THE USE OF FLETTNER ROTORS IN EFFICIENT SHIP DESIGN

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SUMMARY

This paper describes the approach taken to create a software model for the use of auxiliary wind propulsion on common ship types of the UK fleet, giving preliminary indications of the benefits achievable. The wind power technology modelled was Flettner rotors, a unique type of powered sail that has attracted more recent interest for its potential to reduce fuel consumption on ships.

Consideration has been given to some of the practical limitations of retrofitting Flettner rotors to a ship, and also some negative side effects that have been incorporated into the model to attempt to give a balanced and conservative assessment of the potential benefits. The analysis process described within this paper is intended to provide an initial 'first stage' assessment of the viability of retrofitting Flettner rotors to a particular defined ship, before any progression on to analysing specific scenario benefits or other detailed investigations.

NOMENCLATURE

ρ_{air}	Density of air (kg m^{-3})
C_D	Coefficient of Drag (none)
C_L	Coefficient of Lift (none)
Cm	Coefficient of moment (none)
D_{FR}	Drag force (N)
D_{rud}	Rudder drag (N)
D_{side}	Sideways component of Drag (N)
D_{thrust}	Thrust component of Drag (N)
f_{crit}	First critical frequency (Hz)
FR_{res}	Resultant force (N)
L_{FR}	Lift force (N)
L_{rud}	Rudder lift force (N)
L_{side}	Sideways component of Lift (N)
L_{thrust}	Thrust component of Lift (N)
M_{FR}	Heeling moment (N m)
MY_{FR}	Yawing moment (N m)
N	Cylinder rotating speed (rads s^{-1})
$P_{bearing}$	Power to overcome bearing (W)
P_{cyl}	Power for cylinder (W)
P_{disk}	Power for disk (W)
Re_{cyl}	Reynolds number (none)
R_{fr}	Cylinder radius (m)
$T_{bearing}$	Bearing torque (N m)
T_{disk}	Torque on disk (N m)
V_{app}	Apparent wind speed (m s^{-1})
V_{rat}	Velocity ratio (none)
V_{ship}	Ship speed (m s^{-1})
V_{true}	True wind speed (m s^{-1})
β	Apparent wind direction (degrees)
Φ	Angle of static heel (degrees)

1. INTRODUCTION

The Energy Efficiency Design Index (EEDI) was made mandatory for all new built ships, and the Ship Energy Efficiency Management Plan (SEEMP) for all existing ships, under the amendments made to MARPOL Annex VI [1]. As a result of this, modern day shipping faces an enormous challenge: to reduce its fuel consumption and the emission of CO_2 to meet the prescribed MARPOL targets.

Wind propulsion has been a popular research topic for green shipping enthusiasts throughout the 20th and 21st century, particularly at times of high bunker prices. The potential benefits are obvious; with the promise of reducing the fuel consumption of a ship is the possibility of improved profit margins, a reduced freight rate and a reduction in greenhouse gas emissions.

Flettner rotors (FRs) are a form of wind based propulsion that utilizes the 'Magnus effect', a phenomenon exhibited by a spinning body in a fluid flow incident upon it. It is this effect that is responsible for the curving flight path of a ball in many sports, or the deviation of a spinning artillery shell in a crosswind.

A FR typically comprises a cylinder with an endplate affixed to the top, mounted vertically to the deck of a ship. Through the action of a motor, the cylinder rotates in an air stream and a lift force is generated that can contribute to the propulsive needs of the ship (Fig.1).

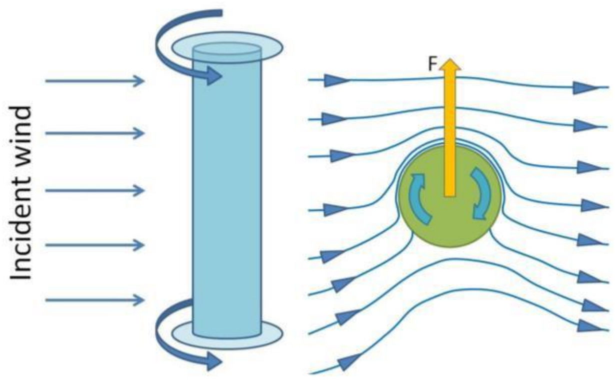

Figure 1: The Magnus effect.

FRs were first installed on a ship named the *Buckau* in the 1920's by a German scientist named Anton Flettner [2], who realised their potential for ship propulsion. This installation was the proof of concept that allowed the *Buckau* to sail across the Atlantic in 1926, and prompted the construction of the *Barbara*, a ship which had FRs installed from original fit in order to supplement rather than replace conventional propulsion.

Although both were successful in achieving their overall goal of saving fuel, the high capital cost alongside reduced bunker prices meant that ultimately these ships disappointed their owners, and the rotors were taken out of commission. However, with the modern focus on energy efficient design and fuel saving technologies, matched with high bunker prices, the focus has once again come round to FRs and their potential to save ship-owners money, as well as improve the green credentials of a ship.

The German wind turbine manufacturer Enercon has constructed a new ship the *E-Ship 1*, which incorporates four large FRs as auxiliary propulsion and has operated successfully at sea since 2010 [3]. This has prompted studies into retrofitting FRs onto existing ships, in order to garner a greater fleet-wide benefit.

There have been a number of previous studies [4][5][6] that have modelled FRs and their benefits to shipping; however for the most part these do not consider the ship fit factors and instead focus on potential savings over set wind routes. This study has sought to address this by creating a model that considers the limitations and locations of rotors on a ship, and makes only general assumptions about a ships voyage routing for a generic assessment of suitability for a given ship type.

2. MODEL APPROACH

The FR model was developed to be used in conjunction with Ptool, BMT's proprietary marine power and propulsion tool [7]. Ptool is used to take account of the hydrodynamic effects caused by the introduction of FRs, and how they affect the ship as an integrated system.

The input into Ptool from the FR model is the net thrust generated for a given wind and sea condition and the FR motor power requirement which is added to the ships electrical load (SEL). This data is used to calculate the overall net efficiency and fuel consumption benefits. For Ptool to make an assessment it requires two broad inputs; the 'Infile', which is used to define the ship under assessment, and the technology 'Options file', used to define all necessary parameters for the technology being applied, in this case FRs.

2.1 SHIP SELECTION

When beginning an assessment for the potential retrofit of FRs on a ship, it must first be ensured that the candidate ship is physically well suited to accommodate them. The ships particulars are used to define the initial dimensions and locations for FRs, and depending on the type of ship, a different logic is applied.

Initial requirements are as follows:

- Sufficient clear deck space;
- No immediately adjacent structure;
- Suitably strong mounting points.

These requirements ultimately mean that a candidate ship must be of a type that has an open area of deck, without extensive superstructure that would inhibit air flow, or deck gear/cranes which may be obstructed by the presence of a FR. Guidance to this effect has recently been published by Lloyds Register [8].

As there will be considerable forces transmitted to the structure of the ship, the mounting sites must be carefully chosen to ensure that the forces can be safely transferred to the ships structure. For an initial assessment, areas that already have deck reinforcement for cranes or capstans etc. are assumed to be an appropriate site. Where this is not possible, sited directly over a bulkhead that can accommodate extra stiffening is an acceptable alternative.

From this approach it becomes clear that certain ship types are unsuitable from the outset; RoPax and container feeder type vessels lack the clear deck space required. For container vessels the installation would require the sacrifice of some container carrying capacity, besides the requirement for clear space around the rotor. However, other vessel types such as dry bulk carriers and tankers represent an ideal platform for the installation of FRs. Their open decks and relatively slow steaming speeds, alongside favourable operating profiles make them a more attractive proposition for the use of FRs.

The operating profile of the ship and the ships speed in different sea states are also key factors to the feasibility of a FR installation, as FRs are more effective for ships travelling at slower speeds in medium/higher winds. The best fuel-saving benefit is for ships that spend the majority of their operational time at a constant cruising speed instead of manoeuvring, such as anchor handlers.

The ship selected to demonstrate the FR model is a chemical tanker of approximately 14,700 tonnes deadweight, which meets all the criteria required to make it a suitable platform for FR retrofit. Prior to use within the model, all its main parameters (overall dimensions, displacement, engine type etc.) are defined in the Infile.

For confidentiality reasons, exact details of the ship are not stated here.

2.2 ROTOR DESIGN

A standard FR is a basic cylinder shape, with an endplate mounted at the top in order to improve the lift/drag ratio [9]. It can include 'Thom fences', additional plates spaced evenly along the length of the cylinder which can also increase the lift coefficient at the cost of greatly increased power requirements [10], named after Dr Alexander Thom who initially proposed their use in FR design [11]. The primary design parameters of a FR are shown in Fig. 2.

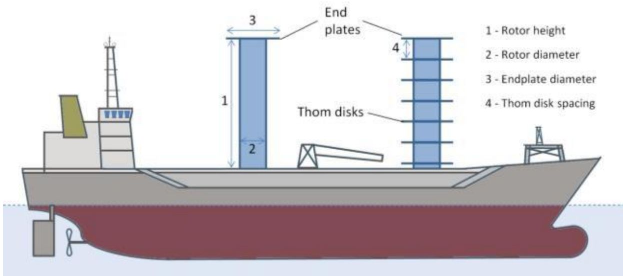

Figure 2: FR features.

The basic structure and major characteristics of the rotor must be defined in the technology options file prior to use within the model. As the model is generic in order to be used with a number of different ships with different sized rotors, the rotor design will automatically generated based on the particulars of the test ship if it is not pre-defined.

The FR height is defined as the vertical distance from the weather deck to the top of the ships tallest mast, so as not to increase the existing air draft of the ship. The diameter of the cylinder is defined based on a fixed aspect ratio of height/diameter, with a lower aspect ratio for the endplates. For the purposes of this model, there are no Thom disks taken into consideration.

2.3 AERODYNAMIC DATA

The only dynamically controlled variable of the FR is the rotational speed, which consequently affects the velocity ratio, which is defined as the ratio of the cylinder surface speed relative to the air speed as shown below:

$$V_{rat} = {}^{N \cdot R_{fr}}\!/_{V_{app}}$$

Coefficients of lift and drag vary with the velocity ratio; therefore FR performance within the model is dependent on the background data used to calculate the coefficients of lift and drag, and the subsequent forces that are generated.

Accurate data regarding the coefficients of lift and drag was limited to a maximum velocity ratio of 8, taken from early experimental results based on the work of Jakob Ackeret [12]. This data is illustrated in Fig. 3.

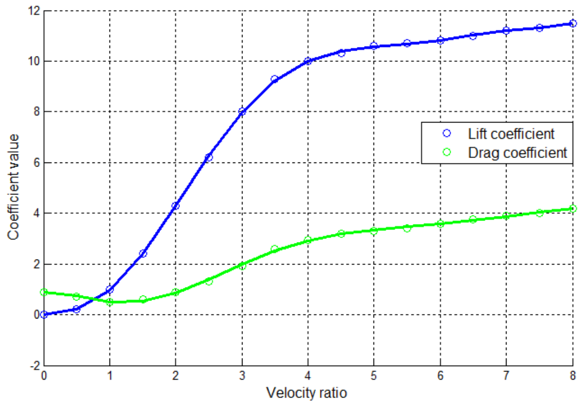

Figure 3: Ackeret values for C_L and C_D

This data was gathered for a simple FR with endplates 1.5 times the cylinder diameter, and a fixed aspect ratio of 5. In order to remain within the bounds of the data, the fixed ratios are the same within the model. The effects of different aspect ratios, disk sizes and surface finishes on the FR coefficients have been well documented [9][13][14], but for the purposes of a preliminary assessment they are not addressed here.

3. MODEL DESCRIPTION

The FR model is a separate program to Ptool, which performs all of the FR related calculations for a simulation and then feeds the results back into the main ship model within Ptool. The logic for this process is shown in Fig. 4.

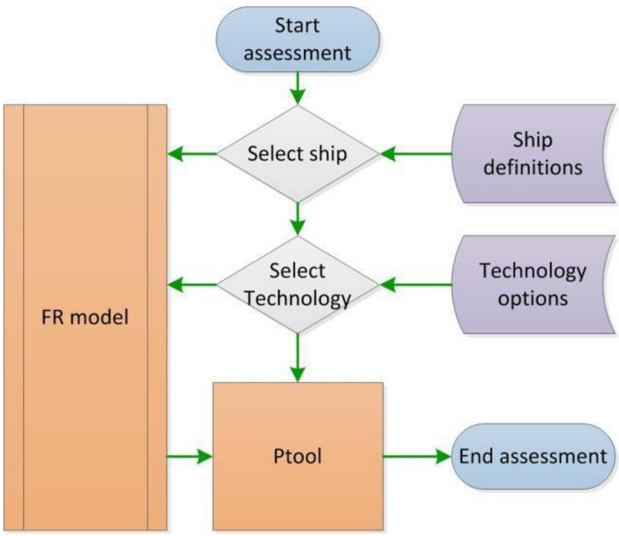

Figure 4: FR model interactions

Once the FR model has been run and the results returned, Ptool will then assess in detail how the ships power and propulsion systems respond to the reduction in resistance.

3.1 WIND AND FORCES

The wind force and direction experienced by the ship as it moves forward will be the resultant of the 'induced wind' (the airflow felt due to the ships forward motion) and the 'true wind' (the direction of the wind were the ship to be stationary) to create the apparent wind.

It is the apparent wind incident upon the ship that is the wind speed used for calculating the velocity ratio. The apparent wind varies in strength and direction for every combination of ship speed, true wind speed and true wind direction, so the FR model must take all potential combinations into account.

As the model is intended to be generic there is no wind routing performed, therefore each instance of true wind direction is assumed to be equally likely to occur.
The resulting lift and drag forces from the FR are then broken into their components and summed to give the net force for that scenario. The apparent wind and forces are illustrated in Fig. 5.

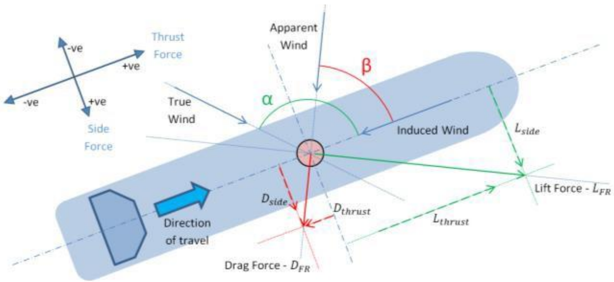

Figure 5: Apparent wind and forces

The magnitude of the lift force for a FR is shown below; the formula for drag is the same but with the corresponding drag coefficient [4].

$$Lift = \frac{\rho_{air} \cdot A \cdot V_{app}^2 \cdot C_L}{2}$$

It is assumed that the rotor will always rotate in the direction that will provide beneficial thrust and at the highest beneficial rotational speed; where that is not possible the rotors are turned off to minimize drag and power consumption. For a full 360 degree azimuth the forces are averaged to provide the thrust input to Ptool, and thus provide a conservative approach to predicting net savings.

3.2 NET POWER

The power consumption of a FR was taken to be the sum of the motor power required to overcome the aerodynamic resistance and the resistance from the bearings. Aerodynamic power is calculated by treating the endplate and cylinder as separate entities and summing the required powers. The relevant equation for each is given below [15]:

$$P_{disk} = Cm_{disk} \cdot \rho_{air} \cdot N^3 \cdot R_{disk}^5$$

$$P_{cyl} = \frac{1}{2} \cdot Cm_{cyl} \cdot \pi \cdot \rho_{air} \cdot N^3 \cdot R_{cyl}^4 \cdot L_{cyl}$$

$$P_{bearing} = \frac{k_{bearing} \cdot F_{bearing} \cdot D_{bearing} \cdot N}{2}$$

In order to ensure the operation of FRs provides a net benefit in a particular scenario, the total power required to drive a rotor is compared against the equivalent main engine power its thrust replaces. In the event the thrust from the FRs does not justify their added power requirements, the rotors are turned off.

The power to drive the rotors is added to the SEL, while the main engine power is reduced to account for the added thrust from FRs. The effect of this extra load to the SEL is taken into account within the ship model; running the main engines away from their original design operating point changes Sfc, the propeller efficiency will improve, and there will be an increased load on the Diesel Generators (DGs).

3.3 NEGATIVE EFFECTS

There are other factors that affect the overall performance of a FR fitted ship, and demonstrate why an early appreciation of ship type and layout are important. Factors considered within this model are:

- Increased heeling moment from side forces;
- Extra rudder drag from increased yaw;
- Forced vibrations (Resonance).

The sideways (sway) forces as illustrated in Fig. 5 can become very large when the apparent wind angle (β) is nearly dead ahead or astern. This large sideways force when combined with the vertical lever arm of a FR creates a large heeling moment on the ship and will thus increase the angle of static heel, just as with a sailing yacht. The increase in static heel angle must therefore be calculated to ensure it does not exceed safe levels and to quantify its effect on the sea keeping of the ship.

This is accomplished within the FR model by using the hydrostatic characteristics of the ship. Moments are equated around the vertical centre of gravity (VCG) and basic geometry allows for a calculation of static heel angle, shown in Fig. 6.

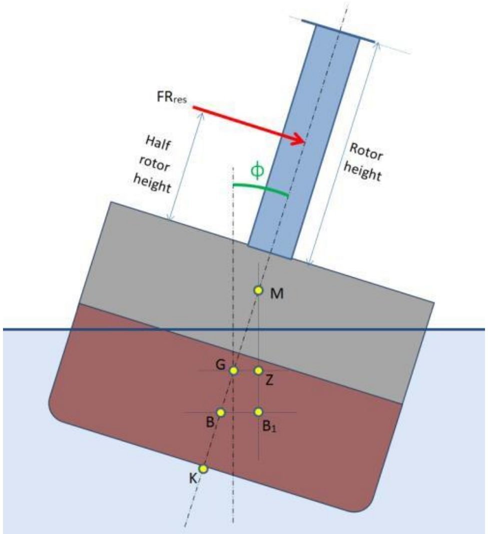

Figure 6: Angle of static heel

From the calculated angle of static heel, the change in the wetted surface area on the hull can be calculated and thus any resultant change in drag taken into account. It was found to have negligible effects (<1%), as the static heel does not exceed any roll angle normally experienced by the ship, thus the effects of static heel were not routinely calculated unless expected to be unusually high for that scenario.

Another potential effect of large sway forces is the ability to create unbalanced yaw moments around the ships Longitudinal Centre of Gravity (LCG). This yaw moment must be countered by applying increased rudder angle which will increase drag and reduce the benefit from the FRs. As part of this problem, there is a maximum yawing moment the rudder can exert for a given ship speed, and at reduced ship speeds and higher winds this could result in the ship losing steerage. This scenario is illustrated below in Fig. 7.

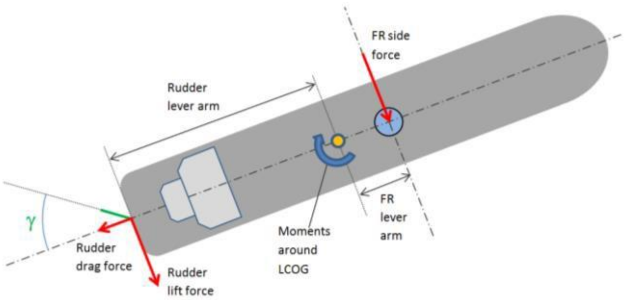

Figure 7: FR yaw forces.

To allow this scenario to be included within the FR model, where rudder characteristics are unknown, they are assumed based on known relationships [16] to account for the turning moment that could be achieved at different speeds. In the event the yaw moment created by the FRs exceeds the rudders capacity to counter it, the rotor speed is reduced in order to retain steerage. The effect of off centred propulsion due to increased heel angles was also considered with its potential to create a yaw moment on the ship; however, the effect was not included as it was calculated to be negligibly small.

4. MODEL OUTPUTS AND RESULTS

The graphs output by the FR model are used to verify its behaviour for input into Ptool. A sample of some of these outputs is displayed below for a sample run at sea state 4.

4.1 FORWARD THRUST

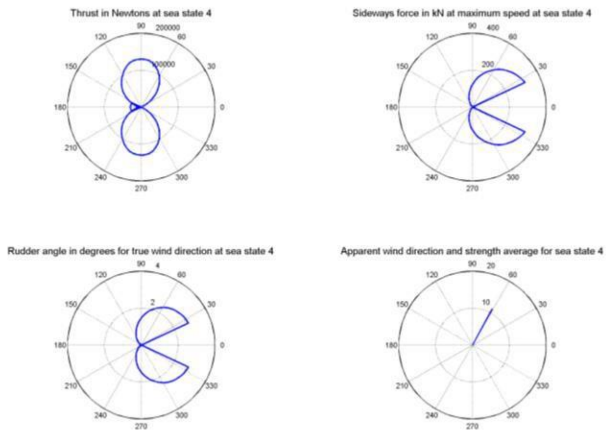

Figure 8: Polar plots of FR model

Shown in Fig. 8 is a selection of parameters measured by true wind direction that are used to verify the behaviour of certain aspects of the FR model. The characteristic shapes described by the polar plots change depending on the ship speed relative to the wind speed for the given sea state.

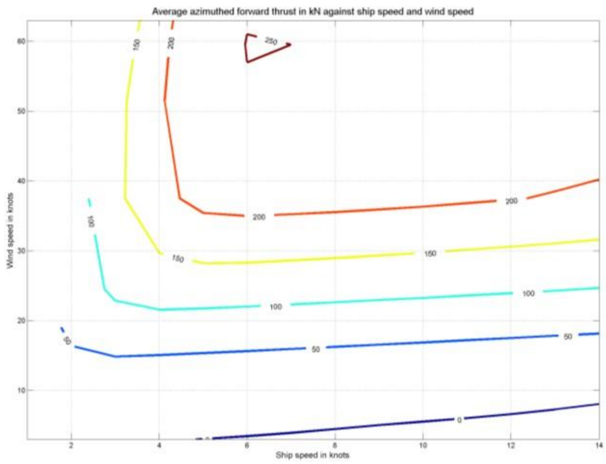

Figure 9: Average forward thrust from FR

The average forward thrust is taken to be the average of all thrust values for every point of true wind direction in a fixed wind speed, displayed in Fig. 9. For the ship in this model run, the highest forward thrust is attained between 6-7 knots of ship speed, for a 60 knot wind.

4.2 RUDDER AND YAW MOMENTS

Yaw moments from FRs are a consequence of having a FR at a different longitudinal distance from the LCG than another on the other side of the LCG. In an ideal scenario FRs would be evenly positioned either side of the LCG, however due to ship fit constraints this is not always possible. Fig. 10 shows the boundaries on the model designed to accommodate this.

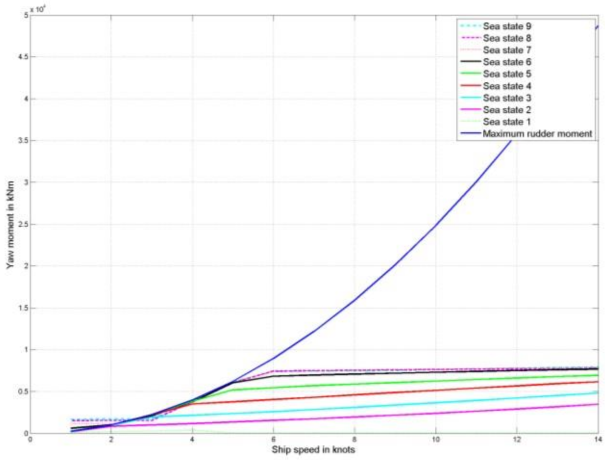

Figure 10: Yaw moment at 50° true wind

The rotors are throttled to stay within the rudders yawing capacity in order to prevent the ship losing steerage from the use of FRs. This behaviour is illustrated in Fig. 10 where it can be seen for a ship speed of 3-6 knots that the yaw moment does not cross the blue boundary line. Beneath 3 knots the ship will lose steerage; however, this would be normal for most unequipped ships and is therefore not considered further.

Illustrated by Fig. 11 is the change in FR rotational speed at sea state 4, with respect to the ship speed and the true wind direction. Left-to-right is the full azimuth from 0-360 degrees of wind direction, and front-to-back is the ship speed increasing.

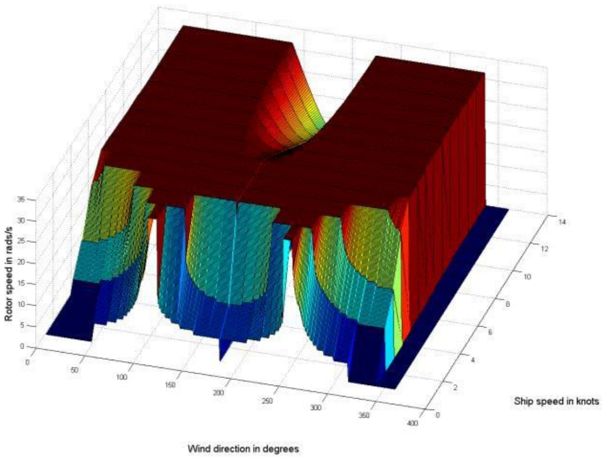

Figure 11: Rotor speed at sea state 4.

The FR model has a maximum rotor speed limit, decided after an initial estimate of the FRs first fundamental frequency based on a starting point design. This limit can be seen in Fig. 11 as the flat plateau on top, with the reduction in speed at low ship speeds a consequence of automatic rotor throttling to prevent the rudders turning capacity being exceeded, and for higher ship speeds it is to prevent the model exceeding a velocity ratio of 8.
The sheer sides before the model reaches head to wind are due to the FRs being deactivated due to negative thrust (i.e. they create more drag than useful thrust).

4.3 POWER AND SAVINGS

Once the FR model is incorporated into the ship model, the effects of fitting FRs to the ship as a whole system is investigated, i.e. resistance changes, fuel savings and power consumption.

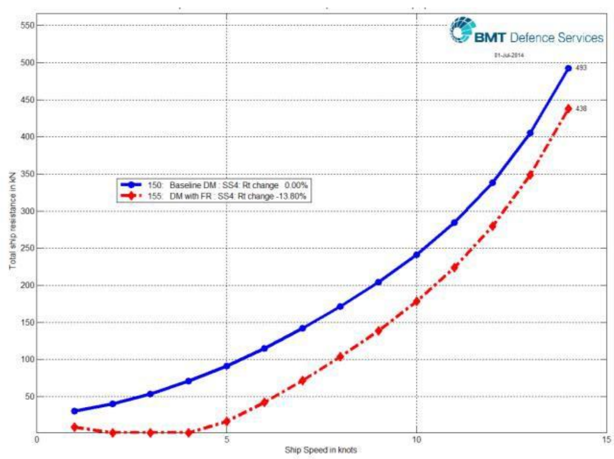

Figure 12: Resistance change with FR

The ships net resistance both with and without FRs fitted can be seen in Fig. 12. A net reduction in the overall resistance across the whole range of ship speeds is clear, with the benefit most pronounced at lower ship speeds for sea state 4. This change in resistance translates into consistent fuel savings for all ship speeds when applied to a generic operating profile, as seen below in Fig. 13.

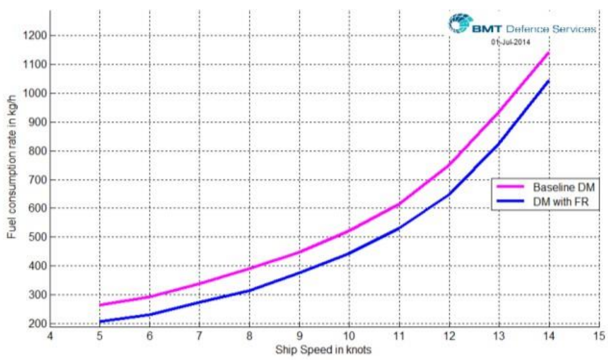

Figure 13: Fuel consumption rate vs Ship speed

When taken into account with this generic operating profile, the ship in this example stands to save up to 10% of its annual total fuel consumption with the installation of two FRs. The conservative approach of averaging around the entire azimuth means that there is good confidence in expecting better results after the application of wind routing.

5. CONCLUSIONS

The EEDI is a non-prescriptive measure that leaves the choice of technologies to industry, and thus was always expected to stimulate innovation [17]. Consequently as a part of this, the interest in wind-assisted propulsion has been renewed again not only for compliance with IMO measures, but also due to the potential of financial benefit in light of increased bunker prices.

The fuel-saving capability, carbon emission reduction potential and overall seaworthiness of FRs has been proven in several full scale installations to date, with positive results being reported as recently as 2013 [3]. It is the opinion of the author that FRs represent an opportunity to improve the net efficiency of suitable ships, both when incorporated into new build ships and when retrofitted.

This study has developed a model that allows for a conservative early stage assessment of the potential fuel saving benefits a FR installation may have, and does so in a manner that considers some of the practicalities of their use. The model is intended to be adapted in the future to incorporate more specific circumstances of a ship where that is appropriate.

6. ACKNOWLEDGEMENTS

This paper represents work carried out by BMT Defence Services Ltd with the permission of the Energy Technologies Institute's Heavy Duty Vehicle (HDV) programme, whose support in the development of this technology model is gratefully acknowledged.

It is BMT's intention to claim copyright for this work. The kind permission and resources granted to the author by BMT are acknowledged with thanks. All findings, ideas, opinions and errors herein are those of the author and are not necessarily those of BMT Defence Services Ltd.

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