Simplified approach for the estimation of the added resistance of ships in waves

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ABSTRACT: The increasing problem of climate change has led to the creation of several laws to tighten restrictions on the fuel oil consumption of ships by maritime organizations. Private and public entities have therefore expanded the research being done on the effects between sailing ships and waves and how these phenomena translate to economic benefits. The wave added resistance is one of these phenomena, and it can contribute up to 30% to the total resistance a ship perceives, and consequently on the fuel consumption. In this dissertation a thorough literature review was conducted to understand and evaluate the methods being used in the field of study of added resistance in waves and in its prediction through numerical simulations and regressions. An experimental database of tank test data was also created to later validate the theoretical and semi-empirical models and applied methodologies. To test the theories several studies were conducted to obtain a methodology that would correctly predict the added resistance for different ship types and sea conditions. Through the computation of the added resistance with a combination of NTUA and Salvesen's methods, a record of observations of added resistance was made for a variety of sea conditions which is based on container ships specifically. A linear regression model was developed which presented an adequate fit to the responses in the previously built database. It also, offers a quick and efficient method to predict the added resistance in irregular waves using a minimal amount of ship and ocean wave parameters. Other methods using machine learning algorithms are discussed as well as their applicability and future work is suggested noting the lack of public data regarding tank tests.

Keywords: Added resistance, Ocean Waves, Numerical Simulation, Linear Regression Modelling

1. INTRODUCTION

The sustainability of an industry is reliant on the advancement and development of new tools and skills. This constant innovation and research are what makes available the growth and expansion of the field. In ship engineering this is no different and in recent years the research has focused its attention on the growing problem of climate change. This conservation mindset created a push towards a more environmentally conscious industry, in which the shipping industry productivity has seen a subsequent improvement in the operational and financial efficiency of ships.

The world's ever growing population (United Nations, 2019) creates a constant demand for the increase in size and scale of the worldwide supply market. The shipping industry responsible for more than eighty percent of the total share of goods and cargo transported by sea worldwide (UNCTAD, 2020), is then understandably challenged to expand. In order to grow and keep up with the demand and at the same time lower costs, larger operations have to be developed in which bigger ships play a fundamental role. These so called economies of scale are then set up, but the entire industry will face challenges since it must be renewed and updated. With the increase in scale, it is also faced with the increase in operating and managing costs.

Fuel consumption is one of the main expenditures when it comes to shipping, both economically and environmentally. The increase in fuel costs along with climate change constraints, have introduced the need to build ships that consume less fuel. Shipping lines have adapted their operations to mitigate fuel oil consumption along with other measures to decrease the pollution in marine environments. This pollution can be originated from many sources, but the ones that have been the most prevalent over the years are related to exhaust gases, water pollution (ballast water, noise, etc.) and some pollutant cargos or wastes (Clark, Frid, & Attrill, 1989). Increasing concerns have been raised about the adverse environmental impacts caused by cargo movement in international trade by stakeholders and international government bodies. The waste produced in the shipping processes can put a burden on the environment which can lead to resource depletion. Many shipping companies have taken the initiative to find ways to minimize the environmental harm of their activities while improving their efficiency in order to better protect the marine ecosystem. The problem is set to deteriorate due to the growing of trade´s globalization. It is also important to increase awareness and improve shipping industry´s public perception which can lead to funding and new stakeholders' interest. As such, the marine industry continues to push for the development of ships that can comply with ever stricter regulations and laws that prevent the aggravation of the climate situation.

The development of maritime guidelines and regulations has an important role in enforcing the necessary measures in preventing the stagnation and deterioration of the environment situation. One of these benchmarks that has been implemented in recent years to regulate the new designs fuel consumption is the Energy Efficiency Design Index (EEDI). EEDI was established and made mandatory for new ships at the Marine Environment Protection Committee (MEPC), 62 in July of 2011 (MEPC, 2011). It can be considered one of the most important measures to be implemented since it will be incrementally tightened over the years for each category of ships to promote the development and research being done on the efficiency of machines and equipment on board. The ultimate goal of this measure is to lower the emissions of carbon dioxide to follow global trends in more efficient technology.

With the advent of the EEDI, the maritime industry has searched for ways to optimize every aspect of a ship, from design to operation. In this dissertation, a method to optimize the performance and efficiency of a ship in operation will be analyzed, in particular the speed loss in real sea conditions. Speed loss is derived from the resistance the ship encounters when sailing through waves and winds. The wave aspect will be further detailed in this study. The factor that is the most relevant however to this phenomenon is the hull form. Hull form optimization performance in a design phase can be optimized to make the full project meet EEDI criteria. Therefore, it is important to gather more knowledge about this subject and make models that can be used as a reliable tool to easily find the wave added resistance for a specific ship hull.

When it comes to the study of resistance in ships, extensive studies have been made which take into account the hydrodynamic capacities of the ship sailing in water. However, in the past, due to the limitations in models, specifically when it is necessary to take into account the navigation in waves, only calm water conditions were computed. Nowadays, the full range of drafts and speeds must be considered in real operational profiles. The detail in these studies must give reliable results to prove that the final ship will always be able to meet the criteria for fuel consumption.

Following the extensive research that has been done over the years, this study will bring together some of the more accepted models by the scientific community. This will allow for a full range of scenarios to be predicted in accordance to ship specific parameters.

2. LITERATURE REVIEW

2.1 Added resistance of a ship advancing in waves

Knowing that the added resistance in waves comes from the differential in energy expenditure when compared to calm water, then it is important to understand how this loss is originated. When ocean waves interact with a body there is a transference of energy to the adjacent water. From this transference there are three main components that can be considered from a dissipation of energy standpoint.

The first are the viscous effects related to the damping of the vertical motions of the ship, which are the smallest contribution to the added resistance (Faltinsen, Minsaas, Liapis, & Skjordal, 1981). These viscous effects are irrelevant when compared to the hydrodynamic damping of ship motions. Therefore, most procedures of calculating the added resistance ignore these effects and are based on potential theory.

The second consideration is the diffraction effect, which is more relevant in the short wave region. The diffraction induced added resistance occurs when the ship hull reflects the incident wave. The third and final component to consider is called the drift force, produced from the ship radiated waves. Dominating for the long wave region where the ship motions are larger this component makes for the largest contribution to the added resistance (Salvesen, 1978).

2.2 Theoretical and semi-empirical methods to calculate added resistance in regular waves

The first attempts at calculating the added resistance in waves were made by Havelock who initially calculated the mean pressure of waves on a fixed object by diffraction theory (Havelock, 1940).

The integrated pressure method would also later be studied by Boese who relied on strip theory to further develop this method. Boese calculated the added resistance through the integration of the longitudinal mean force (caused by the heave and pitch motions and waves) over the waterplane area (Boese, 1970).

Another important method to the analytical potential flow problem of the added resistance was developed by Maruo (Maruo, 1957). His research on added resistance focused on the principal of momentum and energy conservation based on a far field method. By employing the same method used for strip theories nowadays, Maruo evaluated the wave energy and momentum flux generated by a ship around a control volume of infinite radius surrounding the ship. Another, development in Maruo’s formula came from Newman who also analyzed the stability of the ship in oblique waves by computing the vertical moment (Newman, 1967).

The final method of interest when considering analytical solutions to the added resistance numerical problem is the radiated energy method. This is a far field method which computes the energy necessary to create waves when the ship oscillates for one period, in head seas. Gerritsma and Beukelman developed this method with a base on strip theory to describe the form of the sections of the hull (Gerritsma & Beukelman, 1972).

As mentioned in the methods before strip theory was becoming the most prevalent method to calculate the added resistance. This was also seen during the 1970s when Salvensen, Tuck and Faltinsen introduced a method based on linear 2-D strip theory which was more reliable (Salvesen, Tuck, & Faltinsen, 1970). This method calculates the wave induced motions based on a generalized Haskind relation to evaluate the wave exciting moments and forces, which does not require the solution of the diffraction problem and give a more reliable result.

With the development of several methods that focused on the main contribution to the added resistance, the radiation problem, it would become necessary to solve the diffraction problem to find the added resistance for all wavelengths. In the low wavelength region, where the ship motions effect can be neglected, not much research or experiments were being performed due to its complexity. Faltinsen was one of the main authors who contributed to the solution of this problem (Faltinsen et al., 1981).

It was also during the 1970s that empirical formulations started to be developed and published. With the advent of new theories and an ever-growing publicly available database of experimental tests, it would become easier to derive formulas from these datasets. One of the most recognized semi-empirical formulas is the one developed by Fujii and Takahashi. In their formulation of the added resistance the ship motions and the reflection at the bow are considered and it is compared with their own experimental results for the S175 ship (Fujii & Takahashi, 1975).

Later on, Liu et al. (Liu, Shang, Papanikolaou, & Bolbot, 2016) used the reasoning of Kwon (Kwon, Sc, & Upon Tyne, 1981) who adapted the exponential decay of Smith to the wave amplitude and therefore to the decay of the added resistance with the square of the exponential function.

Jinkine and Ferdinand also made their contribution to the solution of the added resistance in long waves (Jinkine & Ferdinande, 1974). Their approach is fully empirical and is intended to be valid for fast cargo ships. Although the authors mention their method is valid for the entire range of wavelengths, only the motion induced added resistance is calculated.

The formulations of Fujii and Jinkine have been established for some time and have more recently been combined to obtain a formulation that can cover all wave lengths. The Maritime Research Institute of Netherlands (MARIN) worked on this type of formulation and made it approved for the evaluation of the EEDI (ITTC, 2014). This led to the proposal of the formulas known as STAWAVE1 and STAWAVE2.

To conclude the subject of the development of semi-empirical formulations over the years, it is also of significance to mention the research that Liu and Papanikolaou have been developing and the NTUA method. This approach was initially developed using Maruo's far field theory combined with Faltinsen's approach (Liu, Papanikolaou, & Zaraphonitis, 2011) and would over the years be reexamined and was recently updated with the development of the formulas of Fujii and Jinkine (Liu & Papanikolaou, 2020). It has offered a fast and easy approach to the estimation of the added resistance in the design stage for engineers who want to predict the added resistance of a ship sailing in a representative seaway (Liu & Papanikolaou, 2017).

To conduct a study on added resistance it is necessary to compile some results of experimental tests in order to assess how well the numerical results match these. A review of some public results was done in order to create a database that can be used to validate analytical results Table 1.

2.3 Added resistance in irregular waves

Although research focus on finding rational models for regular waves, actual sea states are comprised of a set of numerous regular waves with different parameters. Irregular sea states are in other words, the superposition of waves with different wavelengths, amplitudes, and directions. Therefore, the same can be applied to the added resistance of a ship in waves.

As mentioned before, spectra must be applied in accordance with the purpose of research. It was observed that for the case of the calculation of wave loads and ship motions, it is recommended by the International Ship Structures Congress (ISSC) and by the International Towing Tank Conference (ITTC) to use a spectrum which represents fully developed seas (Guedes Soares, 1984). The ISSC spectrum is an example of this, as it is based on the Pierson-Moskowitz spectrum and is a more peaked spectrum to represent rising or falling seas and as well as fully developed seas (ISSC, 1964).

Table 1 - Public published available model experiments.

Ship type	Containership	Containership	Containership	Crude Carrier
Name	S175	DTC	KCS	KVLCC2
LPP [m]	175	355	230	320
Froude number	0.15 / 0.20 / 0.25 / 0.275 / 0.30	0.0 / 0.052 / 0.139	0.26	0.0 / 0.05 / 0.09 / 0.142
Wave Heading [deg]	180 / 150 / 120 / 90 / 60 / 30 / 0	180 / 150 / 120 / 90 / 60 / 30 / 0	180 / 135 / 90 / 45 / 0	180 / 150 / 120 / 90 / 60 / 30 / 0
Reference	(Fujii & Takahashi, 1975; Kim et al., 2017; Nakamura & Naito, 1979)	(El Moctar et al., 2012; Shigunov et al., 2018; Sprenger et al., 2017)	(Sadat-Hosseini et al., 2015; Simonsen et al., 2013; Yasukawa et al., 2019)	(Guo & Steen, 2011; Park et al., 2016; Shigunov et al., 2018; Sprenger et al., 2017)

Most studies of added resistance in waves, tend to simplify the problem by disregarding the direction of waves in a spectrum. The assumption that wave energy will mostly propagate in the same direction as the wind is not comprehensive enough, as the wave energy usually spreads over various directions, even if the majority of it does in fact propagate in the same direction as the wind (Ochi, 1997). Formulations of spread functions were made to find the directional spectrum.

2.4 Regression analysis

The study of regressions has become more relevant with the creation of modern technologies that make accessible this kind of computing capabilities. The creation of regression based models through machine learning and artificial intelligence show signs of being highly accurate inside a broad spectrum of ship hull forms and waves (Cepowski, 2007).

The application of MLR methods to the added resistance is a relatively new concept. Nevertheless, some models are available and it is concluded that simple linear models are not so precise, and to correct this, non-linear variables should be added to the model (Alexandersson, 2009; Cepowski, 2018).

Although the use of MLR methods is clearer and concise, artificial neural networks (ANN) provide a higher level of confidence (Cepowski, 2018, 2020). Neural networks usually present models that rely in very large numbers of coefficients which will present good correlation with the input data. Simpler models derived from tank test data have been implemented and present an acceptable degree of pertinence in a real engineering scenario or in a preliminary design stage when computing EEDI for example (Cepowski, 2020).

3. METHODOLOGY

3.1 Description of the main inputs

In order to simplify and validate the final results, a decision was made to choose ships of the same type to conduct the simulation. The chosen ship type was container ships. These vessels tend to use more slender hull forms and operate at higher velocities. Also, it was important to consider the public availability of experimental data which is higher for containerships (Liu & Papanikolaou, 2020). Three containerships are used, based on the availability as well as the range of different hull shapes and hull characteristics inside this category. These three hulls are the S175 containership, the KRISO containership and the Duisburg Test Case (DTC) containership. Taking this into account for the three hulls that were chosen, the parameters necessary for this computation are listed on Table 2.

Table 2 – Ship hydrostatic properties.

Parameter	S175	KCS	DTC	KVLCC2
L_{pp} [m]	175	230	355	320
B [m]	25.4	32.2	51	58
T [m]	9.5	10.8	14.5	20.8
k_{yy}	43.75	57.5	88.75	80
Cb	0.572	0.651	0.664	0.8098

The most intricate and equally important step in the definition of the ship hull, however, would be the definition of a table of offsets for each hull. The table of offsets indicates the spatial coordinates of the points represented in three dimensions. The lines plan for the chosen ships are shown in Figure 1, Figure 2 and Figure 3.

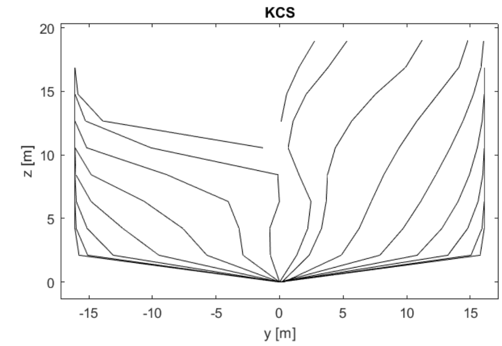

Figure 1 - Lines plan of the KCS ship.

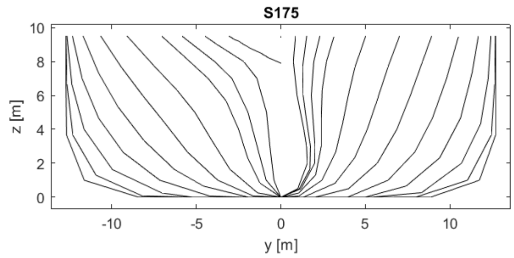

Figure 2 - Lines plan of the S175 ship.

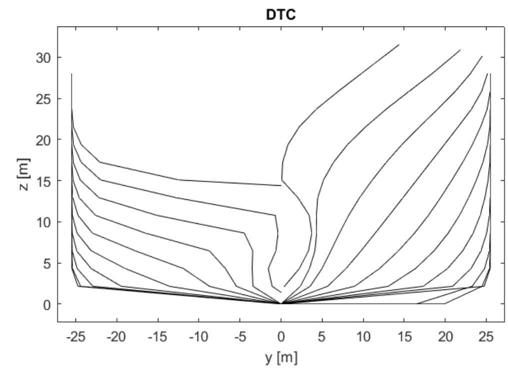

Figure 3 - Lines plan of the DTC ship.

3.2 Faltinsen's asymptotic formulation for added resistance

Faltinsen's formulation for the added resistance in the asymptotic low wavelength region takes into account regular waves that are incident on a ship. It can be considered that these are much smaller than the draught of the ship, meaning only the region of the ship close to the waterline will influence the flow field. It can also be said that the small wave excitation forces on the ship will indicate that it is possible to neglect the effects of the ship motions induced by the waves, on the added resistance. Factoring these considerations, it is possible to replace the ship by an infinitely vertical and static cylinder which has the same cross section as the waterline of the ship. The diffraction problem then becomes similar to that of a wave hitting a vertical wall. The normal average force per unit length on the wall, $\overline{F_n}$, is taken as:

$$\overline{F_n} \sim \frac{1}{2} \rho g \zeta_a^2 \left\{ \sin^2(\theta + \chi) \frac{2\omega_0 U}{g} (1 - \cos\theta \cos(\theta + \chi)) \right\} \quad (1)$$

To then calculate the mean drift force components and yaw moment an integration is done along the region of the ship's waterline which the wave is directly incident on, the incident region as defined on Figure 4. This integration is given as:

$$\bar{F}_i = \int_L \bar{F}_n n_i dl \quad (2)$$

where $n_1 = \sin\theta$.

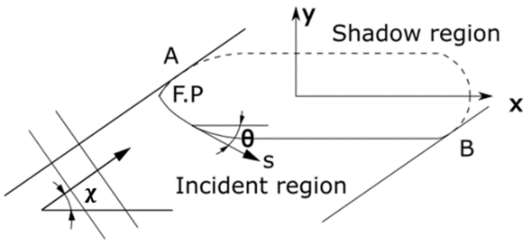

Figure 4 - Coordinates used only in Faltinsen's formulation.

The results obtained from the code were compared to results of implementations by other published authors (Liu, Papanikolaou, & Zaraphonitis, 2015; Vitali, Prpić-Oršić, & Guedes Soares, 2016) for wave headings in the region of 180º (head seas) to 90º (beam seas).

Although Faltinsen's formulation has been regarded as one of the most accepted methods to calculate the added resistance in short waves, it still has some faults which research has been trying to resolve. It is said in Faltinsen's paper that the formulation is applicable to every wave direction, however it can be seen from the results it computes that following seas results are not trustworthy.

3.3 Salvesen method

The Salvesen, Tuck and Faltinsen linear theory (Salvesen et al., 1970) is applicable to both the method of Faltinsen and the method known as the Salvesen method. Salvesen's formula for added resistance is based on the Froude-Krylov approach to calculate hull pressures (Salvesen, 1978). The formula is expressed as:

$$R_{aw} = -\frac{i}{2} k_w \cos\beta \sum_{j=3,5} \zeta_j \{ (\hat{F}_J^{I^*}) + (\hat{F}_J^{D}) \} + R_7 \quad (3)$$

In this equation, $\hat{F}_J^{I^*}$ is the complex conjugate of the Froude-Krylov part of the exciting force and moment and $\hat{F}_J^{D}$ represents the diffraction force and moment but using the complex conjugate of the incident wave potential.

3.4 NTUA semi-empirical method

As mentioned in chapter 2.2.2 one of the more recent methods being developed from the combination of development of previous theories and empirical formulas is the so called NTUA method developed by the National Technical University of Athens. (Liu & Papanikolaou, 2020). The formulation can be consulted in the article of Liu and Papanikolaou, since it is quite extensive and detailed.

The implementation is fully functional for head waves, and the results showed agreement in this range. Promising results are also seen for beam seas where results follow the data very accurately. These results are also in agreement with the experimental data from the S175 containership, which is proof that this method is reliable in head seas.

The implementation of the method does not agree with the results presented in the article on fore quartering and following waves. In this case the original results for following waves maintain the maximum of the added resistance in the same position as the maximum for head waves. This is described in the article however, the results produced do not match this. Instead, the peak is at a lower wavelength which seems to be more in accordance with the real case. The plots are given in Figure 5.

3.5 Added resistance in irregular waves

To make the analysis of a wave group these characteristics are described as:

- Wave peak period, Tp, which describes the wave period with the highest wave energy
- Wave significant height, Hs, describing the mean of the of the highest third of wave height
- Mean wave direction, χ_m

The wave spectrum, Sw, using the ISSC spectrum developed by Bretschneider to represent fully and partially developed sea states, should then be given as:

$$Sw(\omega, \chi) = Sw_{1D}(\omega) \cdot spread \quad (4)$$

$$Sw_{1D}(\omega) = 0.313 \, H_S^2 \frac{\omega_p^4}{\omega^5} e^{-1.25\left(\frac{\omega_p}{\omega}\right)^4} \quad (5)$$

$$Spread = \begin{cases} \frac{2}{\pi}(\cos(\chi_m - \chi))^2 \text{ for, } \chi_m - \frac{\pi}{2} < \chi < \chi_m + \frac{\pi}{2} \\ 0, otherwise \end{cases} \quad (6)$$

$$R_{aw} = 2\int\int S_w \circ \Phi_{AW} \, d\omega \, d\chi \quad (7)$$

3.6 Regression analysis

Since it is important to create a model that can be generic enough to fit a large enough number of ships, within a chosen range, a dimensional analysis was conducted to arrange the variables in a proper fashion. The investigation of which parameters to use was done by converging on the recommendations of the variables

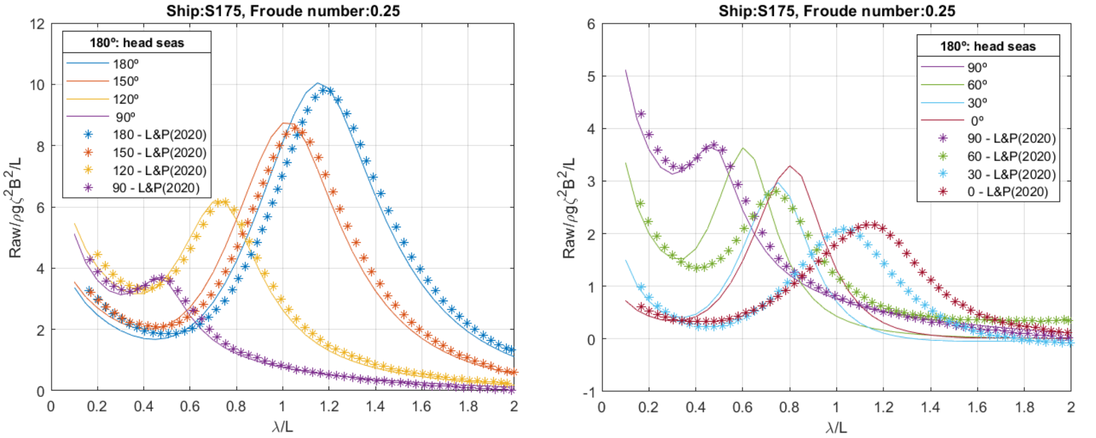

Figure 5 – Comparison of the implemented results of the NTUA method in head waves (left) and following waves

proposed by the research of Liu and Papanikolaou for the NTUA method (Liu & Papanikolaou, 2020). The final dimensionless parameters that were used to train the regression model are:

- Lpp/B
- B/T
- E1
- E2
- Cb
- kyy/Lpp
- Froude number
- H_s/l_p
- $\omega_{e_p}\sqrt{Lpp/g}$
- χ_m
- $Raw/(rgz^2B^2/Lpp)$

Here, E1 and E2 refer to the entrance and exit angle of the waterline, respectively.

The significant height was defined as a function of the peak period, since there is a range of acceptable heights for each peak period. To find this function, the graph of recorded observations from the research published from the ITTC 2005 (Downie et al., 2005) was used.

In this case, the creation of the method to calculate the added resistance based on semi-empirical formulas that have the foundation on experimental data and theory allows for the collection of the necessary data.

The use of a programming code for the computation of the added resistance and for the compilation of data for the database was important to keep a consistency in the creation and production of compatible files and codes. To keep this consistency in the creation of the model with the use of linear regressions, MATLAB was also chosen to perform the regression analysis.

To simplify the problem a multiple linear regression (MLR) model was created. MLR are difficult to fit, especially when a large amount of regressors is being used but offers a simpler solution. The formula of a multiple linear regression is for example of the type:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k \qquad (30)$$

Here y is the response, x_k the regressor and β_k the regressor coefficient estimated.

An analysis of some of the calculated statistical parameters in combination must be performed to evaluate the fit of the model. In order to prevent over-fitting, the model must have some sensitivity to noise and the number of predictors must reflect the general population of occurrences rather than a small portion, even though it would increase the R-squared to a value that would suggest a better fit, for example.

4. RESULTS AND DISCUSSION

4.1 Results from the implementation of the added resistance and database creation

In order to create a database which will be used to train the model, the results from the methodology must be analyzed. Following this analysis, a decision on a range of methods and characteristics will be selected for the model which will give it its range of applicability. In other words, the limits, and restraints of the model. Figure 5 shows an example of the results of this computation.

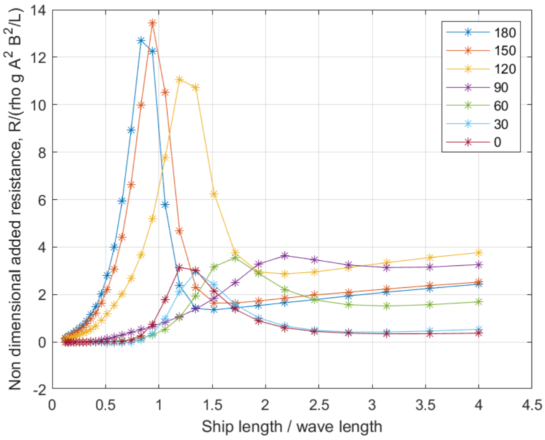

Figure 6 - Added resistance in waves of S175 ship at Fn=0.25, using a combination of Salvesen and NTUA methods.

The test of all the formulations detailed previously formulation supported the conclusion that two methods were better for this application. These two are Salvensen's method and the NTUA method which were picked for their reliable results in a multitude of different scenarios.

Three ships were chosen to train the model, the S175 ship, the KCS ship and the DTC ship. It is then obvious that the model is limited to this range of ship characteristics, but it also allows for more reliable results withing this group. The model is then trained for ships ranging from 175 meters to 355 meters and for Froude numbers of 0.18 to 0.25.

4.2 Numerical model

Initially, a simple regression model was computed. This linear model was not fully developed, and this was suggested by the statistical parameters (R-squared of 0.487 and RMSE of 0.104).

Finally, it was found that for the ship parameters the interaction effects would produce the best results. For the wave parameters better results were found when increasing the power of the predictors as well as when including interaction effects for the wave frequency and wave directions. The final model is comprised of ten predictors including the interception term, including eight terms from the initial ten used in the database to train the model. The formula regression coefficients are given in Table 3 and the general formula as:

$$\begin{aligned} R_{aw_{nd}} \sim \beta_0 + \beta_1 \frac{H_s}{\lambda} + \beta_2 (E_1\, C_b) \\ + \beta_3 \left(\omega_{ep_{nd}}\, \chi_m\right) \\ + \beta_4\, {\omega_{ep_{nd}}}^2 + \beta_5\, {\chi_m}^2 \\ + \beta_6 \left(\frac{L_{PP}}{B} \frac{B}{T} Fn\right) \\ + \beta_7\, {\chi_m}^3 \\ + \beta_8 \left({\omega_{ep_{nd}}}^2\, {\chi_m}^2\right) \\ + \beta_9 \left({\omega_{ep_{nd}}}^3\, {\chi_m}^3\right) \end{aligned} \tag{40}$$

Table 3 - Linear model regression coefficients.

	k	Estimate (b_k)
(Intercept)	0	-0.09541
Hs / λ	1	-0.74541
E1 * Cb	2	1.0453
$\omega_{ep_{nd}} * \chi_m$	3	-0.0149
${\omega_{ep_{nd}}}^2$	4	-6.31E-05
${\chi_m}^2$	5	0.20843
Lpp/B * B/T * Fn	6	0.007247
${\chi_m}^3$	7	-0.05354
${\omega_{ep_{nd}}}^2 * {\chi_m}^2$	8	0.000132
${\omega_{ep_{nd}}}^3 * {\chi_m}^3$	9	-2.67E-07

The fitting is very good considering the type of model. Both the R-squared (and adjusted R-squared of 0.801), and the RMSE (equal to 0.0651) when analyzed together show plausible values.

From Figure 7 and from the detailed analysis of the plots of the model the more evident weaknesses of the model in estimating the added resistance in waves were studied. One of these shortcomings is the severe overestimation of the added resistance for low values compared to the peaks. Seen in Figure 7, the closer the actual responses are to zero, the bigger the variance there is in the model responses.

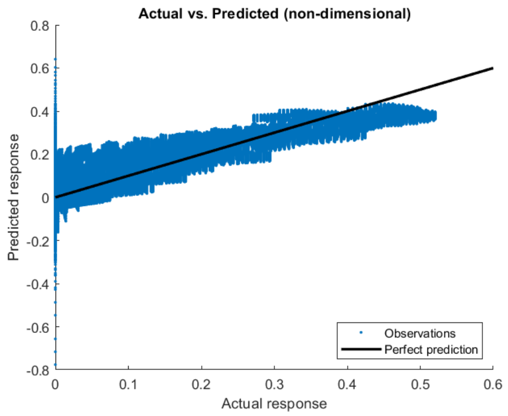

Figure 7 - Actual response plotted against the predicted response from the simple linear model.

4.3 Model validation

In order to fully validate the linear regression model, a test was conducted using hull forms scaled from those that were used to train the model. Changing the parameters of these hulls would test the range of the model and could reveal some limitations and strengths of the model. The hulls that were chosen to scale were the S175 and the KCS. The scaling factors were applied to each axis using the table of offsets of each hull. These scaling factors are recorded in Table 4.

Table 4 – Scale factors applied to ships

	Ship	
Scale factor on:	**S175**	**KCS**
x-axis	1.1	0.9
y-axis	0.9	1.1
z-axis	0.8	0.8

Both were tested by calculating the added resistance in irregular waves through the same method used to build the database to train the model and comparing these results with the predicted values from the model. Both ships were tested for a high standard Froude number of 0.25 to check how the model behaves in limit conditions. The response plots are represented in Figure 8 and in Figure 9.

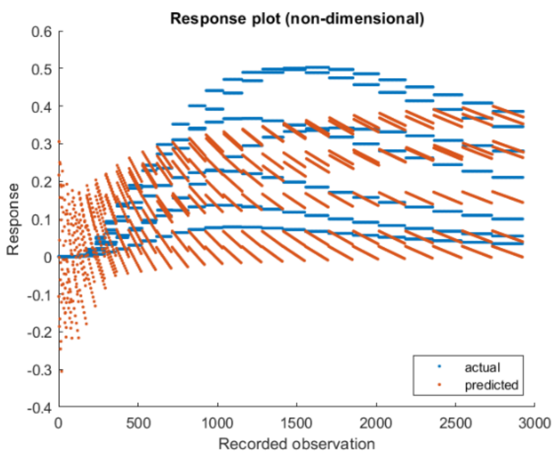

Figure 8 – Response plot of the scaled S175 ship at Fn=0.25 (R^2 = 0.75).

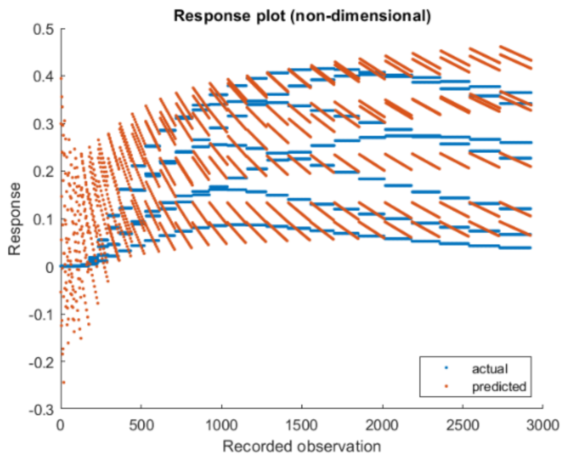

Figure 9 - Response plot of the scaled KCS ship at Fn=0.25 (R^2 = 0.70).

The ease of use of use of the formula, in combination with the simplicity in modifying and testing the regression and its adaptability are the strong points in favor of linear regression models. The disadvantages are carried through the model, specifically on the lower values of the added resistance. However, this is the simplest way of finding a formula that can rapidly and efficiently calculate the added resistance with parameters easily available for any ship.

5. CONCLUSION

5.1 Achievements

The main objective of this dissertation was the creation of a meta-model through a linear regression that would simplify the calculation of the added resistance of a ship in waves. For this purpose, a database was created for the identification of values of the added resistance computed from methods that were analyzed and tested for the solution of this problem.

The extensive literature review defined the history and precedents of methods and techniques used to calculate the added resistance in waves. From this study it was possible to clearly isolate the two main areas of focus on the theory for the solution of the added resistance, which are divided into theoretical and semi-empirical formulations. Having the understanding of the considerations made by each formulation, allowed for the choice of which methods to select for the preliminary testing and decision making of which concepts to further combine for the computation of the final solution.

The study of the theories behind the solution of the added resistance problem should be made in conjunction with the research of the regression models that have been applied to this problem. The detection of a gap in the literature was clear in this area, where there are only a few developed models. This gap was concluded to be related to the lack of knowledge regarding machine learning in the maritime engineering field where it is just starting to become more appealing due to the alternative it provides from the extensive and complex formulations. There will be a public need and demand for more experimental data regarding tank tests and full scale analyses motivated by the development in regression theory.

Through the analysis of the state of the art, it was possible to determine some methodologies to be applied to the problem that would give the necessary results for the implementation of a regression model. The methods of Faltinsen, Salvesen and NTUA were implemented into programming language and duly tested. Faltinsen's method was deemed unnecessary in this context since it had several limitations in the type of ships and directions it could reliably compute. This conclusion is also supported by the fact that the NTUA method is an extension of Faltinsen's asymptotic formulation for short waves. Salvesen's method had previously been implemented in CENTEC's numerical code for the added resistance and also proved to be a reliable method. Although it is known that this method overestimates the peak of the added resistance, it is still reliable enough to predict the added resistance for different ship types in head or fore quartering waves.

Regarding the regression theory, a decision was made to create a linear regression model that would simplify the solution of the problem and could give some more background into the inner workings of the methods used to compute the added resistance in waves. The linear regression model focused on the calculation of the added resistance in irregular waves. For this reason, a database was created, composed of eleven dimensionless terms, computed from the integration of the added resistance in regular waves and the chosen ISSC spectrum.

The process of creating a linear regression model was an iterative procedure. Both in the quantity and form of the terms to add to the model. Using this method, it was possible to achieve the best fit for the regression using a formula that would be simple enough to quickly predict the added resistance of a ship sailing in waves. This formula can calculate the added resistance with quite good reliability (eighty percent or higher) except in the regions where the added resistance becomes quite low, where it overestimates the responses.

However, the main goal of finding a formula that simplifies the problem and meets the needs of quickly predicting the added resistance is met. This was validated with the use of scaled ship hulls which predicted the added resistance with an acceptable degree of accuracy and resulting in a R-squared generally higher than zero point seven which is considered to be very effective taking into account the type of regression. Having this main objective in mind it is possible to conclude that the statistics of the model indicate a good fit for the needed formula, especially considering the phenomenon of the added resistance which is strongly dependent on interactions and effects between ship and waves.

The model presented is capable of computing responses for a wide array of wave parameters, but it is more selective when it comes to ship parameters. The definition for the limit range of the model presented in this dissertation is:

- Ships must be containerships or of similar block coefficient to common containerships (less than 0.7 usually)
- Dimensions not larger than 10% of the maximum and smaller than the minimum of those from the hulls used to train the regression model

This model is valuable since it is defined through a formula that is simple to use and allows for the wide and efficient access to the added resistance in waves. This is especially important in engineering and project scenarios. However, computing a model that has a better fit to the recorded observations and has a wider range of operation than the one presented in this thesis is possible.

In conclusion, it is important to take note that regression models should not be used to make hypotheses about the physical theories or models but rather to gauge how the methodology to the computation of the responses of the added resistance in waves functions. And also, that a regression model must be chosen based on a clearly defined goal, and the statistics must be interpreted to clearly state if that goal was met within some guidelines and considerations.

5.2 Future work

The necessity of simplification of the regression model was in part due to the long formulations that are usually applied in this field and in part due to the lack of experimental data to validate these formulations. The overall lack of information and development that is being done on added resistance in waves will certainly help further build the knowledge base and future works can rely on past experiences and more reliable data.

The regression model was constructed from the database which was lacking variety in terms of ship characteristics which made it overfit these parameters. More ships in the model's database would contribute to the linear regression model. An option of scaling these three hull forms could be adopted, however these would not characterize real or common ships. For this same reason, the validation of the formula using scaled hull forms could be made in more depth with ships whose parameters fall just outside the range described for the model.

As studied in the literature review several methods have been the focus of study for the added resistance in regular waves. Most of these methods have been developed during the seventies and eighties and nowadays most methods rely on an incomplete database of ships. Other methods that are appropriate to apply in the computation of the added resistance could be studied and developed with a basis on formulations developed through regression and machine learning methods. This will contribute to a more realistic approach to better estimate the added resistance in waves. More complex models and the use of advanced software to customize models to the need of the user would highly contribute to the development of the regressions due to the high complexity of the physical phenomena behind the system. It is also important to educate students on regression techniques and their applicability in all fields of engineering, specifically in this case to the study of added resistance.

The foundation of this dissertation and of the accredited and qualified semi-empirical methods used to develop models and formulations to solve this problem are resting on experimental databases that have simply not been built to a necessary extent. The scarcity of test tank data for different headings, mainly over following waves causes some unusual behaviors in formulas that cannot be validated. This is also the case in the small wavelength region where the data is more difficult to obtain due to the low accuracy. Research and development teams working on this area will continue to invest in a public database to develop the field and be able to meet the demands of a growing industry.

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