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The impact of propulsion factors on vessel performance in waves

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ABSTRACT

This paper investigates the effect of varying propulsion factors (wake fraction, thrust deduction, relative rotative efficiency) due to waves on overall vessel performance. Four different ships have been considered where experimental values of propulsion factors in waves are available. Simulations have been performed for a realistic transpacific journey to compute variation in propulsion factors and efficiencies due to waves in realistic operating conditions. The predicted energy consumption was found to vary from -12% to +4% as a result of changes in propulsion factors due to waves. The propulsion efficiency is significantly affected in the presence of waves so it is important to include the effect of changes in propulsion factors, especially thrust deduction and wake fraction, for accurate vessel performance prediction.

Keywords

Vessel performance, propulsion in waves, varying propulsion factors

1 INTRODUCTION

1.1 Motivation

For accurate estimation of ship performance in realistic weather conditions it is essential to understand the effect of waves on resistance and propulsion performance of a vessel. Many researchers have developed methods to predict the added resistance in waves. However, not much research has focused on how propulsion efficiency or propulsion factors get affected in waves. The few experiments that have been performed indicate a significant variation of thrust deduction and wake fraction in waves (Moor & Murdey, 1970; Nakamura & Naito, 1975; Faltinsen et al., 1980; Bhattacharyya & Steen, 2014). Taskar (2017) observed considerable change in average wake fraction using three different calculation methods. Changes in vessel performance in terms of power, fuel consumption and ship speed were reported due to the effect of waves on propulsion efficiency by Taskar et al. (2016). However, variation in thrust deduction was not taken into account due to the lack of experimental data.

Also, the investigations were performed for head waves, mostly in regular waves. The current study has investigated if the extent of changes in propulsion factors observed in these studies have a significant effect on the overall voyage performance prediction in realistic weather conditions. The study has also explored the possibility of improving vessel performance prediction by taking into account the impact of waves on propulsion factors.

1.2 Background

A number of experiments have been performed to calculate propulsive coefficients in the presence of waves. Moor & Murdey (1970) performed self-propulsion tests at the model propulsion point using three ships at ballast and full load condition and in regular head waves. The propulsion factors were calculated at 20 different wavelength to ship length ratios (λ/L) ranging from 0.5 to 3 and a waveheight of 2% of the ship length.

A comparison of propulsion factors in waves for open and ducted propellers was carried out by Bhattacharyya & Steen (2014) for two Froude numbers in head waves. Experiments were performed for regular waves with λ/L ranging from 0.8 to 1.9 and one wave amplitude depending on wavelength. Additionally, tests were also performed at two waveheights at λ/L equal to 1. Uncertainty analysis suggests that the changes in thrust deduction and wake fraction due to waves are significant.

Sigmund & el Moctar (2017) have compared propulsion factors in head waves using CFD for two different vessels. Experimental validation of their computations is only available for a twin screw cruise ship case for λ/L from 0.28 to 1.09.

2 CASE VESSELS

For the present paper, the case vessels were chosen based on the availability of propulsion coefficients in waves. Four different ships were simulated for which the data were taken from Bhattacharyya & Steen (2014) for a cargo vessel, Sigmund & el Moctar (2017) for a twin screw cruise ship and Moor & Murdey (1970) for a fast cargo liner and a tanker. Main dimensions of the vessels can be seen in Table 1. As mentioned in the table, these ships will be referred to as Ship 1, Ship 2, Ship 3 and Ship 4 in this paper.

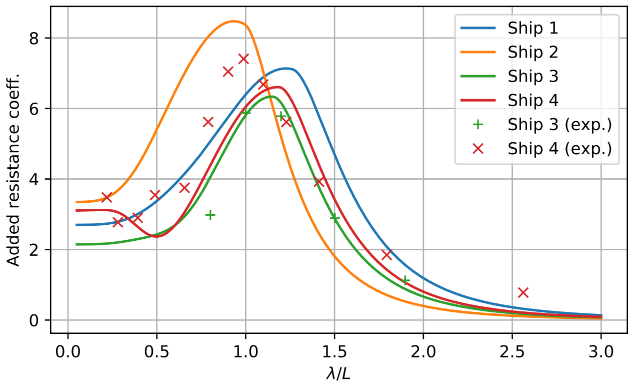

Figure 1: Added resistance computation.

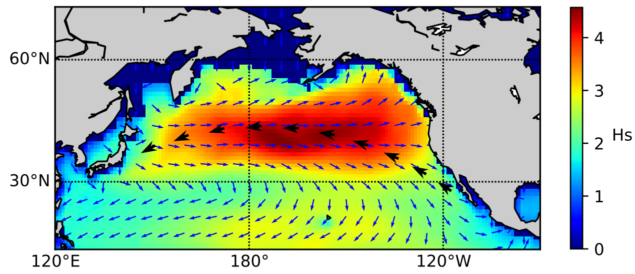

Figure 2: Route from Los Angeles to Osaka in the average weather of March. (Thick black arrows: route, blue arrows: wave directions, color: wave height)

3 METHODS

3.1 Resistance and Propulsion

The calm water resistance was calculated based on the ship's principal particulars using Holtrop & Mennen (1982) for Ships 1 and 2, whereas the method by Hollenbach (1997) was used for the Ship 3 and Ship 4. The resulting calm water resistance coefficients for all four ships can be seen in Table 1.

Added resistance has been computed using the ITTC recommended method (ITTC, 2014), which considers waves coming from 225° to 135° as head waves (180° corresponds to head waves) when computing the added resistance. The added resistance is assumed zero for other wave directions. A Bretschneider wave spectrum was used to calculate added resistance in irregular waves.

Added resistance RAOs obtained using the ITTC method for all ships can be seen in Figure 1. Added resistance coefficients obtained using the ITTC method were compared with the experimental results for Ships 3 and 4 obtained from Bhattacharyya & Steen (2014) and Sigmund & el Moctar (2017) respectively. The experimental results match very well in case of Ship 3, whereas in case of Ship 4, the added resistance is slightly underpredicted for the waves shorter than the ship length. Hence, the ITTC method can be assumed to provide sufficiently accurate results for the calculation of added resistance. Wind resistance has been ignored due to the lack of geometric details above the waterline for these ships.

Propeller open water curves were taken from Bhattacharyya & Steen (2014) and Sigmund & el Moctar (2017) for Ships 3 and 4 respectively. Open water curves were calculated using the B-series polynomials for Ships 1 and 2.

3.2 Weather and Route

As mentioned earlier, the propulsion factors and added resistance estimates were available only in head waves at the design speed of ships. Hence, route and time of year for the simulation were chosen such that the ships face head waves or bow quartering waves for most of the voyage. These conditions are met for a transpacific journey from Los Angeles to Osaka in the average weather of March. In this period the waves propagate towards east, hence a ship traveling from the USA to Japan will encounter head sea or bow quartering sea for almost the entire voyage. The weather data were obtained from ECMWF/Copernicus Climate Change Service (2017).

The chosen route follows the great circle from Los Angeles to Osaka as can be seen in Figure 2. It can also be observed that the ships face head waves for most of the voyage. Weather conditions along the route have been plotted in Figure 4. A part of the voyage, marked by a red patch in Figure 4, indicates where wave heading with respect to the ship drops below 135°. As the wave direction is towards east, the peak periods are higher towards west coast of USA as the rough sea develops. Hence peak period of waves drops from 13 seconds to 8 seconds along the voyage.

By choosing such a route and weather condition, it was possible to simulate a realistic voyage using the limited available data. The choice of this particular route also leads to a reasonably realistic added resistance estimation as the ITTC method only calculates the added resistance for head and bow quartering waves.

3.3 Propulsion Factors in Irregular Waves

All previous experimental and computational investigations of propulsion factors in waves have been performed in regular waves. Hence a method needs to be formulated to calculate average thrust deduction, wake fraction and relative rotative efficiency in irregular waves using the data in regular waves. For the present work, this was done using the concept of a response amplitude operator (RAO), where the response for propulsion factors was defined as the difference between the values in the presence of waves and calm water. The square of the RAO was multiplied with the Bretschneider wave spectrum to obtain the response spectrum; average values of thrust deduction, wake fraction and relative rotative efficiency were derived from the respective response spectra using the following equation (Newman, 1977).

$$\text{average value} = \sqrt{2\pi m_0} \tag{1}$$

where m_0 is the area under the response spectrum.

The analysis performed by Bhattacharyya & Steen (2014) suggests that the dependence of propulsion factors on ship speed is small. However, based on one measurement point at different wave amplitude, it seems that the changes in propulsion factors may not vary linearly with wave amplitude.

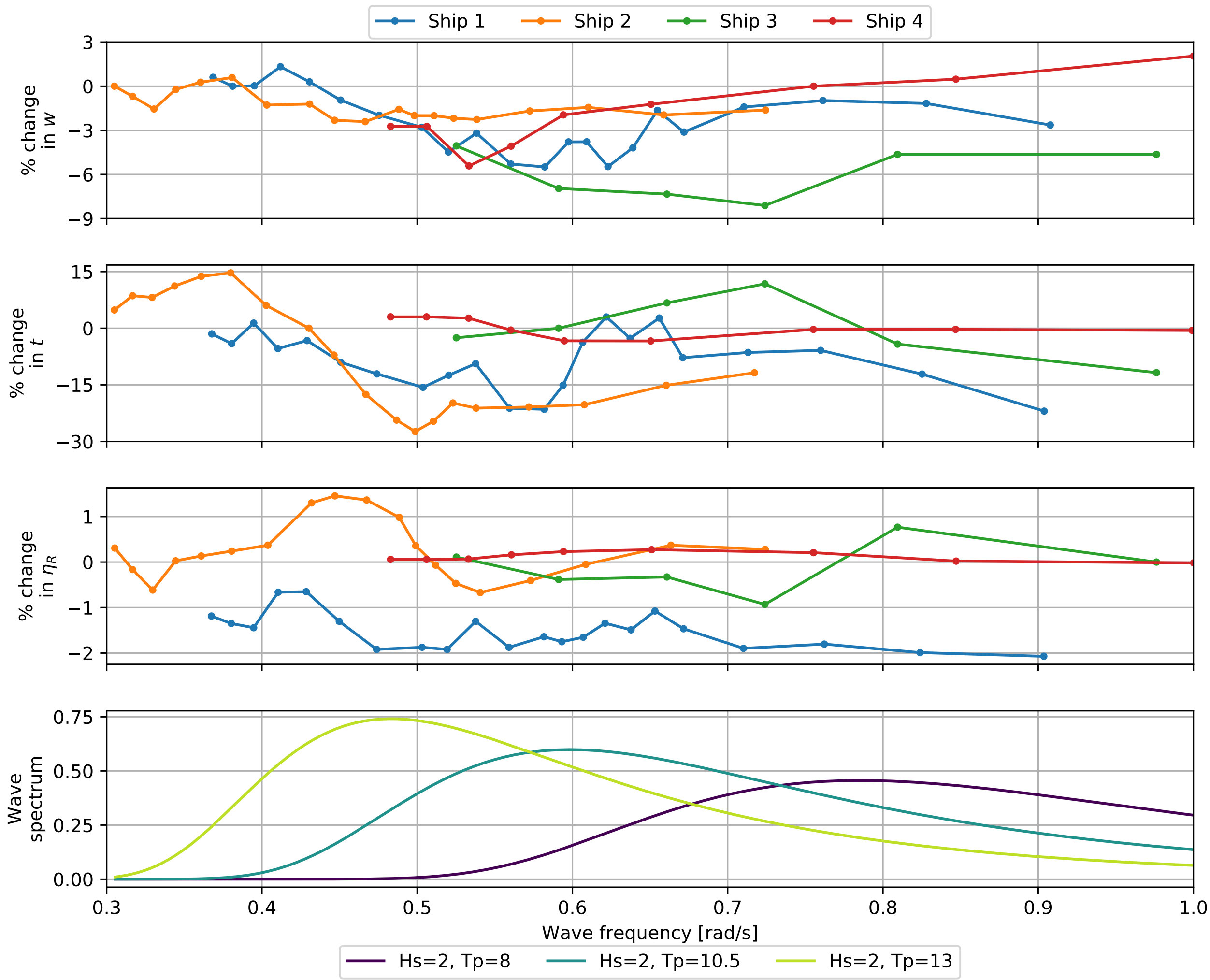

Figure 3: Percentage change in propulsion factors compared to calm water values per unit wave amplitude and a range of wave spectra encountered on the route

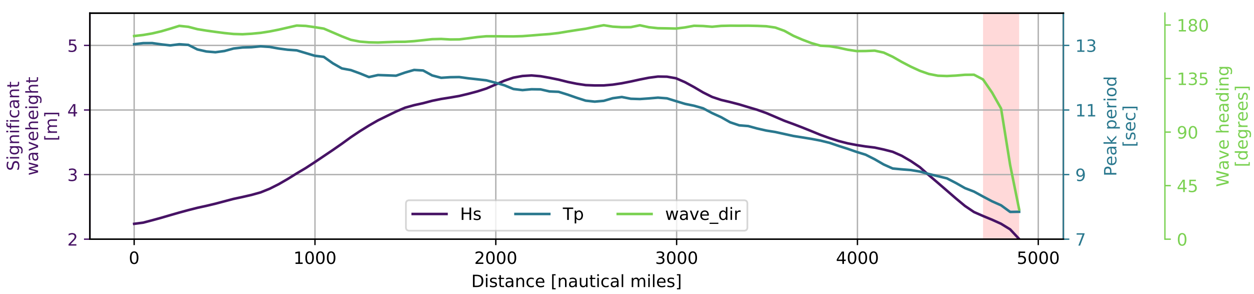

Figure 4: Wave parameters along the route. (Red band: wave heading drops below 135°)

In the absence of data at multiple waveheights, propulsion factors are assumed to vary linearly with waveheight.

The percentage change in propulsion factors in different waves as compared to calm water values can be seen in the upper three plots of Figure 3. To provide some context to the wave frequencies, the lower plot of the figure also shows wave spectra for the range of peak periods observed along the route. The propulsion factors were available for a different range of frequencies for all ships. The propulsion factors in waves were considered equal to those in calm water beyond the available range.

3.4 Simulation methodology

Simulations were performed at multiple points on the route equally spaced at 50 nautical miles distance along the great circle. The propulsion points were calculated at each location assuming the ships in steady-state condition. The ship speed was assumed constant, equal to the design speed of the respective ship. This assumption of constant ship speed simplifies the calculations as added resistance and propulsion factors in waves are all available at the design speed of ships. The propeller speed ("rpm") was calculated to balance total thrust with total resistance at design speed. The propeller rpm and torque were further used to calculate delivered power.

Two sets of simulations were performed for each ship – one assuming constant propulsion factors, same as that in calm water. In the second set of simulations, the propulsion factors were calculated in the particular wave condition, that is significant waveheight (Hs) and peak period (Tp) at the location of the ship. The average propulsion factors needed for the individual steady-state calculations were computed using the method described earlier (see Sec. 3.3).

4 RESULTS AND DISCUSSION

Results of the simulations will be discussed starting with the trends of propulsion factors in regular waves.

4.1 Propulsion factors in regular waves

In Figure 3 it can be observed that among wake fraction (w), thrust deduction (t) and relative rotative efficiency (η_R), the thrust deduction exhibits the largest changes in the presence of waves as compared to its calm water value followed by wake fraction and relative rotative efficiency. In most of the cases, the change in wake fraction is negative meaning that the wake fraction decreases in waves; which is also observed in the experiments performed by Nakamura & Naito (1975). Faltinsen et al. (1980) have shown that the decrease in wake fraction is due to potential flow effects of the pitching motion of the ship. However, no particular trend is observed in the case of thrust deduction as Ships 2 and 3 show both positive and negative change in thrust deduction, whereas in case of Ship 1, the thrust deduction decreases at most of the wave frequencies. It can be observed that Ship 4, being a twin screw ship, shows a relatively small change in propulsion factors. In the case of twin screw vessels, the magnitudes of calm water thrust deduction and wake fraction values are much smaller than for single screw ships as hull-propeller interactions are naturally limited. This is one of the reasons that the wave-induced variation of propulsion factors (that is accounted for as a relative change to the calm water values) has a rather small influence on overall performance and propulsive efficiency.

As these results are based on model tests, it is essential to know how much variation is due to experimental uncertainties and how much is the effect of waves. However, an uncertainty analysis is available only for Ship 3 (Bhattacharyya & Steen, 2014) where precision limits for 95% accuracy have been estimated at 6.65%, 1.94% and 1.95% for thrust deduction, wake fraction and relative rotative efficiency respectively. The variations in thrust deduction and wake fraction (see Figure 3) are generally higher than the precision limit which means the trends are significant. In the case of relative rotative efficiency the variations are below the precision limit and the difference could well be due to measurement uncertainties.

4.2 The effect of changes in propulsion factors on η_O

Change in thrust deduction affects propeller open water efficiency (η_O). This is because, for example, a reduction in thrust deduction results in a lower thrust requirement to maintain the same ship speed. The propulsion point moves to the right in the open water diagram (higher advance ratio) due to reduced rpm. This leads to a different and often higher open water efficiency. In case of a reduction in wake fraction, the K_T vs. J^2 curve will shift downwards as is clear from Eq. (2). Therefore, the propeller operating point, which is the intersection point between K_T and K_T vs. J^2 curve will shift to a higher advance ratio leading to higher open water efficiency. Hence, a decrease in thrust deduction and wake fraction both lead to higher open water efficiency.

$$\frac{K_T}{J^2} = \frac{T}{\rho D^2 \left(V\left(1-w\right)\right)^2} \tag{2}$$

4.3 Propulsion factors on the route

Propulsion factors (w, t, η_R) and efficiencies (including hull efficiency η_H, open water efficiency η_O) at different locations on the route can be seen in Figure 5 with constant and varying propulsion factors. Similarly, Figure 6 describes vessel performance in terms of speed, power, rpm, and resistance along the route considering constant and varying propulsion factors. The red band in these plots show the area where wave heading is less than 135°. For these conditions the added resistance is considered zero due to the limitations of the ITTC added resistance method. Since experimental propulsion factors in waves were all calculated for head waves, w, t and η_R are considered constant, equal to calm water value, when the wave heading is significantly different from the head wave i.e. 180°. Since the propulsion factors on this part of the voyage are assumed the same as in calm water, the solid lines and dotted lines merge in this area. Values in this part of the journey correspond to the calm water condition.

As wake fraction decreases for all four ships at most wave frequencies, the simulations with varying propulsion factors show a slight decrease in wake fraction along the route as compared to calm water wake fraction. The thrust deduction

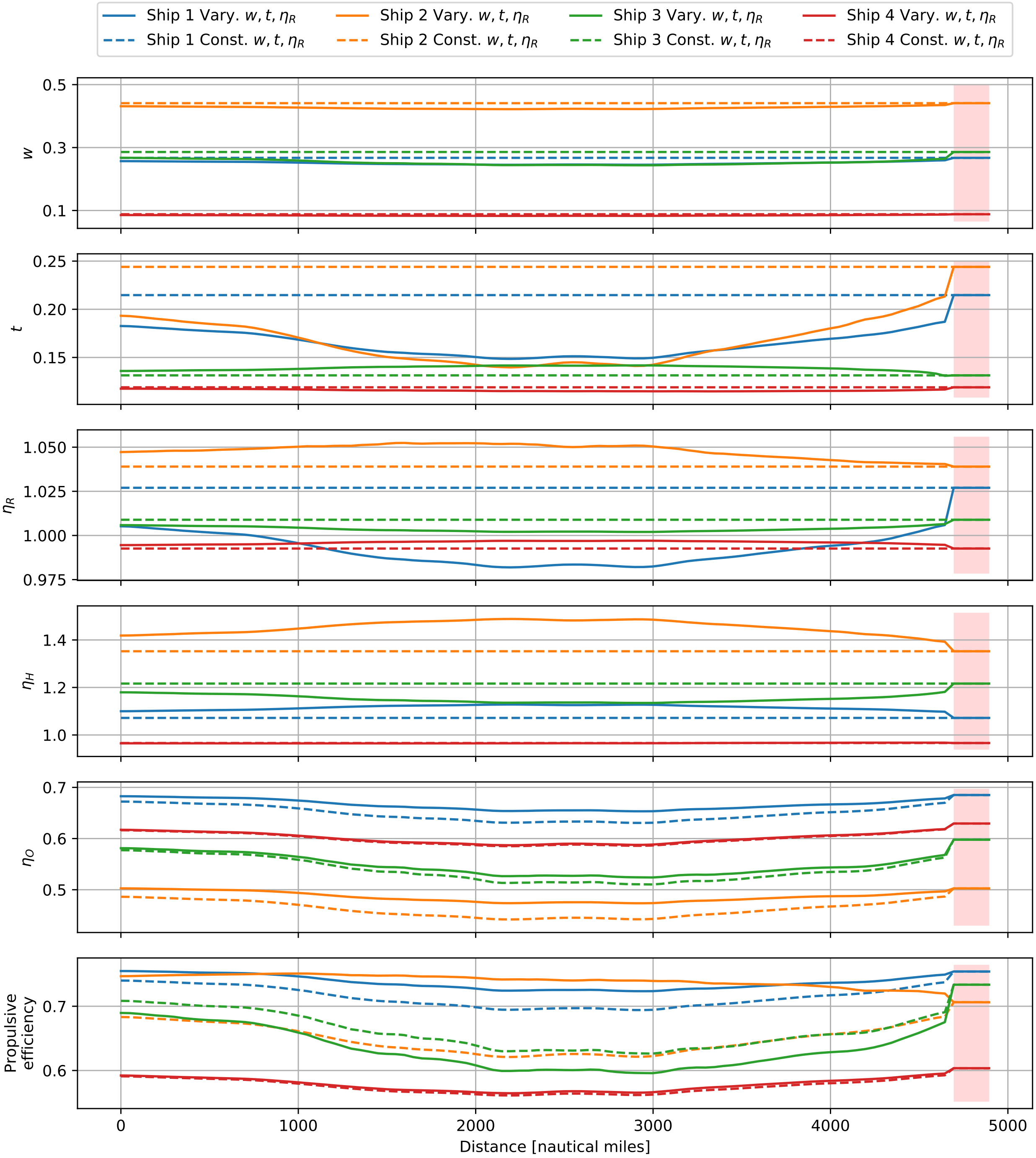

Figure 5: Changes in propulsion factors and efficiencies due to waves along the route. (Red band: wave heading drops below 135°, hence zero added resistance and no changes in propulsion factors)

Table 1: Principal Particulars

Reference	Moor et. al (1970)	Moor et. al (1970)	Bhattacharyya et. al (2014)	Sigmund et. al (2017)
Ship name in reference	STA 1148	STA 832	–	Cruise ship
Ship type	Fast cargo liner	Tanker	Cargo vessel	Cruise ship
Name in this paper	Ship 1	Ship 2	Ship 3	Ship 4
Length	152.40 m	236.20 m	117.60 m	220.27 m
Breadth	23.50 m	34.29 m	20.80 m	32.20 m
Design draft	9.14 m	12.92 m	5.50 m	7.20 m
Wetted surface area	4475 m^2	11793 m^2	2686 m^2	7822 m^2
Block coefficient	0.594	0.798	0.657	0.650
Design Froude number	0.287	0.192	0.203	0.223
Number of propellers	1	1	1	2
Number of blades	4	5	4	5
Propeller diameter	6.40 m	7.01 m	4.20 m	5.20 m
Propeller pitch ratio	0.92	0.77	0.98	1.09
Propeller blade area ratio	0.60	0.68	0.52	0.89
$C_T \cdot 10^3$	3.595	3.242	2.540	2.424

Table 2: Changes in propulsion factors and efficiencies on the route due to waves

Quantity	Symbol	Ship 1	Ship 2	Ship 3	Ship 4
Wake fraction	w	Decreases	Decreases	Decreases	Decreases
Thrust deduction	t	Decreases	Decreases	Increases	Decreases
Relative rotative efficiency	η_R	Decreases	Increases	Decreases	Increases
Hull efficiency	η_H	Increases	Increases	Decreases	Negligible change
Open water efficiency	η_O	Increases	Increases	Increases	Negligible change
Quasi propulsive efficiency	η_D	Increases	Increases	Decreases	Increases

along the route shows significant variation in waves as compared to calm water and the trends are different in all 4 cases. It decreases significantly in the case of Ships 1 and 2 whereas in the case of Ship 3, it increases slightly. The changes in relative rotative efficiency are much smaller than those in wake fraction and thrust deduction.

Trends in propulsion factors and propulsion efficiencies due to waves can be seen in Table 2. In the case of Ships 1 and 2, the thrust deduction and wake fraction decrease in the presence of waves on the route. However, the effect of reduction in thrust deduction dominates as the hull efficiency (η_H) increases. Open water efficiency also increases in both cases due to lower thrust deduction and wake fraction as explained earlier. Hence, the total propulsive efficiency is higher for these ships when changes in propulsion factors due to waves are taken into consideration.

In the case of Ship 3, the wake fraction drops whereas the thrust deduction goes up as compared to the calm water values. As explained in the Section 4.2, a decrease in wake fraction often increases the open water efficiency whereas an increase in thrust deduction typically reduces the open water efficiency. The combined effect in this case is the increase in open water efficiency, which means the effect of a reduction in wake fraction dominates over the effect of an increase in thrust deduction. Moreover, the hull efficiency

Table 3: Difference in energy consumption due to varying propulsion factors

Ship 1	Ship 2	Ship 3	Ship 4
-3.1%	-12.3%	+4.4%	-0.5%

(decreases) and open water efficiency (increases) also show opposing trends as is summarized in Table 2. The decrease in hull efficiency dominates as the total propulsive efficiency goes down.

As there is negligible variation in the propulsion factors of Ship 4 in the presence of waves, the propulsive efficiencies also show negligible variation.

4.4 Vessel performance for the route

The performance of four ships can be seen in Figure 6. The total resistance varies over the course, but the variation is the same irrespective of whether the simulations have been performed with constant or varying propulsion factors. This is due to ship speed being kept constant, equal to the design speed of the respective vessels. Propeller rpm and power vary depending on added resistance as well as on total propulsive efficiency. Power and rpm increase in the simulations with varying propulsion factors when the total

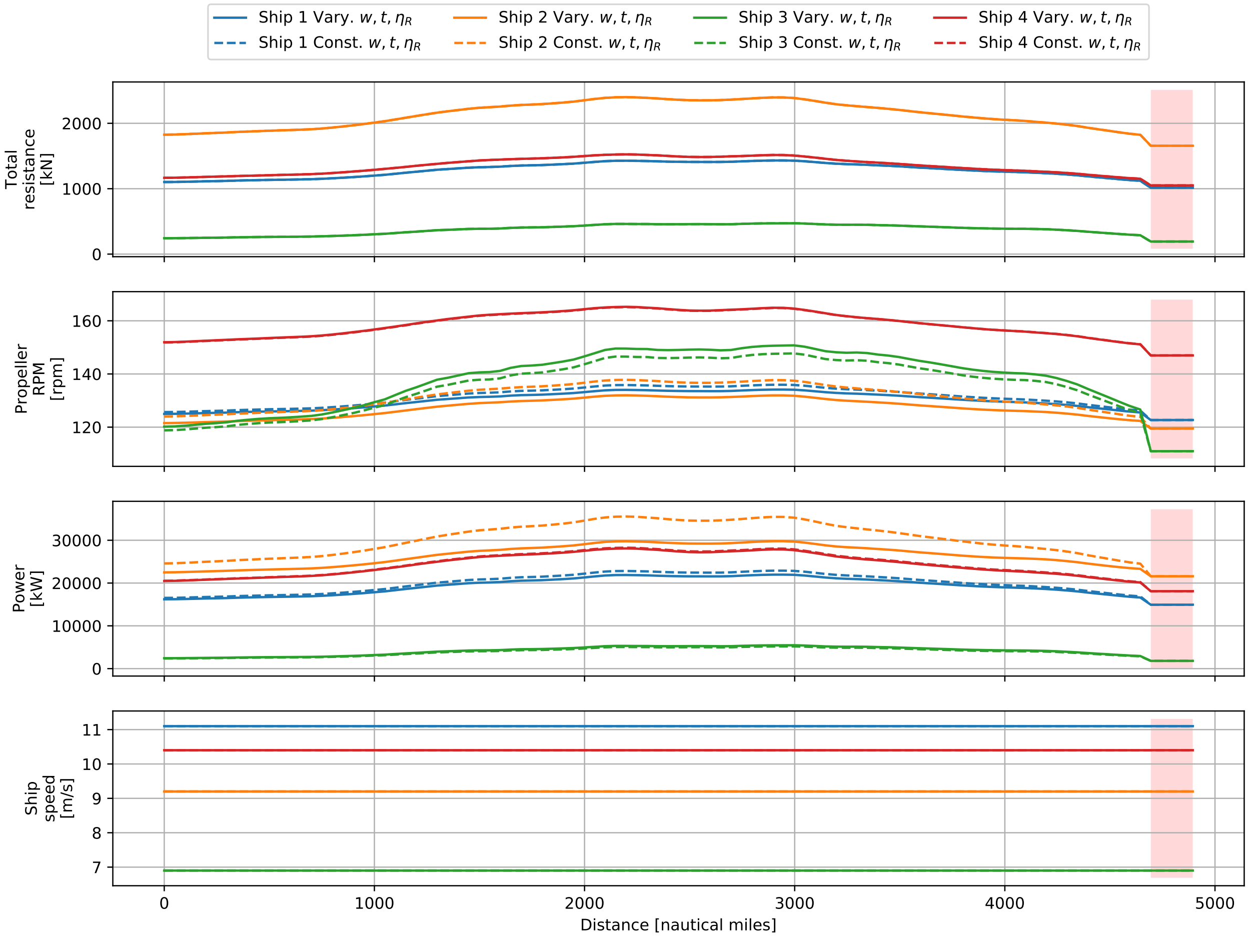

Figure 6: Vessel performance over the route with constant and varying propulsion factors. (Red band: wave heading drops below 135°, hence zero added resistance and no changes in propulsion factors)

propulsive efficiency decreases and vice versa. The total energy consumption of each ship was calculated using the power and total time taken for the voyage and is provided as a simplified indicator for fuel consumption and emissions. The relative change in energy consumption due to the effect of waves on propulsion factors can be seen in Table 3. The magnitudes of these changes indicate that hull-propeller interaction in waves has a substantial influence on predicted vessel performance and energy consumption in realistic operating conditions. Ships 1 and 2 show a reduction in energy consumption whereas Ship 3 shows the opposite trend.

4.5 Conclusions, limitations, and future work

Based on the results in the previous section, changes in thrust deduction and wake fraction due to waves can significantly affect vessel performance prediction. Assuming constant propulsion factors can also affect data-based performance analysis. If the propulsion factors are considered constant, equal to the calm water value, the effects of wave-induced variation in hull-propeller interaction are likely to be falsely identified as a part of added resistance. Therefore, for the accurate evaluation of vessel performance in realistic conditions, it is essential to consider the effect of waves on propulsion efficiency.

In the current analysis, the concept of RAO has been used to compute propulsion factors in irregular waves. However, further investigations need to be performed to check if there indeed is a linear relationship between propulsion factors and wave amplitude.

The analysis was performed for constant ship speeds and for a route where the ships face predominantly head waves. As a remarkable variation in performance has been observed, changes in propulsion factors in other wave conditions and at different ship speeds should be investigated. There are methods to calculate wake fraction in waves, however most significant variations are observed in thrust deduction without any clear trend. Hence, understanding the underlying effect that causes a change in thrust deduction in waves would be a major step towards accurate estimation of vessel performance.

Variation of propulsion factors in waves will also have implications for other measures to improve fleet efficiency, such as weather routing.

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