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MODELLING THE PERFORMANCE OF ENERGY SAVING TECHNOLOGIES ON SHIPS

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SUMMARY

This paper presents the approach taken to develop a software based ship model, used to assess the potential fuel saving benefits of retrofitted Energy Saving Technologies (EST) for defined vessels. It has been described in three sections:

- How data is obtained, and subsequently used to develop, inform, and validate the ship model. This covers Fleet Performance Monitoring (FPM), meteorological and ship definition data, and an exploration of the issues and challenges encountered;
- The modelling of voyages with this data, using a specifically defined real-world vessel and incorporating meteorological effects;
- The modelling of ESTs, how they are operated, and quantifying their benefits for the purpose of subsequently informing a business case to support their installation.

This model has been developed by BMT as part of a funded programme by the Energy Technologies Institute (ETI), advocating for the appropriate use of ESTs to save fuel, lower operating costs, and reduce Greenhouse Gas (GHG) emissions for the marine industry.

NOMENCLATURE

[Symbol]	[Definition] [(Unit)]
υ	Kinematic viscosity (N s m^{-2})
ρ	Density of water (kg m^{-3})
P	Pressure (N m^{-2})
BAR	Blade Area Ratio
ECMWF	European Centre for Medium Range Weather Forecasting
EEDI	Energy Efficiency Design Index
EST	Energy Saving Technology
ETI	Energy Technologies Institute
FPM	Fleet Performance Monitoring
HFO	Heavy Fuel Oil
IMO	International Maritime Organisation
MRV	Monitoring, Reporting, Verification
ORC	Organic Rankine Cycle
PD	Pitch Diameter
SEEMP	Ship Energy Efficiency Management Plan
Sfc	Specific Fuel Consumption (kg kwh^{-1})
SOO	Ship Owner/Operator
TPC	Tonnes per Centimetre
VTAS	Vessel Technology Assessment System
WHR	Waste Heat Recovery

1. INTRODUCTION

The introduction of the EEDI, MRV and SEEMP have driven an increased uptake in the use of Fleet Performance Monitoring (FPM) technologies, and are now at the point where reasonably accurate and comprehensive measurements of vessel propulsive performance can be undertaken.

In conjunction with this change, the 2020 IMO sulphur emissions limit [1] and 2050 IMO CO2 reduction target [2] have driven increased interest in the retrofitting of low sulphur fuel capability and/or Energy Saving Technologies (EST) in order to comply with these targets.

Different ships between different owners may have radically differing characteristics and operating profiles, which may drastically alter the financial business case for installing these ESTs. As the market for ESTs begins to strengthen there is clearly a need to gain a more accurate understanding of the potential fuel saving and performance benefits of these EST, and to inform the business case for their installation on a given ship.

The benefits of most EST are subject to weather conditions and their specific use case, with reliable performance estimates only possible in calm water conditions. This becomes problematic when trying to quantify the benefits for real-world use cases, particularly for wind-based devices such as Flettner Rotors. Using the FPM data from real ships on real voyages, the performance of a ship before and after the installation of ESTs has been modelled and estimated, and compared to a known baseline for a vessel.

This FPM ship data is paired with adapted ship models, created using a variety of methods in order to achieve a valid ship definition. A range of resistance and power calculation methods are employed to provide a distribution for statistical confidence analysis.

2. DATA

2.1 SHIP-DATA

Increasingly shipboard machinery and the fluid systems that support it are calibrated with sensors to facilitate the monitoring of equipment health and performance. This data can be used to regularly record the operating state of the ship’s power and propulsion systems so that the operating efficiency and system behaviour can be studied to understand how they respond to internal and external stimuli.

This information can be captured, stored, processed and supplied to the ship owner/operator (SOO) by any one of a set of FPM hardware and software systems, or through systems that have been developed by the SOO themselves.

In this work a variety of shipboard data from BMT SMART and a number of SOO’s with whom we are co-operating has been utilised. Some data has been anonymised to protect commercial interests.

2.2 METEO-DATA

The key to understanding the behaviour of a ship in a seaway is to have a good understanding of its environment. Although shipboard sensors for wind are commonplace, we have also used meteorological data from the European Centre for Medium Range Weather Forecasting (ECMWF) to cross reference wind and wave data with the vessel time and location. Although LIDAR-based devices can be used to measure local wave patterns and equipment and environmental data recording rates of over 1 Hz can be applied, we believe that for an techno-economic assessment, data averages over 1 to 5 minute intervals is sufficient.

2.3 ENGINE DATA

When quantifying the fuel consumption changes triggered by different operating scenarios and ESTs, the main and auxiliary engines must be monitored to understand their behaviour when taken outside normal operating bounds.

From onboard FPM data including fuel flowmeter data, engine power, shaft revolutions and torque where available we obtain a baseline Specific Fuel Consumption characteristic (Sfc) for a vessel. Where data is not available, manufacturer engine data is incorporated to derive the baseline.

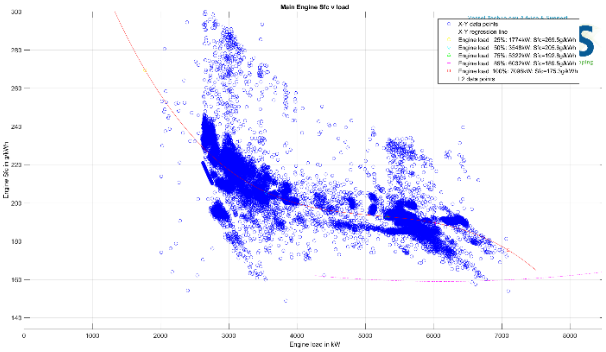

Figure 1: Recorded main engine Sfc vs engine loading

An example of recorded main engine power vs engine speed data is shown in Fig 2, which illustrates 3 months of engine power vs engine speed data taken from a 62k GT bulker, sampled every 5 minutes. The scale is logarithmic, with yellow regions representing 1000’s of points, orange as 100’s, etc.

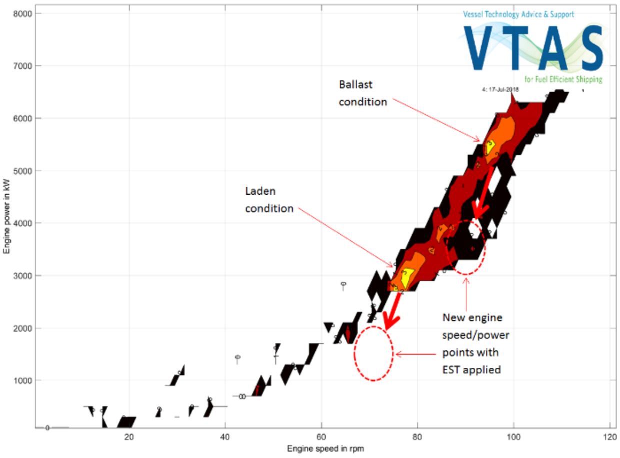

Figure 2: Engine power/speed curve data frequency

When adding an EST to a vessel that either provides supplementary propulsion (wind) or a reduced resistance (hydrodynamic efficiency) the consequences to the main engine are much the same, and manifest as a reduction in engine speed and power away from the normal speed/power curve. This is illustrated in the highlighted areas, where it can be seen there is little or no operational data for the engine and consequently an unknown Specific Fuel Consumption (Sfc).

Understanding the main engine Sfc at new operating points with an EST installed is critical for calculating the realistic fuel savings available, particularly when the economic case for installation may be marginal.

3. MODELLING

In order to model a ship and its associated machinery with acceptable levels of confidence, we require detailed definitions of 3 things:

- The ship, with all of its principal particulars that have any bearing on powering and resistance calculations;
- The voyage being modelled, with start and end dates, locations, and meteorological data throughout;
- The main engine/s, especially with regard to how the specific fuel consumption (Sfc) varies with different engine speeds and power outputs.

Once these have been defined, an overall model of the ship on the voyage can be conducted, and compared to known voyage data for validating the model outputs prior to adding an EST.

3.1 SHIP DEFINITION

On a per voyage basis, the recorded ship speed and environmental conditions are fed into a mathematical model which predicts the ship's resistance, hull efficiency and propeller characteristics. The hullform model is based on the Holtrop & Mennen method: for each time step the fore and after draft readings are used to re-assess effective resistance whilst the ratio and change of such readings also indicate the kind of sea state being experienced.
This is an important step for vetting the data in order to eliminate values which detract from the assessment. Other instances include where the ship is accelerating, manoeuvring or in ballast with a pronounced trim.

Wake fraction and thrust deduction factors are either taken from a model test report, or are derived from a statistical analysis of a range of empirical prediction methods. With experience, those models which are best suited to specific ship types and sizes can be identified.

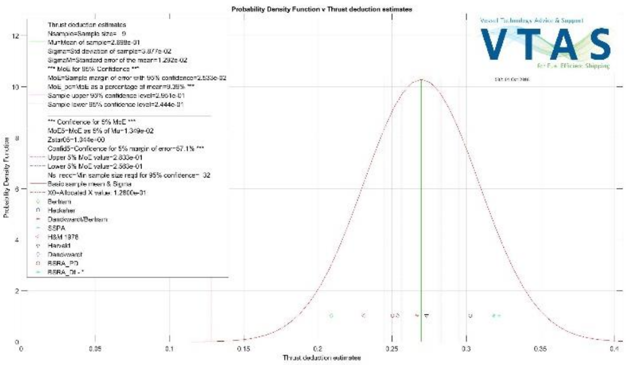

Figure 3: Thrust deduction estimates against probability density function

Although the propeller characteristic can sometimes be supplied, where this is not possible, using the Wageningen B-series, the principal propeller characteristics are estimated (i.e. BAR & PD ratio) and refined when compared to operating data.

At each time step throughout a specific voyage, the predicted shaft speed and power are compared with the known ship data. With several iterations, deviations are identified and reduced by tailoring the resistance properties. The key variable is the form factor (1+k), which can vary considerably away from the standard prediction method when the ship condition is significantly away from the design point i.e. at severe trim and/or at low draft.

3.2 VOYAGE DEFINITION

In order to run the model and compare a vessel with and without EST with appropriate confidence, it is necessary to have data for a known voyage for a known vessel. Since the fuel consumption from point A to point B for the vessel is known, it serves as the baseline for means of comparison when the vessel is modelled with an EST.

The historical voyage data is included in the output from the FPM provider, and ideally provides the following at minimum 5 minute intervals:

Navigational	Machinery	Meteorological
Vessel location	Shaft revolutions per minute (rpm)	Wind Speed & Direction
Time & Date	Shaft power	Significant Wave Height (SWH)
Course over Ground (COG)	Main Engine fuel mass flow	Current Speed & Direction
Heading	Non-propulsive fuel mass flow	Air temperature
Speed Through Water (STW)	Draught fwd & aft	Water temperature
Speed over Ground (SOG)		Relative humidity

Meteorological data is also included, though the bulk of it is typically taken from a 3rd party meteo data provider rather than directly measured on-board.

3.3 ENGINE DEFINITION

The shaft power and speed and the main engine fuel flow data allows a Specific Fuel Consumption (Sfc) map of the engine to be generated which can then be used with the ship model. The engine model will comprise of a set of cells 1 rpm by 100kW as shown in Figure 4. The average of the set of Sfc points that fall within each cell is used to create an Sfc carpet plot more extensive in range than anything usually offered by the engine supplier.

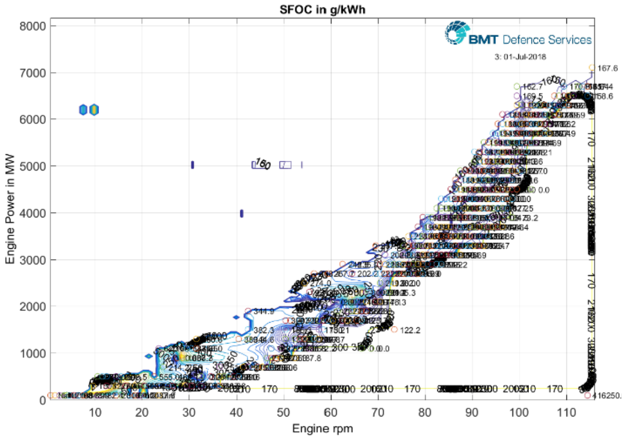

Figure 4: Main engine Sfc contour map based on recorded fuel flow/engine power data

However, even with 65,000 data points it is clear from Figure 2 that the engine spends the vast majority of time at two operating points, one for the loaded condition and one when in ballast. Consequently there are specific cells which are unpopulated and into these are inserted two-way estimates based on interpolations from the adjacent cells.

The use of a wind-based device will lead to a lower engine load and speed and the engine may then operate at a condition not hitherto experienced. It is not reasonable to use the data set approach to extrapolate to these new operating conditions and so a diesel engine mathematical model is used to estimate them.

4. DATA HANDLING

A single voyage may yield several thousand data records at 5 minute intervals, and the VTAS process seeks to make the average of the whole set of deviations between the data record with the ship model outputs as small as possible. The process recognises that there will always be accuracy issues with both the ship data and the ship model.

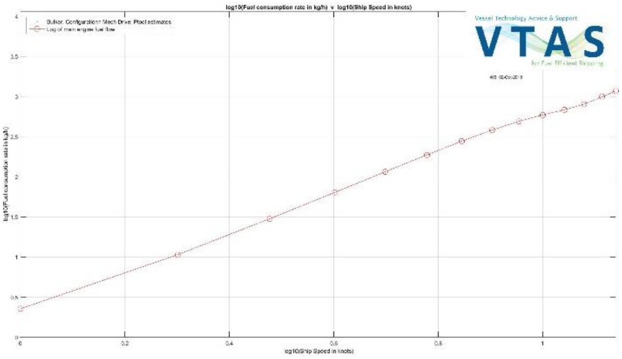

Figure 5: Fuel flow vs ship speed

Figure 5 shows a plot of log fuel flow versus a log of ship speed, with the variance of the data points from the mean. This is often used in charter party agreements for the application and performance of hull coatings. Whilst ship speed measurement can be undertaken with good accuracy (< 1%) using GPS, a recent 2018 IMO publication [1] has shown that fuel flow meters have ~8% uncertainty for measuring HFO flow, despite manufacturer's claims of 0.1% accuracy. Whilst the referenced report is not completely authoritative, it does support anecdotal assertions that fuel flow meters are vulnerable to significantly misstating actual fuel flows.

To mitigate some of these issues with data accuracy, data from a non-steady state ship condition is filtered out as it does not represent the performance of the vessel over a long voyage. In practice this means disregarding data where the vessel is accelerating, decelerating, manoeuvring, in ballast with pronounced trim or experiencing exceptional weather conditions.

5. SHIP MODEL DEVELOPMENT

At present the development of the modelling approach is performed with a limited set of ship data, and relies upon the estimation of key parameters such as wake fraction and thrust deduction factor where model test reports are not available. When the ship is away from its design displacement, as often is the case, the tonne per centimetre (TPC) factor is used to determine the actual displacement. From this the set of hydro-dynamic coefficients and factors can be calculated to determine the best estimate of resistance in this condition. This approach is far from perfect theoretically but currently represents the best way to use limited information.

The twin sided approach is therefore bound to have difficulty achieving close alignment on each individual data record, but the objective is to achieve a minimum **average** deviation so that the economic effects can be gauged. Most important is the ability to establish a ship model as a basis from which to assess the impact of an EST fit, especially a wind-based device.

6. ENERGY SAVING TECH MODEL

The energy saving technologies considered as part of this study generally fall into 3 categories, euphemistically referred to as "wet, warm and windy":

Wet: Hydrodynamic efficiency technologies, primarily consisting of specialist hull paints, propeller pre/post swirl devices, and other water-side technologies.

Warm: Refers to Waste Heat Recovery (WHR) technologies such as Organic Rankine Cycles (ORC), and Turbo-Generator (TG), utilising heat from jacket water or exhaust gas.

Windy: Wind-based auxiliary propulsion such as Wingsails, Flettner rotors, Kites or other types of sailing method.

When modelling an EST for inclusion in a ship model, its behaviour is characterised in a MatLab environment, and it is called over each step of the voyage modelling process. As seen in Fig 6 this involves passing the ship data, voyage data and weather to the ship model, which in turn simulates the vessel performance both with and without the EST installed.

The reduction in resistance and consequent fuel saving (if any) is logged and the result recorded for comparison with the known ship data.

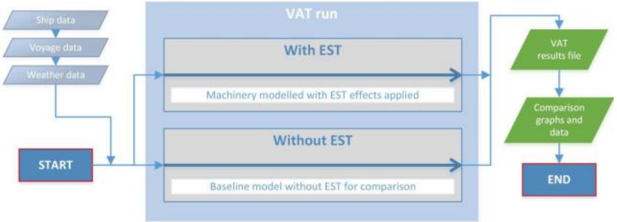

Figure 6: High level EST assessment process

For the purposes of this paper we have focused on Flettner Rotors for demonstration, as they have had significant recent installations.

6.1 FLETTNER MODEL

The Flettner Rotor model is based on previous work performed in this area [4] and has been updated using data gleaned from recent Flettner Rotor installations, and embodying the developments in calculating the main engine Sfc at a lower loading point.

As Flettner rotors are a wind based device, the benefit provided by them is highly dependent on the environmental conditions experienced by the vessel. Thus, at each 5 minute time step encountered by the ship model, the wind speed and direction along with the vessel speed, direction and location are input into the Flettner rotor model which in turn modifies the rotational speed of the rotor to achieve optimal thrust.

Within the mathematical model the Flettner rotor operates under a set of operational rules that simulate the behaviour on a real vessel, which restrict operation unless it achieves a net propulsive benefit, i.e. the equivalent propulsive power outweighs parasitic losses created by rotor power requirements and any generated drag.

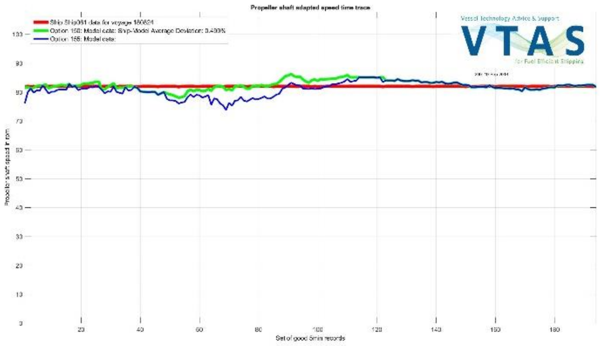

Figure 7: Prop shaft speed over 24 hours (laden condition)

Fig 7 illustrates the propeller shaft speed over a 24 hour period for a 62k dwt bulker. Red denotes the FPM shaft speed data recorded from the vessel, Green the shaft speed for those conditions as predicted by the ship model, and Blue the shaft speed as predicted with the inclusion of the Flettner Rotor.

As discussed at section 3.1, data where the ship was accelerating, decelerating or otherwise outside of a 1% deviation from the previous rolling average was discarded. As a result, rather than 288 instances of 5 minute samples over this 24 hour period there are 194.

The average deviation for the model against the recorded vessel data was 0.499% in this instance, representing an acceptable level of accuracy to demonstrate savings when the Flettner Rotor is applied.

When verifying the correct behaviour of the model, it can be seen where the blue line follows the green line that the Flettner Rotor model has determined that the conditions are unfavourable, and the rotor has been deactivated.

6.2 EST BENEFITS

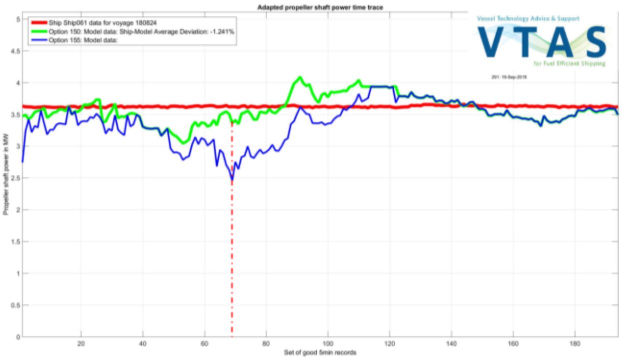

Figure 8: Shaft Power over 24 hours (laden condition)

It can be seen in Fig 8 that the Green line (baseline model) does not precisely follow the Red (recorded voyage data). This deviation is due to the model interpretation of the environmental conditions such as wind and wave data, and modifying the propulsive steady state conditions faster than can be achieved in practice. The key observation from Fig 8 is the average mean deviation on modelled shaft power of 1.241%, providing an average baseline for a day that can be used for a comparison.

At around data point 70 marked on the figure there is a peak difference in required shaft power of ~ 1MW, a reduction of approximately 30%. This correlates with a shaft speed reduction seen in Fig 7 of approximately 9 rpm. When correlated against the speed/power frequency plot in Fig 2 it can be seen that the new operating point is outside the typical region for the laden vessel.

The area between the blue and green lines represents a propulsive power reduction over a 24 hour period during a voyage. At each of these points, the main engine Sfc for the new operating point is calculated via the mapped Sfc contour illustrated in Fig 4, and the fuel consumption summed over the entire voyage period.

7. CONCLUSIONS

The model described in this paper has been validated through the use of recorded vessel data, demonstrating an acceptable level of accuracy for performance estimates. It provides a more bespoke means of assessing the potential benefits of Energy Saving Technologies when applied to individual vessels and their operating profiles.

As more operating information on the performance of various ESTs in different operating conditions becomes available, the individual EST models will be refined to more accurately capture these effects and provide an increasingly reliable estimate of their future performance.

8. ACKNOWLEDGEMENTS

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10. AUTHORS BIOGRAPHY

David Pearson holds the position of Senior Engineer at BMT Defence and Security Ltd. His primary domain is marine consultancy and auxiliaries design, with a focus on new and innovative Energy Saving Technologies. His previous experience includes modelling wind-based technologies for the Energy Technologies Institute, among a range of other EST projects.

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John leads studies into marine power and propulsion, HVAC and hydraulics within the company and has published several papers on these subjects. He has also published other papers on a range of subjects from biofuels, organic Rankine cycles to rail-gun cooling. Since 1999, John has been involved in a range of studies to assess the utility of energy saving technologies for the commercial and military marine.