DERIVATION OF THE CALM WATER PERFORMANCE OF A SHIP THROUGH NORMALISATION OF SHAFT POWER FROM FULL SCALE MEASUREMENTS

M. Limelette, Mechanical Engineering, Faculty of Science and Technology, University of Western Brittany, Brest, France
P. A. Lakshmynarayanana and **Dominic A. Hudson,** Fluid Structure Interactions Group, Faculty of Engineering and Environment, University of Southampton, U.K.

SUMMARY

This paper presents a method to normalise the shaft power data recorded at high-frequency to derive the baseline (calm water power) curves by applying a shaft power correction. This is carried out using two correction methods for added power due to waves developed for sea-trial measurements - namely, STAWAVE-1 and STAWAVE-2. The calm water power is then obtained as a difference between the measured power and the added power. The results obtained using this normalisation method is compared to filtering techniques. It is shown that the differences between the predictions using the two methods are minimal, with a maximum of 6% at the normal operational speed of the vessel. The normalising method retains about 40 % of the total data, nearly 4 times more than the datasets retained with filtering methods.

NOMENCLATURE

g	Gravitational acceleration (m s^{-2})
ρ	Density of water (kg m^{-3})
P	Power (kg m^{2} s^{-3})
V	Ship speed (m s^{-1})
R	Resistance (kg m s^{-2})

1. INTRODUCTION

The need to monitor performance of ships at full scale has increased in recent years due to the influence of factors such as new regulations (e.g. EEDI, SEEMP) coming into force, environmental concerns and the need to improve fuel efficiency. Traditionally, noon-reports were used to carry out in-service monitoring of a vessel and to inform ship operators of the total fuel consumption per day, however this introduces significant uncertainties and also has a high potential for human error [1-2]. Automatic high-frequency data acquisition has, however, given the opportunity of continuous monitoring of a vessel during the course of her operations and offers the possibility to take preventative actions at shorter time intervals [3]. However, most analyses to monitor the performance of a vessel through speed-power curves, or using Key Performance Indicators over time, focus on filtering and 'binning' methods to derive a calm water condition. This is also recommended in the ISO 19030 standard [4-5]. In this method the influence of weather is reduced and the operational condition is approximated to a calm water condition by filtering out the data points for wind speeds and wave heights above a threshold value and by retaining only a narrow range of draft and trim conditions [6]. Unfortunately, this method filters out a large amount of data and only about 9-11% of the total data are retained to derive calm water power vs speed relationships [1, 4]. Filtering and 'binning' methods generally produce reliable calm water power vs speed curves and allow comparisons to be made with sea trials, but require a large quantity of data and hence time for measurements is increased. However, the advantage of in-service performance monitoring over conventional sea trials is that whilst the latter focuses on a comparison to predicted (or design) values of power, the objective of the former is to make comparisons between reference baseline curves and subsequent measurements. This in turn allows generation of multiple reference baseline curves, reducing the need for using strict filtering criteria or corrections for big differences in the vessel operational conditions like draft, trim etc. [7]. An alternative way to derive the power-speed curves in calm seas from operational data is to normalise the measured data by applying shaft power corrections [6, 8]. Realistically, a vessel operates in stochastic weather and wind and wave influences are one of the biggest uncertainties in measured shaft power. However, there are methods that naval architects employ to calculate the added power in waves and wind. These may be applied as a correction to normalise the shaft power to calm water conditions [9-10]. Applying shaft power corrections for the added power in wind and waves to normalise the shaft power creates the possibility of retaining more data. However, this has to be done without sacrificing the accuracy of predictions.

This study investigates a method of obtaining calm water power-speed curves by applying a shaft power correction for added power in waves. The influence of wind is not included in this study. The results obtained from the normalised method are compared to those from filtering methods. The purpose of this study is to investigate the possibility of retaining more data, without sacrificing accuracy, rather than applying strict filtering constraints, that can reduce datasets by up to 90%.

2. METHODOLOGY

2.1 ANALYSIS APPROACH

The methodology developed to normalise the shaft power by applying corrections for the added power in waves is described in this section. A vessel operating in waves experiences an added power to maintain its speed when compared to calm water. The calm water power is calculated as a difference between the total shaft power and the added power in waves. Please note that the added power due to wind is not considered for calculations in this particular study, but would be included in the more general sense.

$$P_{Calm} = P_{Total} - P_{Added} \quad (1)$$

$$P_{Added} = f\,(V_{Ship}, H_{1/3}, V_{Wind}, \text{Heading})$$

and $$P_{Calm} = f\,(V_{Ship}, \text{Trim}, \text{Draught}),$$

where $H_{1/3}$ is the significant wave height (m), V_{Ship} is the ship speed (ms^{-1}), V_{Wind} is the wind speed (ms^{-1}) and Heading is the angle between the ship's heading and the direction of the waves (θ).

P_{Total} (kW) is determined from on-board power measurements and P_{Added} (kW) is estimated using the recommended International Towing Tank Conference (ITTC) procedures and guidelines for the correction of power measured on sea-trials due to the effects of waves and designated as STAWAVE-1 and STAWAVE-2 [9]. A more detailed description of the method for calculating the added power using these guidelines is given in Section 2.4.

2.2 SHIP DATA ACQUISITION

High-frequency continuously monitored data was obtained for three sister merchant ships along with the weather data from a MetOcean hindcast model. The data logger installed on board recorded the shaft parameters at a sampling frequency of 1 Hz and averaged over 5 min intervals. The wind speed and direction were measured using an onboard anemometer. The total period of the measured data for the three ships was different with the maximum being 18 months and the minimum being 6 months. The ship with maximum data was only considered for this study, due to the greater quantity of data. The raw data for this ship yielded a total of 143000 data points. Figure 1 shows the operational profile of the vessel with reference to the ship speed, draft, trim and the significant wave height from the MetOcean dataset. The encountered significant wave heights mainly fall in the range of 1 to 3 m and the number of data points for a wave height ≤ 2.0 m is 63385, which comprises 44% of the total dataset.

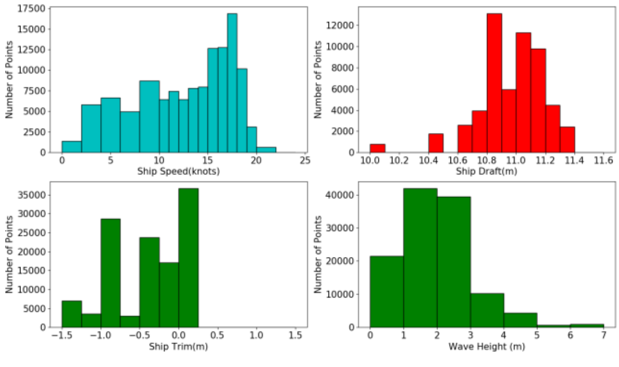

Figure 1: Histograms of ship speed, draft, trim and $H_{1/3}$

2.3 DATA HANDLING

Ship data and weather data are stored in a secure SQL database in a virtual server at the University of Southampton. Data manipulation and analysis was performed using Python via a powerful data structure for data analysis package called Pandas. Pandas provides fast, flexible and organised data structures designed for working with 'labelled' or 'relational' data in an easy and intuitive way. It facilitates selective querying and slicing of the data based on a chosen operational parameter, allowing the data for different weather and ship scenarios to be efficiently manipulated.

2.4 STAWAVE-1 AND STAWAVE-2

The added resistance a vessel experiences in waves arises primarily due to two components, one due to the motion of the vessel and the other due to the wave reflections. The encounter frequency of the waves is high in short head waves. In these conditions, for a large vessel, the effect of wave induced motions will in general be small and can be neglected. The added resistance in this case can be assumed to be predominately due to wave reflection. The STAWAVE-1 method [9], shown in equation 2, can be used to calculate the added resistance in head waves in this case, where the heave and pitch motions are small. STAWAVE-1 can be applied to wave height equal to or below the criteria in equation 3 (taken from [9]).

$$R_{AWL} = \frac{1}{16}\rho g H_{1/3}^2 B \sqrt{\frac{B}{L_{BWL}}} \quad (2)$$

where B is the beam of the ship (m) and L_{BWL} is the length of from the bow, on the waterline, to a point at which the beam is 95% of the maximum beam (m).

$$H_{1/3} = 2.25\sqrt{\frac{L_{BWL}}{100}} \quad (3)$$

The second method to calculate added resistance in waves is STAWAVE-2. In long crested irregular waves the mean increase in wave resistance R_{AWL} is considered in this method to be due to the mean increase in resistance due to both the wave reflections and the motion-induced resistance as shown in equation 4 and 5. Irregular waves can be represented as a linear superposition of the components of regular waves.

$$R_{AWL} = 2\int_0^\infty \frac{R_{wave}(\omega;V_{ship})}{\zeta_a^2} S_\eta(\omega)\,d\omega \quad (4)$$

where R_{wave} is the transfer function of mean resistance increase in regular waves, ζ_a is the wave amplitude, ω is the circular frequency of regular waves, S_η is a frequency spectrum.

$$R_{wave} = R_{AWRL} + R_{AWML} \quad (5)$$

where R_{AWRL} is the mean resistance increase due to wave resistance and R_{AWML} is the motion induced resistance.

STAWAVE-2 is considered to be more accurate because it includes the resistance increase due to both the reflection and the motion. In equation 4, a standard form of the frequency spectrum S_η can be assumed for calculation. In this paper the Bretschneider spectrum is used. The application of both STAWAVE 1 and 2 is restricted to waves in the range of +/- 45 deg. off the bow, hence the waves outside of this range are not corrected. A detailed description of the application of these methods can be found in the ITTC-Recommended Procedures and Guidelines [9].

2.5 CALCULATING THE ADDED POWER TO ESTIMATE THE CALM WATER POWER

The added power in waves can be calculated from the resistance estimated as shown in the previous section using the equation 6 given below. Furthermore, the calm water power is calculated as per equation 1.

$$P_{added} = R_{wave} * V_{ship} \tag{6}$$

The added power is calculated only for wave heights greater than zero and for head waves between +/-45 deg. off the bow. There are data points with wave height equal to zero and in these cases the recorded shaft power is taken as equal to the calm water power. To be able to calculate the wave resistance using STAWAVE-1 the wave height condition in equation 3 was applied, which is approximately a wave height of less than 3.75m for the ship used in this study.

Beam waves are considered as waves with a significant wave height of less than 2.0m encountering the ship at an angle of +/- 45 to 135 deg. off the bow. The added power due to these waves is neglected and the total power measured is considered equal to calm water power.

A counter was added in the program to enumerate the number of data points when in head and beam wave directions and also data with zero wave heights which is shown in Table 1. In table 1, it can be seen that approximately 41 % of the data are used to estimate the calm water power-speed curve using the normalising method illustrated in this paper.

Table1: Number of data points distribution

Head waves (STAWAVE-1)	24348
Beam waves	29226
Wave heights equal to zero	5520
Total data used	59094
Measured	143000
Used (%)	41.3

2.6 COMPARISON WITH FILTERING TECHNIQUES

The regressed power-speed curves using the normalising method are compared against the curves obtained from the filtering technique. To calculate the calm water powering using the filtering technique the following constraints are applied.

- True Wind less than 10 knots
- Significant wave height less than 1.5m.
- The difference between speed over ground and the speed through water is less than 1 knot.
- Shaft power greater than 30% MCR
- Change in speed over ground between successive samples does not exceed 0.5 knots.

The power vs speed relationship is generally represented as in equation 7, where *k* is the coefficient and *n* is the polynomial order (usually close to 3).

$$P_{calm} = k * V_{ship}^{n} \tag{7}$$

Power-speed curves can be derived using this relationship from the data points obtained both using the filtering and the normalising method. The curves drawn are compared and the difference is estimated in the form of a percentage difference in power. Please note that only ship speeds between 9 and 19 knots are used for deriving the regressed curves.

3. RESULTS AND DISCUSSION

The comparison drawn between the power-speed curves derived using the filtering and normalising method is detailed in this section and the differences are discussed, highlighting the possible reasons. Prior to investigating the power vs speed relationship it is important to validate the numerical routines developed for STAWAVE 1 and 2.

Figure 1 shows the added resistance (N) in waves calculated using STAWAVE 1 and 2 for the vessel considered. The wave resistance calculated using the STAWAVE-2 method produces an almost constant value for approximately a wave period ≤ 7.0s. In this region the mean added resistance is dominated by the reflection of waves from the body. The value of added resistance calculated using STAWAVE-1 for a wave height of 2.0m is equal to the one calculated for a wave period ≤ 7.0s using STAWAVE-2. This comparison can also be noted in Figure 2 where for short waves the resistance calculated by the two methods agree with each other and the STAWAVE-2 is more accurate for long waves, since it takes into account the resistance added due to motion of the vessel, namely heave and pitch, in waves.

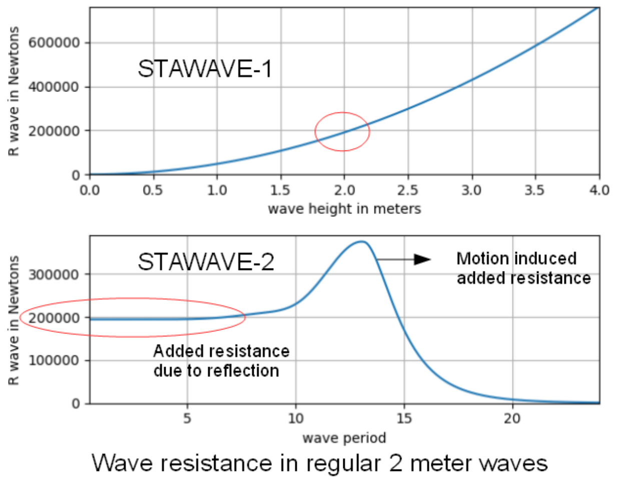

Figure 1: Added resistance calculated using STAWAVE 1 & 2

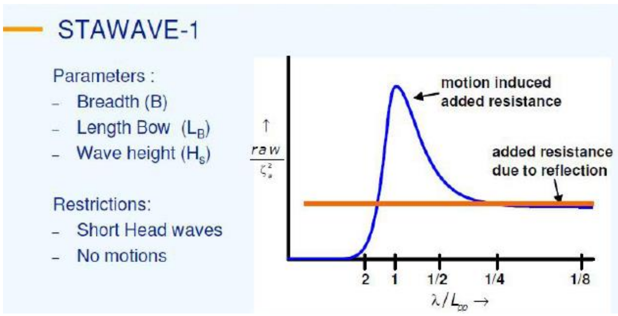

Figure 2: Added resistance in waves calculated using the two methods compare well for short waves [10].

Figure 3 displays the STAWAVE-2 wave resistance curve which is used to compare to the curves shown in Figure 4 for a previous study [10]. Table 2 shows the main particulars of the ships that were used in the investigations. The results confirm that the implementation of the added resistance method using STAWAVE-2 in Python is performed correctly.

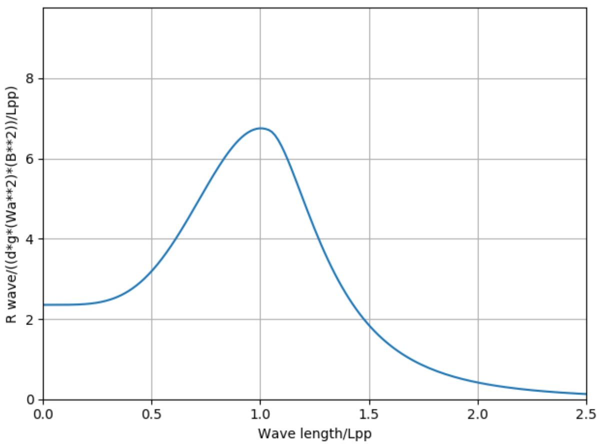

Figure 3. Normalised added resistance in waves using STAWAVE-2

Table 2: Main Particulars of the ships investigated

Ship	L (m)	B (m)	T (m)	C_B
KVLCC2	320	58	20.8	0.808
Bulk Carrier	285	50	18.5	0.829
S175	175	25.4	9.5	0.572
WILS II	324	48.4	15	0.602
1446 Design	214.85	40.12	11	0.564
Cruise Ship	220.32	32.04	7.2	0.654
S60 models	121.92	-	-	0.6-0.8

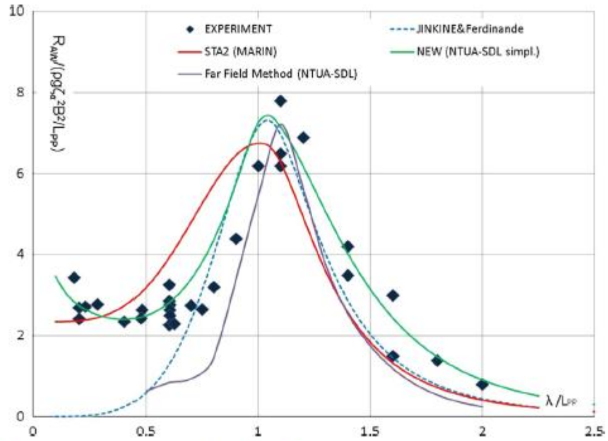

Fig. 15. Added resistance of KVLCC2 ship in head waves by various methods, $Fn = 0.142$.

Figure 4: Added resistance in waves published in original paper [10].

The data points for calm water power vs speed using STAWAVE-1 and 2 are shown in Figures 6 and 7, respectively. The power vs speed relationship from the data points is approximated as a curve using a regression method as described below.

The shaft power is related to the ship speed as $P_{calm} = k * V_{ship}^n$. This can be modified to a linear relationship by taking logarithms on both sides, transforming the equation to

$$log(P_{calm}) = log(k * V_{ship}^n)$$

$$log(P_{calm}) = log(k) + n\,log(V_{ship}) \quad (8)$$

The above equation takes the form of a linear curve fit $y = b + a * x$ where b is the intercept and a is the slope of the curve. The coefficients a and b from the linear curve fit will produce the order n and coefficient k for equation 7.

The calm water power vs speed data points using STAWAVE-1, shown in Figure 6, shows less scatter than the for STAWAVE-2, shown in figure 7. One of the important factors influencing this could be due to the wave height filter used for STAWAVE-1. As per the filtering criteria given in equation 3, the wave heights above 3.75m were not included in the correction method, whereas this was not the case with respect to

STAWAVE-2. Therefore, the calm water powering curve derived using STAWAVE-1 is used to compare to the results obtained using the filtering method.

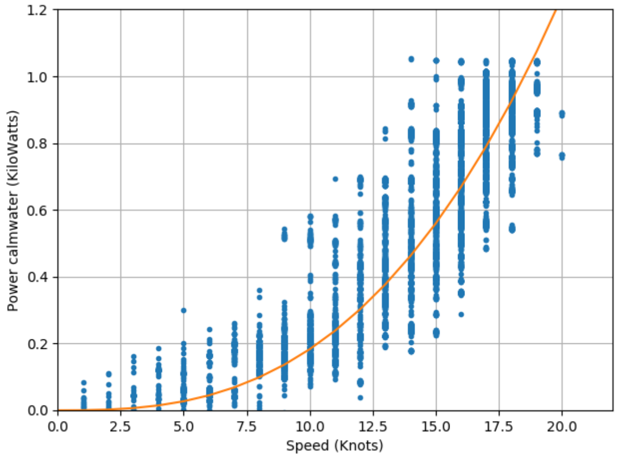

Figure 6: Calm water power vs speed using STAWAVE-1

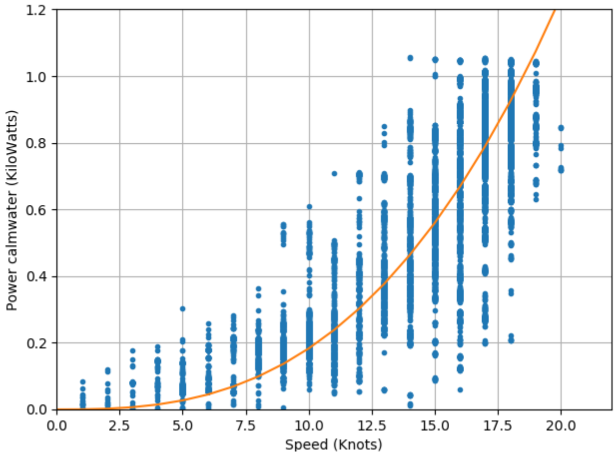

Figure 7: Calm water power vs speed using STAWAVE-2

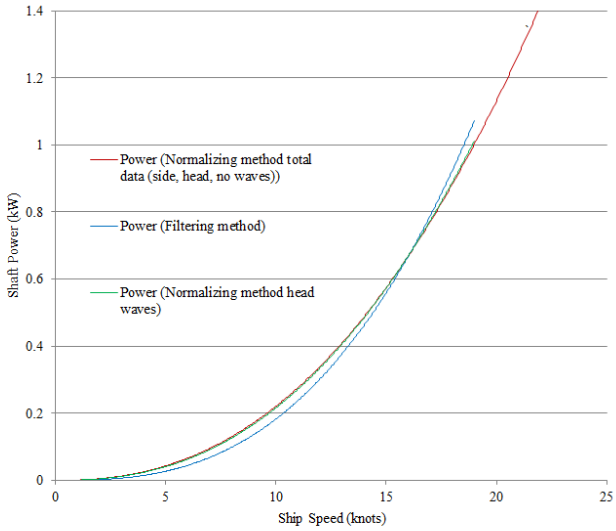

Figure 9: Comparison between power vs speed from filtering and normalizing method.

Figure 9 displays the power vs speed curves obtained from the filtering and the normalising method, including all the data points. In the case of the normalising method, the regressed curves were plotted for the shaft power corrections considering only head waves and also including head, beam and zero wave height conditions. It can be seen from the figure that the two curves calculated using the normalising method (STAWAVE-1) are in close agreement with each other. The difference between the curves obtained by normalising and filtering methods is very small.

Table 3 shoes the coefficients *k* and *n* of the regressed curves obtained using the two methods. The coefficients obtained for the normalising method by including waves from the beam and of zero height are similar to the ones calculated including only head waves. Even though the value of k differs largely between the normalising and the filtering method, the polynomial orders of ship speed are comparable to each other.

Table 3: Coefficients obtained using normalizing and filtering method

Method	n	k
Normalising (head, beam and zero)	2.35	17.453
Normalising (head)	2.407	15.23
Filtering	2.7563	5.7699

Figure 10 shows a comparison of the regressed curves obtained using the filtering and normalising method, including 99 % and 95% confidence intervals, denoted as 'C.I'. It can be seen from the plots that the curves compare very well with each other and the differences are minimal.

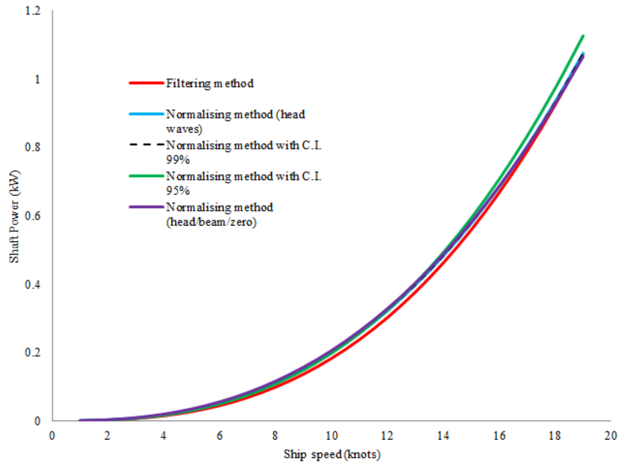

Figure 10: Regressed curves using the filtering and normalizing methods, presented with confidence intervals.

It was possible to compare the calm water power vs speed curves determined using the two methods utilising the plots shown in Figures 8 and 9. To quantify the difference between them, the results were post-processed in an excel file was done and approximately 4%

difference of estimation of calm water power for ship speed from 15 to 22 knots between both methods was observed and for ship speed from 12 to 14 knots there was less than 6% difference.

From the above comparisons it is shown that a reliable estimation of the added power in waves, and further, the calm water power estimation is possible using the ITTC sea trial correction methods, applied to continuous monitoring data. Furthermore, it has been shown that STAWAVE-1 gives a reasonable estimation of the added power due to waves. The data points after correction show less scatter using the STAWAVE-1 method, compared to STAWAVE-2. However, STAWAVE-2 is likely to give a better estimation for waves that will generate motion of the ship.

4. CONCLUSIONS

A correction to the total measured shaft power is applied to calculate the baseline (calm water) power by estimating the added power in waves using the methodologies detailed in STAWAVE-1 and STAWAVE-2. The added power experienced by the vessel due to the wind that is proposed by the ITTC Procedure was not carried out in this paper.

The normalising method has been validated by comparing it to filtering techniques and maximum a difference in the predicted shaft power in the operating speed range of 9-19 knots is approximately 6%. The initial investigations presented in this paper open the possibility of retaining and using more datasets to monitor the in-service performance of a ship, without sacrificing the accuracy. It is believed that applying corrections for the added wind resistance would decrease the percentage difference even further, improving the accuracy of the normalisation method used. This will be examined in future work.

The comparison of this method with the filtering techniques also provides the opportunity of predicting the total power for a particular (forecast) weather condition when a good estimation of the calm water from model tests, sea trials etc. is known. Moreover, the weather conditions where the total power may be estimated are those when the added power in waves can be estimated. For this vessel this corresponds to head waves less than 3.75 metres, for beam waves under 2 metres and no wave height. That means that we are able to estimate the total power for these special conditions, which is about 70% of the time.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. ALDUOS, L., SMITH, T., and BUCKNALL, R., 'Uncertainty analysis in ship performance modelling', *Ocean Engineering*, 2015.
2. PEDERSEN, B.P. and LARSEN, J., 'Modeling of ship performance', *World Maritime Technology Conference*, 2009.
3. DUCKERT, T., SCHMODE, D. and TULLBERG, M., 'Computing hull and propeller performance: Ship model alternatives and data acquisition methods', *1st Hull Performance and Insight Conference*, 2016.
4. LAKSHMYNARAYANANA, P. and HUDSON, D.A., 'Estimating Added Power in Waves for Ships Through Analysis of Operational Data', *2nd Hull Performance and Insight Conference*, 2017.
5. ISO 19030., 'Ship and marine technology-Measurements of changes in hull and propeller performance', 2015.
6. DINHAM-PEREN, T.A. and DAND, I.W., 'The need for full scale measurements', *William Froude Conference: Advances in Theoretical and Applied Hydrodynamics - Past and Future*, 2010
7. CARCHEN, A., PAZOUKI, K. and ATLAR, M.., 'Development of an online ship performance monitoring system dedicated for biofouling and anti-fouling coating analysis', *3rd Hull Performance and Insight Conference* 2017.
8. ORIHARA, H., YOSHIDA, H. and AMAYA, I.., 'Big Data Analysis for Service Performance Evaluation and Ship Design', *COMPIT*, 2017.
9. ITTC., 'Analysis of Speed and power trial data', Procedures, 2014 and 2017.
10. MAGNUSSEN, K.A., 'Rational calculation of sea margin', *NTNU Master Thesis*, 2017.
11. LIU, S. and PAPANIKOLAOU, A., 'Fast approach to the estimation of the added resistance of ships in head waves', *Ocean Engineering*, 2015.

7. AUTHORS BIOGRAPHY

Brief biographies are required for all authors e.g.:

Maxime Limelette is an undergraduate student in Mechanical Engineering in the Faculty of Science and Technology at the University of Western Brittany, Brest, France

Puram Arun Lakshmynarayana is currently a Research Fellow in the Fluid Structure Interactions Research Group at the University of Southampton. His research focuses on the performance management of merchant ships and improving the vessel efficiency using continuously monitored operational data together with

Computational Fluid Dynamics simulations. He is developing methods for investigating models of ship performance and fuel efficiency in weather using data analytic techniques.

Dominic Hudson is the Shell Professor of Ship Safety and Efficiency at the University of Southampton. He has research interests in all aspects of ship hydrodynamics, performance management and operational efficiency. He has published over 110 papers in journals and proceedings of refereed conferences. He is a Chartered Engineer and member of both RINA and IMechE. He is presently a member of the 29th ITTC Specialist Committee on Ships in Operation at Sea.