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On the prediction of the added resistance of large ships in representative seaways

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ABSTRACT
The importance of the sufficiently accurate prediction of the added resistance and powering of large ships in representative seaways is discussed. We introduce an updated empirical formula that may be used by engineers for the fast estimation of the added resistance of ships in waves and validate this formula for ships with $L_{pp} > 250$ m operating in realistic sea conditions. The importance of the accurate prediction of added resistance of large ships is demonstrated by numerical and experimental studies on both full and fine hull forms. It is shown that for large ships sailing in representative seaways, properly quantifying the spectral contribution of the added resistance in the region of $\lambda/L_{pp} \approx 0.1{\sim}0.5$ is of paramount importance and further studies are necessary to resolve this issue for large ships. This also leads to a critical discussion about the ITTC recommended experimental procedure, when assessing the overall seakeeping performance of large size ships in representative seaways.

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1. Introduction

Recently the prediction of the added resistance of ships in waves has attracted more attention in view of the increased interest of the shipping industry to reduce fuel consumption, while complying with relevant requirements (MEPC.203(62) 2011; MEPC.232(65) 2013). Traditionally, when dealing with this problem, designers and operators are supported by laborious tank tests and/or numerical computational fluid dynamics (CFD) tools leading to the RAOs of the added resistance for the range of wave length to ship length ratio $\lambda/L_{PP} = 0.5{\sim}2.0$. This is based on the assumption that the added resistance phenomenon is a derivative of the ship motion problem, thus correlated to the seakeeping problem, the experimental study of which is explicitly specified by ITTC recommended procedures (2002): "For conventional ship forms, a sufficient number of tests should be carried out … for a minimum range of wavelengths from 0.5 L_{PP} to 2.0 L_{PP}". Nowadays, however, noting the continuous increase of ship sizes, the ratio λ/L_{PP} of practical interest is being shifted to much lower values. When considering a ship of 300 m, in typical natural seaways in coastal water, with $T_P \approx 5.5$ s, the peak wave length of the corresponding spectrum is about 45 m, corresponding to a λ/L_{PP} of merely 0.15. If we treat the problem in the traditional way, a significant part of the problem *will be inherently neglected, when the mean value of the added resistance in irregular waves has to be determined*. Figure 1 shows the tank results of a 320 m VLCC in regular waves (Lu et al. 2012), together with the spectra of typical seaways (ITTC spectrum, $H_S = 1.5$ m, $T_P = 5.5$ s) and the representative condition for the *EEDIweather* calculation ($H_S = 3$ m, $T = 6.7$ s, MEPC.1/Circ.796). Obviously, when evaluating the mean value of added resistance in representative seaways it is not sufficient to execute the tank tests with the lower limit standing at $\lambda/L_{PP} = 0.4$.

In order to predict accurately the statistical *mean value* of the added resistance of large ships in typical seaway conditions, the added resistance in (relatively) very short waves must be predicted accurately. Experimental methods and to some extent CFD simulations are currently the most reliable means for the determination of the added resistance; however, this is accomplished at high time effort and/or cost. The intrinsic problem with the tank tests is due to the limitation of the model size. Typically tanks are using 3–6 m long models for seakeeping tests. In the wave range recommended by ITTC, i.e. $\lambda/L_{PP} = 0.5{\sim}2$, serious scattering in the results, especially in the lower region, has been observed, indicating the uncertainty of tank tests in short waves. In the much shorter wave region of particular interest herein, this problem is becoming even worse. In recent tank tests conducted at MARINTEK within SHOPERA project (2013–2016), the DTC model was 5.58 m long and a serious scattering and strong uncertainty was observed in the results for $\lambda/L_{PP} \approx 0.1$ (Sprenger et al. 2015). In such a case, the measured absolute value of the total resistance was about 14 N, considering that the corresponding calm water resistance was 11 N ($F_n = 0.14$), the added resistance resulted to a value of merely 3 N (wave height 0.010–0.016–0.024 m for the three conducted tests, respectively). Note that these small absolute values were measured using rather high wave steepness, in any case higher than the amplitude according to linear wave theory. This, however, may distort the quadratic dependence of the added resistance on the incoming waves' height. It is evident that even if the tanks follow the most stringent measuring techniques, they are pushed, in this case, to their technical limits.

The problem with the CFD simulations of added resistance in short waves results from the dense grids required to capture the flow changes; thus, CFD methods are pushed as well to their computational limits. Simpler numerical tools

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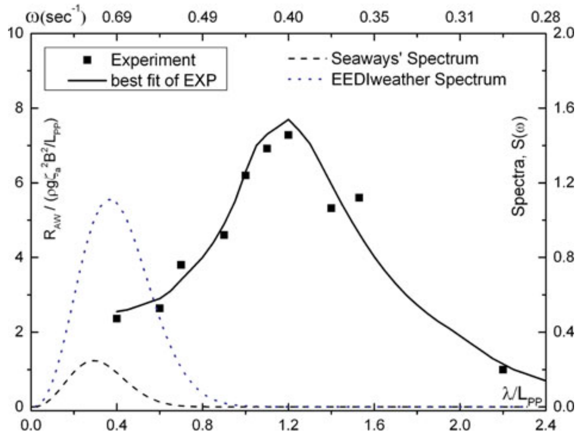

Figure 1. Typical added resistance transfer function of a VLCC ship together with a representative seaway spectrum and the *EEDIweather* calculation spectrum.

based on potential flow theory suffer in the short wave region also difficulties: besides having typical problems with proper panelling, which needs to be more dense for short waves (Söding et al. 2014), they also suffer from the irregular frequencies issue, when using pulsating source/dipole distribution for the solution of the basic Boundary Value Problem. Additional problems arise due to the neglect of viscous flow effects of the incoming wave's impact on ship's bow or stern or side walls, depending on wave heading; also, the neglect of the influence of the above-calm-waterline hull form and of the swell-up/steady wave profile phenomenon and its interaction with the incoming wave system adds difficulties to the satisfactory solution. Therefore, when using experimental or numerical data for optimising large ship's bow and hull form for representative seaways, or in *EEDIweather* calculations as defined in IMO guidelines, the results need to be used with caution due to the reasons explained above.

Various semi-empirical methods have been proposed to satisfactorily predict the added resistance in short waves. Fujii and Takahashi (1975) were the first to propose a semi-empirical formula to include the reflection effect at the bow. This was followed by Takahashi (1988) and later on by Tsujimoto et al. (2008) by fine-tuning the corrective coefficients based on experimental data. Earlier, Faltinsen et al. (1980) proposed an asymptotic formula for the added resistance of *wall-sided* hull forms in short waves, considering the basic flow around the ship according to the slender body theory. As pointed out by Sakamoto and Baba (1986), for a ship with fore-aft symmetry advancing in beam seas, the added resistance predicted by Faltinsen et al.'s theory does not go to zero because the wave field gets asymmetrical with respect to midship. Liu et al. (2015) considered all above works and proposed an improved formula, which works satisfactorily for both full and fine hull forms. It seems that semi-empirical methods, which have roots in theoretical approaches, but also exploit the knowledge from experiments, are a valid choice for tackling such a problem. In this paper, it is demonstrated that for large ships, properly quantifying the spectral contribution of the added resistance in the region of $\lambda/L_{PP} \approx 0.1 \sim 0.5$ is of paramount importance. This also triggers a critical discussion on the ITTC recommended procedure regarding the representativeness of typically tested seaway profiles.

2. The development of a new empirical formula

For the prediction of added resistance of ships in head waves at any wave length, we proceed with the following formula:

$$R_{\mathrm{AW}} = R_{\mathrm{AWR}} + R_{\mathrm{AWM}} \tag{1}$$

where R_{AW}, R_{AWR} and $\mathrm{R_{AWM}}$ denote the total added resistance, the added resistance due to diffraction/reflection effect and the added resistance due to motion effect in regular waves, respectively.

2.1. Added resistance in very short waves

The added resistance in short waves is mainly due to diffraction/reflection effects. Based on Faltinsen et al.'s work (1980), we proposed a practical approximating method (Liu et al. 2015):

$$\begin{aligned} R_{\mathrm{AWR}} &= \int_L \bar{F}_e \sin\theta \, d\ell \\ \bar{F}_e &\approx \frac{1}{2}\rho g \zeta_a^2 \sec\alpha_{\mathrm{WL}} \sin^2\theta \left(1 + 5\sqrt{\frac{L}{\lambda}} F_{\mathrm{n}}\right) \left(\frac{0.87}{C_B}\right)^{1+4\sqrt{F_{\mathrm{n}}}} \end{aligned} \tag{2}$$

The above expression has been simplified by inference of typical design data and the following formula has been developed for the calculation of added resistance in short waves:

$$R_{\mathrm{AWR}} = \frac{2.25}{2}\rho g B \zeta_a^2 \sin^2 E \left(1 + 5\sqrt{\frac{L_{\mathrm{pp}}}{\lambda}} F_{\mathrm{n}}\right) \left(\frac{0.87}{C_B}\right)^{1+4\sqrt{F_{\mathrm{n}}}} \tag{3}$$

where $E = \mathrm{atan}(B/2L_{\mathrm{E}})$ is the angle of waterline's entrance; L_{E} is the length of waterline entrance, as defined in Figure 2.

2.2. Added resistance in long waves

For the prediction of added resistance in long waves, we refer to Jinkine and Ferdinande (1974)'s formula. To better capture the added resistance of ships of various types for a wider range of speed, the parameters in the original formula were further adjusted. The following expression was obtained:

$$R_{\mathrm{AWM}} = 4\rho g \zeta_a^2 B^2 / L_{\mathrm{pp}} \bar{\omega}^{b_1} \exp\left[\frac{b_1}{d_1}\left(1 - \bar{\omega}^{d_1}\right)\right] a_1 a_2 \tag{4}$$

where

$$\begin{aligned} a_1 &= 60.3 {C_B}^{1.34} \left(\tfrac{0.87}{C_B}\right)^{1+F_{\mathrm{n}}} \\ a_2 &= \begin{cases} 0.0072 + 0.1676 F_{\mathrm{n}} \text{ for } F_{\mathrm{n}} < 0.12 \\ {F_{\mathrm{n}}}^{1.5} \exp\left(-3.5 F_{\mathrm{n}}\right) \text{ for } F_{\mathrm{n}} \geq 0.12 \end{cases} \\ \bar{\omega} &= \begin{cases} \dfrac{\sqrt{L_{\mathrm{pp}}/g}\sqrt[3]{\frac{k_{\mathrm{yy}}}{L_{\mathrm{pp}}}}\, 0.05^{0.143}}{1.17} \omega \text{ for } F_{\mathrm{n}} < 0.05 \\ \\ \dfrac{\sqrt{L_{\mathrm{pp}}/g}\sqrt[3]{\frac{k_{\mathrm{yy}}}{L_{\mathrm{pp}}}}\, {F_{\mathrm{n}}}^{0.143}}{1.17} \omega \text{ for } F_{\mathrm{n}} \geq 0.05 \end{cases} \end{aligned}$$

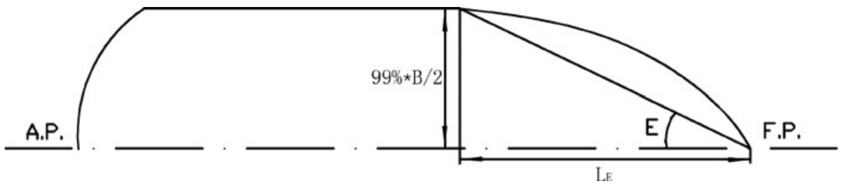

Figure 2. Definition of length L_E and angle E of entrance of waterline.

for $C_B \leq 0.75$

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

$$d_1 = \begin{cases} 14.0 \text{ for } \bar{\omega} < 1 \\ -566\left(\frac{L_{pp}}{B}\right)^{-2.66} \\ \times 6 \text{ elsewhere} \end{cases}$$

for $C_B > 0.75$

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

$$d_1 = \begin{cases} 566\left(\frac{L_{pp}}{B}\right)^{-2.66} \text{ for } \bar{\omega} < 1 \\ -566\left(\frac{L_{pp}}{B}\right)^{-2.66} \\ \times 6 \text{ elsewhere} \end{cases}$$

2.3. The draft effect on the added resistance due to the diffraction effect

The formula in Section 2.1 has been derived by assuming that the wave length is very short; hence the incoming wave will be completely reflected. As the wave length increases, this assumption is no longer valid. To approximate this partial reflection phenomenon, Fujii and Takahashi (1975) adopted a *draft coefficient*, which was followed by Kuroda et al. (2008) in their formula. The latter one is defined as follows:

$$\alpha_T = \frac{\pi^2 I_1^2 (k_e T)}{\pi^2 I_1^2 (k_e T) + K_1^2 (k_e T)} \tag{5}$$

In our earlier formula (Liu and Papanikolaou 2016), this coefficient was adopted.

Herein we proceed with a further update by referring to Kwon (1981), who reached another, simpler solution following the exponential decay concept of Smith (1883). His reasoning is that, if the wave amplitude decay is of exponential manner, then the added resistance, which is an equivalent to the dissipation of the incoming wave energy, will decay with the square of the exponential function. Thus, the added resistance of the ship equals the drift force generated by the wave pressure extending from the free surface and down to ship's draft T. Thus, the following coefficient has been derived:

$$a_T = 1 - e^{-2kT} \tag{6}$$

This coefficient appears to be physically more meaningful than previous approaches and in practice much simpler.

Obtaining the added resistance in regular waves, the mean value in long crested irregular waves is calculated as follows:

$$\bar{R}_{AW} = 2\int_0^\infty S(\omega)\frac{R_{AW}(\omega)}{\zeta_a^2}d\omega \tag{7}$$

where $S(\omega)$ is the incoming wave spectrum and $R_{AW}(\omega)/\zeta_a^2$ is the Response Amplitude Operator (RAO).

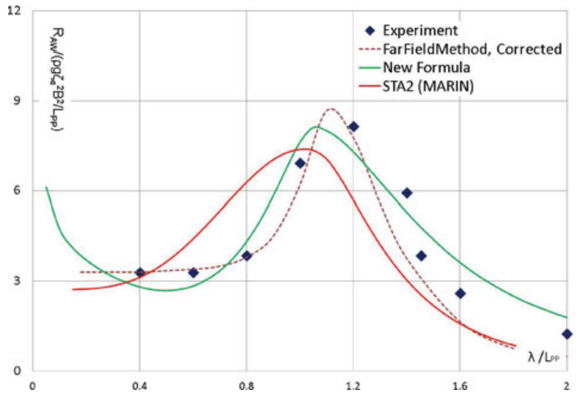

Figure 3. Added resistance of a bulk carrier in head waves by various methods, $F_n = 0.15$. (This figure is available in colour online.)

To assess the quality of the numerical prediction, two parameters are used, namely the Pearson's R correlation and the mean absolute percentage error defined as follows:

$$R_{\text{Exp,Pre}} = \frac{\text{cov}(\text{Exp, Pre})}{\sigma_{\text{Exp}}\sigma_{\text{Pre}}} \tag{8}$$

$$\varepsilon = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{\bar{R}_{AW}^{\text{Pre}} - \bar{R}_{AW}^{\text{Exp}}}{\bar{R}_{AW}^{\text{Exp}}}\right| \tag{9}$$

where cov is the covariance and σ is the standard deviation.

3. Numerical results and discussions

3.1. Numerical results in regular waves

Extensive validations of the proposed formula for both regular and irregular sea cases can be found in relevant published work (Liu and Papanikolaou 2016); we focus on the added resistance of large ships in this section.

Figure 3 shows the added resistance of a 285 m bulk carrier in regular head waves predicted by various methods together with experimental data (Kadomatsu 1988). The used methods for the numerical predictions are based on far field method (Liu et al. 2011), STA2 formula (ITTC 2012) and current formula. Figure 4 shows the correlation of the numerical predictions with experimental data in regular head waves. Here the experimental database covers the DTC (El Moctar et al. 2012), the KVLCC2 (Guo & Steen 2010), a bulk carrier and a second VLCC (Lu et al. 2012). Admittedly, the experimental database used for comparison is not rich, thus the shown results are more illustrative and cannot be generalized without further validation

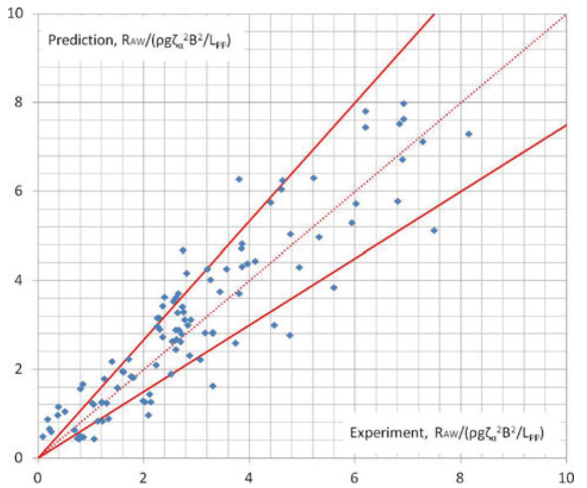

Figure 4. Correlation of the results based on present formula and experimental results in regular waves for ships of $L_{PP} > 250$ m. (This figure is available in colour online.)

studies. The conducted correlation analysis between the numerical results of the currently proposed formula and the experimental data show a remarkable correlation coefficient of $R = 0.91$, while the mean error is $\varepsilon = 39.6\%$. Besides the high correlation between the two sets of data, the relatively high mean absolute percentage error may be alarming. However, this is partly due to the uncertainty and scattering of the results of the tank tests, which do not follow a smooth trend, but greatly vary for the studied ship types.

3.2. Mean value of added resistance in representative seaways

Figures 5 and 6 show the prediction for the KVLCC2 taker and the DTC containership together with experimental data. Three sets of numerical results, as explained afore, are presented together with the results based on experimental results. The seaways' condition is defined by ITTC spectrum with $H_S = 1.5$ m and $T = 5.5$ s and the representative condition for *EEDIweather* calculation with $H_S = 3$ m and $T = 6.7$ s.

When examining the results in regular waves, the first observation refers to the wave range of interest: for ships of 300 m+, the region of interest is practically up to about 1.0 in terms of λ/L_{PP} for EEDI calculation and only up to 0.7 for seaways. Hence, for large ships, when calculating the mean value of added resistance in head waves it is necessary to conduct the experiment in relatively short waves. The second interesting observation is the asymptotic behaviour of the current formula[1] in very short wave, which seems to agree better with the experimental results than the other two methods. For the DTC ship, the prediction based on the current formula is consistently lower than experimental results in short waves. This might have to do with the extremely steep wave tested in the experiment for respective measurements, which eventually put the quadratic dependency of the added resistance on wave amplitude under question.

There is also considerable deviation among various numerical methods. This is well reflected in the mean values of added resistance in irregular waves. For KVLCC2 case, the far field method (with correction for short wave region, following the ITTC recommendation, 2012) gives a prediction very close to the results based on the best fit of experimental results. On the other hand, the STA2 formula underestimates, while the current formula overestimates the mean value. This is mainly has due to the behaviour of respective formula in short waves. For the DTC case, a very large deviation among the various predictions is observed. First of all, a reasonable agreement between the current formula and the more advanced far field method is observed, similar to the previous KVLCC2 case. But both are well below the results based on the best fit of experiment. As commented before, the experimental results of this case are uncertain due to the very steep wave used. The STA2 formula gives a prediction close to the result based on the best fit of experiment for this case.

3.3. The importance of added resistance in short waves

As shown in Equation (7), the mean value of added resistance is obtained by spectral integration over frequency ω. In short waves, ω changes drastically (quadratic relationship between λ

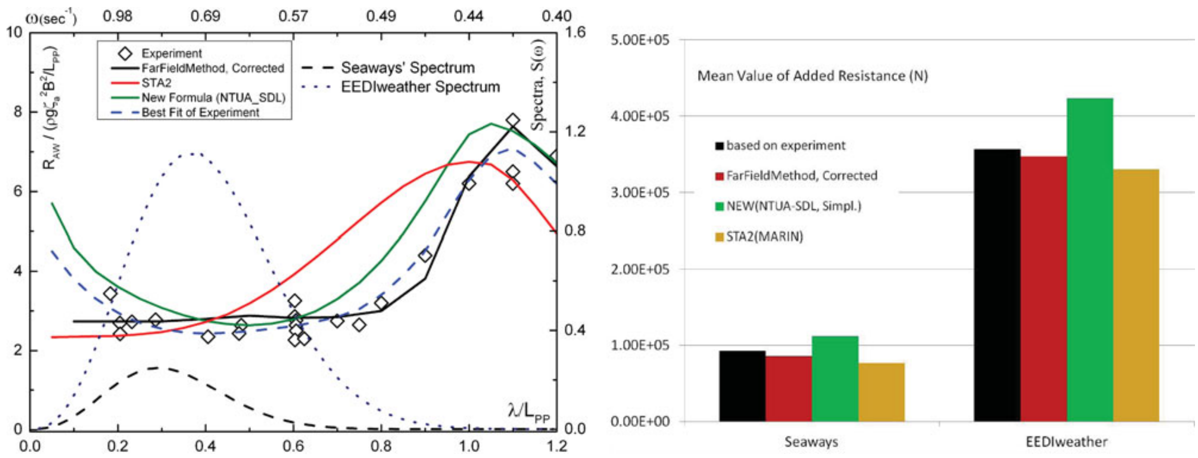

Figure 5. Added resistance of KVLCC2 in head waves, $F_n = 0.142$. (This figure is available in colour online.)

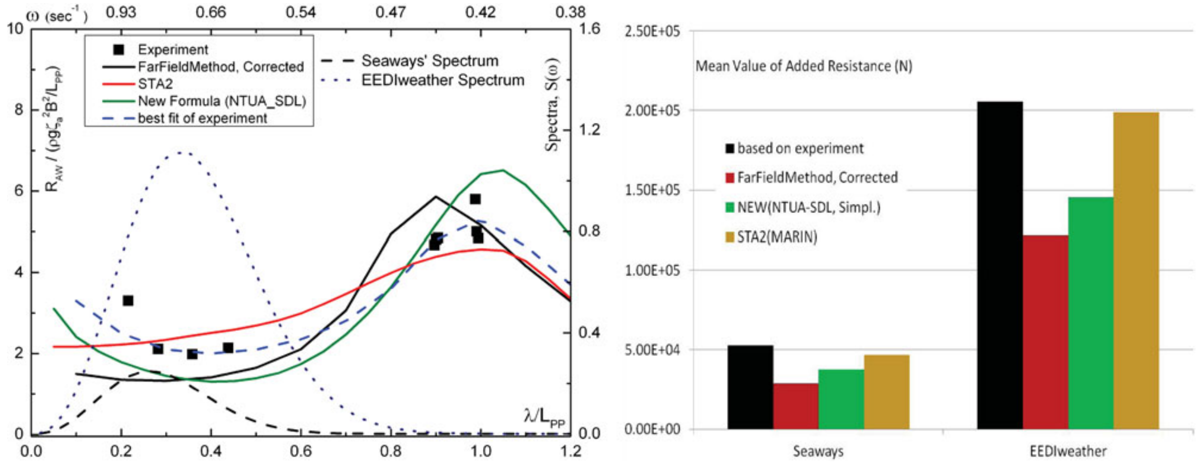

Figure 6. Added resistance of DTC in head waves, $F_n = 0.139$. (This figure is available in colour online.)

and ω), compared to the change of λ, hence the spectral contribution is actually much larger than it appears in the graphs. Recalling the VLCC study case (Figure 1), an interesting demonstration study is presented in Figure 7. In this graph, the added resistance of this VLCC ship in head waves is predicted by both STA2 formula and the currently proposed formula. The experimental data and two typical sea spectra are also presented. The mean value of added resistance for the two sea spectra are then evaluated, as shown in Table 1. The contributions from waves with λ/L_{PP} of 0∼0.2 and 0∼0.4 are also evaluated. Numerical results based on both methods prove that the contribution from the short waves is very significant and make up about 90% of the total spectral value. However, in the region of $\lambda/L_{PP} = 0$∼0.2, there is little research so far, neither numerical nor experimental, and the uncertainty of results actually makes a rational evaluation of both methods impossible.

4. A comment on the IMO recommended procedure

The IMO MEPC.1/Circ.796, 2012 Interim Guidelines for the calculation of the coefficient f_w and the guidelines on minimum power assessment are based on the spectral description of the ensuing seaway, with the latter specifying explicitly that "The quadratic transfer function of the added resistance can be obtained from the added resistance test in regular waves … as per ITTC procedures 7.5-02 07-02.1 and 7.5-02 07-02.2, or from equivalent method verified by the Administration". The mean value of added resistance in long crested irregular waves is calculated by the integration defined in Equation (7).

The ITTC Procedures 7.5-02 and 07-02.1 refer to the conduct of seakeeping experiments. Besides that there is no guideline on the measurement of the added resistance, it specifies that "For conventional ship forms, a sufficient number of tests should be carried out at each speed to provide adequate data for a minimum range of wavelengths from 0.5 L_{PP} to 2.0 L_{PP} …". However, in practice this does not meet the demand in the design and operation of large ships. It is recommended to critically review the target sea spectrum before setting up the tank tests. For very short waves ($\lambda/L_{PP} < 0.2$), it is a challenge for many tanks to dispose proper measuring equipment. As demonstrated by numerical calculations, this region has a significant contribution to

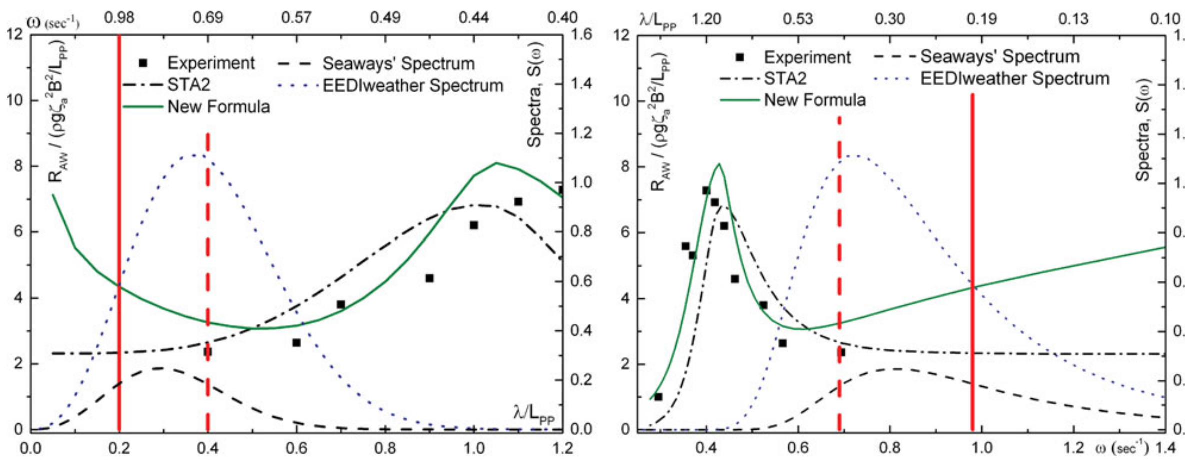

Figure 7. Added resistance of a VLCC in head waves, $L_{PP} = 320$ m, $F_n = 0.145$. (This figure is available in colour online.)

Table 1. Mean value of the added resistance of a VLCC in representative sea states.

	Seaways' spectrum			*EEDIweather* spectrum		
		Portion of R_{AW} in between (λ/L_{PP})			1. Portion of R_{AW} in between (λ/L_{PP})	
	Mean value R_{AW} (N)	0∼0.2	0∼0.4	Mean value R_{AW} (N)	0∼0.2	2. 0∼0.4
STA2	77,209.7	45.2%	89.3%	328470.8	30.1%	73.2%
New Formula	140,325.6	56.5%	93.9%	522075.9	42.5%	83.5%

the mean value of the added resistance thus should not be left out. In addition, the words "sufficient" and "adequate" should be more rationally defined to ensure a satisfactory outcome of the tests.

5. Conclusion

We hereby initiated a discussion on an important issue affecting modern ship design and operation, namely the accurate prediction of added resistance of large ships in representative sea conditions.

As revealed by numerical studies, there is a considerable deviation among various methods used in predicting the added resistance in short waves. The established semi-empirical formula introduced by Tsujimoto et al. (ITTC 2012) appears calibrated with tank results down to $\lambda/L_{PP} = 0.3$; for the STA2 formula, which is based on statistical regression of experimental data, there was no specific reference to the very short wave region. Hence, the application of these empirical formulas to such wave region seems debatable. The presently proposed formula has its roots in the work of Faltinsen et al. (1980), and was further developed to include a variety of additional aspects of added resistance through several correction factors; the proposed formula was tuned in short waves with available experimental data from public domain and confidential sources. Inherently the limitation of the present formula (as of any empirical formula) is given by the fact that it is significantly affected by the quality and richness of the employed experimental database.

On the way ahead, there is a big challenge for the tanks, when testing large ships for the added resistance; also, they should carefully review the test conditions to better reflect representative seaways. In parallel, high-fidelity CFD tools may better contribute to the understanding of the associated complicated physical phenomena. However, the efficiency and practicability of such tools needs to be improved, even though the expected improvement of computer hardware will facilitate such development. Finally, the development of improved analytical/numerical potential theory solvers, adjusted with empirical corrections, where necessary and justified by the physics of the problem, will remain an "evergreen" of ship hydrodynamics, offering reliable and practical solutions with modest effort.

Note

1. The non-dimensional added resistance predicted by the current formula has the asymptotic trend and goes to infinite in very short waves. However, the absolute value can be re-written as $R_{\mathrm{AWR}} = \frac{2.25}{2}\rho g B \sin^2 E (\frac{0.87}{C_B})^{1+4\sqrt{F_n}} (\zeta_a^2 + 5F_n\sqrt{L_{pp}}\zeta_a^{1.5}\sqrt{\frac{\zeta_a}{\lambda}})$. For gravitational water waves, when the wave length goes to zero, the wave amplitude ζ_α will trivially also goes to zero, while the ratio of ζ_α/λ retains a nonzero, definite value; therefore, the absolute added resistance in very short waves still approaches zero.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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