A Model for Prediction of Propulsion Power and Emissions – Tankers and Bulk Carriers

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A MODEL FOR PREDICTION OF PROPULSION POWER AND EMISSIONS – TANKERS AND BULK CARRIERS

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ABSTRACT

To get an idea of the reduction in propulsion power and associated emissions by varying the speed and other ship design main parameters, a generic model for parameter studies of tankers and bulk carriers has been developed.

With only a few input parameters of which the maximum deadweight capacity is the primary input a proposal for the main dimensions is made. Based on these dimensions and other ship particulars which are determined by the program the necessary installed propulsion power can be calculated. By adjusting the vessel design, i.e. the suggested main dimensions, and varying the speed it is possible to estimate the influence of the different parameters on the power demand. The model is based on previously well-established power prediction methods which have been updated and verified by model test results and full-scale data, meaning that the predictions are up to date according to modern ship design standards.

The IHS Fairplay World Fleet Statistics for vessels built in the period 1990 – 2010 is used as a basis for the modeling of the main dimensions.

The model can be used to calculate exhaust gas emissions, including emissions of carbon dioxide (CO_2), from bulk carriers and tankers. A calculation procedure for estimating the Energy Efficiency Design Index (EEDI) which is presently being developed by the International Maritime Organization (IMO) is also included in the model. Different ship design parameters have been varied to see the influence of these parameters on the EEDI. The paper will focus on the technical and the design measures which can improve the environmental performance and will not take into account operational measures.

INTRODUCTION

As a consequence of the increased focus on the environmental impact from shipping - especially from exhaust gas emissions - a generic ship design model for tankers and bulk carriers has been developed by Department of Mechanical Engineering at the Technical University of Denmark (DTU) and Institute of Technology and Innovation, University of Southern Denmark (SDU).

With the deadweight capacity as the only input parameter, it is possible to estimate the main parameters of length (L_{pp}), breadth (B), depth (D) and draught (T). Furthermore, the lightweight ($W_{lightweight}$) of the ship and the normal service speed are also calculated. Based on these parameters the model can estimate the total resistance and the installed power under given design conditions, taking into account different service allowances as regards the ship resistance and the main engine. The model is based on previously well-established power prediction methods which have been updated and verified by model test results and full-scale data, meaning that the predictions are up to date according to modern ship design standards.

By adjusting the vessel design, i.e. the main dimensions, and varying the speed it is possible to estimate the influence of different parameters on the power demand and thus be able to investigate the influence on the Energy Efficiency Design Index, EEDI.

The present paper is separated into four parts. First, a detailed description of the developed generic model including the resistance and power prediction parts is given. The power prediction part is used for determining the difference between the power given in the IHS Fairplay database (IHS 2010) and the power calculated by the power prediction procedure in the generic model. A parameter study is performed to investigate the variation in power for varying main particulars. The influence on the EEDI when the main dimensions are subjected to small changes is analysed and the results are given at the end of the paper. The

parameter study and the EEDI analyses are performed for Panamax tankers only.

1. GENERIC SHIP DESIGN MODEL

1.1. Introduction

The generic ship design model consists of three parts, a ship design, a resistance and a power prediction part. In the design part a proposal for the main dimension of a vessel is calculated with only the maximum deadweight as input. On the basis of the main particulars and a speed requirement, it is possible to calculate the total resistance of the vessel and to estimate the still water power requirement of the ship. By taking into account effects from heavy weather, fouled hull and engine margin request, an estimate of the power to be installed in the vessel may be made.

The model is based on a previously well-established power prediction method by Harvald (Harvald, 1983). Harvalds method has been updated and verified by model test results and full-scale data, so that the predictions are up to date according to modern ship design standards. The model has specially been updated with respect to the influence of a bulbous bow on the resistance. Moreover, procedures for calculation of wake fraction and thrust deduction have been updated and, finally, more accurate empirical formulas for calculation of the wetted surface are established by an update of Mumford´s formula.

1.2. Design Part – Main Particulars of the Vessel

The IHS Fairplay World Fleet Statistics for vessels built in the period 1990 – 2010 (IHS 2010) has been used as a basis for the design part of the generic ship design model. The data in the database have been analysed and possible outliers been left out, i.e. vessels with obvious errors in data and vessels with abnormal hull proportions.

As tankers and bulk carriers are normally subdivided into different categories based on their deadweight, the data in the IHS Fairplay database have been subdivided into seven categories and equations for the main parameters for all ship categories have been found by regression analysis. As the main particulars L_{pp}, B, T and D are very closely connected with the deadweight, these parameters are expressed as functions of the maximum deadweight, DWT, corresponding to the summer load line draught T. The equations including a plot of the main dimensions are given in Appendix A and B.

The main particular equations have been implemented in the power prediction model so that the model calculates the ship main dimensions on the basis of only one specified input parameter, namely the maximum deadweight.

The following ship categories are used:

- Small < 10,000 DWT
- Handysize 10,000 – 25,000 DWT
- Handymax 25,000 – 55,000 DWT
- Panamax 55,000 – 80,000 DWT
- Aframax 80,000 – 120,000 DWT
- Suezmax 120,000 – 170,000 DWT
- Very large 170,000 – 330,000 DWT

1.3. Resistance Part – Determination of the Total Resistance of the Ship

In order to calculate the propulsion power of a ship, the resistance has to be determined with the highest possible accuracy. The resistance calculation procedures used for the new power prediction method are described in detail in the following.

The total resistance of the ship is defined by

$$R_T = \tfrac{1}{2} \cdot C_T \cdot \rho \cdot S \cdot V^2 \qquad (1)$$

where S is the wetted surface of the hull, V the speed and ρ the water density. The total resistance coefficient is denoted C_T and is here determined by use of four elements as defined by the original ITTC1957 method from the International Towing Tank Committee (ITTC 1957):

$$C_T = C_F + C_A + C_{AA} + C_R \qquad (2)$$

The frictional resistance coefficient is described by C_F, the incremental resistance coefficient is denoted C_A, the air resistance coefficient C_{AA} and, finally, C_R describes the residual resistance coefficient. Compared to the original method proposed by Harvald in 1983, a few parameters are updated to account for newer design, namely the wetted surface, the air resistance and the influence of a more "up-to-date" bulbous bow. The frictional resistance (ITTC 1957) and the incremental resistance are kept unchanged. A short description of the three updated parameters is given in the following.

The wetted surface is normally calculated by hydrostatic programs. However, for a quick and fairly accurate estimation of the wetted surface there are many different methods based on only a few ship main dimensions, as for example Mumford´s formula. In the present project, an analysis of the wetted surface data of 35 different newer bulk carriers and tankers shows that the wetted surface calculated by use of Mumford´s formula may give an error of up to 5-7 %. Therefore, it has been analysed if the formula, i.e. the constants in the Mumford formula, can be adjusted in order to increase the accuracy. The

original and the new formula are given by the following equations:

$$S = 1.025 \cdot \left(\frac{\nabla}{T} + 1.7 \cdot L_{wl} \cdot T \right) \text{ (Mumford)} \quad (3)$$

$$S = 0.99 \cdot \left(\frac{\nabla}{T} + 1.9 \cdot L_{wl} \cdot T \right) \text{ (New formula)} \quad (4)$$

The air resistance caused by the movement of the ship through the air is here estimated by

$$C_{AA} = C_X \cdot \frac{\rho_{air}}{\rho_w} \cdot \frac{A_{VT}}{S} \quad (5)$$

The wind resistance coefficient C_X can, according to Blendermann (Blendermann, 1994), be taken as 0.8 for bulk carriers and tankers. The front area A_{VT} is here estimated by $A_{VT} = B \cdot (D - T + h)$, where the accommodation height, h, is defined by the number and height of floors. Based on photo observations and examination of GA plans, the number of floors is estimated. A floor height of 3 m is used and an additional height of 2 m is added to account for equipment at the top of the vessel. From these analyses, C_{AA} values as given in Table 1 are recommended.

Tab. 1: *Recommended C_{AA} values.*

	C_{AA} ·1000
< 55,000 DWT	0.07
55,000 - 250,000 DWT	0.05
250,000 - 320,000 DWT	0.04

The method for estimating the residual resistance coefficient proposed by Harvald was based on an extensive analysis of many published model test results. In Harvald's method it is initially assumed that the ship has a standard non-bulbous bow. Then the method includes corrections for a bulbous bow having a cross section area of at least 10 % of the mid ship section area of the ship. The bulb correction, $\Delta C_{R,bulb}$, is treated as part of the residual resistance coefficient:

$$C_R = C_{R,nobulb} + \Delta C_{R,bulb} \quad (6)$$

The design and form of bulbous bows have changed over the last several decades. The form has been optimised so that bulbs developed in recent years can reduce the resistance quite considerably. Earlier non-projecting bulbous bows decreased resistance at best by some 5–10 %, whereas modern and more pronounced bulbs can decrease resistance by up to15-20% (Schneekluth and Bertram, 1998).

As the wave pattern, and therefore the residual resistance, varies with the speed of the vessel, the bulbous bow correction will here be defined as a function of the Froude number. The bulb correction will also be dependent on draught and trim, but to keep the method simple the bulb correction will be assumed to be independent of these two parameters, i.e. it is assumed that the power estimate is made for draughts not deviating much from the draught where the bulbous bow has its maximum influence (the design draught). For draughts deviating much from the design draught, as for example ballast draught, the bulbous bow correction is suggested to be set to zero, i.e. no influence at all.

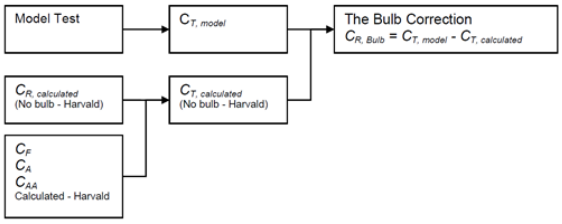

Fig. 1: *Method for bulb correction determination.*

The analyses of the new bulb correction are based on resistance data obtained from newer model test results. The test includes 13 different model ships, 3 Handysize vessels, 4 Handymax, 5 Panamax and 1 Aframax vessel. All tests have been performed with variable speed and loading condition, giving 277 test results in total. The total resistance coefficient of each individual ship has been calculated according to Harvald without any bulbous bow corrections. Subtracting this value from the total resistance coefficient found by model tests gives the bulbous bow correction which is needed for updating the method, see Figure 1. It is found that the bulb correction can be approximated by the following equation:

$$\Delta C_{R,bulb} = \Delta C_{R,bulb}(Fn) = \max(-0.4; -0.1 - 1.6 \cdot Fn) \quad (7)$$

A comparison of the total resistance coefficient obtained by the model tests and the method by Harvald is performed. It is decided to use the same corrections for all parameters except for the bulb correction, so that the bulb correction can be compared directly by the C_T-residuals defined as follows:

$$Residual\ (C_T) = \frac{C_{T,\mathrm{model}} - C_{T,Harvald}}{C_{T,Harvald}} \cdot 100\,\% \quad (8)$$

All residuals are calculated and a probability density diagram is made, see Figure 2. From the probability analysis a mean value of approximately -14% and a standard deviation of 7% are found. The negative residual indicates that the total resistance coefficient, determined by the original method of Harvald is too large because this method as expected is based on older vessels as just outlined.

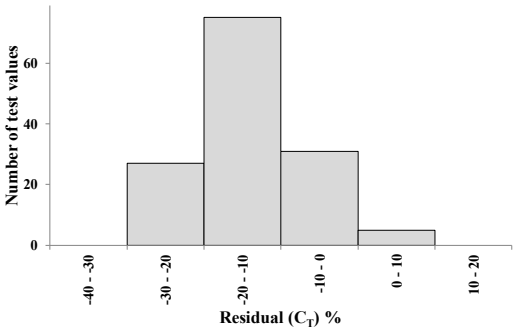

Fig. 2: *Probability density diagram, C_T-residuals.*

1.4. Power Prediction Part – Determination of the Installed Power

On the basis of the total resistance and a speed requirement, it is possible to calculate the effective power P_E to tow the vessel through the water in calm weather. By taking into account the different components of the total propulsion efficiencies, the necessary propulsion power, P_P can be calculated.

$$P_P = \frac{P_E}{\eta_T} = \frac{R_T \cdot V}{\eta_T} = \frac{R_T \cdot V}{\eta_H \cdot \eta_o \cdot \eta_R \cdot \eta_S} \qquad (9)$$

Here η_T is the total efficiency. The hull efficiency is denoted η_H, the propeller efficiency in open water η_o, the relative rotative efficiency η_R and the transmission efficiency η_S. The hull efficiency η_H is a function of the wake fraction, *w*, and the thrust deduction fraction, *t*, which are both functions of the geometric underwater properties of the ship including the propeller diameter. An analysis of the wake fraction and the trust deduction fraction on newer vessels has been performed (the same vessels as were used for the deduction of the bulbous bow resistance coefficient). Results from 26 model tests on tankers and bulk carriers are analysed and the following corrections for the Harvald method are estimated:

$$w_{corrected} = w_{Harvald} - 0.45 + 0.08 \cdot M \qquad (10)$$

$$t_{corrected} = t_{Harvald} - 0.26 + 0.04 \cdot M \qquad (11)$$

where M is the length–displacement ratio $\left(\frac{L}{\Delta^{1/3}}\right)$.

A proposal for estimating a typical propeller diameter on tankers and bulk carriers has been made by simple regression analysis using statistical ship data from Significant Ships (1990-2010):

$$D_{prop} = 0.395 \cdot T_{\max} + 1.30 \qquad (12)$$

The behind efficiency of the propeller $\eta_B = \eta_o \cdot \eta_R$ may be approximated by the open water propeller efficiency η_o, as the relative rotative efficiency on average is close to one. Breslin and Andersen (1994) give curves for approximated values of η_o for different propeller types including nozzle and conventional Wageningen B – series of propellers, see Figure 3. The propeller efficiency is here defined as a function of the thrust loading coefficient C_{Th}.

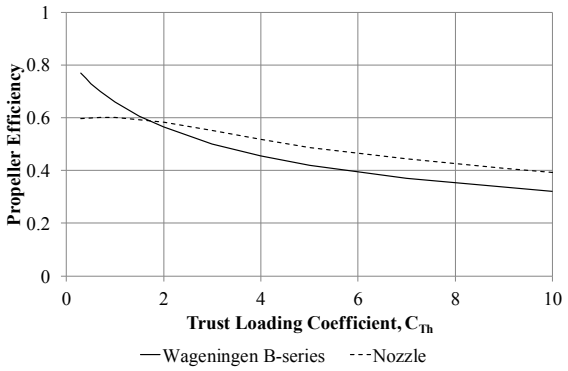

Fig. 3: *Propeller efficiency as a function of trust loading coefficient, Breslin and Andersen (1994).*

The transmission efficiency η_S depends on the propeller shaft length, the number of bearings and gearboxes if fitted. For a shaft line with a directly mounted propeller, η_S is 0.97-0.98 while the shaft efficiency is 0.96–0.97 for a shaft system with a gearbox.

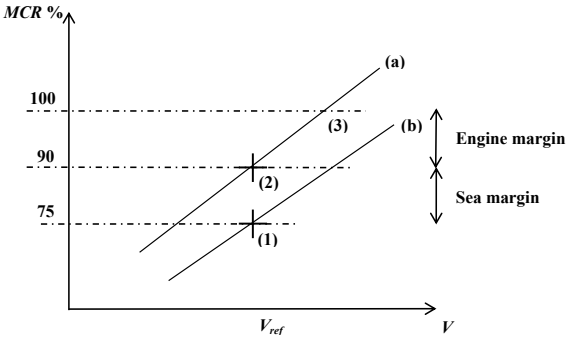

Fig. 4: *Power–velocity curve.*

Definition of lines and points, Figure 4:

(a) Propulsion curve, fouled hull and heavy weather induced resistance included (used for engine layout)
(b) Propulsion curve, clean hull and calm weather
(1) Necessary power, clean hull and calm weather at speed V_{ref}
(2) Power including sea margin, here 15% of the propulsion power at speed V_{ref}
(3) Installed power, maximum continuous rating (100% MCR), P_{MCR}

The installed power of a ship will depend on different types of service margins. One type of margin, the sea margin, is added to take into account extra resistance caused by wind, waves and fouling of the hull during operation. Additionally, an engine margin is often

used as the main engine is not operated at its maximum output (100% MCR), but at a reduced power, typically 90% or even lower. Figure 4 shows the sketch of a power–speed curve for a ship with two different service margins.

2. DEVIATION OF POWER IN THE DATABASE

The maximum engine power listed in the IHS Fairplay database is compared with the calculated power for the same ship using the power prediction method described in this paper. According to IHS Fairplay information, the power given in the database is the maximum installed power, i.e. 100% MCR. The power calculated by the new power prediction method is based on the assumption of a 15% sea margin and a 10% engine margin. The calculated power is directly compared with the IHS database power value by definition of the following residual:

$$Residual\ (database) = \frac{P_{calc} - P_{database}}{P_{database}} \cdot 100\,\% \qquad (13)$$

These analyses are made for all tankers and bulk carriers in the database. In Figures 5-8 probability density functions are presented on the assumption that the residuals are normally distributed. This assumption seems reasonable; see Appendix C, where detailed probability density diagrams for the power residuals of tankers of the sizes Small, Panamax and Aframax are seen.

The reason why the residual calculation has been carried out by assuming a 25 % margin is that IMO, in order to determine the so-called EEDI reference line, has assumed that the speed listed in the IHS Fairplay database corresponds to the service speed at 75 % MCR in calm water, when the ship is loaded to its maximum draught (for tankers and bulk carriers). Calculation of the residual is therefore an attempt to check the validity of this assumption.

The analyses in Figures 5-8 show that the smaller and the larger vessels have negative residuals, which means that the power in the database is larger than the calculated power. These negative residuals are probably due to the updated bulb correction used in the new power prediction model being based on model tests for vessels of sizes from Handysize to Aframax. The correction is extrapolated to include smaller and larger vessels as well. This approximation must be examined further when more test results are available. The large standard deviations for Small and Handysize vessels are probably due to the fact that these vessels are special purpose vessels optimised mostly for maximum loading capacity and not minimised power.

For the remaining ship types, i.e. Handymax, Panamax, Aframax and Suezmax, the residuals are centered from around zero and up to approximately 15 percent. The positive residuals mean that the installed power is lower than the power calculated. This might indicate that the speed given in the IHS database is too optimistic or rounded up.
Unfortunately, there is no clear definition of the speed reported to the database.

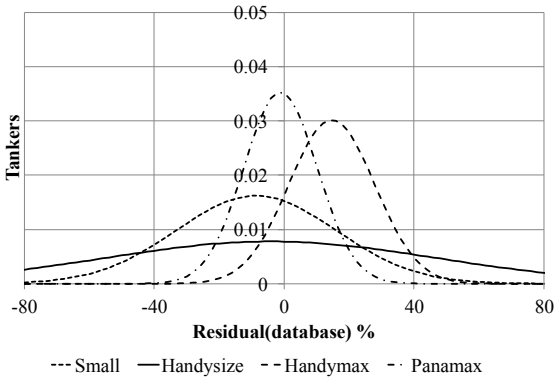

Fig. 5: *Probability density function, assuming normal distribution, tankers.*

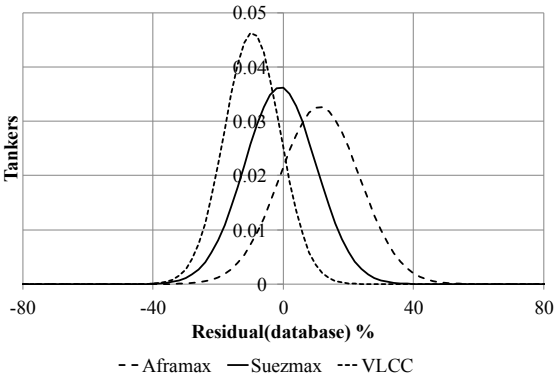

Fig. 6: *Probability density function, assuming normal distribution, tankers.*

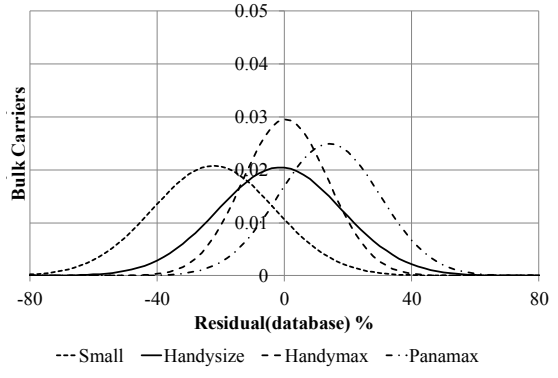

Fig. 7: *Probability density function, assuming normal distribution, bulk carriers.*

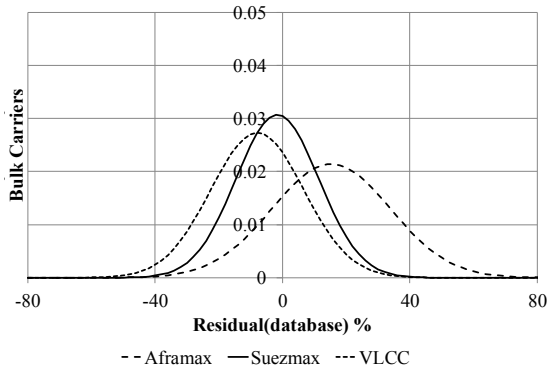

Fig. 8: *Probability density function, assuming normal distribution, bulk carriers.*

3. PARAMETER STUDY – PANAMAX SHIP

The parameter studies in the present section are performed to investigate the influence of the change in length, breadth, draught and speed on the power demand. The IHS Fairplay database is used as a basis for the parameter study and all analyses are performed for Panamax tankers only. A total number of 232 vessels are included in the analyses. Changing the breadth is of course not possible for a Panamax vessel, but is in the present paper included as an illustrative example.

The section starts with a discussion about increase of weight for modified main dimensions. Changing weight and main dimensions of a vessel will cause the block coefficient as well as the length–displacement ratio to be changed. The influence on the power demand for 1% and 3% increase in length, breadth or draught is determined and, finally, in the last part of the section the increase in power demand for an increase of 1% in speed is examined. For the main dimension and the speed analyses the power listed in the IHS Fairplay database is compared to the power calculated by the new power prediction method by use of residuals.

3.1. Weight Discussion

An increase in length, breadth or depth of a vessel will result in increased lightweight, primarily due to a higher steel weight. The influence of this must be examined and included in the analyses. Three parameters will be discussed, namely the increase in displacement, change of block coefficient and length-displacement ratio, respectively.

It is here assumed that the lightweight can be estimated as a function of the deadweight and correlated to three of the most important main dimensions of the ship, length, breadth and depth, as follows:

$$W_{lightweigh} = L \cdot B \cdot D \cdot f(DWT) \qquad (14)$$

The maximum deadweight (*DWT*) is kept constant for each vessel, so that the function *f* is a constant and that the change in lightweight will be proportional to the change in the main dimensions. If the original lightweight is known as in the present analyses, where the displacement and the deadweight are both listed in the IHS database, the new displacement can be calculated as

$$\Delta_{new} = DWT + W_{lightweigh} \cdot \frac{(L \cdot B \cdot D)_{new}}{(L \cdot B \cdot D)_{old}} \qquad (15)$$

In Figures 9 and 10 the percentage increase in the displacement and in the block coefficient is shown. The results are given as a function of the deadweight of the vessel. In both diagrams values are plotted for an increase in length or breadth, as the results will be the same no matter which parameters are changed. The results for increase in displacement show that length or breadth increased by up to 3% will result in a displacement increase of less than 0.6%. Draught changes will, on the present lightweight assumption, cause the block coefficient to change. However, as the displacement is unchanged a given percentage change in draught will result in the same percentage change in the displacement, which means that a 3% draught increase will also reduce the block coefficient by 3%. From Figure 10 it is seen that the draught change has the largest influence on the block coefficient. The change in C_B is negative so that the block coefficient will be smaller for increasing length and breadth.

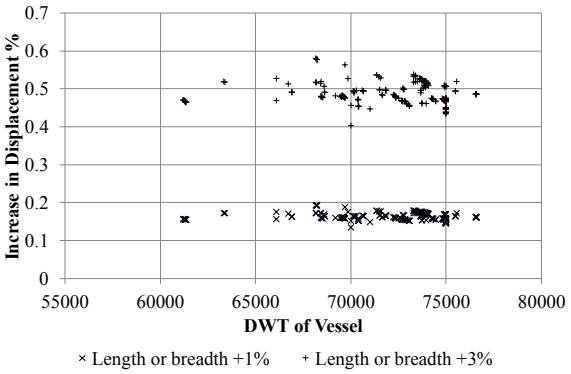

Fig. 9: *Change in displacement as a function of DWT.*

The change in length-displacement ratio *M* is analysed for length changes only. The length-displacement ratio is decreasing for increasing *DWT* of the vessel, see Figure 11. The increase of *M* strongly depends on the length increase, as the displacement increase is very small when the length is increased.

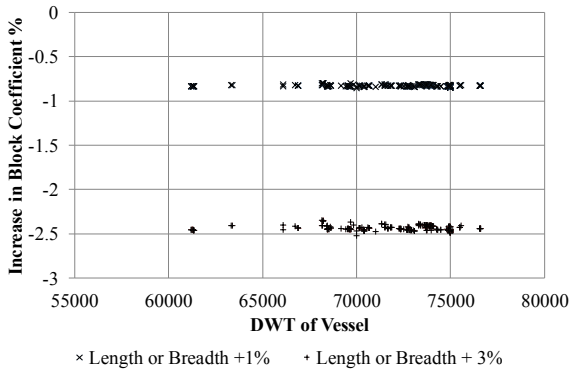

Fig. 10: *Change in C_B as a function of DWT.*

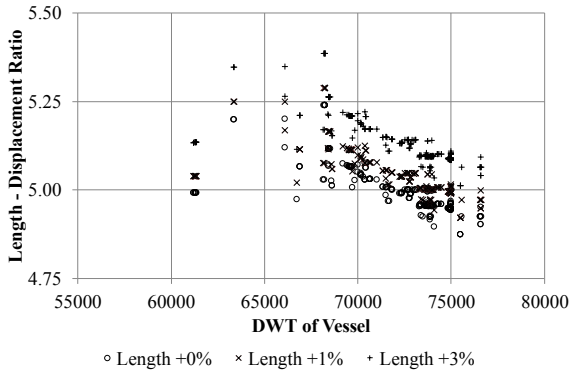

Fig. 11: *Length–displacement ratio as a function of DWT.*

3.2. Parameter Study – Length, Breadth and Draught

Results from an analysis of the power demand for an increase of 1% at one of the main particulars, length, breadth or draught, are given in the present section. Only one parameter is changed in each analysis, the rest of the parameters including the deadweight and the speed are all kept unchanged. The block coefficient will decrease for all analyses. The displacement will increase for increasing length and breadth, whereas it will remain unchanged for draught changes, as the lightweight is only assumed to be dependent on length, breadth and depth, see the weight discussion section as well. The power results are all given as a function of the deadweight (*DWT*). The coefficient of determination (R-squared) is calculated and considerations about correlations are made. For the original situation the mean of the residuals between the calculated and the database value is calculated to 4.1%.

Length

The R-squared is calculated to 0.02, which means no correlation between change in power and deadweight capacity. The power is on average decreased by 4.6%, so that the power is decreasing for increase of length. This is due to the combined positive influence on the residual resistance coefficient C_R of a reduced block coefficient, an increased length-displacement ratio and a slightly reduced Froude number.

Breadth

The R-squared is calculated to 0.03, meaning nearly no correlation between change in power and deadweight. The power is on average decreased by 2.0%, so that the power is decreasing for increase of breadth. The positive influence of changing the breadth is not as pronounced as the length changes, mainly because the resulting increase of the breadth-draught ratio (*B/T*) increases the residual resistance of the ship. This counteracts to a certain degree the positive influence of the decrease of the block coefficient.

Draught

The R-squared is calculated to 0.07, which means nearly no correlation between change in power and deadweight. The power is on average decreased by 2.8%, so that the power is decreasing for increase of draught. The positive influence of the higher draught is a combined influence of a better *B/T* ratio, a lower block coefficient and the possibility of having a larger propeller diameter.

3.3. Parameter Study – Speed

In the present section the change in power demand for an increase in speed of 1% is examined. The analyses are made for unchanged main particulars as well as an increase of 1% at the length or at the breadth.

The R-squared is calculated to 0.001, which means no correlation between change of speed and loading condition. The mean value of the speed is calculated to 15.0 knots with a deviation of 0.6 knots.

The difference between the power calculated for the situation with 1% increased speed and the situation with unchanged speed is used for a comparison. It is found that the power will increase with approximately 2.9% for all vessels in the analysis.

4. ENERGY EFFICIENCY DESIGN INDEX - EEDI

In the IMO MEPC Committee an Energy Efficiency Design Index (EEDI) is being developed since the MEPC 57 meeting in 2008, in order to stimulate innovation and technical development of all elements influencing the energy efficiency of new ships.

The present power prediction model is a good tool for exploring how different ship parameters will influence the EEDI in order to find the most efficient way to reduce CO_2 emissions. The influence on the power demand for design changes is shown in the previous sections. In the present section a few examples of EEDI calculations will be given. Using

the same assumptions as agreed on by IMO, the EEDI has been calculated for all ships. The EEDI is calculated according to MEPC 62/6/4, where the EEDI reference line for tankers is given by

$$EEDI = 1218.8 \cdot DWT^{-0.488} \quad (16)$$

In Figure 12 the results of EEDI calculations using the vessel main dimensions and the speed from the IHS Fairplay database are given. The Figure also shows the EEDI reference line for tankers. The diagram clearly shows a good correlation between the EEDI base line and the individual EEDI values calculated by application of the model prediction tool developed by DTU and SDU.

Figure 13 illustrates the change of EEDI for an increase of 1% in length or breadth, respectively. The differences are slightly increasing for increasing *DWT*. It is seen that for an increase of 1% in length it is possible to decrease the EEDI by 2-2.5%. For a breadth increased by 1% a decrease of 0.7-1.2% is seen. As in the previous section breadth is only included as an illustrative example.

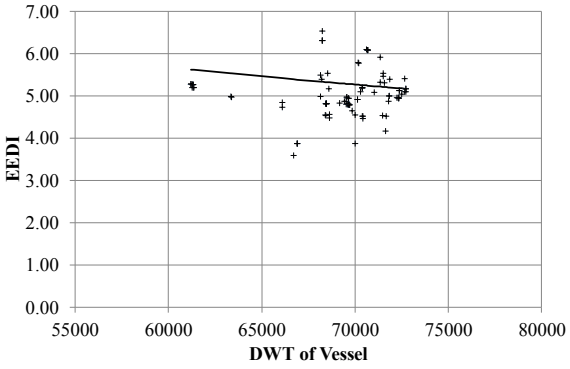

Fig. 12: *EEDI as a function of DWT, database vessel and IMO reference line.*

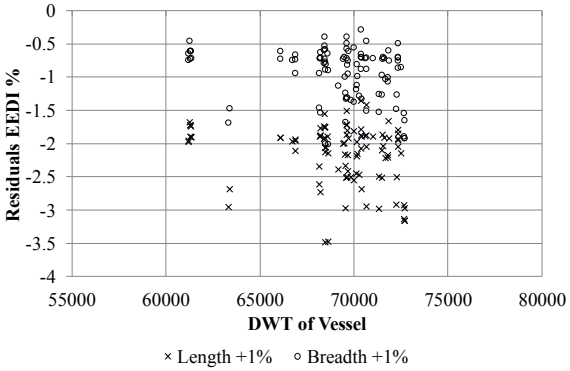

Fig. 13: *Residual of EEDI as a function of DWT. Increase in length or breadth.*

CONCLUSIONS

A new model for prediction of the propulsion power of ships has been presented. The model is based on a previously well-established power prediction method, based on work done by Harvald (presented as a whole in 1983). Harvald's method has been updated and verified by model test results and full-scale data, so that the predictions are up to date according to modern ship design standards. Updated parameters account for newer bulbous bow designs, updated empirical formulas for the wetted surface, updated air resistance corrections and, finally, updated formulas for calculation of the wake fraction and the thrust deduction.

The power for each tanker and bulk carrier listed in the IHS Fairplay database is compared with the calculated power determined by the new power prediction method. The mean and the standard deviation of the power residuals are determined.
Parameter studies have been carried out to investigate the change in power demand for the change in speed, length, breadth or draught. All analyses are performed on Panamax tankers. It is found that an increase of 1% in length, breadth or draught will result in a decrease in the power demand of 4.6%, 2.0% and 2.8%, respectively. An increase of 1% in speed results in an increase in the power demand of approximately 2.9%.

The influence on the Energy Efficiency Design Index (EEDI) for small changes in main dimensions is analysed. The analyses have been performed for an increase of 1% in length or breadth, respectively. The EEDI analyses have been performed for Panamax tankers only. It is found that by an increase of 1% in length it is possible to decrease the EEDI by 2-2.5%. For an increase in breadth of 1% a decrease of approximately 0.7-1.2% of the EEDI is seen.

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APPENDIX A - TANKERS

Small tankers (< 10000 DWT)

L_{pp} = $6.809 \cdot DWT^{0.3048}$
B = $1.406 \cdot DWT^{0.285}$
D = $4.4 + 6.81 \cdot 10^{-4} \cdot DWT$
T = $0.33 \cdot DWT^{0.343}$
$\frac{W_{lightweight}}{L_{pp} \cdot B \cdot D}$ = $0.2096 - 7.2410^{-6} \cdot DWT$

Handysize tankers (10000 - 25000 DWT)

L_{pp} = $3.9537 \cdot DWT^{0.3684}$
B = $8.99 + 8.74 \cdot 10^{-4} \cdot DWT$
D = $7.56 + 2.405 \cdot 10^{-4} \cdot DWT$
T = $7 + 5.23 \cdot 10^{-5} \cdot DWT$
$\frac{W_{lightweight}}{L_{pp} \cdot B \cdot D}$ = $0.1584 - 1.45 \cdot 10^{-6} \cdot DWT$

Handymax tankers (25000 - 55000 DWT)

L_{pp} = $41.647 \cdot DWT^{0.133}$
B = $\min(15.04 + 3.69 \cdot 10^{-4} \cdot DWT;\ 32.23)$
D = $9.69 + 1.88 \cdot 10^{-4} \cdot DWT$
T = $7.41 + 1.06 \cdot 10^{-4} \cdot DWT$
$\frac{W_{lightweight}}{L_{pp} \cdot B \cdot D}$ = $1.05 \cdot (0.1765 - 1.75 \cdot 10^{-6} \cdot DWT)$

Panamax tankers (55000 - 75000 DWT)

L_{pp} = $193.26 + 3.53 \cdot 10^{-4} \cdot DWT$
B = 32.23
D = $6.14 + 1.96 \cdot 10^{-4} \cdot DWT$
T = $2.76 + 1.56 \cdot 10^{-4} \cdot DWT$
$\frac{W_{lightweight}}{L_{pp} \cdot B \cdot D}$ = 0.103

Aframax tankers (75000 - 120000 DWT)

L_{pp} = $187.92 + 4.31 \cdot 10^{-4} \cdot DWT$
B = $1.5658 \cdot DWT^{0.285}$
D = $13.97 + 6.7 \cdot 10^{-5} \cdot DWT$
T = $0.0848 \cdot DWT^{0.4454}$
$\frac{W_{lightweight}}{L_{pp} \cdot B \cdot D}$ = $1.05 \cdot (0.0859 - 2.35 \cdot \cdot 10^{-8}\ DWT)$

Suezmax tankers (120000 - 170000 DWT)

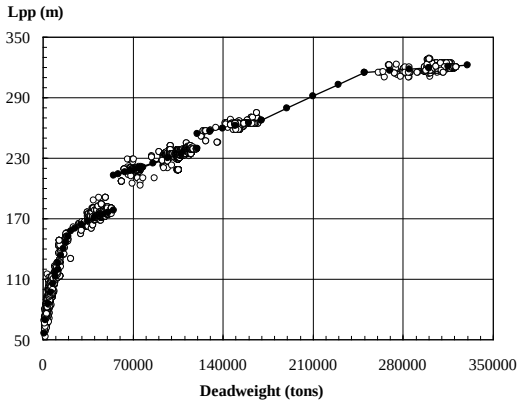
L_{pp} = $222.41 + 2.63 \cdot 10^{-4} \cdot DWT$
B = $23.95 + 1.53 \cdot 10^{-4} \cdot DWT$
D = $22.61 + 4.647 \cdot 10^{-6} \cdot DWT$
T = $0.2476 \cdot DWT^{0.353}$
$\frac{W_{lightweight}}{L_{pp} \cdot B \cdot D}$ = $1.05 \cdot (0.1296 - 3.08 \cdot 10^{-7} \cdot DWT)$

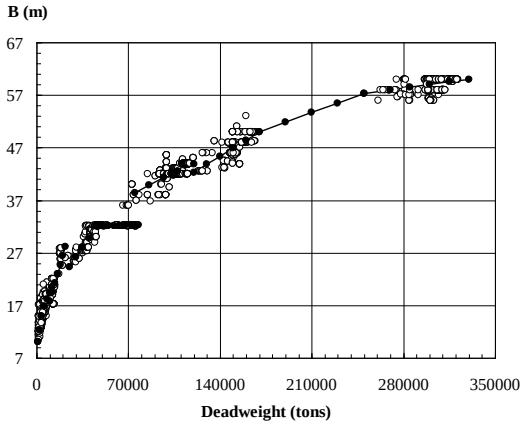
VLCC (170000 - 250000 DWT)

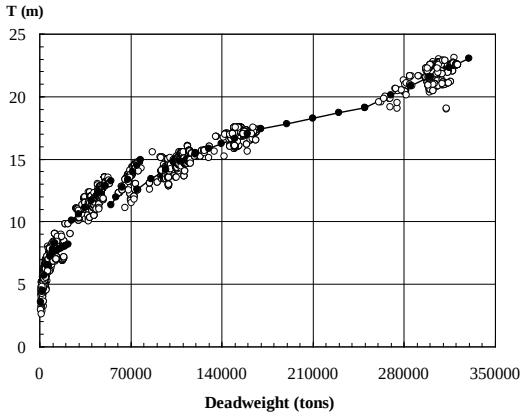
L_{pp} = $267.12 + (DWT - 170000) \cdot 5.975 \cdot 10^{-4}$
B = $49.96 + (DWT - 170000) \cdot 9.219 \cdot 10^{-5}$
D = $23.4 + (DWT - 170000) \cdot 8.25 \cdot 10^{-5}$
T = $17.38 + (DWT - 170000) \cdot 2.147 \cdot 10^{-5}$
$\frac{W_{lightweight}}{L_{pp} \cdot B \cdot D}$ = $1.05 \cdot (0.0772 - (DWT - 170000) \cdot 1.574 \cdot 10^{-7})$

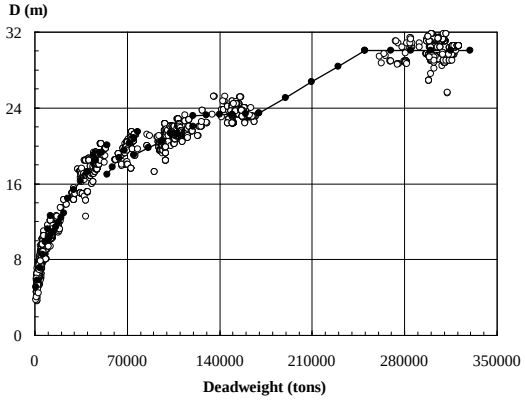
VLCC (250000 - 330000 DWT)

L_{pp} = $293.67 + 8.5 \cdot 10^{-5} \cdot DWT$
B = $49.01 + 3.33 \cdot 10^{-5} \cdot DWT$
D = 30
T = $6.85 + 4.9 \cdot 10^{-5} \cdot DWT$
$\frac{W_{lightweight}}{L_{pp} \cdot B \cdot D}$ = $1.05 \cdot (0.01912 + 1.8212 \cdot 10^{-7} \cdot DWT)$









APPENDIX B – BULK CARRIERS

Small bulk carriers (< 10000 DWT)

L_{pp} $= 5.582 \cdot DWT^{0.329}$
B $= 11 + 0.001 \cdot DWT - 1.675 \cdot 10^{-8} \cdot DWT^2$
D $= 5.22 + 4.85 \cdot 10^{-4} \cdot DWT$
T $= 0.529 \cdot DWT^{0.285}$
$\frac{W_{lightweigh}}{L_{pp} \cdot B \cdot D}$ $= 0.831 \cdot DWT^{-0.2}$

Handysize bulk carriers (10000 - 25000 DWT)

L_{pp} $= 5.463 \cdot DWT^{0.3285}$
B $= 14.86 + 4.5 \cdot 10^{-4} \cdot DWT$
D $= 7.84 + 2.32 \cdot 10^{-4} \cdot DWT$
T $= 6.2 + 1.41 \cdot 10^{-4} \cdot DWT$
$\frac{W_{lightweigh}}{L_{pp} \cdot B \cdot D}$ $= 0.153 - 1.58 \cdot 10^{-6} \cdot DWT$

Handymax bulk carriers (25000 - 55000 DWT)

L_{pp} $= 25.66 \cdot DWT^{0.1813}$
B $= \min(18.93 + 2.72 \cdot 10^{-4} \cdot DWT;\ 32.23)$
D $= 9.32 + 1.58 \cdot 10^{-4} \cdot DWT$
T $= 6.84 + 1.01 \cdot 10^{-4} \cdot DWT$
$\frac{W_{lightweigh}}{L_{pp} \cdot B \cdot D}$ $= 1.05 \cdot (0.151 - 1.27 \cdot 10^{-6} \cdot DWT)$

Panamax bulk carriers (55000 - 75000 DWT)

L_{pp} $DWT < 60000$
$= 124.18 + 1.07 \cdot 10^{-3} \cdot DWT$
$60000 \le DWT \le 65000$
$= 5.17 \cdot 10^{-3} \cdot DWT - 121.52$
$DWT > 65000$
$= 195.16 + 2.93 \cdot 10^{-4} \cdot DWT$
B $= 32.23$
D $= 13.66 + 7.47 \cdot 10^{-5} \cdot DWT$
T $= 8.43 + 7.35 \cdot 10^{-5} \cdot DWT$
$\frac{W_{lightweigh}}{L_{pp} \cdot B \cdot D}$ $= 0.083$

Aframax bulk carriers (75000 - 120000 DWT)

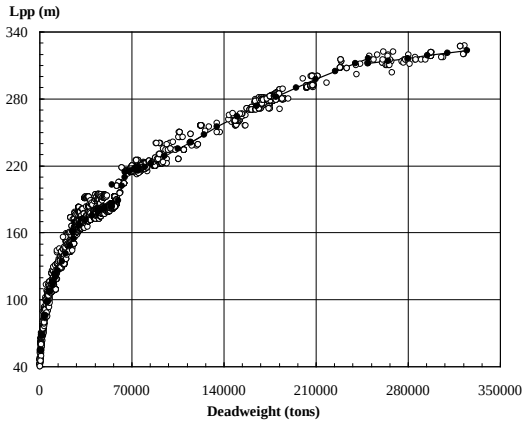
L_{pp} $= 167.39 + 6.421 \cdot 10^{-4} \cdot DWT$
B $DWT < 85000$
$= 36.5$
$85000 \le DWT \le 105000$
$= 8.875 + 3.25 \cdot 10^{-4} \cdot DWT$
$DWT > 105000$
$= 43.0$
D $= 10.7 + 1.00 \cdot 10^{-4} \cdot DWT$
T $= 7.35 + DWT \cdot 7.00 \cdot 10^{-5}$
$\frac{W_{lightweigh}}{L_{pp} \cdot B \cdot D}$ $= 0.084$

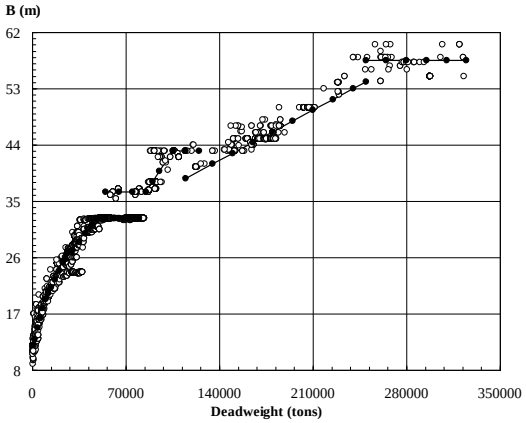
Suezmax bulk carrier (120000 - 250000 DWT)

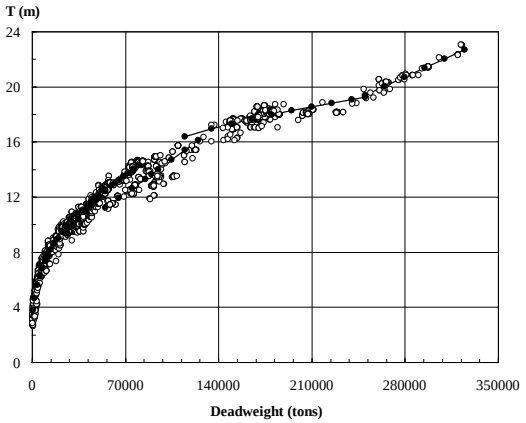
L_{pp} $= 4.046 \cdot DWT^{0.3506}$
B $= 25.49 + 1.145 \cdot 10^{-4} \cdot DWT$
D $= 20.27 + 2.32 \cdot 10^{-5} \cdot DWT$
T $= 1.476 \cdot DWT^{0.2065}$
$\frac{W_{lightweigh}}{L_{pp} \cdot B \cdot D}$ $= 0.0756$

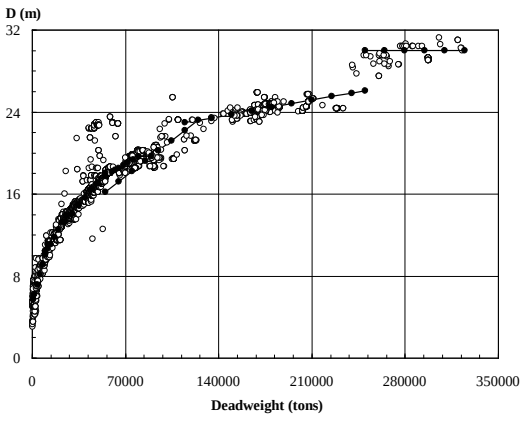
VLBC (250000 - 330000 DWT)

L_{pp} $= 271.49 + 1.594 \cdot 10^{-4} \cdot DWT$
B $= 57.5$
D $= 30$
T $= 8.32 + 4.424 \cdot 10^{-5} \cdot DWT$
$\frac{W_{lightweigh}}{L_{pp} \cdot B \cdot D}$ $= 0.068$









APPENDIX C – POWER RESIDUALS

Difference (residual) between power calculated using the DTU-SDU power prediction model and the power given in the IHS Fairplay database. Probability density diagrams are presented for Small, Panamax and Aframax tankers.