

# Improvement of the Prediction of the Added Resistance in Waves of Ships with Extreme Main Dimensional Ratios Through Numerical Experiments

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## ABSTRACT

After a decade of development, the semi-empirical SNNM (SHOPERA-NTUA-NTU-MARIC) method for the prediction of the added resistance of ships in waves (Liu & Papanikolaou, 2020) was successfully developed and is being widely used by the maritime industry (IMO, 2021; ITTC, 2021). The method is herein updated by use of numerical simulations for the consideration of ships *with extreme dimensional ratios*, for which experimental data are scarce or non-existent. Numerical experiments are designed to investigate the joint effect of the variation of  $C_B$ ,  $L/B$ , and  $B/T$  using well-established numerical tools for the added resistance in waves. The patterns observed in the results are then correlated to the parameters through explicit, readily usable mathematical expressions. The improved formula is benchmarked with an experimental database of 11 ships with extreme dimensional ratios of various types. The validation study shows that the improved formula achieved a higher correlation coefficient and a smaller mean percentage error. Thus, the introduced expressions can significantly improve the prediction of the added resistance of various types of ships in waves, including those with extreme dimensional ratios. This study demonstrates how to combine the merits of both numerical and physical experiments to gain insight into complex physical problems.

**Keywords:** Added resistance of ships in waves; design of numerical experiments; parametric analysis; empirical method; seakeeping; EEDI

## 1. INTRODUCTION

In everlasting IMO's deliberations on measures to mitigate the environmental impact of ship operations, it became evident that the maritime industry needs fast and transparent methods to quickly estimate ship's fuel consumption and engine emissions in realistic sea conditions. Considering the prediction of the *calm water* powering and fuel consumption of ships manageable by use of a variety of methods, this particularly means that there is an urgent need for the provision of readily usable, engineering methods for the prediction of the *added resistance of ships in waves*. Even more, employing semi-empirical methods that do not require the details of the ship's hull form that are often not available in practice, is of high engineering value, as required by the different levels of calculation effort embedded in the international regulations on EEDI and minimum propulsive power in adverse conditions (IMO, 2012a & 2021), by industry standards (ITTC, 2021; ISO, 2015), as well as in many specific tasks in ship design and operation (Guo et al., 2022; Liu et al., 2022; Orihara & Tsujimoto, 2018; Strasser et al., 2015).

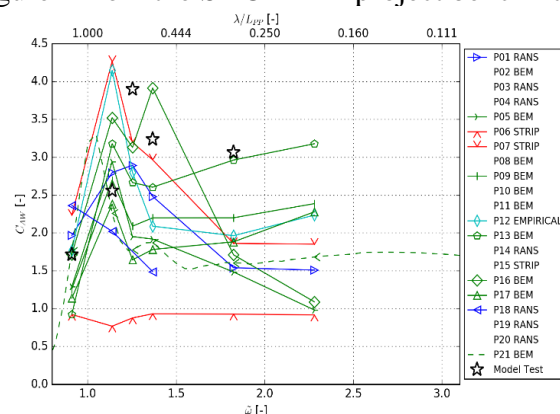
The establishment of a scientific method for solving a problem is generally based on both theoretical analysis and on laboratory, physical model experiments, next to full-scale observations and measurements. For ships, relevant laboratory experiments are carried out in towing tanks, using ship models of different sizes that are adjusted to the size of the towing tank and the spent effort. Systematic model experiments for the resistance of ship in clam water and in waves are tedious and very costly in many respects, thus large-scale experimental

campaigns were rare in the history of ship hydrodynamics and limited to those institutions with distinct large experimental facilities.

A very well-known work in that respect is the experiments carried out at David Taylor Model Basin (DTMB) in the 1960s, namely, the systematic experimental study on the Series 60 models to establish a *calm water resistance database* for the development of new hull forms to achieve minimum resistance (Todd, 1963). Later on, there were some valuable works, which are based on the regression analysis of extensive accumulated experimental data to derive empirical formulas and/or diagrams for the prediction of ship’s calm water resistance and powering, thus to support ship design. Typical examples thereof are the FORMDATA (Guldhammer, 1962) and the Holtrop-Mennen method (1982) for estimating the resistance and powering of displacement type ships in the conceptual/preliminary design stage. As the resources of experimental facilities are limited and the cost for conducting systematic series of experiments is high, various mathematical/numerical models and computer codes of different levels of complexity have been developed to conduct “numerical experiments” and to support, supplement, and even ultimately to replace the physical tank tests for determining the hydrodynamic performance of a ship in water (“numerical towing tank”). Nowadays, these numerical tools are routinely applied to the evaluation of the performance of a design, which is sort of a deterministic computer simulation of the ensuing physical phenomena.

Another important development in the processing of ship design data was noted in relation to advanced applications in parametric ship design optimization problems and the use of *surrogate models* (Papanikolaou et al., 2022). Surrogate models may be developed by first using a SOBOL sampling procedure and then polynomial regression, Kriging and Artificial Neural Networks (ANNs). However, the resulting surrogate models are not transparent, nor can they be readily used by the industry, unless as black boxes.

When it comes to the prediction of ship’s resistance and powering in realistic sea conditions for engineering applications, relevant research has remained at embryonic level until the recent request for mature methods became evident with the introduction of the Energy Efficiency Design Index (EEDI) by the International Maritime Organisation (IMO, 2012a&b). The added resistance in waves is a physical quantity derived from ship’s seakeeping analysis. Despite the fact that much fundamental work has been done on this subject in the past, both theoretically, experimentally and numerically, satisfactory measurements, in terms of accuracy and overall quality, of the added resistance are lacking in general (Kashiwagi et al., 2019; Park et al., 2015; Sogihara et al., 2020; van Essen et al., 2020) and large uncertainties pose a serious problem in the validation of the developed numerical tools, regardless of their complexity. As such, a huge scattering has been observed in the results of several international benchmark studies, for instance, as shown in Figure 1 from the SHOPERA project benchmark study.



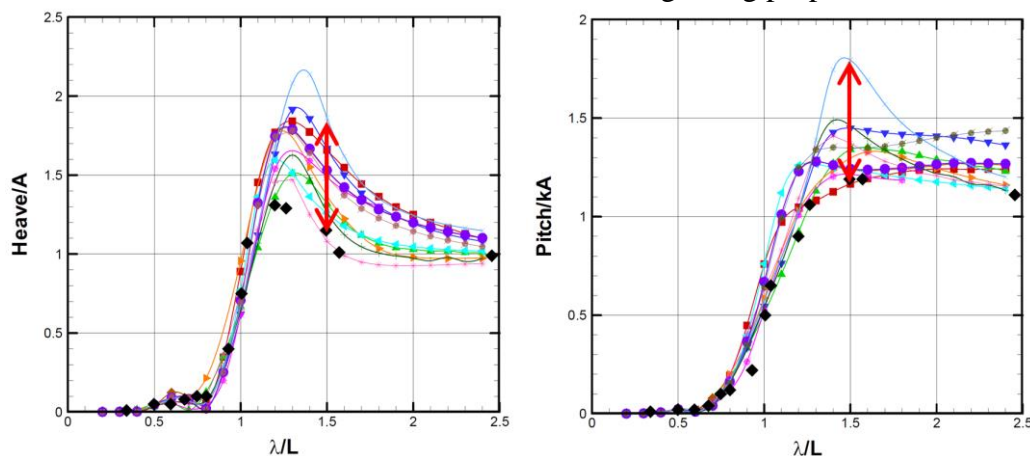
**Figure 1.** Time-average wave-induced surge force in head waves (added resistance) of KVLCC2 ship at 6 knots (Shigunov et al., 2018)

In this benchmark study methods of various complexity (RANS, Potential-flow-Theory based strip/panel codes, semi-empirical methods) were compared to experimental results and no type of method could prove superiority. The scattering of results observed in Figure 1 may be attributed to the following main reasons:

1. The benchmarked software may be not fit for the set problem that is quite complex in view of actual physics of the added resistance in short waves. Note that this is a demanding problem also from the point of view of experimental techniques.
2. The use of advanced CFD software tools does not ensure good results and the obtained results are greatly dependent on the user's experience in solving similar wave-body interaction problems.
3. The experimental data may have significant uncertainties, thus there is an uncertainty about the yardstick against which the numerical predictions are measured.

The first and third issues are highly correlated to uncertainties involved in the measurements. The classic method of validating various theoretical/numerical methods is by comparison of numerical results with the experimental ones for one or a few sets of data, thus such comparison may be not conclusive. It should be herein noted that the range of tested wave lengths in the above benchmark covers regions up to very small  $\lambda/L$  values (*relatively short waves*), for which measurements are generally problematic in view of their very small absolute values (Liu and Papanikolaou, 2016b). A solution to this particular problem might be experiments with larger models and the systematic variation of wave steepness next to wavelength. On the other hand, beyond the limitations of various theories in the background, even a well-established method may have been improperly implemented or the associated code may have been used by less experienced staff, producing non-satisfactory results.

Figure 2 shows the results of an international benchmark study on the prediction of the heave and pitch motions of the classical S175 containership model (ITTC, 2010). As shown here, a large spreading can be observed among the predicted results. When comparing with the benchmark results published by ITTC for the same ship *more than 3 decades earlier* (ITTC, 1978), it is clear that the scattering has not been reduced, in spite of more than 30 years' continuous research and development in the field. As there is such a large spreading in the 1<sup>st</sup>-order motion prediction, it is then well expected to observe a more serious scattering in the prediction of a 2<sup>nd</sup>-order quantity, like the added wave resistance. In conclusion, the problem in hand is complex and it is evident that the reduction of the ensuing uncertainties, if possible at all, in foreseeable future, needs careful consideration regarding proper solutions.



**Figure 2.** Comparative study of the heave and pitch motions of the S175 in regular head waves,  $F_n=0.275$  (ITTC, 2010)

As the demand of the maritime industry is urgent, an immediate solution of the set problem may be the development of a transparent semi-empirical method, for which at least the

uncertainties of wrong use of the ensuing method can be considered minimised. Considering that the regulations and standards are normally used by representatives of various stakeholders, including surveyors, engineers and administrative officers, a general principle for accepting a method should be based on its robustness, accuracy, transparency and un-ambiguity of the obtained results, thus also fit for easy spreadsheet implementations. With this in mind, the authors proceeded to the development of a new semi-empirical method for the prediction of added resistance in regular waves, namely, the SNNM method (Liu and Papanikolaou, 2016a & 2017 & 2020), following systematic, long-standing research in the field (Liu and Papanikolaou, 2011), and based on an experimental database that includes about 5 000 datapoints of more than 120 ships of various types and sizes. In the meantime, this new empirical method is part of the official guidelines of the International Maritime Organisation (2021) and is accepted as recommended procedure of International Towing Tank Conference (ITTC) for sea trial results analysis (2021).

Prior to its acceptance by ITTC, the method was scrutinised in an independent international benchmark study, coordinated by the SOS committee of ITTC (Wang et al., 2021). The new empirical method showed a high degree of accuracy based on statistical merits, namely, achieving a high correlation coefficient and small average percentage error, when evaluating it against a third-party database specially set up by the ITTC. Yet though, the performance of the method for some uncommon ships was not fully satisfactory. It is noted that these ships featured *abnormal combination of main dimensions, particularly extreme length to beam ratios  $L/B$* , for which experimental data are very scarce.

To rectify this issue, we introduce herein some new ship characteristics into the SNNM formula. For this purpose, a series of hull forms for an extended range of dimensional ratios are parametrically generated by using the classic *simple affine distortion* method. Thereafter, extensive numerical experiments by use of a 3D panel code for the estimation of the added resistance (Liu and Papanikolaou, 2011) are carried out to determine the pattern that the added resistance follows, when the ship's dimensions vary systematically. The identified pattern, which can be expressed by mathematical expressions, is readily introduced into the existing formula. An experimental database including 131 data points of 11 ships has been established to examine the performance of the improved formula. The validation study shows that the introduced  $L/B$ -based expressions can significantly improve the prediction of the added resistance of ships with extreme main dimensional ratios. This article is elaborating how these numerical experiments can be designed and be conducted in order to generate systematic data sets, which can be analysed and postprocessed to support the improvement of a transparent empirical model for predicting the added resistance of a ship advancing in waves.

## **2. PROBLEM STATEMENT & CRITICAL EXAMINATION OF SHIP'S MAIN DIMENSIONS**

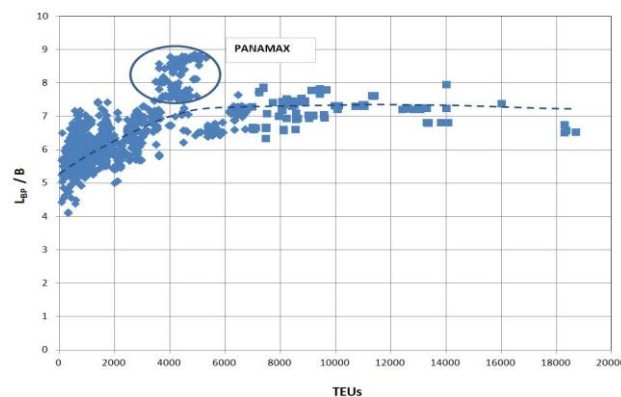
The SNNM method involves the use of the main dimensions of a ship, including her length  $L$ , beam  $B$ , draft  $T$ , trim  $\delta T$ , as well as the block coefficient  $C_B$  and some characteristics of ship's waterplane. To improve the range of applicability of the method, we need to assess how these quantities are determined, what are their limits and what their impact on the added resistance especially at the limits.

The proper selection of the main dimensions of a ship determines to which extent a ship will be optimally satisfying a shipowner's requirements. From hydrodynamic performance perspective, the ratios of main particulars are very important as they determine the resistance/powering, stability, seakeeping and manoeuvring performances of a ship. Fast ships are normally designed with higher  $L/B$  (6.5~7.3) and smaller  $C_B$  while slow ships are with smaller  $L/B$  (5.3~6.3) and higher  $C_B$ . (Papanikolaou, 2014). The  $B/T$  ratio is usually selected close to 2.5 to minimize resistance from the point of view of minimal wetted surface area and

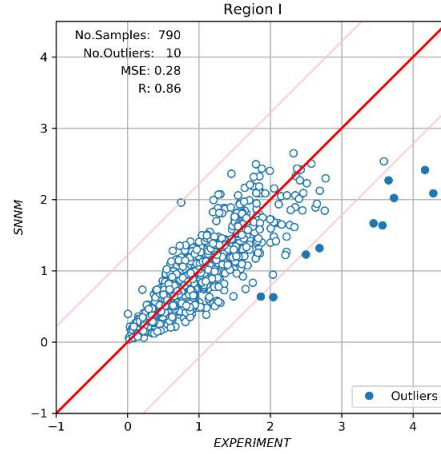
possible exceedances are usually due to topological restrictions, related to limitations of the ship's draft and beam (often for large tankers and bulk carriers) or due to enhanced requirements on stability (e.g., for Roll-On-Roll-Off Passenger ships, RoPAX). Values of  $B/T$  significantly smaller than 2.5 are very rare.

Restrictions on ship's main dimensions  $L$ ,  $B$ ,  $T$  due to *topological limits of the route* that a ship needs to pass through generally lead to hydrodynamically non-optimal designs. For example, Figure 3 shows the  $L/B$  ratio of container ships. The  $L/B$  ratio of these ships passing through the (old) Panama Canal (old PANAMAX), featuring a  $B_{\max}=32.26$  m, is much higher. Also, there may be limitations on ship's operational draft due to a ship's approach to river estuaries, transiting through canals or channels, calling at certain ports of limited depth, etc. For these ships, draft is constrained for enabling docking of large ferries at existing port infrastructure and accounting for restricted draft en route. In addition, Ro-Ro Passenger ships are constrained by intact and damage stability requirements, leading to comparatively larger beams. Draft is constrained by the water depth at port, thus large  $B/T$ . Their lengths are often limited for reasons of berth-length and construction cost, etc., thus, their  $L/B$  ratios are rather small for their design speeds. Special service type of ships, such as offshore support vessels, tugs and icebreakers, often manifest small  $L/B$  ratios due to their high requirement on manoeuvrability. Many icebreakers and ice-class ships feature a  $L/B$  close to 5. Their design, construction and operation are of high contemporary interest due to the increased usability of the arctic shipping route. More detailed information of these design features of ships of various types maybe found in the literature (Papanikolaou, 2014).

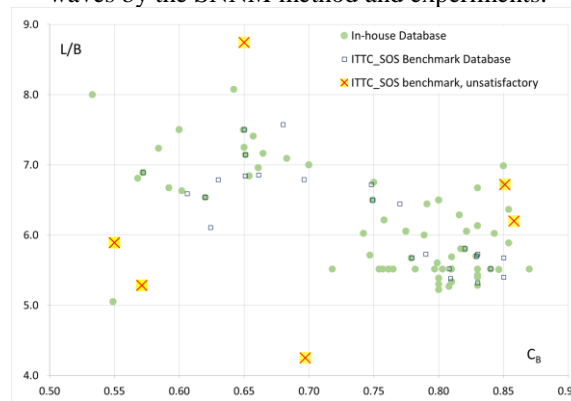
In a recent benchmark study organized by the International Towing Tank Conference (Wang et al., 2021), the performance of the SNNM method was examined and it was proven to be of fully satisfactory accuracy for practical applications, as shown in Figure 4. Yet though, there were several benchmark points apparently off the general trend. Further examination revealed that these points refer to the prediction of a bulk carrier and a containership with constrained beam (from *old Panama Canal*), a RoPAX, a pure car carrier (PCC), and a platform supply vessel, etc. All these ships feature unusual  $L/B$  ratios for their specific block coefficient, as shown in Figure 5. However, the  $L/B$  ratio is not used in the SNNM method.



**Figure 3.** Scattering of the  $L_{PP}/B$  ratio as a function of the total number of transported containers of containerships. (Papanikolaou, 2014)



**Figure 4.** The scatter plot of results of the predicted dimensionless coefficient of added resistance in regular waves by the SNNM method and experiments.



**Figure 5.** The L/B ratios of ships in the ITTC-SOS database versus that in the in-house database.

### 3. OBJECTIVE FUNCTION

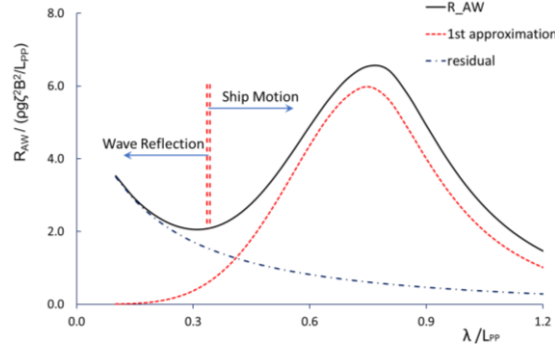
In the frame of a common approach to the set problem, the added resistance in regular waves  $R_{wave}$  is calculated as the sum of a first approximation and a residual/correction term. Mathematically, this is expressed as follows:

$$R_{AW}(\omega, \alpha; V_S) = R_{AW,M} + R_{AW,R} \quad (1)$$

where  $\omega$  is the circular frequency of a regular wave,  $\alpha$  is the angle between ship heading and incident wave,  $V_S$  is the ship speed through water.  $R_{AW,M}$  is the contribution to the added resistance mainly from ship motions, and  $R_{AW,R}$  is the residual contribution. In relatively short waves, the residual/correction is primarily due to the *wave diffraction/reflection effect*, particularly in relatively short waves, that in waves of length much smaller than a ship's length, but not necessary of small absolute wavelength. Both components can be approximated empirically. For the residual term, extensive discussions and developments have been noted over the years (Fujii & Takahashi, 1975; Kwon, 1980; Faltinsen et al., 1980; Takahashi, 1988; Kuroda, et al., 2008; Liu et al., 2015; Yang et al., 2018; Liu, 2020; Mourkogiannis & Liu, 2021). In the present work, we focus, however, mainly on the first approximation.

Originally, Jinkine and Ferdinande (1976) proposed an empirical formula by analysing the experimental results of several fast cargo ships at moderate to high speeds in head waves. Liu and Papanikolaou (2016, 2017, 2020) extended that formula to cover wider speed range and arbitrary wave headings for more types of ships. As shown in Figure 6, the prediction of the formula in relatively short waves and in very long waves approaches zero, as the motions of a ship in response to an income wave in these two scenarios tend to zero, thus the added resistances due to motion effect  $R_{AW,M}$  will also approach zero. Note that this formula is a function of only ship's main dimensions (and indirectly of ship's displacement), thus, it is in

line with the basic knowledge that the seakeeping performance of a ship is mainly a function of ship's main dimensions (NATO-STG, 2001), and to a lesser degree of ship's hull form geometry (geometric nonlinearity).



**Figure 6.** Generic decomposition of added resistance in waves versus relative wavelength in empirical concepts

The expression of  $R_{AW,M}$  is given as follows (Liu and Papanikolaou, 2020):

$$R_{AW,M} = 4\rho g \zeta_A^2 \frac{B^2}{L_{PP}} a_1 a_2 a_3 \bar{\omega}^{b_1} e^{\frac{b_1}{d_1}(1-\bar{\omega}^{d_1})} \quad (2)$$

where

$$\bar{\omega} = 2.142^3 \sqrt{k_{yy}} \sqrt{\frac{L_{PP}}{\lambda}} \left[ 1 - \frac{0.111}{c_B} \left( \ln \frac{B}{T_{max}} - \ln 2.75 \right) \right] \left( \frac{c_B}{0.65} \right)^{0.17} \left[ (-1.377 Fr^2 + 1.157 Fr) |\cos \alpha| + \frac{0.618(13 + \cos 2\alpha)}{14} \right] \quad (3)$$

$\zeta_A$  is the wave amplitude,  $k_{yy}$  is the longitudinal radius of gyration non-dimensionalized by  $L_{PP}$ .  $a_1$ ,  $a_2$ ,  $a_3$  are three parameters determining the magnitude of the added resistance. From this expression, it can be observed that:

- 1) the location of the peak of the added resistance is determined by  $\bar{\omega}=1$ ;
- 2) The amplitude of the peak of added resistance is determined by the parameters of  $a_1$ ,  $a_2$ , and  $a_3$ ;
- 3) The profile of the added resistance curve is determined by the parameters of  $b_1$  and  $d_1$ .

The original formula of Jinkine and Ferdinande was established by examining and post-processing the values of several sets of experimental data of fast cargo ships in the 1960s and 1970s, with  $6.7 \leq L/B \leq 7.5$  and  $2.4 \leq B/T \leq 2.72$ . Note that modern cargo and tanker ships, especially in ballast condition and passenger ships in general feature a much larger  $B/T$  and the performance of the original formula of Jinkine and Ferdinande for these ships could not be satisfactory. In view of this, a parametric analysis was conducted in a previous study of the authors to investigate the influence of  $B/T$  and subsequently the formula was revised (Liu & Papanikolaou, 2017). In this section, we are going to extend this methodology by conducting a further analysis to investigate the influence of  $L/B$  and to introduce it into the formula, if proven valuable.

#### 4. DESIGN OF NUMERICAL EXPERIMENTS

With the establishment of valuable computational hard- and software tools, it is nowadays feasible to conduct massive numerical simulations at low cost and to enable numerical parametric studies to gain insight into the hydrodynamic performances of parametrically varied designs. In a previous study, Liu and Papanikolaou (2017) investigated the effect of ship's draft, or rather of  $B/T$  ratio, especially in view of the fact that many ships are frequently operating in ballast condition (e.g., tankers and bulk carriers). In this study, we are going to investigate the interactive/combined influence of multiple parameters by varying systematically the  $L/B$  and  $B/T$  ratios of given hull forms. This requires a careful planning of a numerical experiment for retrieving the necessary information on the effects on a response variable due to the involved parameters.

A series of hull forms with systematic variation of main dimension ratios need to be prepared to investigate their influences. In ship design, normally the deadweight (for cargo ships) and speed are specified by a shipowner. Given this information, the displacement  $\nabla$  and the block coefficient  $C_B$  of the ship can be estimated (at least for displacement type of ships). Introducing the ratios of  $L/B$  and  $B/T$ , which significantly influence ship's resistance ( $L/B$ ) and ship's stability ( $B/T$ ), the form of the displacement equation can be rearranged as follows (Papanikolaou, 2014):

$$B = \left[ \frac{\nabla \cdot (B/T)}{C_B \cdot (L/B)} \right]^{1/3} \quad (4)$$

Given the lines plan of a parent ship (thus  $\nabla$  and  $C_B$ ), if the target  $B/T$  and  $L/B$  ratios are specified, the above Eq. (4) can then be applied to find out the beam of the intended design, followed by the length  $L$  and draft  $T$ . Then a *simple affine distortion* can be applied to the parent hull form to generate a new hull form.

Four classical hull forms with modest hull changes near the waterline are assumed for the numerical experiments, namely, the Series 60 models with  $C_B=0.60, 0.70, 0.75$  and  $0.80$ . The approximate vertical mass centre  $KG$  is set according to empirical values for the ship type and corresponding to the main dimensional ratios (Papanikolaou, 2014). Then the resulting metacentric height  $GM$  can be estimated, while considering the calculated values for  $KM$  corresponding to the generated hull forms. During the investigation, radii of gyration of roll and pitch are kept proportional to the beam and length of the ship, respectively.

## 5. NUMERICAL EXPERIMENTS & DATA COLLECTION

Considering that the combined effects between multiple parameters is of concern and many numerical experiments need to be carried out to determine the responses to the variations of these parameters, only fast and efficient procedures can be employed. A potential-flow-theory 3D panel code method NEWDRIFT+ has been successfully developed in the past by the authors for the prediction of added resistance of a ship in waves of arbitrary heading (Liu et al., 2011; Liu&Papanikolaou, 2016c) and this software has been extensively validated and widely applied in industry projects (Liu et al., 2019). It is herein used to conduct the numerical experiments and to generate data for further analysis.

Figure 7 is one complete data set generated using the software. It shows the variations of the added resistance of the family of parametrically generated S60 ships in regular waves at  $F_n=0.15$ . This set of data includes about 900 datapoints for 62 ship models. It has been prepared with the effort of about 10 man-days, including hull form preparation, model set-up and simulation, data presentation, etc. If physical experiments were to be executed, the 10 man-days effort might have been not sufficient even for the preparation of one ship model, not to mention that the required budget to support such a study and the subsequent effort for executing such an experimental matrix would be immense, if not impossible. Practically, such a study can be efficiently carried out only by planning computerised numerical experiments and using inexpensive and fast calculation methods.

As shown in Figures 7, for any one of these graphs, given  $B/T$ , the decrease of  $L/B$  from a large to smaller values leads to a shift of the peak location of the added resistance to larger  $\lambda/L_{PP}$ . The pattern of the change of the amplitude of the peak values is more complex. On the other hand, the results of forms with different block coefficient  $C_B$  exhibit different trends. Apparently, the change of  $L/B$ , has an impact on both the amplitude and the position of the peak of the added resistance. Therefore, it is necessary to reconsider the added resistance due to motion effect by introducing a new parameter  $L/B$  to improve the empirical formula.

## 6. DATA ANALYSIS, POSTPROCESSING AND INTERPRETATION



Figure 8 shows the predicted added resistance of the parametric variations of a fine ship with  $C_B=0.65$  at  $Fn=0.2$ . As  $B/T$  and  $L/B$  change systematically, the peak location also varies with certain pattern. Picking out the location of the added resistance resonance, it is observed that  $\bar{\omega}_{ARmax}$  is approximately a linear function of both  $\ln \frac{B}{T}$  and  $\ln \frac{L}{B}$ , and its rate of change has to do with the block coefficient of the ship, as shown in Figure 9. Interestingly,  $\bar{\omega}_{ARmax}$  approaches to unity at approximately  $\ln \frac{B}{T} = 1.0$  and  $\ln \frac{L}{B} = 2.0$ , namely,  $\frac{B}{T} \approx 2.72$  and  $\frac{L}{B} \approx 7.39$ , which are the mean values of the models that were examined by Jinkine and Ferdinande (1976) to derive the original formula.

Using these two reference conditions in preliminary settings, the location of the peak values in each condition is compared with the reference condition to derive an optimal ratio, which needs to be captured properly by some expression. Noting that the location of the peak is determined by  $\bar{\omega} = 1$ , a satisfactory result can be obtained with some effort in a fine-tuning process. With these observations and supported by extensive numerical results, after some trial-and-errors, the  $g_2 \left( \frac{L}{B} \right)$  function can be determined. It is also dependent on  $C_B$ .

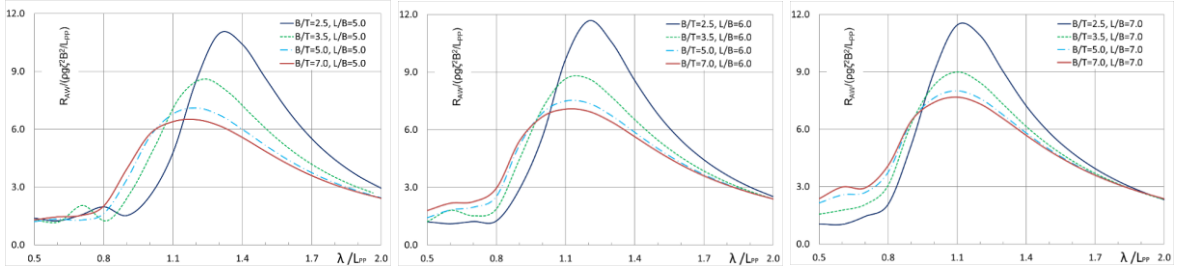


Figure 8. Added resistance of parametric variations of a fine ship at  $Fn=0.2$ , head waves.

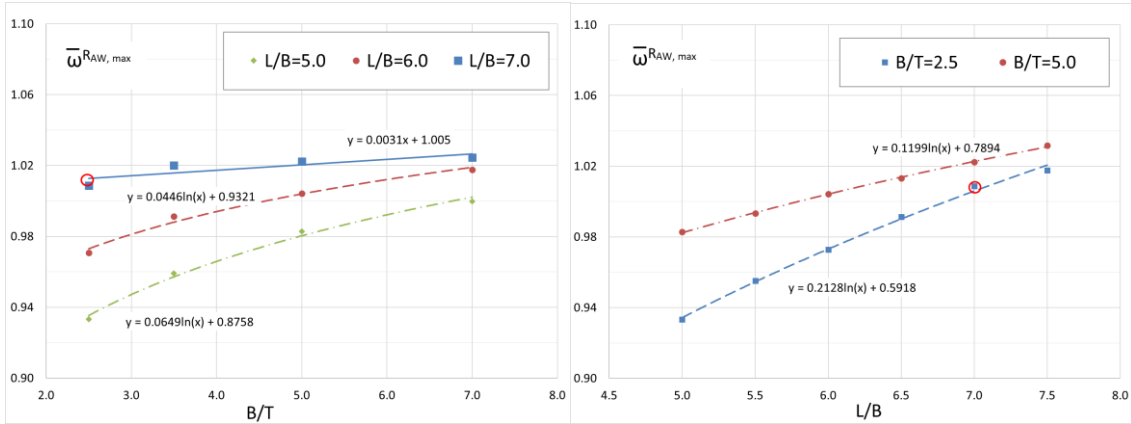


Figure 9. The peak location of the added resistance for the parametric variations of a fine ship as function of  $B/T$  and  $L/B$ , respectively.

We consider next the change in the peak value of the added resistance. From the data sets presented in Figures 7, the maxima of the added resistance can be picked out for further analysis. Here we consider the following expression by introducing a new parameter as a function of  $L/B$ :

$$R_{AW,M} = 4\rho g \zeta_A^2 \frac{B^2}{L_{PP}} \bar{\omega}^{b_1} \exp \left[ \frac{b_1}{a_1} (1 - \bar{\omega}^{a_1}) \right] a_1 a_2 a_3 f_1 \left( \frac{B}{T} \right) f_2 \left( \frac{L}{B} \right) \quad (8)$$

The maxima of the added resistance is observed at

$$\bar{\omega} = 1 \quad (9)$$

Thus, we have

$$\bar{\omega}^{b_1} \exp\left[\frac{b_1}{d_1}(1 - \bar{\omega}^{d_1})\right] = 1 \quad (10)$$

Hence,

$$R_{AW,M}^{MAX} = 4\rho g \zeta_a^2 \frac{B^2}{L_{PP}} a_1 a_2 a_3 f_1\left(\frac{B}{T}\right) f_2\left(\frac{L}{B}\right) \quad (11)$$

Previously, the function  $\left(\ln \frac{B}{T_{max}}\right)^{-1}$  was introduced into  $a_1$  to capture the change of the amplitude against  $B/T$  and the influence of  $L/B$  ratio was not accounted for. With further analysis, this expression  $a_1$  is slightly revised:

$$a_1 = 60.3 C_B^{1.34} (4k_{yy})^2 \left(\frac{0.87}{C_B}\right)^{-(1+Fr)\cos\alpha} \frac{2.0}{\ln \frac{B}{T_{max}} + \left(\ln \frac{B}{T_{max}}\right)^{0.35}} \frac{(1-2\cos\alpha)}{3} \quad \text{for } \frac{\pi}{2} \leq \alpha \leq \pi \quad (12)$$

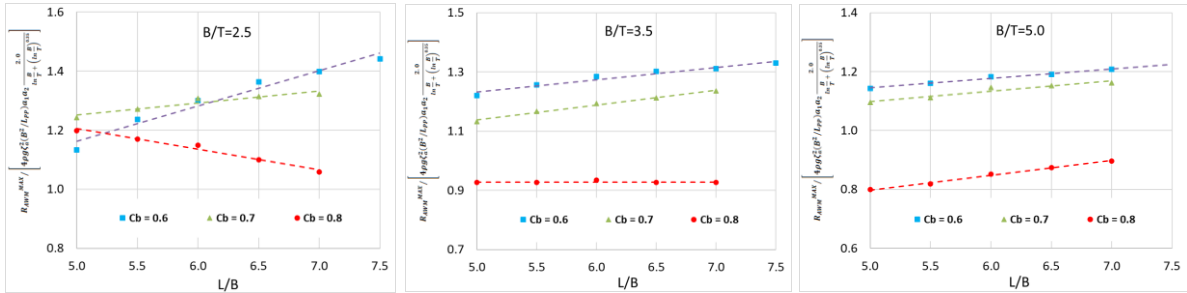
Subsequently, we can have the following expression

$$f_1\left(\frac{B}{T}\right) f_2\left(\frac{L}{B}\right) = R_{AW,M}^{MAX} / \left[4\rho g \zeta_a^2 \frac{B^2}{L_{PP}} a_1 a_2 a_3\right] \quad (13)$$

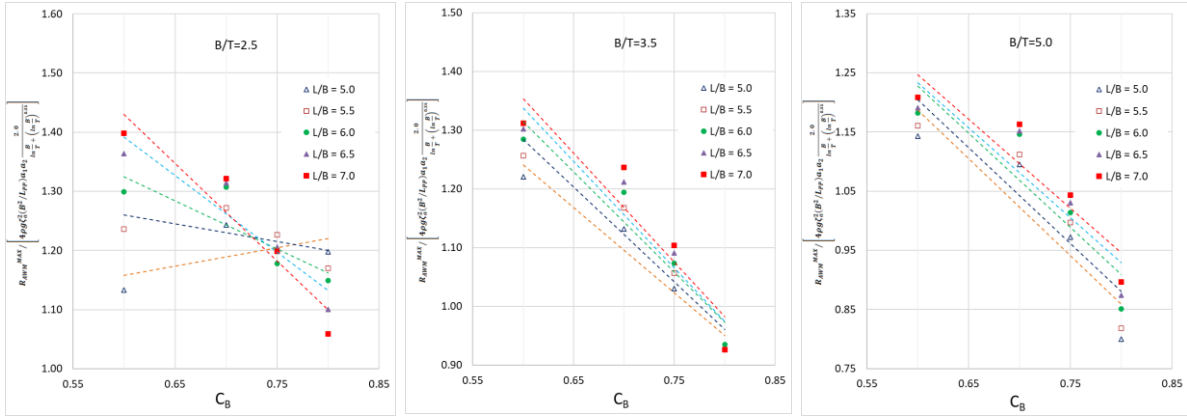
The algebraic manipulations here is to eliminate the influences of the ship speed, wave heading, etc., from the observed  $R_{AW,M}^{MAX}$ . Following this, the resonance amplitude of the added resistances of the generated hull variations are analyzed and plotted in Figures 10 and 11. It is observed that the product  $f_1\left(\frac{B}{T}\right) f_2\left(\frac{L}{B}\right)$  is approximately a linear function of either  $\frac{L}{B}$  or  $C_B$ , when other parameters are set fixed. Therefore, it is assumed to take the following form:

$$f_1\left(\frac{B}{T}\right) f_2\left(\frac{L}{B}\right) = h_1\left(\frac{B}{T}\right) C_B \frac{L}{B} + h_2\left(\frac{B}{T}\right) C_B + h_3\left(\frac{B}{T}\right) \frac{L}{B} + h_4\left(\frac{B}{T}\right) \quad (14)$$

Using these derived data sets, the  $h_i\left(\frac{B}{T}\right)$  functions can be determined.

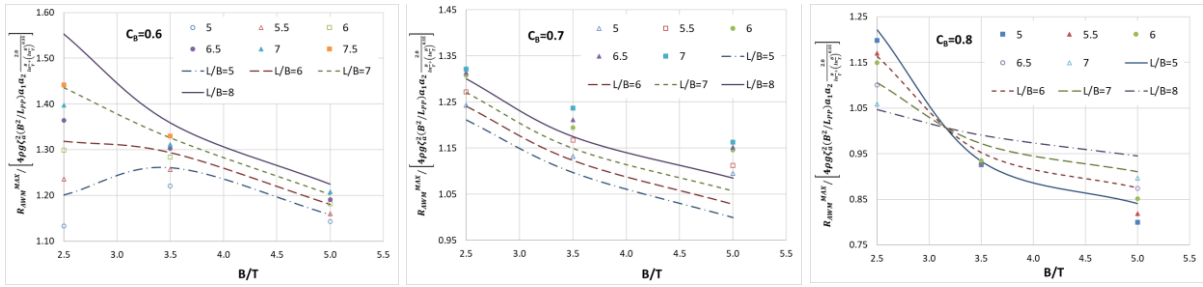


**Figure 10.** The amplitude of the added resistances of the generated hull variations at its resonance as a function of  $L/B$  ratio for a given  $B/T$  ratio.



**Figure 11.** The amplitude of the added resistances of the generated hull variations at its resonance as a function of block coefficient  $C_B$  for a given  $B/T$  ratio.

Applying these functions, the amplitude of the added resistance can be satisfactorily approximated, as shown in Figure 12. The pattern of the changing of amplitude of the added resistances of the variations of three hull forms with the variation of  $B/T$  and  $L/B$  ratios is well captured by the derived functions, despite some differences in the absolute values. As elaborated, in practice there are a lot of uncertainties in measuring the “true” maximum value of the added resistance in waves, thus, it is not possible nor necessary to pursue an absolutely “accurate” solution. The most important thing is to determine how the prediction changes when these key design factors/parameters change.



**Figure 12.** Approximation of the amplitude of the added resistances of the variations of three hull forms of systematically changing  $B/T$  and  $L/B$  at  $Fn=0.15$ .

With this study, the SNNM formula is revised to take the following form in head to beam waves:

$$R_{AW,M} = 4\rho g \zeta_A^2 \frac{B^2}{L_{PP}} a_1 a_2 a_3 f_1 \left( \frac{B}{T} \right) f_2 \left( \frac{L}{B} \right) \bar{\omega} b_1 e^{\frac{b_1}{d_1} (1 - \bar{\omega}^{d_1})} \quad (15)$$

where

$$\bar{\omega} = 2.142 \sqrt[3]{k_{yy}} \sqrt{\frac{L_{PP}}{\lambda}} \left( \frac{C_B}{0.60} \right)^{0.13} \left[ (-1.377 Fr^2 + 1.157 Fr) |\cos \alpha| + \frac{0.618(13 + \cos 2\alpha)}{14} \right] g_1 \left( \frac{B}{T} \right) g_2 \left( \frac{L}{B} \right)$$

$$a_1 = 60.3 C_B^{1.34} (4k_{yy})^2 \left( \frac{0.87}{C_B} \right)^{-(1+Fr)\cos\alpha} \frac{2.0}{\ln \frac{B}{T_{max}} + \left( \ln \frac{B}{T_{max}} \right)^{0.35}} \frac{(1 - 2\cos\alpha)}{3} \quad \text{for } \frac{\pi}{2} \leq \alpha \leq \pi$$

$$a_2 = \begin{cases} 0.0072 + 0.1676 Fr & \text{for } Fr < 0.12 \\ Fr^{1.5} \exp(-3.5 Fr) & \text{for } Fr \geq 0.12 \end{cases}$$

$$a_3 = 1.0 + 19.1 \tan \frac{|T_a - T_f|}{L_{PP}}$$

$$b_1 = \begin{cases} 11.0 & \text{for } \bar{\omega} < 1 \\ -8.5 & \text{elsewhere} \end{cases}$$

$$d_1 = \begin{cases} 566 \left( \frac{L_{pp} C_B}{B} \right)^{-2.66} & \text{for } \bar{\omega} < 1 \\ -566 \left( \frac{L_{pp}}{B} \right)^{-2.66} \times \left( 4 - 125 \operatorname{atan} \frac{|T_a - T_f|}{L_{pp}} \right) & \text{elsewhere} \end{cases}$$

## 7. VALIDATION

For validation purposes, an experimental database of 11 ships of various types is set up to assess the performance of the improved formula. As shown in Table 1, this database consists of experimental results of various types of cargo ships, with  $76.5 \leq L_{PP} \leq 323.0$ ,  $0.55 \leq C_B \leq 0.85$ ,  $4.3 \leq L/B \leq 8.4$ ,  $2.3 \leq B/T \leq 6.3$ ,  $0.10 \leq Fn \leq 0.30$ . Most of these ships feature extreme L/B and B/T ratios for their block coefficient and they are challenging cases.

**Table 1.** Main particulars of the ships of various types

	L	B	T <sub>m</sub>	C <sub>B</sub>	L/B	B/T	Fn	Ship Type
<b>Ship-1</b>	76.5	18.0	6.0	0.70	4.3	3.0	0.19	OSV
<b>Ship-2</b>	150.0	28.4	6.7	0.57	5.3	4.2	0.27/0.3	RoPAX
<b>Ship-3</b>	157.0	26.2	6.2	0.62	6.0	4.2	0.3	RoPAX
<b>Ship-4</b>	190.0	32.3	9.0	0.55	5.9	3.6	0.2/0.25	PCC
<b>Ship-5</b>	217.2	32.3	14.0	0.85	6.7	2.3	0.17	Bulk Carrier, laden
<b>Ship-6</b>	217.2	32.3	5.2	0.75	6.7	6.3	0.19	Bulk Carrier, ballast
<b>Ship-7</b>	225.4	32.3	12.2	0.85	7.0	2.6	0.18	Bulk Carrier (Li et al., 2017)
<b>Ship-8</b>	270.0	32.3	10.9	0.60	8.4	3.0	0.25	Containership (Bunnik et al., 2010)
<b>Ship-9</b>	300.0	40.0	14.0	0.65	7.5	2.9	0.2	Containership
<b>Ship-10</b>	315.0	47.2	18.9	0.83	6.7	2.5	0.0	Tanker, (Soeding & Shigunov, 2015)
<b>Ship-11</b>	323.0	60.0	21.0	0.81	5.4	2.9	0.1/0.14	VLCC

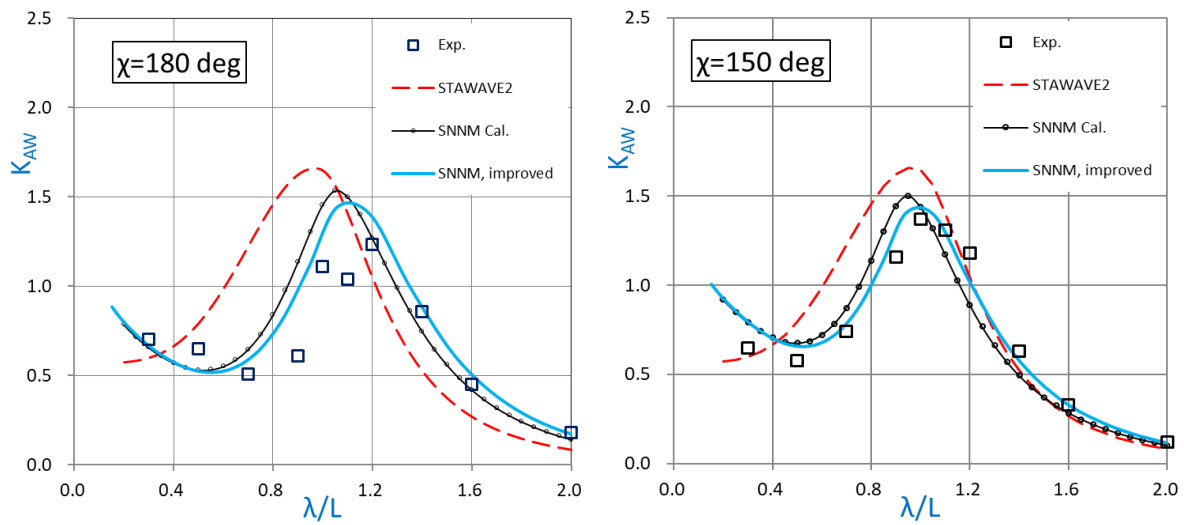
Figures 13 to 15 show the nondimensional added resistance of several ships in regular head and bow waves predicted by alternative empirical methods, namely the STAWAVE2 method (ITTC, 2021), used frequently by the industry in the past, the original SNNM method, and the improved SNNM method. In these graphs, the results are presented in the nondimensional form,

$$K_{AW} = R_{AW} / \left( 4 \rho g \zeta_A^2 \frac{B^2}{L_{pp}} \right).$$

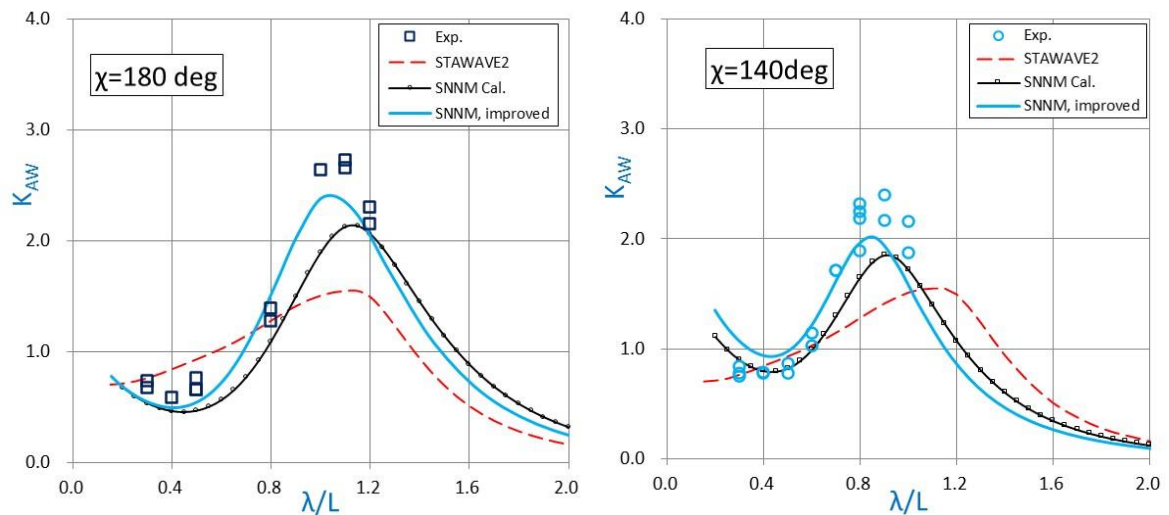
Figure 13 is a typical case of a ship has “normal” dimensional ratios. The difference between the predictions of the original SNNM and the improved SNNM method is very modest, while the improved formula is slightly better. The purpose of this comparative case is to demonstrate that the improvement of the formula for extreme main dimensional ratios does not sacrifice the quality of predictions of the original SNNM method for normal ships. Figure 14 is a Panamax containership case featuring high L/B ratio. The original formula slightly missed the amplitude and location of the peak of the added resistance. The prediction based on the improved method agrees well with experimental results. Figure 15 is a RoPAX case featuring a relatively low L/B ratio. The prediction based on the new formula agrees better with experimental results, demonstrating an apparent improvement over the original formula. The performance of the STAWAVE2 method in these shown case studies is rather problematic. It is worthy noting that these case studies refer not only the head wave case but also for bow quartering waves.

Figure 16 is the scatter plot of the predicted added resistance in regular head waves by the original and the improved SNNM methods against experimental results, respectively. Apparently, the points based on the improved method are closer to the red base line than those based on the original method, particularly for the large values, which represent the values close to the maxima of the added resistance curves. The tighter correlation of the results based on the improved method indicates a better performance, which can only be measured by statistical

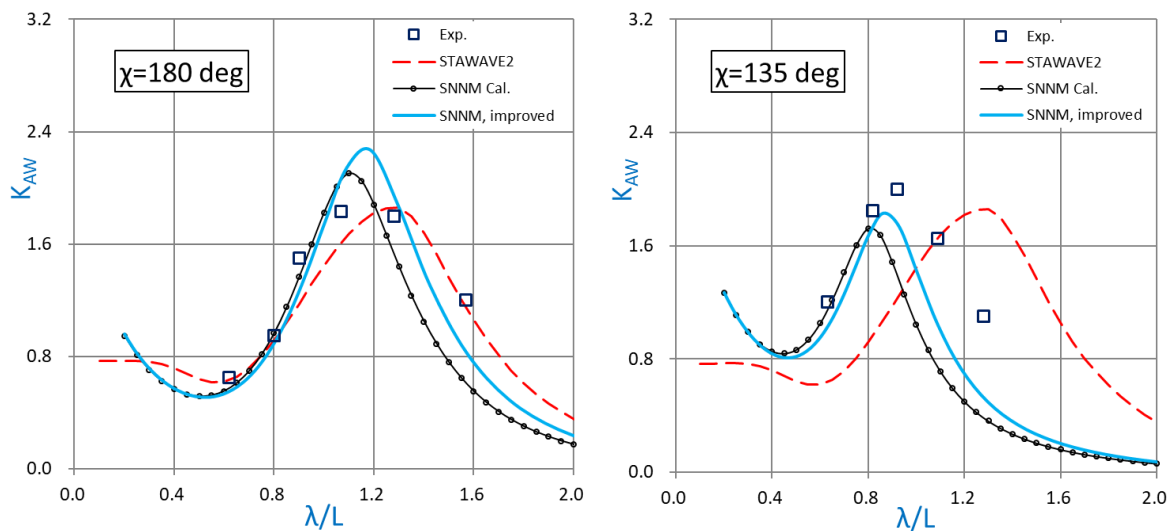
metrics, particularly when considering the uncertainties in the experimental results of added resistance in waves.



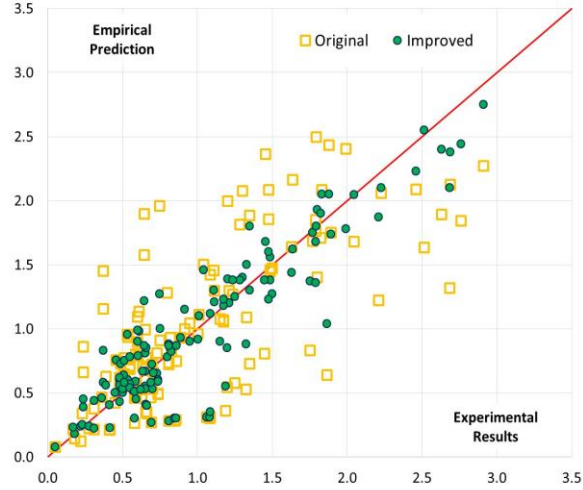
**Figure 13.** Added resistance of a tanker (Ship-11,  $L/B=5.4$ ,  $B/T=2.9$ ) in head and bow waves,  $Fn=0.14$



**Figure 14.** Added resistance of a containership (Ship-9,  $L/B=7.0$ ,  $B/T=2.9$ ) in head and bow waves,  $Fn=0.2$



**Figure 15.** Added resistance of a RoPAX (Ship-3,  $L/B=6.0$ ,  $B/T=4.2$ ) in head and bow waves,  $Fn=0.3$



**Figure 16.** Scatter plot of the predicted added resistance in regular head waves by the original (square) and improved (circle) methods versus experimental results.

The Pearson’s correlation coefficient  $R$ , as well-known and proven statistical metrics, is typically used for quantifying the degree of association between variables of interest. This correlation coefficient between two variables  $X$  and  $Y$  is defined as follows.

$$R_{X,Y} = \frac{cov(X,Y)}{\sigma_X \sigma_Y} = \frac{E(XY) - E(X)E(Y)}{\sigma_X \sigma_Y} \quad (16)$$

where  $X$  is the prediction using the semi-empirical methods,  $Y$  is the experimental result;  $cov$  is the covariance,  $\sigma$  the standard deviation, and  $E$  the expected value. The relationship between two variables is generally considered strong, if the  $R_{X,Y}$  is larger than 0.70.

The mean percentage error is defined as follows:

$$\varepsilon_{mean} = \frac{1}{n} \sum_{i=1}^n \frac{X_i - Y_i}{Y_i} \quad (17)$$

where  $Y_i$  is the experimental value and  $X_i$  is the predicted value using the formula.

Table 2 presents the obtained statistical values for different prediction methods and the components for obtaining Pearson  $R$  coefficients, based on the results of all of the 11 ships in head waves as presented in Table 1. The improved SNNM method achieved a higher correlation coefficient (0.91) than the original method (0.72), which indicates that the improved method has much stronger correlation with the experimental results than the original method. The mean percentage error of the improved method is also smaller than that of the original method, which indicates a higher accuracy.

Lastly, it is noted that this quantitative analysis is constrained to head waves due to the limited number of available experimental points in oblique waves.

**Table 2.** Components of Pearson  $R$  coefficients and statistical values from different prediction method

Method	No. of samples	$E(X)$	$E(Y)$	$E(XY)$	$\sigma_X$	$\sigma_Y$	Pearson’s Corr. $R$	$\varepsilon_{mean}$
Original SNNM	131	1.00	1.01	1.30	0.62	0.63	0.72	10.9%
Improved SNNM	131	0.98	1.01	1.34	0.60	0.63	0.91	3.2%

## 9. SUMMARY & CONCLUSIONS

The IMO has set up an ambitious agenda for reducing greenhouse gas emissions from maritime sector in view of the worrisome climate change. This requires a further development of the maritime regulatory framework. One of the key issues in this development refers to the fast and transparent prediction of the added resistance of a ship advancing in waves, which is required for the implementation of international regulations, of maritime industry standard, as well as in many specific tasks in ship design and operation.

In a recent benchmark study of the newly developed semi-empirical SNNM method, it was observed that the method does not perform satisfactorily for some types of ships *with extreme dimensional ratios*. After a critical examination of the design features of the ships in the experimental database, as they are used for assessing the performance of the semi-empirical formula, it was found that the associated extreme L/B values for these ships are responsible for the degradation of the prediction in these cases.

For rectifying this issue, we introduced the parameter L/B into the SNNM method. To accomplish this task, a large-scale numerical experiment is designed, performed and analysed. The parameters of  $C_B$ , L/B, and B/T are chosen as the key parameters affecting the added resistance in waves. A series of hulls forms are generated for the preparation of data related to the variation of  $C_B$ , L/B, and B/T. The added resistance of these hull forms is then evaluated using well-established numerical tools. The patterns observed in the numerical results are post-processed and then correlated to the parameters through some explicit mathematical expressions, which can be readily introduced into the existing SNNM formula. The improved SNNM formula is benchmarked with an experimental database of 131 data points of 11 ships with extreme dimensional ratios of various types. Two indices, namely, the correlation coefficient and the mean percentage error, are used to assess the performance of the improvement. The validation study shows that the improved formula achieved a higher correlation coefficient (0.91 vs 0.72) and a smaller error (3.2% vs 10.9%) than the original formula. Thus, it is proven that the introduced expressions can significantly improve the prediction of the added resistance of various types of ships in waves, including those with extreme dimensional ratios.

This study demonstrates how to combine the merits of both numerical and physical experiments to gain insight into complex physical problems and to make solid progress in building up robust, transparent, and satisfactorily accurate semi-empirical methods to efficiently support developments of the maritime industry.

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