flettner rotors do not increase the nonlinearity of roll motion. Also, it was found that at large heel angles, the driving force becomes almost zero.

In [11] the economical side of Flettner rotor used by container carrier with DWT 4000 ton is addressed. In the analysed case, the economic benefits resulted very low.

The literature review showed the lack of knowledge regarding the optimisation of the combined diesel-rotor propulsion, taking into account the shift of the engine working point due to rotor thrust, the related fuel consumption and the additional power required to spin the rotor.

The paper aims to set the foundation of a ship propulsion model able to address fuel consumption optimisation from a design and operational perspective. The results highlight the effects of the rotor size and wind speed on the ship resistance.

2 NUMERICAL MODEL

2.1 Ship propulsion and rotor interaction

Ship propulsion models traditionally combine propeller and engine stationary characteristics to define a matching space where the overall system performance in terms of fuel consumption can be computed [12,13].

The presence of the rotor introduces a new propulsion force that has to be combined with the propeller force to identify the new equilibrium point in terms of propeller revolution and engine delivered torque.

The effective rotor force along the ship motion direction is the rotor thrust (T_{FR}) which is computed by combining the two aerodynamical forces of the rotor with the apparent wind vector.

The new propeller thrust is calculated as the difference between the total thrust required to overcome the total ship resistance (increased due to the presence of the rotor) and the rotor thrust: $T_P = T_R - T_{FR}$.

For each combination of wind condition and ship speed, there is a different propeller working point that has to be identified.

In Figure 1 the forces generated by the rotor are reported. The Lift (L) and Drag (D) direction is perpendicular and parallel to the Apparent Wind (AW) direction, respectively. The total generated force, in black, can be projected along the ship longitudinal axis, obtaining the effective rotor thrust in ship motion direction (T_{FR}), and, perpendicular to it, the rotor sway force (F_{SW}).

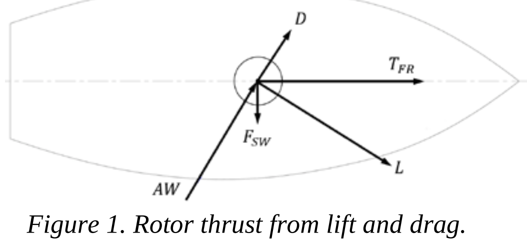

Figure 1. Rotor thrust from lift and drag.

Once T_{FR} has been evaluated, it is possible to determine the new total ship resistance (R_{TW}) by subtracting it from the original ship resistance (R_T), and by adding the wind added resistance (R_W), as reported in Equation 1:

$$R_{TW} = R_T - T_{FR} + R_W \quad (1)$$

The wind added resistance is calculated, taking into consideration wind speed and direction, as reported in Equation 2:

$$R_W = K\frac{1}{2}\rho_{AIR}(A_L \sin\alpha\, A_T \cos\alpha)U^2 \quad (2)$$

Where K is the air resistance coefficient, ρ_{AIR} is the air density, A_L is the projected longitudinal area, A_T is the projected transversal area, α is the angle of the apparent wind with respect to the bow, and U is the flux velocity.

R_{TW} is the effective total ship resistance used to determine the propeller working point on the open water diagram and, subsequently, the power required by the propeller.

2.2 Flettner rotor mathematical model

A mathematical model has been developed to evaluate the thrust force generated by the rotor for each vessel speed and wind condition.

The first step of the model is finding the coefficient of lift (C_L) and drag (C_D) as a function of the main dimension of the rotor, as reported in Equation 3.

$$C_L = \sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{k=1}^{3} a_{ijk} \cdot SR^i \cdot AR^j \cdot \left(\frac{d_e}{d}\right)^k$$

$$C_D = \sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{k=1}^{3} b_{ijk} \cdot SR^i \cdot AR^j \cdot \left(\frac{d_e}{d}\right)^k \quad (3)$$

C_L and C_D equations are taken from [14], where De Marco et al. describe the numerical analysis carried out, the value of a_{ijk} and b_{ijk} coefficients, and validity ranges. In Equation 3, SR represents the rotor spin ratio, AR the rotor aspect ratio, d_e is the endplate diameter, and d the rotor diameter.

By knowing the coefficients and wind speed, it is possible to evaluate lift and drag as reported in Equation 4:

$$L = C_L \cdot p_{st} \cdot A$$

$$D = C_D \cdot p_{st} \cdot A \quad (4)$$

Where p_{ST} is the stagnation pressure, calculated as $p_{ST} = \rho_{AIR}\, U^2$.

This part of the model has been validated by comparing the obtained results with data available in the literature [14].

3 NUMERICAL RESULTS

3.1 Case study

The ship chosen as a case study is a 3000 tons Ro-ro ferry operating in the Messina Strait. The authors virtually equipped her with a Flettner rotor of different geometrical dimensions.

The model is tested at various wind speeds and directions, considering the particular area of operation.

The parameters studied are rotor dimensions, ship speed, wind speed and direction.

For each case, the results are expressed in terms of rotor forces, rotor thrust and the ratio between rotor thrust and total ship resistance.

3.2 Wind direction effect

The main dimension of the rotor tested for Figures 2 to 5 are reported in Table 1, together with the initial true wind assumed.

Table 1. Rotor main dimensions and true wind

Height [m]	Diameter [m]	AR	Wind speed [m/s]	Wind direction [°]
12.5	2.1	5.95	12	110

In Figure 2, the forces generated by the rotor are reported. The true wind is 15 m/s from 110° (being 0° head wind). Four forces are reported: rotor lift and drag (dashed lines), rotor thrust (force in ship direction), and sway force (perpendicular to ship direction).

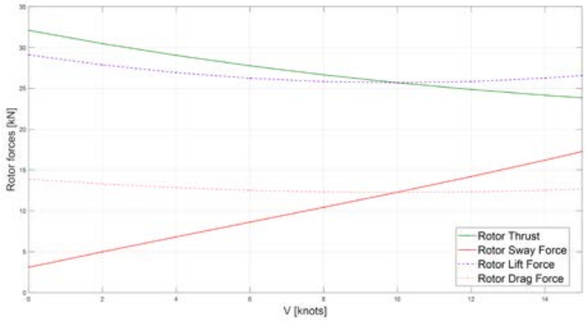

Figure 2. Rotor forces.

Rotor thrust (higher solid line) decreases with increasing ship speed because of apparent wind, which moves progressively towards the bow, becoming less advantageous.

Figure 3 shows the saving in terms of delivered power when the rotor is on. The propeller delivered power is computed by considering the equilibrium between propeller thrust and ship resistance, as described in [15].

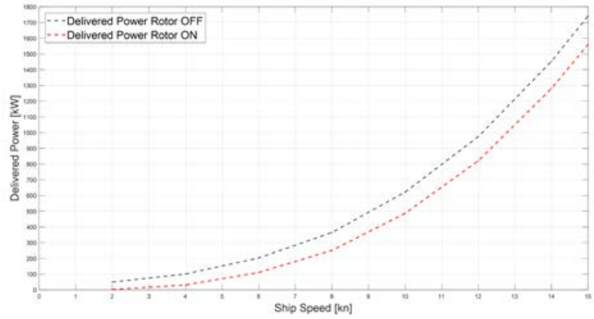

Figure 3. Delivered power (P_D) with or without rotor.

It can be observed that there is a saving of about 100 kW in the entire ship speed range, in respect to the condition without rotor, when the true wind is 15 m/s from 110°.

From Figure 4 to 6, the ratio between rotor thrust and total ship resistance is reported to give an immediate idea of the benefits the rotor could bring.

The influence of the true wind direction is shown in Figure 4, where the true wind speed is kept constant at 15 m/s.

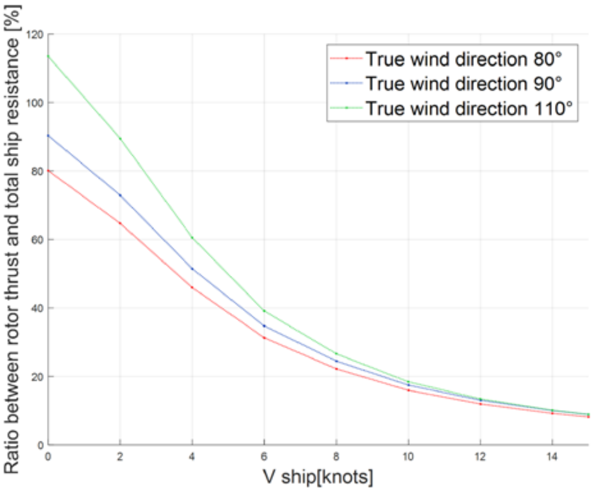

Figure 4. Influence of true wind direction on rotor thrust.

As expected, the aft wind has a more significant impact, particularly at lower ship speed. Again the distance between the lines taper off as the ship speed increases because of the increasing influence of the latter in the apparent wind direction composition.

The influence of the true wind speed is shown in Figure 5, where the true wind direction is kept constant at 80°. As expected, the stronger the wind, the better the effect on the contribution to propulsion.

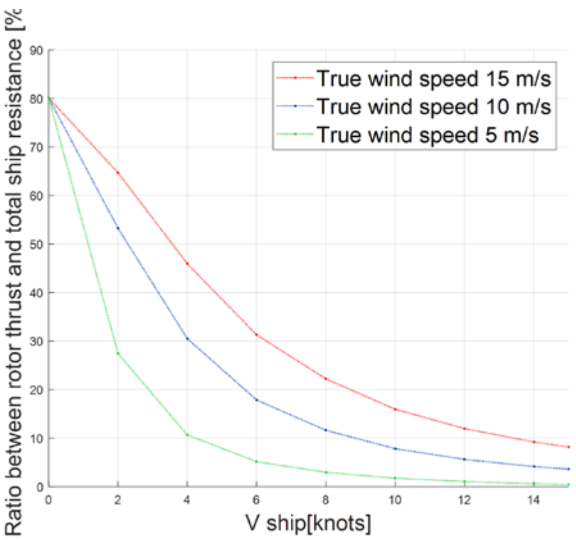

Figure 5. Influence of true wind speed on rotor thrust.

3.3 Rotor size

The influence of the main rotor dimensions is shown in Figure 6, while Table 2 shows the wind speed and direction kept constant during this simulation.

Table 2. Wind condition

Speed [m/s]	Direction [°]
15	110

From this figure, it can be deduced that enlarging the rotor has a more substantial effect on the thrust generated rather than an increase in ship resistance, despite the wind added resistance is always taken into consideration. Increasing the rotor diameter seems more effective than increasing its height.

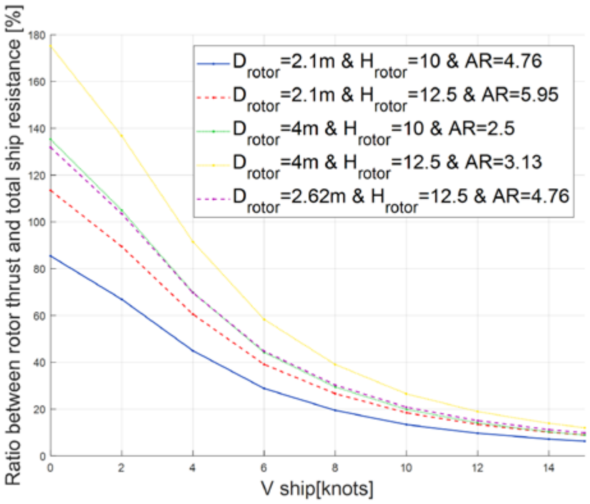

Figure 6. Influence of rotor geometry on rotor thrust.

4 CONCLUSIONS

This research's main goal was to improve the ship's energy efficiency by reducing the total fuel consumption of the vessel achieved using a virtual wind assisted propulsion framework.

This paper presented the study of a mathematical model, able to determine the thrust force given by the rotor at different vessel speed and wind condition, to assess the potential reduction in the propeller delivered power using the rotor as an auxiliary propulsion device.

Results show that an increase in wind speed leads to an increase in the ratio between rotor thrust and total ship resistance. In particular, it has been found that a crosswind slightly from the stern seems to be the optimal option.

As expected, the bigger the rotor, the better the solution. An increase in height or diameter causes a visible gain in thrust generated but a negligible rise in ship resistance. More specifically, the diameter has a more significant influence than the height. Limitation in terms of dimension, weight and position have to be accounted for to ensure vessel stability.

Those preliminary results will be integrated in the future with the classical ship power and propulsion modelling framework to assess ship fuel consumption savings.

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NOMENCLATURE

A	reference area, m^2
A_L	projected longitudinal area, m^2
A_T	projected transversal area, m^2
AR	rotor aspect ratio
C_L	coefficient of lift
C_D	coefficient of drag
D	drag force, N
D_{rotor}	cylinder diameter, m
d_e	end plate diameter, m
F_{SW}	rotor sway force, N
H_{rotor}	rotor height, m
K	air resistance coefficient
L	lift force, N
p_{ST}	stagnation pressure, Pa
SR	rotor spin ratio
T_{FR}	rotor thrust, N
T_P	propeller thrust, N
T_R	ship total thrust (R_T/(1-t)), N
U	flux velocity, m/s

Greek symbols

α	angle of the apparent wind with respect to the bow
ρ	*density, Kg/m^3*

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