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Uncertainties related to the estimation of added resistance of a ship in waves

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ABSTRACT: Reliable estimation of added resistance represents an important step in ship design for realistic conditions, giving a more accurate picture of ship behaviour complementing the traditional calm water considerations. In this work a comparison of different methods of added resistance assessment is given, along with the associated uncertainties that originate from their theoretical assumptions, simplifications, neglected effects or theory implementation. Assessment of the uncertainties, acknowledging limitations and inaccuracies of added resistance estimations, is necessary in order to establish the range on which the methods show satisfactory representation of the reality. When errors and modelling uncertainties in outputs are identified and/or quantified, various approaches can be considered in order to reduce uncertainty and improve overall accuracy and reliability of added resistance predictions.

1 INTRODUCTION

Added resistance estimation is one of the major factors in the pursuit of making greener and more efficient ships. Traditionally, performance estimation of a ship is based on calm water conditions with added value based on the experience with similar ships or routes. With this estimated value the question is whether the ship could sustain sufficient speed in heavy weather, or would the engine run efficiently in moderate conditions. Theoretical models for added resistance are developed in order to improve the accuracy of power predictions in actual operating conditions. Generally, added resistance is considered an increase of ship resistance in relation to still water conditions due to ship motions and waves. It is a complex problem that is not yet fully understood and various approaches have been developed in attempt of describing it. Added resistance of a ship in regular waves was initially obtained by model experiments, but due to the limitations of that approach, more suitable methods had to be formulated.

One of the first to calculate the added resistance was Havelock (1942) relating the pitch and heave motions to the added resistance. Influential papers for added resistance calculations include the work of Maruo (1957), Boese (1970), Gerritsma & Beukelmann (1972), Salvesen (1978) and Faltinsen (1980). The mentioned papers describe methods based on potential theory and can be separated in far field and near field methods and special formulations for short wave regions of which some will be further elaborated in this work. The far field methods have the advantage of performing the integration over the control surface that can be located far from the ship. The integration surface can be assumed to be of simple shape and the far field approximations can simplify the calculations. The near field methods are using pressure integration over the ship's wetted surface, therefore complicating the calculations, but they are representing, physically, an approach that is easier to understand.

Most added resistance formulations are found to under predict the results for regions of short waves where the effect of diffraction was found to be most influential, so separate formulations are established for that region. Short range methods can be observed as a correction of a more general formulation in order to cover the entire wanted frequency range. The far field and the near field methods give reasonable results for regions where the hydrodynamic damping is dominant over the viscous damping effects. The far field methods are described in Maruo (1957), and Salvesen (1978) and the near field methods by Havelock (1942) and Faltinsen (1980).

Recently, progress has been made with boundary element methods (as described in Joncquez 2008, Kim & Kim 2010, Liu et al. 2011), and viscous flow calculations (Söding et al. 2014). Söding et al. (2014) reported results that show reasonably good predictions of added resistance of RANS computations, but they do not result in a significant improvement when taking into account computational expenses when compared to the potential flow methods.

Opposed to complex CFD computations potential flow methods require much less computational effort. In this work the simplest, but still widely used strip method is employed. Strip based methods are known for their easy implementation and low numerical requirements as well as the fact that they are well established and broadly used. Due to the lack of agreement on which method best describes added resistance as well as the lack of available data for validation, mathematical models are very often used in a non-critical manner, often disregarding their inherent inadequacies and limitations.

This paper deals with added resistance calculations based on strip theory approach. Many of the methods are limited to head seas only so a selection is made to include only the methods capable of describing added resistance in oblique waves. Although it is reasonable to assume that head seas will result in maximum responses, it is not realistic to expect only for head seas to be encountered. Realistic conditions that researchers are trying to model include different routes, weather conditions so a method capable of describing added resistance in any heading angle would be valuable tool. One of the problems for which the added resistance is of great influence is the calculation of speed loss in a seaway. The reliability of speed loss calculations reflects on estimation of fuel consumption and greenhouse gas emissions of a ship.

The purpose of this work is to present the uncertainties of the selected formulations while giving the overview of the methods. Comparison with gathered experimental data is made and the range of applicability of the methods is stated.

2 STRIP-THEORY BASED METHODS

Added resistance of a ship is a highly non-linear phenomenon but it was found that the principle of superposition can be applied to the problem. The added resistance in irregular waves is obtained by combining the added resistance in regular waves with predictions of statistical values of irregular waves. In this paper, only uncertainties related to the prediction of added resistance in regular waves will be considered leaving the latter to further research.

There exists several different methods for assessing the added resistance, but most of them do not cover all ship speeds, heading angles or ship forms. A comparison of some methods can be found in Matulja et al. (2011). In this paper, one near field and one far field method are chosen as well as the special formulation for short waves. The methods were selected for their ability to calculate added resistance in oblique waves.

2.1 *Near field method*

The near field approach developed by Faltinsen et al. (1980) uses direct integration of steady second order pressure p_s on the instantaneous wetted surface to express added resistance. The pressure is expressed as:

$$p_s = -\rho gz - \rho\left(\frac{\partial\varphi^{(1)}}{\partial t} + U\frac{\partial\varphi^{(1)}}{\partial x}\right)_m - \rho\left(\frac{\partial\varphi^{(2)}}{\partial t} + U\frac{\partial\varphi^{(2)}}{\partial x}\right)_m - \rho(\eta_2 + x\eta_6 + y\eta_4)\frac{\partial}{\partial y}\left(\frac{\partial\varphi^{(1)}}{\partial t} + U\frac{\partial\varphi^{(1)}}{\partial x}\right)_m - \rho(\eta_3 + x\eta_5 + y\eta_4)\frac{\partial}{\partial z}\left(\frac{\partial\varphi^{(1)}}{\partial t} + U\frac{\partial\varphi^{(1)}}{\partial x}\right)_m - \frac{\rho}{2}\left[\left(\frac{\partial\varphi^{(1)}}{\partial x}\right)^2 + \left(\frac{\partial\varphi^{(1)}}{\partial y}\right)^2 + \left(\frac{\partial\varphi^{(1)}}{\partial z}\right)^2\right]_m + p_0 \quad (1)$$

where ρ is fluid density, g acceleration of gravity, $\varphi^{(1)}$ linear first order potential, $\varphi^{(2)}$ second order approximation proportional to the square of wave amplitude, U is ship's speed and p_0 atmospheric pressure. Translatory displacements in x, y and z directions are η_1 (surge), η_2 (sway) and η_3 (heave). Angular displacements of the rotational motion about the x, y and z axis are η_4 (roll), η_5 (pitch) and η_6 (yaw). The subscript m indicates that the variables are to be expressed on the average position of the wetted ship hull. Taking the contributions of all the pressure terms and the modification for the integration over the corrected wetted area added resistance can now be written as:

$$F = \int_C \left\{\frac{\rho g}{2}\,\overline{\zeta_r^2}\right\} n_1 \mathrm{d}s - \omega_e^2 M\overline{\eta_3\eta_5} + \omega_e^2 M\overline{(\eta_2 - z_G\eta_4)\eta_6} + \rho\int_{S_B}\overline{\left[(\eta_2 + x\eta_6 - y\eta_4)\frac{\partial}{\partial y}\left(\frac{\partial\varphi^{(1)}}{\partial t} + U\frac{\partial\varphi^{(1)}}{\partial x}\right)\right|_m + (\eta_3 + x\eta_5 - y\eta_4)\frac{\partial}{\partial z}\left(\frac{\partial\varphi^{(1)}}{\partial t} + U\frac{\partial\varphi^{(1)}}{\partial x}\right)\right|_m + \frac{1}{2}\left\{\left(\frac{\partial\varphi^{(1)}}{\partial x}\right)^2 + \left(\frac{\partial\varphi^{(1)}}{\partial y}\right)^2 + \left(\frac{\partial\varphi^{(1)}}{\partial z}\right)^2\right\}}\, n_1 \mathrm{d}s \quad (2)$$

where C is the waterline curve, ζ_r the relative wave amplitude along the ship, ω_e circular frequency of encounter, M is the mass of the ship, z_G vertical coordinate of the center of gravity and S_B average wetted surface of the body.

This method takes into consideration the influence of sway, roll and yaw, asymmetric flow and includes second order pressure term on the wetted surface.

2.2 *Far field method*

Salvesen (1978) derives added resistance in a manner similar to deriving second-order mean forces and moments in oblique waves. It is based on two-dimensional approach and uses first order potential to assess second order forces under the assumption that the body is a "weak scatterer" and slender.

The derived formula for added resistance force is:

$$F = -\frac{i}{2}\,k\cos\beta\sum_{j=3,5}\eta_j\left[\left(F_j^I\right)^* + F_j^D\right] + R_7 \quad (3)$$

where $(F_j^I)^*$ is the complex conjugate of the Froude–Krylov exciting force and moment and F_j^D complex conjugate of the diffraction exciting force and

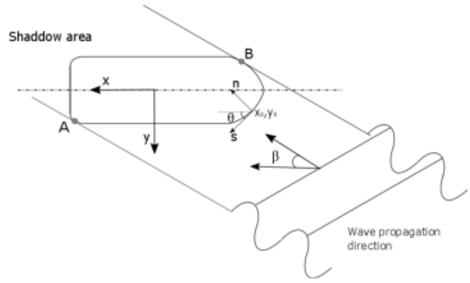

Figure 1. Coordinate system for low wave lengths.

moment, k wave number and β angle between mean wave direction and ship heading. Added resistance component R_7 that represents the influence of the diffraction potential can be expressed as:

$$R_7 = -\frac{1}{2} A^2 \frac{\omega_e^2}{\omega} k \cos\beta \int_L e^{-kds} (b_{33} + b_{22} \sin^2 \beta) \mathrm{d}x \quad (4)$$

with A being incident wave amplitude, ω wave frequency, d is sectional draft and s is sectional area coefficient, b_{22} and b_{33} are sectional damping coefficients in sway and heave, respectively.

2.3 *Asymptotic formulation for short waves*

Faltinsen et al. (1980) proposed a formulation that includes wave reflection effect. It is assumed that the ship has vertical sides at the waterplane and that the wave induced ship motions can be neglected. Wave energy is taken to decay exponentially with the depth. Together with the small wave length assumption it can be said that only the part of the ship close to the waterplane will influence the flow field. The ship is replaced by infinitely long vertical cylinder with cross section same as the ship's waterplane. It is assumed that the change in waterplane area is small over the wave length. The problem of diffraction is then solved equivalently to the case of incident waves on an infinite vertical wall.

Normal average force F_n per unit length on the wall can be expressed as:

$$F_n \sim \frac{1}{2} \rho g A^2 \left\{ \sin^2(\theta + \beta) + \frac{2\omega_0 U}{g} [1 - \cos\theta \cos(\theta + \beta)] \right\} \quad (5)$$

where θ is described in Figure 1. Knowing the average force, mean drift force components and yaw moment can be obtained using the expression:

$$F_i = \int_L F_n n_i \mathrm{d}l \quad (6)$$

with $i = 1, 2,$ and 6 (F_1 being the added resistance, F_2 transverse drift force and F_6 yaw moment). Integration is done along a non-shadow part of the waterplane, as shown in Figure 1. For added resistance (F_1) the normal vector component $n_1 = \sin\theta$.

3 UNCERTAINTIES IN ADDED RESISTANCE ESTIMATION

The errors in the seakeeping calculations, added resistance amongst them, are rarely presented due to the fact that they are difficult to estimate. However, the use of the developed theoretical formulations is expanding and there is more and more studies incorporating seakeeping, or specifically, added resistance calculations into more complex models as is the case with the models for estimation for greenhouse gas emissions from ships (Prpić-Oršić et al. 2015, 2016) The reliability of such a model depends greatly on the errors in its input components (prediction of ship motions, added resistance, etc.). Additional level of confidence could be established in all the related calculations in case the uncertainties and errors in basic seakeeping calculations are properly stated. Further on, accurate experimental predictions are necessary for validating the results so they ought to be considered in the overall uncertainty analysis.

3.1 *General uncertainties of the strip theory*

Strip theory calculations are the basis for the above mentioned added resistance formulations. The uncertainties from the loads and motions calculation propagate in the added resistance calculation and will therefore be observed as a common source of errors for all the methods.

Strip theory is linear, slender body, potential flow based theory. In order to be valid, certain basic assumptions are specified: the ship is slender (considerably larger in length that in the beam and the draught), rigid body, with moderate speeds, motions relatively small, hull sections wall sided, in the condition of unlimited depth and with no interaction of the hull and the waves.

Potential flow theory considers an ideal fluid, homogenous, irrotational, non-viscous and incompressible. The disregarded viscous effects are most pronounced in predicting roll, however, it was found by Beukelmann (1983) that it may have an influence on vertical ship motions as well. Viscous effects are introduced using various empirical corrections.

When reducing the problem from three-dimensional space to two-dimensions the frequency is taken to be relatively high and the variation in flow in the cross sectional direction is taken to be higher than that in the longitudinal direction. The results of these assumptions are visible in the better applicability of the method to the head than the following seas. Low frequencies in the following seas often result in less accurate predictions, a problem that is often solved by artificially forcing wave loads to zero. For higher speeds the divergent wave system may occur, so the simplification that states that the unsteady wave system generated by the ship propagates in a direction perpendicular to the center plane and neglects realistic wave system introduces an error that limits the application of the theory to low Froude numbers.

The linearity assumption states that the wave amplitudes are taken to be small in relation to the ship draft and that there are only hydrodynamic effects of the hull under the free surface. Due to the fact that the method is insensitive to the above water form, it is more accurate for the forms with wall sided sections. The presence of flair may introduce additional non-linear effects which can be influential for the cases of slamming and green water on deck.

The errors that are a result of viscosity or linear potential flow can be regarded as physical errors, and reflect certain simplifications of real world processes. Another type of errors are numerical errors and they are most often related to the occurrence of irregular frequencies in two dimensional added mass and damping coefficients as well as the errors due to the size, number and placements of the strips and offset points. Proper description of segments for describing ship's hull influence the accuracy of the volume calculations, added mass and damping coefficients, hydrostatic restoring coefficients, Froude–Krylov and diffraction forces and moments. The numerical procedure used for integration of each strips contribution can also be a source of numerical error (Faltinsen & Svensen, 1990).

To assess the effect of such uncertainties it is possible to model them all as well as their effect on the final result. Alternatively it is possible to model directly their combined effect by comparing the numerical predictions with model test results. This is the approach followed by Guedes Soares (1990), who collected results of experimental and numerical studies with various strip theories and from there assessed the uncertainty of the transfer functions, which reflect in short term (Guedes Soares, 1991) and in long term predictions (Guedes Soares, 1993).

3.2 *Experimental estimation and its uncertainties*

When assessing the accuracy and validity of various mathematical methods in seakeeping it is common to compare the numerical results to the experimental measurements. The available experimental data for the added resistance of ships are particularly meager. The reason could be the high expenses, the capabilities of the testing facilities, a large number of experiments to be conducted under different conditions leading to the high time consumption. Most of the experiments are done in head seas and there are very few experiments made in oblique seas. The presentation of the available experimental data is very often inadequate (the results are significantly scattered and the uncertainty level is not properly, or at all, stated) as is the case in Strom-Tejsen et al. (1973). The International Towing Tank Conference Seakeeping Committee in 2011 has adopted the ISO GUM procedure for measuring the uncertainties in the seakeeping experiments (ITTC (2011)).

The numerical computations should go through verification and validation process after which an uncertainty level could be stated. The uncertainty measurements of the numerical methods were introduced in the work of Guedes Soares (1991) where he assessed the uncertainties of the computational models by comparing their results to the model experiments. Having properly stated experimental procedure and its uncertainties could greatly improve the process of verification and validation and the evaluation of the numerical uncertainties. The uncertainties related to the experimental procedure (as discussed in Park et al. (2015)) and numerical calculations are summarized in the Table 1.

Table 1. The sources of uncertainties in the experimental procedures and numerical modelling (Park et al. 2015).

	Sources of uncertainties	Explanation
Experiments (model tests)	Model geometry	Model scaling and tolerances
	Mass distribution	Positions of the vertical center of gravity and pitch radius of gyration
	Installation and calibration	Misalignment, calibration curve fitting, A/D conversion
	Instruments	Uncertainty of the measuring devices
	Measurement uncertainty	When obtaining values from measured time-history data
	Data reduction equations	From the variables in the equations
Numerical modeling	Physical errors	Simplification of reality (linear potential flow, viscous effects, non-linear effects)
	Numerical errors	Strip and offset points distribution, numerical approximations
	Human errors	Input errors, misinterpretations

3.3 *Comparison of the mathematical methods with the experimental results*

The comparison of the theories to the experimental results are presented for 8 different ships and different speeds but all for head seas due to the lack of data for oblique seas. The observed ships are given in the Table 2 and they cover a range from fine to full ship forms. The results of the comparisons are given in Figures 2–11. The ships from the Table 2. are presented for one specific speed for each ship. The calculations are done with three different methods and compared to the experimental results. The results for ITTC S175 containership and general cargo ship is obtained from Arribas (2007), Series 60 hulls are taken from Strom-Tejsen et al. (1973). The data for KVLCC2 ship is taken from the work of Park et al. (2015).

Table 2. Characteristics of the ships included in the analysis.

	L m	B m	T m	C_B	Fn
General cargo	152.50	22.80	5.20	0.50	0.15, 0.2, 0.25
Containership	175.00	25.40	8.50	0.57	0.15, 0.2, 0.25, 0.3
Series 60 $C_B = 0.6$	190.50	25.40	10.16	0.60	0.266 0.283
Series 60 $C_B = 0.65$	190.50	26.28	10.51	0.65	0.237 0.254
Series 60 $C_B = 0.7$	190.50	27.21	10.89	0.70	0.207 0.222
Series 60 $C_B = 0.75$	190.50	28.22	11.29	0.75	0.177 0.196
Series 60 $C_B = 0.8$	190.50	29.31	11.72	0.80	0.147 0.165
KVLCC2	320.00	58.00	20.80	0.81	0.142

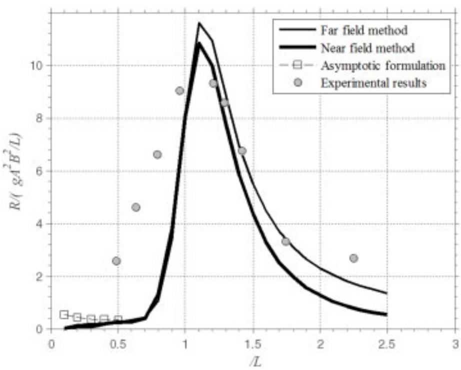

Figure 2. Added resistance of a containership in head waves and $Fr = 0.15$.

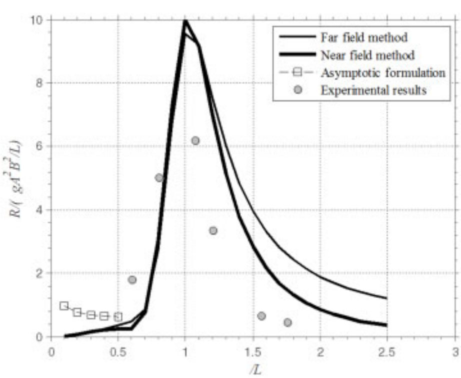

Figure 3. Added resistance of a general cargo ship in head waves and $Fr = 0.15$.

Both the near field and the far field method show rather good agreement with the experimental data for the ships with finer forms, with the near field method exhibiting somewhat more accurate predictions for the mentioned ships. Larger discrepancies are visible for fuller ship forms, as is the Series60 $C_B = 0.7$ shown in Figure 6 and $C_B = 0.8$ (Figure 8) and KVLCC2 (Figure 9) where the near field method fails to give realistic results.

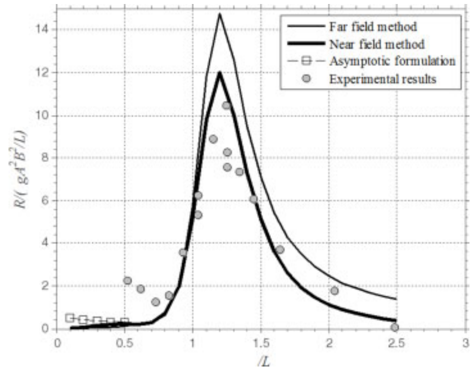

Figure 4. Added resistance of a Series 60, $C_B = 0.6$ ship in head waves and $Fr = 0.266$.

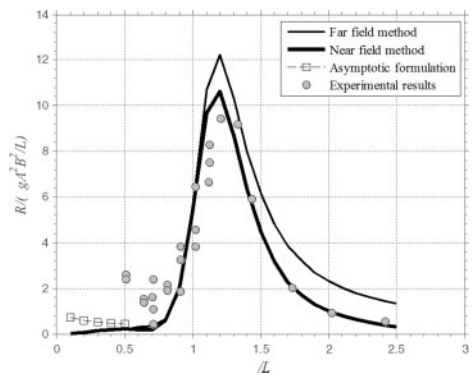

Figure 5. Added resistance of a Series 60, $C_B = 0.65$ ship in head waves and $Fr = 0.237$.

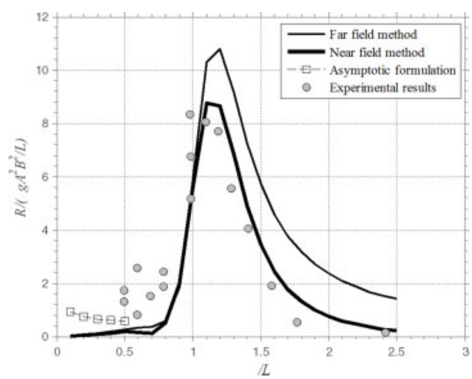

Figure 6. Added resistance of a Series 60, $C_B = 0.70$ ship in head waves and $Fr = 0.207$.

The far field methods seems to be more accurate in these cases, apart from the case of KVLCC2 where neither method shows agreement either in magnitude of a peak or the frequency corresponding to it. It can

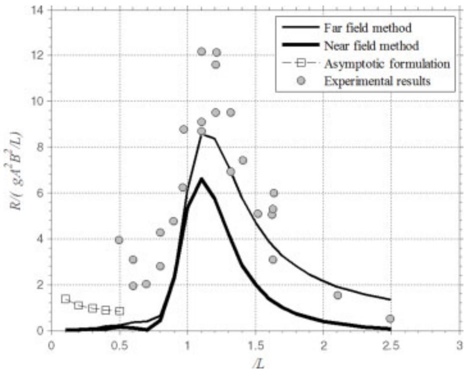

Figure 7. Added resistance of a Series 60, $C_B = 0.75$ ship in head waves and $Fr = 0.177$.

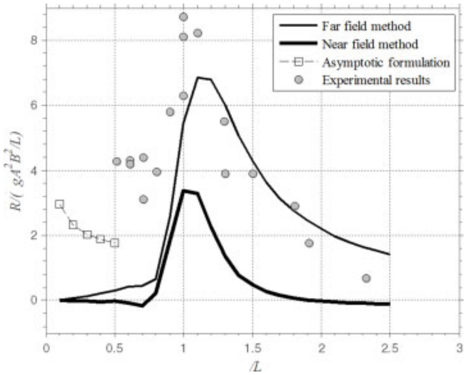

Figure 8. Added resistance of a Series 60, $C_B = 0.80$ ship in head waves and $Fr = 0.147$.

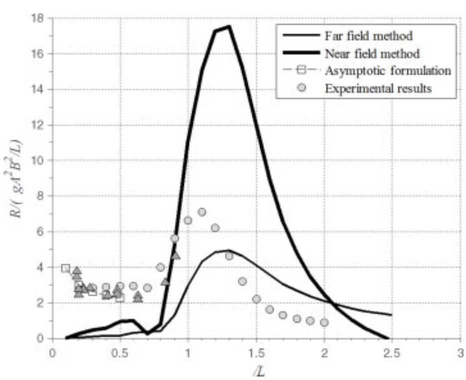

Figure 9. Added resistance of a KVLCC2 ship in head waves and $Fr = 0.142$.

be noticed that the far field formulation is slightly less accurate but with the wider range of applicability. The error in prediction of the added resistance of KVLCC2 could be caused by the ship's dimensions, large beam and very blunt bulbous form which do not agree well with the assumption of slenderness of the mathematical formulations.

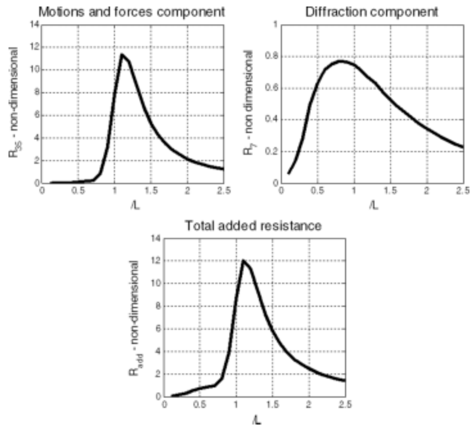

Figure 10. Influence of the motion and forces component and the diffraction component to the added resistance in total.

Neglecting the three-dimensional effects could also result in errors. The asymptotic formulation shows poor results for fine ship forms (Figures 5–7), where it underestimates experimentally measured added resistance, but that is to be expected when taking into account the theoretical background of the method. The methods shows good correspondence to the experimental results for fuller ship forms with particularly good results for KVLCC2 as can be seen in Figure 9.

3.4 *Uncertainty analysis of the added resistance estimation using far field method*

In the following paragraph only the far field method will be studied. It is chosen due to the fact that it seems to have generally wider range of applicability compared to the near field method also observed in this work. The uncertainty analysis will include determination of all the error sources of the formulation, the sensitivity analysis of the most influential factors and the estimation of the propagation of errors in the final results.

The far field formulation developed by Salvesen (1970) depends on several different factors. The most influential ones in the formulation are the heave and pitch motions as well as the exciting forces and moments. The diffraction component described by the two dimensional damping coefficients that are included in the analysis are of little influence (less than 10% of the total value of added resistance) and they are not observed in this work. The influence of the motions and forces and the diffraction part of the formulation are shown in Figure 10.

Having identified motion amplitudes and exciting forces and moments as the main source of errors in this particular added resistance formulation an analysis is done to understand how much the output values are affected by the changes in the model input values.

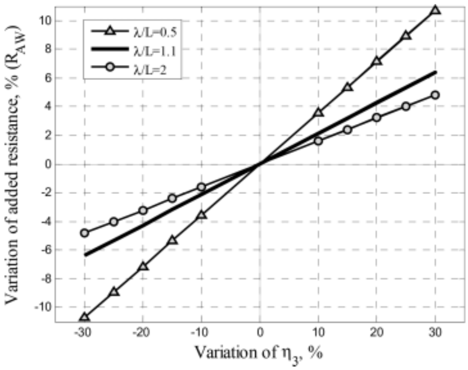

Figure 11. Influence of the variation of the heave motion component to the added resistance estimation.

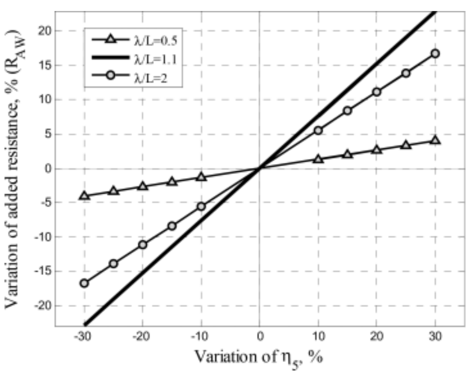

Figure 12. Influence of the variation of the pitch motion component to the added resistance estimation.

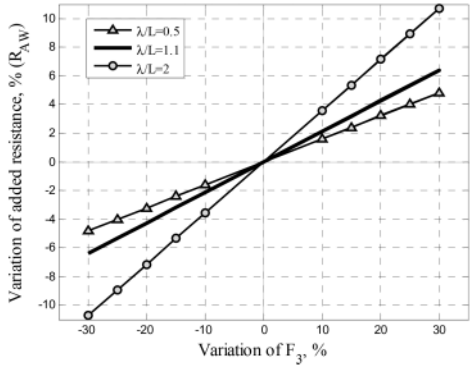

Figure 13. Influence of the variation of the heave exciting force component to the added resistance estimation.

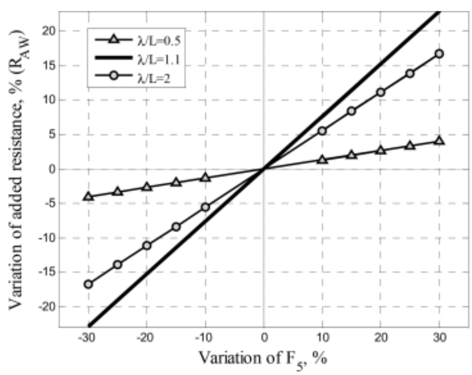

Figure 14. Influence of the variation of the pitch exciting force component to the added resistance estimation.

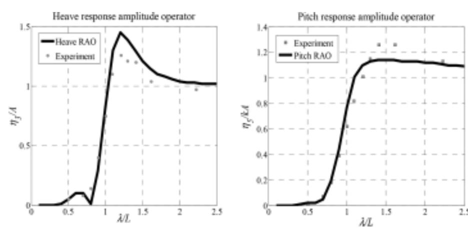

Figure 15. Heave and pitch motion amplitudes compared to the experiments

3.4.1 *Sensitivity analysis*

The analysed ship is the S175 containership sailing in head seas with the speed corresponding to the Froude number of 0.25. The influence of the heave and pitch motions as well as the heave and pitch exciting forces are given for three different frequencies, one higher, one corresponding with the peak frequency and one lower frequency. The components are varied one at the time and the effect on the outcome is observed. The results given in the Figures 11–14 demonstrate how the change of the input component influences added resistance with the variations in input variables given as the percentage of their original values, and the output and the increase of the added resistance relative to the initial value of unvaried parameters.

The results indicate that the change of 10% in heave components would result in increase of added resistance of 2.1% for the peak frequency expressed by $\lambda/L = 1.1$ while the change of 10% in pitch components would result in the increase of the added resistance of 7.6%.

3.4.2 *Propagation of motion assessment error*

Taking a scenario where the error in the estimation of motions is known, it could be possible to express how those errors propagate to the assessment of the added resistance. Heave and pitch motions for the containership S175 and observed speed ($Fr = 0.25$) are taken from Seo et al. (2013) and are shown in Figure 15.

Figure 16 shows a comparison of added resistance coefficient calculated using motions from strip theory program with the results obtained using experimental values of the motions and the uncertainty range of added resistance coefficient related to the motions for frequencies with available data.

Table 3 presents sensitivity estimates of added resistance coefficient to motion parameter values. The range of the motion parameters is taken to be in range from experimental to calculated values. For a given case it can be seen that the influence of the pitch

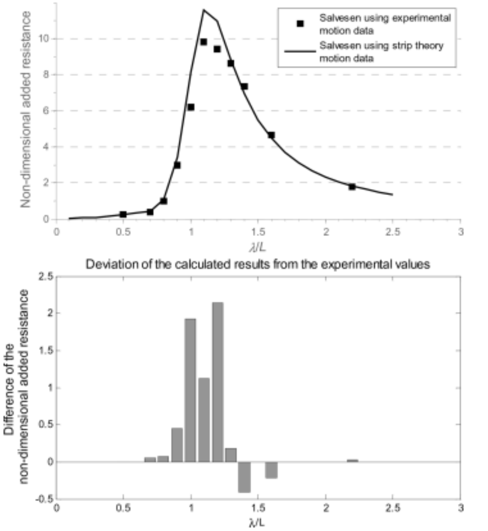

Figure 16. Comparison of added resistance coefficient using different values of motion parameters.

Table 3. Calculation of motion parameter sensitivity coefficients.

Variable (X)	Experimental	Calculated	R_{AWlow}	R_{AWhigh}
Non-dimensional heave amplitude	1.1	1.26	11.21	11.581
Non-dimensional pitch amplitude	0.82	0.988	9.809	11.581
	$\partial R/\partial X$	Std. dev.(X)	$(\partial R/\partial X)^2$ Var(X)	%
Non-dimensional heave amplitude	2.313	0.0485	0.013	4.18
Non-dimensional pitch amplitude	10.548	0.051	0.29	95.82

motions is dominant with over 95% of influence. The same procedure was conducted for the whole range of frequencies and the averaged result over them shows that, for this ship and this particular speed, heave motions influence the results with around 28% and pitch motions with 72%.

For the case of the peak frequency given by $\lambda/L = 1.1$ the error in the estimation of heave amplitude is 15% and of pitch 20%. These errors would propagate to added resistance estimation and result in overall increase of non-dimensional added resistance. The calculated value of the added resistance coefficient for a given frequency using experimental values of motion amplitudes (amplitudes obtained from Seo et al. (2013) is 9.44, and experimental value of added resistance coefficient (from the same author) is 9.04.

Added resistance coefficient obtained when using motion data calculated by the strip theory is 11.581, and it can be concluded that, in this case the error in motion approximations represents 84% of the overall error. Averaging it over the whole frequency range it was found that 68% of the error is related with motion parameters. The remaining error can be attributed to the other sources of uncertainty as are the estimations of exciting forces or hydrodynamic coefficients.

Due to the fact that their errors either cannot be quantified, or represent a minor influence to the overall uncertainty they are not individually analysed in this work. The remaining uncertainties include the effect of simplifications and assumptions of the underlying theory. It should be noted that this analysis is made for one speed. In order to get more accurate picture various types of ships should be taken into account, providing that the values of motions and added resistance obtained from well conducted experiments are available.

4 CONCLUSIONS

This paper considers three different added resistance formulations and their application to ships with a wide range of speeds and block coefficients. After considering the uncertainties of the underlying theories the numerical results were compared with the available experimental results where it was found that the near field pressure integration method seems unsuitable for application to full ship forms, where the far field momentum and energy method gives reasonable results for a wider range of ships. Asymptotic formulation was found suitable only for blunt bow ships and fuller forms.

A sensitivity analysis was made with the far field formulation and it was described how the changes in input parameters influence the results where it was determined that the biggest influence on the added resistance results come from the prediction of the ship's motions (84% of the total error for the observed peak condition or 68% over the whole frequency range for a specific speed).

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