V International Conference on Computational Methods for Coupled Problems in Science and Engineering
COUPLED PROBLEMS 2013
S. Idelsohn, M. Papadrakakis and B. Schrefler (Eds)

ADDED RESISTANCE OF SHIPS IN QUARTERING SEAS

SHUKUI LIU* AND APOSTOLOS D. PAPANIKOLAOU†

School of Naval Architecture and Marine Engineering
National Technical University of Athens
9, Heroon Polytechniou, 15773,
Zografou-Athens, Greece
http://www.naval.ntua.gr/sdl
*email: liushukui@deslab.ntua.gr, †email: papa@deslab.ntua.gr

Key words: added resistance in waves, quartering seas, short sea formula, far field method.
Abstract. In this paper, the 3D panel method of NTUA-SDL for calculating the added resistance of a ship in bow seas has been extended and validated for the quartering seas case. At first we studied the drift force on a semi-submersible in quartering seas. Comparison has been made between numerical results of a near field and far field approach, and good agreement has been observed. In the following, we applied our method to the study of the added resistance of the S175 ITTC standard container ship and a bulk carrier for different forward speeds and different heading angles. The obtained numerical results agree also well with available experimental data, except for the short waves range. In the short waves range, the actual physical phenomenon is very complicated, involving strong viscous and other nonlinear effects, consequently the present method based on potential theory, cannot be satisfactory. In order to improve the prediction, a new semi-empirical formula is proposed to include the aforementioned effects arising in the short, oblique waves scenario. Initial tests with this formula have shown that the proposed formula provides a good approximation for the added resistance in short oblique seas. We expect that this practical formula can be further improved if additional experiments will be available in the future.

1 INTRODUCTION

The accurate prediction of ship's added resistance in seaways is nowadays of high scientific and practical interest, for both researchers, ship designers, yards, and shipowners/operators; this because it greatly affects the selection of ship's engine/propulsion system and influences ship's performance in terms of sustainable speed and safety, fuel consumption and engine air emissions in realistic sea conditions. This calls for optimizations of ship's hull in terms of her *total resistance in waves*. Even more, accurate and efficient predictions of the added resistance in natural seaways are necessary for the implementation of modern and reliable on-board ship routeing systems[1].

In a previous study[2], the authors presented a numerical method to predict the added resistance of ships sailing in waves, but the validation has been limited to head seas only. The current paper presents a follow-up validation work. In addition, emphasis has been put on the prediction of added resistance in *short waves*, thus in waves of length of about less than half ship's length. Noting the continuous increase of ship sizes in recent years (in view of the *economy of scale*) it is obvious that the range of relative wave length λ/L of practical interest is being shifted to lower values, which makes the prediction of added resistance of ships in such ranges more and more important. For the short wave range added resistance prediction, the asymptotic formula of Faltinsen[3] and the improved expression of Takahashi[4] are the most widely used formulas. However, Faltinsen's formula, which is based on theoretical considerations for very short waves, is practically not very accurate, because it does not account for viscous effects. On the other hand, Kuroda & Tsujimoto's[5,6] proposed empirical formula, which is based on conducted tank tests, yields improved prediction results, but their recommendation appears not to cover all practical cases. In this paper, starting from the above pioneering achievements, we propose a new practical formula to predict the added resistance of ships in short oblique seas.

2 THEORETICAL BACKGROUND

2.1 Far field method for the added resistance in waves

The theoretical background for the calculation of the added resistance in waves has been described in detailed in our previous paper[2]. Here only the final formulation will be given without further explanation.

The added resistance based on Maruo's theory[7] may be expressed by using the Kochin function as:

$$\begin{aligned} R_{AW} &= \frac{\rho}{8\pi}\left\{\int_{-\frac{\pi}{2}}^{-\alpha_0} + \int_{\alpha_0}^{\frac{\pi}{2}} - \int_{\frac{\pi}{2}}^{\frac{3\pi}{2}}\right\}\left|H\left(k_1,\theta\right)\right|^2 \frac{k_1\left[k_1\cos\theta - K\cos\chi\right]}{\sqrt{1-4\Omega\cos\theta}}d\theta \\ &+ \frac{\rho}{8\pi}\int_{\alpha_0}^{2\pi-\alpha_0}\left|H\left(k_2,\theta\right)\right|^2 \frac{k_2\left[k_2\cos\theta - K\cos\chi\right]}{\sqrt{1-4\Omega\cos\theta}}d\theta \end{aligned} \tag{1}$$

The complex Kochin function describes the elementary waves radiated from the ship and is expressed as:

$$H\left(k_j,\theta\right) = \iint_S \left(\phi\frac{\partial}{\partial n} - \frac{\partial\phi}{\partial n}\right)G_j\left(\theta\right)ds \tag{2}$$

where $G_j\left(\theta\right) = \exp\left[k_j\left(\theta\right)z + ik_j\left(\theta\right)\left(x\cos\theta + y\sin\theta\right)\right]$. It is an integrated effect of the body's geometry and motions.

In current study, the 3D frequency domain panel code NEWDRIFT[8,9] is used to solve the diffraction and radiation velocity potentials on each panel of ship's wetted surface and then the above formula is implemented to obtain the added resistance. Results from application of this formula to various case studies are denoted as *ND far* in the following graphs.

2.2 Semi-empirical correction for short waves range

In our previous study, the semi-empirical formulae proposed by Faltinsen[3] and Kuroda &Tsujimoto[5,6] have been investigated. However, Faltinsen's formula is practically not very accurate, while Kuroda & Tsujimoto's proposed formula, which is based on the tank tests and yields much better results, appears not cover some practical cases, at least theoretically. We focus in the following on deriving a more versatile, simple but rational formula.

In the short waves range we may assume that radiation (ship motion) effects are negligible, thus we deal mainly with phenomena related to diffracted/transmitted/reflected waves, viscous and other nonlinear, hull form phenomena, encountered by a ship sailing in oblique seas at certain speed.

The added resistance in short waves based on Takahashi's formula[4] is written as:

$$R_{AW}^{D,v} = 1/2\rho g \zeta_\alpha^2 B B_f \alpha_d \, [1 + \alpha_V * f(Fn)] \qquad (3)$$

$$\text{where} \quad B_f = \left[\int_I \sin^2(\theta - \alpha) \sin\theta dl + \int_{II} \sin^2(\theta + \alpha) \sin\theta dl \right] / B$$

$$\alpha_d = \frac{\pi^2 I_1^2(kd)}{\pi^2 I_1^2(kd) + K_1^2(kd)}$$

The first part, i.e., $1/2\rho g \zeta_\alpha^2 B B_f \alpha_d$, accounts for ship's waterplane contour, the main particulars of the hull and the wave characteristics; it is obviously an approximation of the added resistance due to the zero speed diffraction phenomenon. Figure 1 shows the integration interval in B_f's expression, i.e., the non-shaded part (A-F-B) of the waterplane, facing the incoming wave. The term in the bracket is a correction term for the speed of advance of the ship and the wave heading. A critical review of results of the experimental study [5,6] with respect to the validity of the above formula reveals that the coefficient for the speed correction is related to ship's hull form as well. Nevertheless, the above formula exhibits the beauty of simplicity as it expresses the effect of each fundamental physical phenomenon separately, and not coupled.

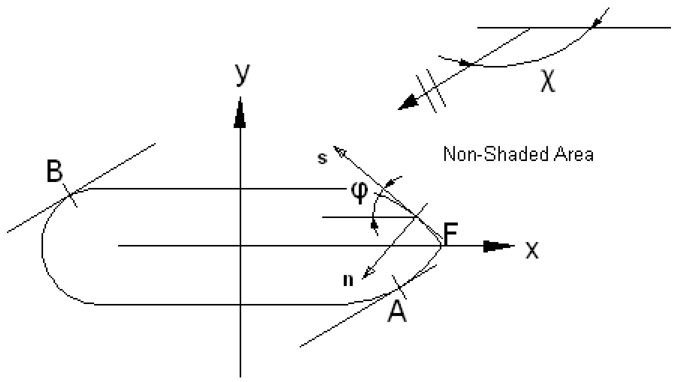

Figure 1: Coordinate system for short wave approximate method

It is well established that the added resistance due to zero speed diffraction can be easily calculated based on theoretical methods, and at least theoretically, these calculations can exactly include the hull form and wave excitation effects. So it is rational to replace the above approximation term in (3) with it and then we have a formula as follows:

$$R_{AW}^{D,v} = R_{AW}^{D,0} \, [1 + \alpha_V * f(Fn)] \qquad (4)$$

Then the problem is how to improve the forward speed effect. As shown in the original work of Takahashi, this term is actually equal to $3.5\sqrt{F_n}\,(-\cos\chi)$. This expresses the effect of forward speed in the way similar to the concept of calculating the frequency of encounter and clearly states the necessity to include the effect of forward speed on the diffraction problem.

But it also says that in beam seas the correction vanishes. However, we know that the added resistance in actual (short) seaways is certainly not only due to the diffraction effect but also due to other effects, such as wave and hull form nonlinearities and viscosity effects, which should be linked to ship's projected area to the wave direction. This has been also revealed by the known experimental work [5,6]: based on the recommended line of C_U for practical use, the speed parameter C_U has a minimum value of 10, which indicates the necessity of correction for forward speed in whatever heading. Reinvestigating the results of the experimental work and in consideration of deriving a more straightforward expression, we propose the following formula:

$$R_{AW}^{Refl,v} = R_{AW}^{D,0} \{1+ C_1 Fn(-\cos\chi) + C_2[(L-B) \sin\chi+B]/B*(1-C_B)/(1+\cos\chi C_B)Fn\} \quad (5)$$

This expression expresses the influence of forward speed on diffraction problem and other contributions more clearly. It says that the added resistance in short waves has two parts, one part is due to diffraction, which can be calculated based on zero speed diffraction problem and corrected for speed, corresponding to the first two term in the last bracket; the other part is due to nonlinearity, viscosity etc and it has to do with ship's projected area in the wave heading direction, which is denoted approximately by $[(L-B)\ \sin\chi+B]/B$. The hull form influence is further corrected by using the block coefficient $(1-C_B)/(1+\cos\chi C_B)$. Finally, the added resistance in short waves is calculated as follows:

$$R_{AW} = R_{AW}^{Ra} + R_{AW}^{D,0} + R_{AW}^{D,0} \{C_1 F_n(-\cos\chi) + C_2[(L-B) \sin\chi+B]/B*(1-C_B)/(1+\cos\chi C_B)F_n\} \quad (6)$$

where R_{AW} is the total added resistance, $R_{AW}^{Ra}+R_{AW}^{D,0}$ is calculated based on the far field method and the third term will be the correction; but we have to first determine the related parameters for practical use of this formula.

3 VALIDATIONS AND DISCUSSIONS

3.1 Semi-submersible case

The first study has been conducted for a semi-submersible, which has been investigated extensively in previous ITTC studies[10,11,12]. The scope of this study is to validate the newly extended computer code for the added resistance. The principal dimensions of the model used in the calculations are shown in Table 1.

Table 1: Main dimensions and other data of the model

Length	1.797 m	L_{GM}	0.037 m
Draft	0.313 m	T_{GM}	0.045 m
X_G	Midship	R_{XX}	0.536 m
Y_G	Centerline	R_{YY}	0.556 m
Z_G	0.273 m above keel	R_{ZZ}	0.634 m

Figure 2 shows the comparison of the results from far field method (ND far), near field method(direct integration method)[13] with free motion mode (ND FM) and due to diffraction effect only (ND DIFRAC), all of which are based on NEWDRIFT potential. As shown, a good agreement between the results from far field method and near field method is observed and they all fall into the experimental data range (though not presented here), which verifies the correctness of the extended computer code.

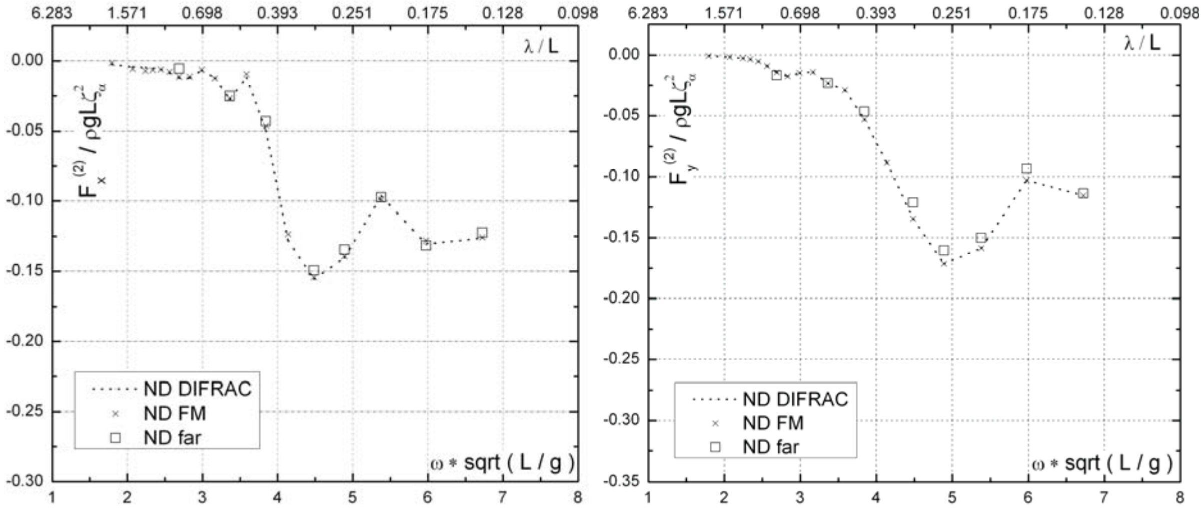

Figure 2: Drift forces of a semi-submersible in quartering seas

3.2 S-175 containership case

The S175 ITTC standard hull[14] is chosen for the second case study. This ship has a low block coefficient C_B=0.5716 and large length to beam ratio L/B = 6.89; her main particulars are shown in Table 2. In order to identify the influence of forward speed and heading angle on the added resistance of S175 containership in short waves, the following numerical experiment is carried out. Table 3 shows the available experimental data collected from different sources[4,14]. The drift force from numerical calculation by using NEWDRIFT is also included. As can be seen, there are sufficient experimental data only for head seas, hence we will try to determine the parameters based on these data.

Table 2: Main dimensions of the S175 containership

L_{pp}	175.0 m	C_B	0.5716
B	25.4 m	KM	10.52 m
T	9.5 m	GM	1 m
D	15.4 m	K_{XX}/B	0.328
Δ	24 742 t	K_{YY}/L_{pp}	0.24

Based on the available 9 experimental points, the sum C_1+C_2 is approximated by using a weighted least square method with the results of $C_1+C_2\approx 12$, as plotted in Figure 3. In order to determine their value respectively, they are assumed with different ratios, as listed in Table 4.

In the following we present the obtained results from the above elaborated methods, in comparison with the experimental data, as shown in Figure 4. From the comparison at both Fn=0.15 and Fn=0.25 for heading angle of χ=150°, 120° and 90°, it is observed that the far field method can predict the added resistance of S175 ship with satisfactory accuracy in the range other than short waves, i.e. λ/L<0.5. For short waves, the results based on three different assumptions are plotted. It is observed that, the predicted added resistance decreases from case-1 to case-3, which demonstrates the sensitivity/dependency of added resistance on these chosen parameters. However, due to the limitation/shortage of experiment data, we cannot make further comments on this point. On the other hand, the predicted value does agree reasonably with the available experimental data, in term of both quantity and tendency, thus proves that the proposed formula is capable of capturing the added resistance in short waves.

Table 3: Added resistance of S175 hull, λ/L=0.5

R_{AW}	Fn=0.0 (NEWDRFIT)	Fn=0.15 (EXP)	Fn=0.20 (EXP)	Fn=0.25 (EXP)	Fn=0.275 (EXP)	Fn=0.30 (EXP)
$\chi=180^o$	0.584	1.06	1.09 1.71 2.18	3.23 2.50	2.942	2.6
$\chi=150^o$	0.290	1.8	-	5.2	-	-
$\chi=120^o$	0.475	3.7	-	4.2	-	-
$\chi=90^o$	0.850	2.9	-	4.9	-	-

Table 4: Assumption of C_1 : C_2 ratio for S175 ship

Case-1	C_1:C_2=1:2	C_1 =4, C_2=8
Case-2	C_1:C_2=1:1	C_1 =6, C_2=6
Case-3	C_1:C_2=2:1	C_1 =8, C_2=4

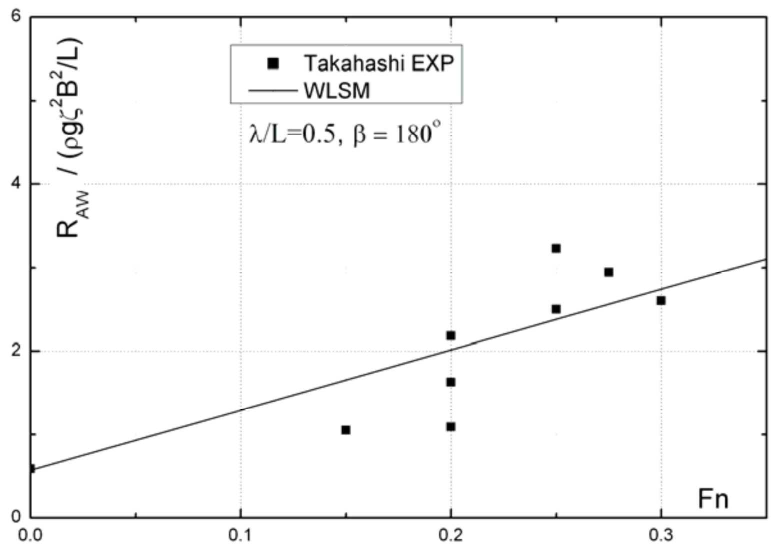

Figure 3: Added resistance VS Froude number for S175 ship, λ/L=0.5, heading angle β=180°

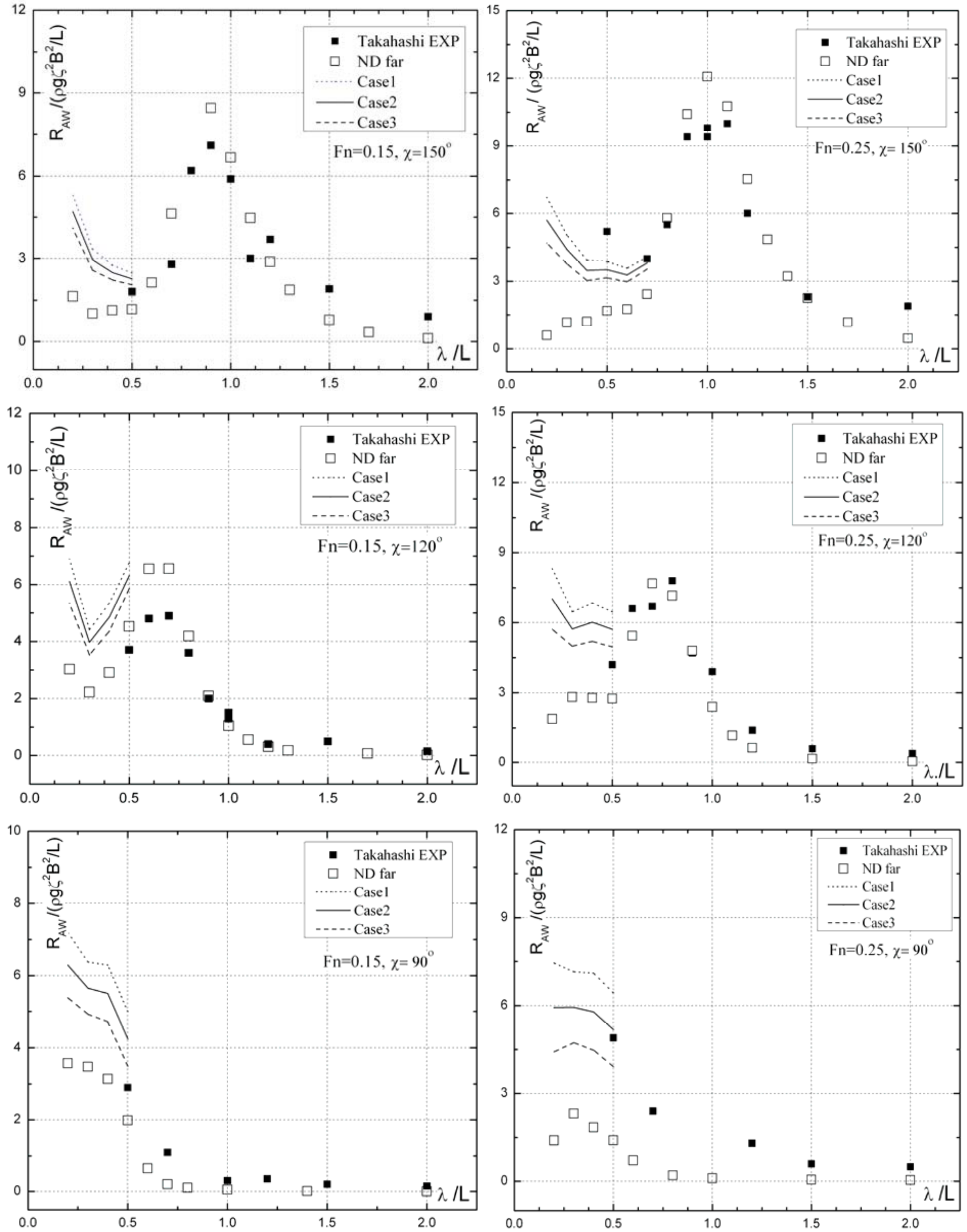

Figure 4: Added resistance of S175 ship in quartering seas

3.3 Bulk carrier ship case

The bulk-carrier that has been studied by Kadomatsu[15] is chosen as a 2nd investigation object, because it covers the range of applications of full type ships. This ship has a L_{pp}=285m, B=50.0m D=18.5m with C_B=0.829 and L/B = 5.7. Based on the available 4 experimental points, the sum C_1+C_2 is approximated by using a weighted least square method with the result of $C_1+C_2 \approx 16.5$, as plotted in Figure 5. In order to determine their value respectively, they are assumed with different ratios, as listed in Table 5.

The added resistance results are shown in Figure 6 against experimental data. Generally speaking, the calculated results based on the far field method agree well with experimental data except in short wave range, where the added resistance is under predicted. For this range, the results based on the newly proposed formula with different assumptions are presented and they are very close to the available experimental data. Considering the fact that the C_1 and C_2 parameters are regressed from data corresponding to λ/L=0.4, we believe that more added resistance data in truly short waves will be necessary to find/verify the correctness of the parameters. For beam seas, the deviation is obvious; however, as the amplitude is much lower, it is of secondary importance from the design point of view.

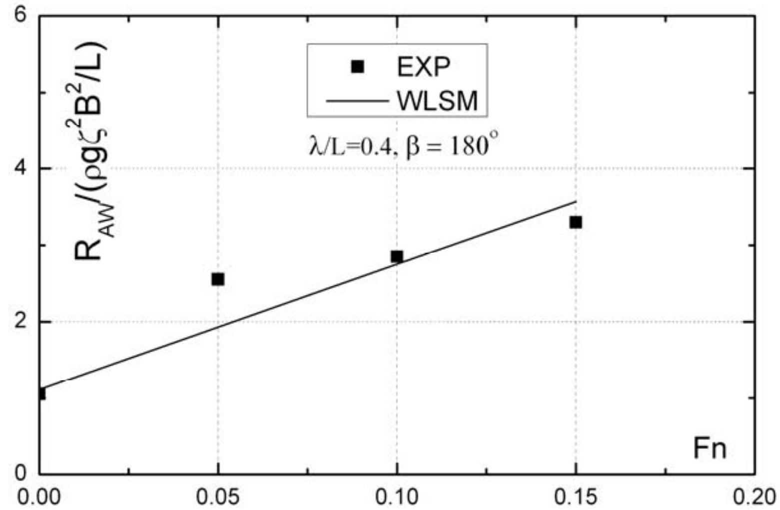

Figure 5: Added resistance VS Froude number for a bulkcarrier ship, λ/L=0.4, heading angle β=180°

Table 5: Assumption of C_1 : C_2 ratio for a bulkcarrier

Case-1	C_1:C_2=1:2	C_1 =5.5, C_2=11
Case-2	C_1:C_2=1:1	C_1 =8.25, C_2=8.25
Case-3	C_1:C_2=2:1	C_1 =11, C_2=5.5

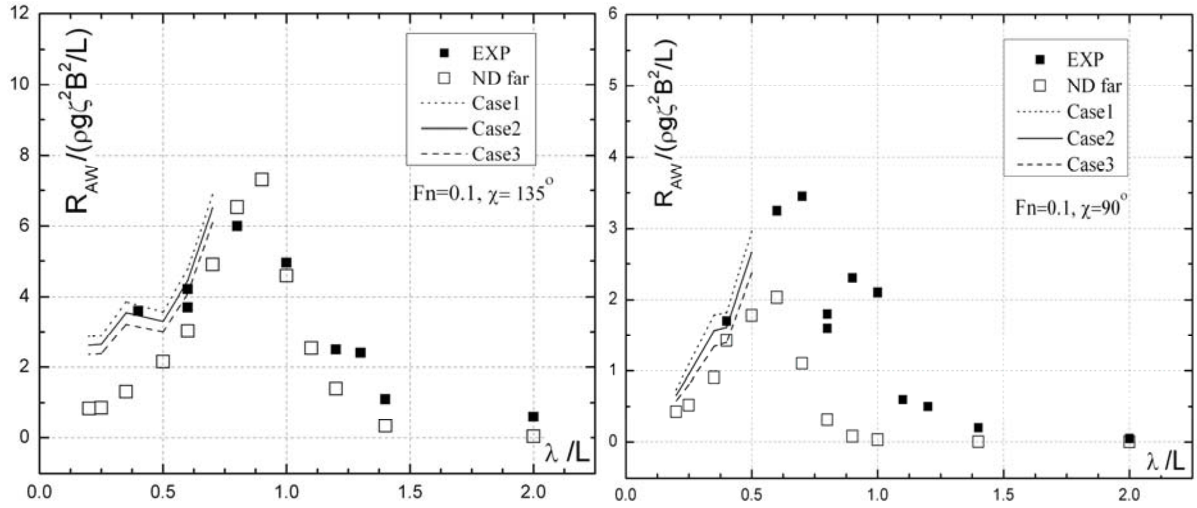

Figure 6: Added resistance of a bulkcarrier ship at different headings, Fn=0.1

4 SUMMARY AND CONCLUSIONS

1) The developed analytical/numerical method and computer code for the calculation of the added resistance of ships of different types sailing in head quartering seas based on the far field method, in combination with velocity potential solver NEWDRIFT of NTUA-SDL, yields satisfactory predictions, except in the short waves range.

2) For the short waves range, it appears that the newly developed semi-empirical formula, with parameter setting *case-2* , i.e. $C_1=C_2$, can give good prediction, i.e.

$$R_{AW}^{Refl,v}= R_{AW}^{D,0} \{1+ C\, Fn(-\cos\chi) + C\, [(L-B) \sin\chi+B]/B*(1-C_B)/(1+\cos\chi C_B)Fn\}$$

The constant C should be determined by careful studying of available experimental data. In case of lack of experimental data, we recommend for fine hull form, C=6; for full hull form, C=8 is recommended. The introduction of the forward speed correction factor $[(L-B)\sin\chi+B]/B$ indicates that viscous effects are highly correlated to the projected area.

3) Experimental data on added resistance scatter a lot and this is in the nature of this complicated phenomenon; repeating the experiments for the same conditions may lead to significant data variation, even if measurement techniques are highly accurate; hence we cannot expect an excellent agreement with theoretical predictions which rely on well-defined deterministic models.

4) The present research needs to be continued, as its outcome should be continuously improved, considering that: a) in the employed experiments there may be still motion effects, not considered in our recommended formula, b) there are not enough experimental samples. Obviously, further experiments need to be carried out to verify the validity of the proposed practical formula.

5 ACKNOWLEDGEMENTS

The presented work is a PostDoc study of the first author; the financial support of NTUA-SDL and the continuous guidance by Professor A. Papanikolaou is acknowledged. Professor G. Zaraphonitis' contribution to the current study through many discussions is highly appreciated.

REFERENCES

[1] Papatzanakis, G. Papanikolaou, A.D. and Liu, S.K. Optimization of Routing considering Uncertainties. *Journal of Marine Science Applications*, Springer Publ. (2012), Harbin.

[2] Liu S.K. Papanikolaou A.D. and Zaraphonitis G. Prediction of Added Resistance of Ships in waves, *Ocean Engineering* (2011).

[3] Faltinsen O.M. Minsaas K.J. Liapis N. and Skjordal S. O. Prediction of resistance and propulsion of a ship in a seaway, *Proc. 13th Symposium on Naval Hydrodynamics* (1980).

[4] Takahashi T. A practical prediction method of added resistance of a ship in waves and the direction of its application to hull form design. *Trans West Jpn Soc Nav Archit* (1988) **75**:75–95.

[5] Kuroda M. Tsujimoto M. and Fujiwara T. Investigation on components of added resistance in short waves, *Journal of the Japan Society of Naval Architects and Ocean Engineers* (2008) **8.**

[6] Tsujimoto M. Shibata K. Kuroda M. A practical correction method for added resistance in waves , *Journal of the Japan Society of Naval Architects and Ocean Engineers* (2008) **8**.

[7] Maruo H. Resistance in waves, *60th anniversary series of the society of naval architects of Japan*(1963)**8**.

[8] Papanikolaou A.D. On Integral-Equation-Methods for the Evaluation of Motions and Loads of Arbitrary Bodies in Waves. *Journal Ingenieur - Archiv* (1985) **55**:17-29.

[9] Papanikolaou A.D. and Schellin Th. A Three Dimensional Panel Method for Motions and Loads of Ships with Forward Speed. *Ship Technology Research*, (1992) **39**:147-156.

[10] ITTC Ocean Engineering Committee. Report of Ocean Engineering Committee. Proceedings of ITTC conference (1984).

[11] ITTC Ocean Engineering Committee. Report of Ocean Engineering Committee. Proceedings of ITTC conference (1987).

[12] ITTC Ocean Engineering Committee. Report of Ocean Engineering Committee. Proceedings of ITTC conference (1993).

[13] Papanikolaou A.D. and Zaraphonitis G. On an improved method for the evaluation of second-order motions and loads on 3D floating bodies in waves. *Journal Schiffstechnik-Ship Technology Research* (1987)**34**:170-211.

[14] ITTC Seakeeping Committee. Comparison of results obtained with compute programs to predict ship motions in six-degrees-of-freedom and associated responses, Proceedings of 15th ITTC(1978)79-92.

[15] Kadomatsu, K. Study on the required minimum output of main propulsion engine considering maneuverability in rough sea, *PhD thesis*, Ship Design Lab., Yokohama National University, Japan (1988).