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Validation of potential flow method for ship resistance prediction

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Validation of potential flow method for ship resistance prediction

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Abstract. Considering the extensive use of numerical methods in naval design, a question about the accuracy numerical tools that could estimate the flow around the ship and which are the limitations of these tools for practical design applications. In this context, experimental test on scaled models play an important role in validation of numerical simulations. This work is dedicated to validation of the method used to calculate the non-linear potential free-surface flow around the ship. Global quantities, as total resistance, wave resistance coefficient, residual resistance coefficient are flow characteristics concentrated in a single value, and their validation provides a criterion for choosing the optimum hull. Validation of physical phenomena is done using the wave profile, the pressure distribution on the body or the free surface topology. Validations were developed by comparing experimental data published for benchmark test cases, results of the resistance test performed in ICEPRONAV towing tank, against the results of numerical calculation performed by the author. Numerical simulations were performed using the XPAN module of the SHIPFLOW program, dedicated to the calculation of non-linear potential free-surface flow. Therefore, in order that the validation to be consistent and not influenced by scale effects, all calculations have been performed for the model scale. For this purpose, numerical studies have been considered for three ship models with different complex geometries. Two of the three hulls, the 60 Series and the DTMB 5415, are benchmark tests, chosen due to a wide range of detailed experimental and numerical results. The other one is case study for which experimental measurements were carried out in the frame of research projects.

1. Introduction

Generally, CFD simulation methods are based on a series of hypotheses and approximations that lead to numerical errors. For the proper use of these methods, it is important to define a range of simulation validity and, as far as possible, to estimate the magnitude of errors in this area. The paper focuses on the validation of the non-linear potential flow method for ship hydrodynamics by comparing the numerical results with experimental measurements. Validation is the process that tests the ability to predict physical phenomena and to assess the accuracy of solutions according to physical reality. To prove the consistency of the numerical flow simulations the solutions should be validated. Experimental test measurements play an important role in the development of numerical modelling as they can be employed to determine the level of accuracy of modelling physical phenomena. Experimental tests also help clarify local flow characteristics (speed distribution and wave profile) to understand the relationship between hull shape and global forces, such as ship resistance and propulsion performance. Generally, for global CFD validation in ship

hydrodynamics, parameters such as total resistance, wave resistance coefficient, residual resistance coefficient are used. Global parameters are flow characteristics concentrated in a single value, and their validation provides a criterion for choosing the optimum hull. Validation of physical phenomena is done using the wave profile, the pressure distribution on the body or the free surface topology. They support the decisions of local body modification in the design of the hull forms.

Validations were developed by comparing experimental data published for benchmark test cases, results of the resistance test performed in ICEPRONAV towing tank, against the results of numerical calculation performed by the author. Numerical simulations were performed using the XPAN module of the SHIPFLOW program, dedicated to the calculation of potential free-surface flow. Mathematical and numerical model for non-linear potential flow method were reported [1]. Based on the analysis [2], the computation domain has been extended to 0.75Lpp upstream, 2.5Lpp downstream and 1.0Lpp laterally. The size of the domain proves to be enough to eliminate the risk of numerical reflection that may occur on the borders and which may contaminate the overall accuracy of the solution. Higher order panels were used for both, the panelling of the hull and the free surface. To achieve good accuracy solutions, the penalization has been refined in areas where large gradients were expected. All calculations were performed using the non-linear method. The same conditions as experimental measurements regarding the trim and sikage were considered in the calculation methodology. The simulations have been carried out for the model scale in order to be consistent and to avoid scale effects. For this purpose, numerical studies have been considered for three ship models with different complex geometries. The Series 60 hull is a slender body with a block coefficient of 0.6 and a spoon stern. The fore hull shape of the DTMB 5415 is dominated by the presence of a prominent sonar in the lower part of the bow, which increases the complexity of the surface to be panelised. In the aft, the ship has pram stern with slightly submerged transom. The geometry of the 7500 tdw chemical tank is characterized by full shapes (0.77 block coefficient) and a large parallel area. The bow has a gooseneck bulb, and the transition from the bow to the cylindrical area is fast, leading to areas with large curvature. The bow is pram type, as in the case of the combatant, but the transom is not submerged. In addition, the aft has a gondola attached to create space for the engine. The geometrical characteristics of the four ship bodies are shown in figure 1.
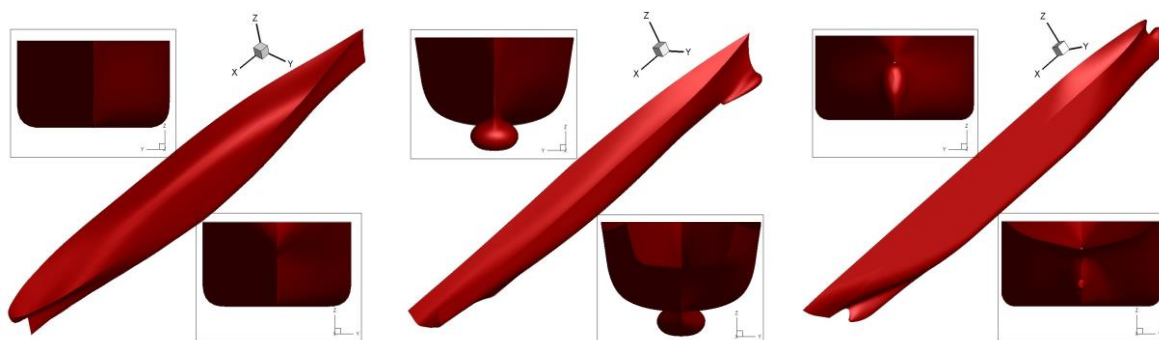

Figure 1. Hull geometries: Seriei 60 (left), DTMB 5415 (middle) and 7500 tdw chemical tanker.

Two of the three hulls, the 60 Series and the DTMB 5415, are benchmark tests, chosen because the literature offers a wide range of detailed experimental results. The other two are case study studies for which experimental measurements were carried out in the frame of different research projects. Thus, the 7500 tdw tank was the hull studied during the project [3]. In order to have an image of the ship models used in the validation process, table 1 summarizes the main geometric features of studied models. In the following chapter, the towing tank measurements performed for the ship hulls described above have been compared with the computation results obtained based on the non-linear free-surface potential flow approach.
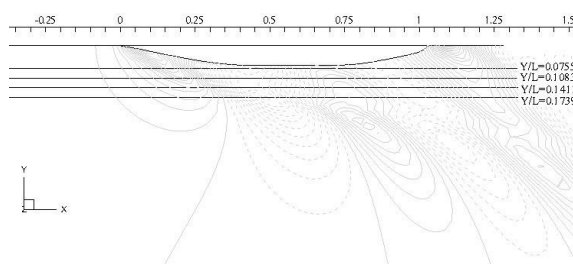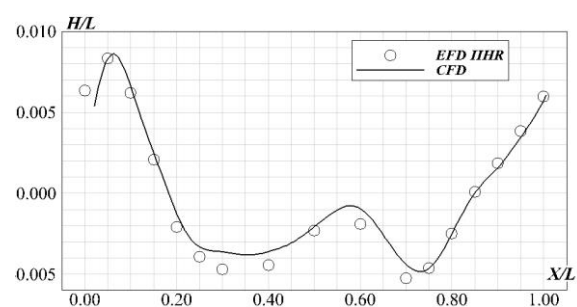
Table 1. Main dimensions of models tested.

Dimension	Symbol	Units	Seria 60	DTMB 5415	Tanc 7500
Length	Lpp	m	3.048	5.72	5.505
Breadth	B	m	0.406	0.724	0.890
Draft	T	m	0.163	0.248	0.313
Block coefficient	C_B	-	0.60	0.506	0.775
Froude number	Fn	-	0.1-0.3	0.15-0.4	0.21-0.25

2. Validation cases

The Model Series 60 is a single-screw commercial ship that has become the standard model in hydrodynamics research. For this reason, it was chosen for the comparative study of numerical calculation and experimental measurements. Series 60 is a slender body with a block coefficient of 0.6 and it has cruiser stern. The 60 Series hull has been designated by the International Towing Tank Conference (ITTC) as a benchmark test hull for ship resistance and propulsion. This hull is often used for validation due to the simple hull form and the extensive amount of experimental results in the literature that can be found in [4, 5]. It should be noted that in the numerical simulations, the model is free to move on the vertical and longitudinal direction, same as in the case of measurements in order to make the quantitative comparison between the two types of results. A series of 18 numerical simulations were performed for a range of Froude numbers between 0.11 and 0.31. the wave resistance and residual resistance coefficients, respectively the ship resistance, as global parameters and wave profile as a local parameter have been compered.

First, wave profiles (projection of waterline on the surface of the ship) and vertical-longitudinal sections traced through the free-surface will be analysed. Their position with respect to the centre line is shown in figure 2. The wave profiles calculated and measured along the body surface for the Froude numbers, 0.25 and 0.31, are compared in figures 3 and 4. It can be observed that in both cases there is a good correlation of the calculation with the experimental data in terms of shape, magnitude and phase. The height of the wave seems to be very well reproduced, but for Fn = 0.31 there is a slight difference in phase next to that the second wave surge.

Figure 2. Positions of the longitudinal wave cuts.

Figure 3. Comparison of computed and measured wave profiles at Fn=0.25.

To continue with the CFD-EFD comparative analysis, the vertical-longitudinal sections at Y/L = 0.0755, 0.1083, 0.1411, 0.1739 were represented in the same manner, figures 5-8. When the four figures mentioned above are analysed, one can see that the main characteristics of the wave system were well reproduced by calculation. A slight overestimation of the amplitude of the wave calculated downstream of the body can be seen in all sections studied, most likely due to the viscous effects that occur in stern area and which cannot be captured by the potential flow method. Viscous effects at Fn = 0.25 were confirmed by [6]. On the other hand, if the curves are analysed upstream of the ship hull, a

very good correlation between the calculated results and the measurements can be seen, which reveals that, from the numerical point of view, the condition of radiation is well imposed on the free surface. To support the aforementioned assertions, the good correlation of the free surface topologies, calculated and measured at the speed corresponding to the Froude number 0.31, is presented in figure 9, where the line contours represents positive and by dotted lines are plotted negative one. Distance between two consecutive contours is 0.002.

Figure 4. Comparison of computed and measured wave profiles at Fn=0.31.

Figure 5. Comparison of computed and measured wave cut at Y/L=0.0755, Fn=0.25.
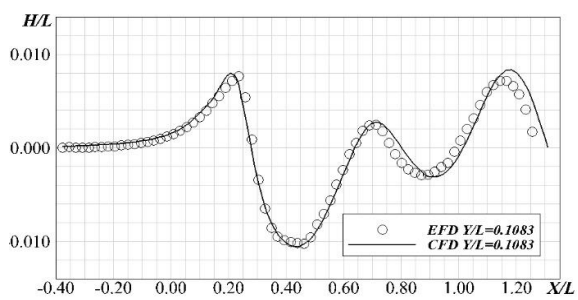

Figure 6. Comparison of computed and measured wave cut at Y/L=0.1083, Fn=0.25.
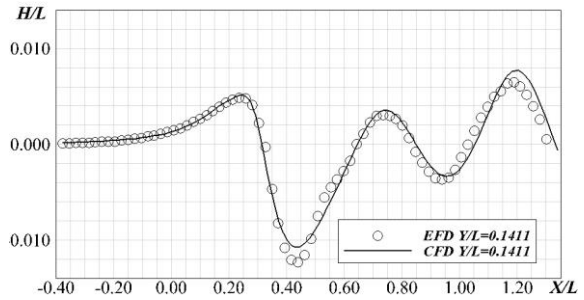

Figure 7. Comparison of computed and measured wave cut at Y/L=0.1411, Fn=0.25.
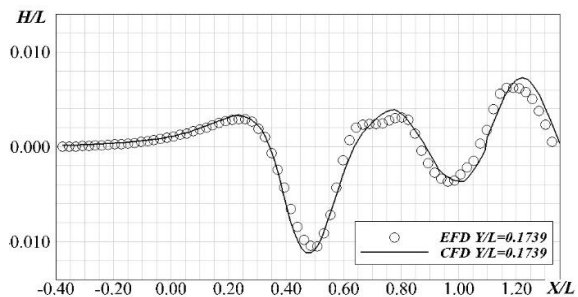

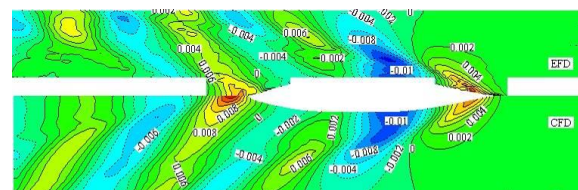**Figure 8.** Comparison of computed and measured wave cut at Y/L=0.1739, Fn=0.25.

Figure 9. Comparison of computed and measured free-surface topology, Fn=0.31.

In the following, a quantitative validation of potential flow solutions it is proposed. Knowing the form factor for the 60 Series model, (1+k)=1.08, it has been possible to experimentally determine the wave resistance coefficient extracting the product (1+k)cF0 from the coefficient of total resistance. Consequently, the wave resistance coefficient (cw_{CFD}), calculated by integrating the pressure on the hull, can be comparatively analyzed against the coefficient of wave resistance (cw_{EFD}) and the coefficient of residual resistance (cr_{EFD}) determined from the measurements. Analysing the figure 10, in which cw_{CFD}, cw_{EFD} and cr_{EFD} were represented in relation to Froude number, it can be noticed a good correlation between the numerical and the experimental results over the entire range of Froude

numbers. Moreover, the shape of the curve closely follows the one given by the experiment, each slope changes of the experimental curve being accurately captured. In the same manner, figure 11 shows a comparison between the curves of the total resistance of the model, calculated and measured, for Froude numbers between 0.11 and 0.31. The percentage difference between the two categories of values is between -0.28 and 2.76%, which reveals a high degree of accuracy of numerical simulation, as confirmed by the local parameter comparisons presented above.
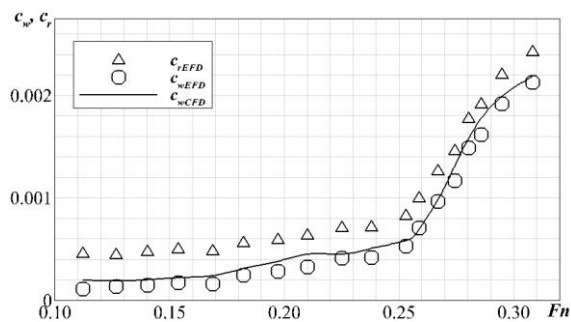

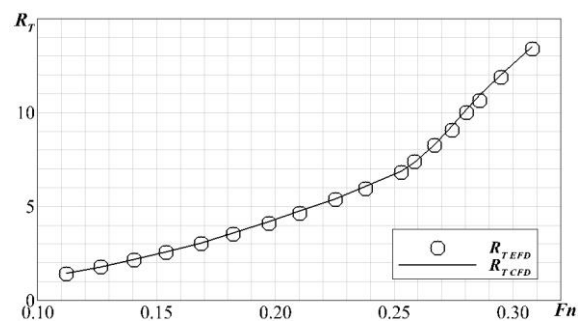**Figure 10.** Comparison between computed and measured wave coefficient.

Figure 11. Comparison between computed and measured total resistance.

The free-surface flow around the DTMB 5145 model was calculated for the case when the ship moving in calm water for a Froude numbers ranging from 0.1 to 0.41. [7, 8, 9] provides experimental data as resistance, wave and wave profile to validate different numerical computation methods. Most recently, validation for different simulation tests have been reported in [10, 11, 12]. Figure 12 shows a comparison of the wave system, calculated and measured, at the speed corresponding to the Froude 0.28 number.
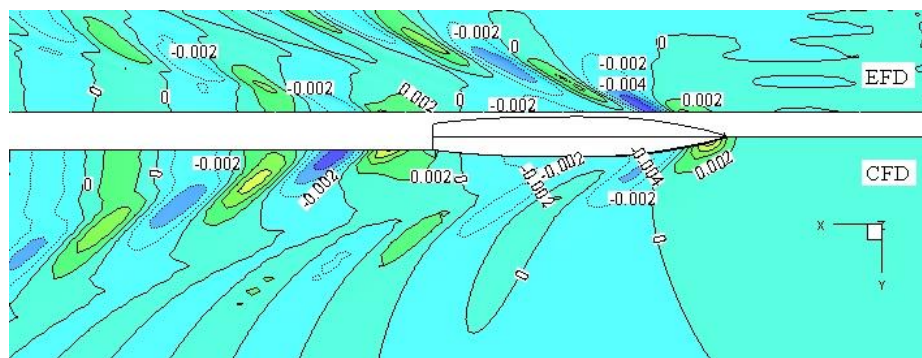

Figure 12. Comparison between calculated and measured free-surface topologies (INSEAN) at Fn = 0.28.

The positive contours are plotted with solid line and negative contours with dotted line and the distance between two contour line is 0.002. In both representations, one can notice the development of three increased wave along the hull. The diverging waves generated by the bow of the ship are propagating downstream, while the development of the secondary system of transverse waves, immediately in the aft of the ship. Low values of the hull block coefficient and the waterline entrance angle determine a low amplitude bow wave. On the other hand, the wave generated by the ship in the stern region is significant, their amplitude being almost equal to the height of the forward wave, as can be seen in figure 14. This seems to be due to the geometry of the transom and the high speed.

In order to continue the CFD-EFD comparative analysis, a series of vertical-longitudinal sections through the free surface were represented in the same way as in the previous calculation. The positions

of the studied sections in relation to the central line plane, Y/L = 0.082, 0.172 and 0.301, are presented in figure 13. From the examination of figures 14-16, it can be seen that the main characteristics of the ship wave system were reproduced by calculation. In general, one can see a good correlation between the two wave profiles (calculated and measured) in terms of shape and phase, but in terms of magnitude, the numerical solution seems to underestimate the amplitude of the wave crest and trough. If the curves are analysed immediately upstream of the ship's body (-0.25-0), a very good correlation can be observed between the calculated results and the measurements, which reveals that, from the numerical point of view, the condition of radiation is well imposed on the free surface. As can be seen in the three figures, the forward wave system is well predicted, except underestimating the first wave through that can be seen in figure 14.

In the first section (figure 14), a slight phase difference and an overestimation of the wave velocity calculated downstream of the body can be noticed, most probably due to the neglect of the viscous effects occurring in that area. In figure 15, the same slight underestimation of the theoretical calculations downstream of the body remains, but there are no phase differences between the wave profiles. In the third figure (figure 16), it can be seen that the downstream wave in the Y/L = 0.301 section was well reproduced by calculation both in phase and amplitude.
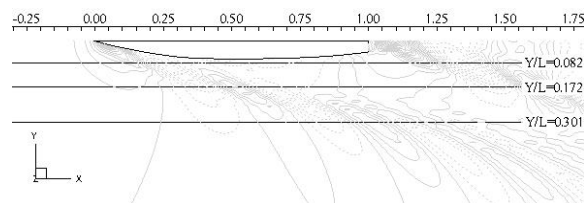

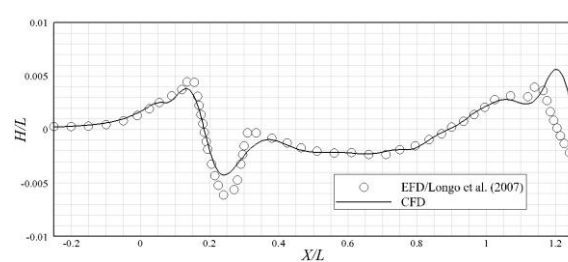**Figure 13.** The longitudinal positions of the wave cut sections. DTMB 5415 hull.

Figure 14. Comparison of the wave profiles calculated and measured at y / L = 0.082 (INSEAN) at Fn = 0.28.
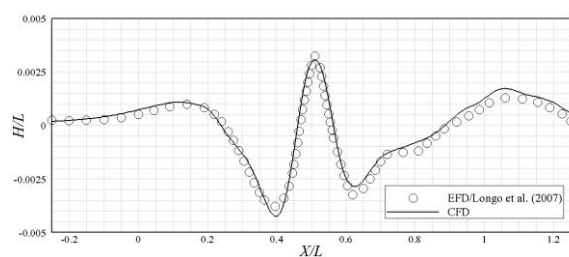

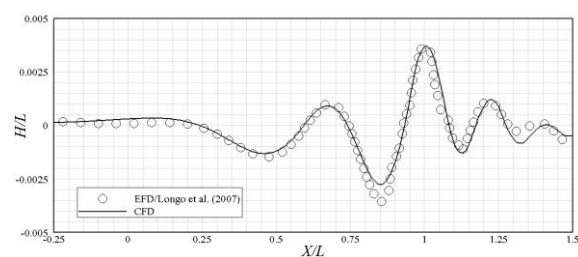**Figure 15.** Comparison of the wave profiles calculated and measured at y / L = 0.172 (INSEAN) to Fn = 0.28.

Figura 16. Comparison of the wave profiles calculated and measured at y/L=0.301 (INSEAN) la Fn=0.28.

Finally, a quantitatively validation of the numerical global variables obtained by means of the non-linear potential flow solver has been proposed. To consistently compare experimental and numerical wave resistance coefficients, the form factor is needed. In [4] is described in detail how to estimate the form factor value for the DTMB model using the Prohaska method. The value obtained for the form factor, $(1+k)=1.15$, was determined by experimental tests for numbers Fn ranging from 0.05 to 0.2. Once the form factor is determined, cw_{EFD} is can be obtained by the same approach as in the previous calculation. In figure 17, the coefficients cw_{CFD}, cw_{EFD} and cr_{EFD} curves against Froude number are shown. It can be noticed that there is a good correlation between the calculated and measured wave resistance coefficients over the entire length of the curve. Moreover, the curve of wave resistance coefficients obtained by calculations closely follows the one given by the experiment, and each slope

change of the experimental curve was reproduced by calculation. On the basis of the resistance coefficients obtained numerically, the total resistance coefficient is calculated, the resistance curves can be compared, as in figure 18. The comparative analysis of results reveals that the differences between the measured and calculated drag resistance are between -0.76 and + 4.30%.
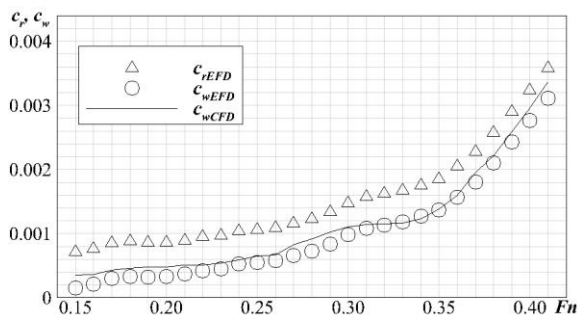

Figure 17. Comparison of calculated wave coefficient and measured residual resistance (IIHR).
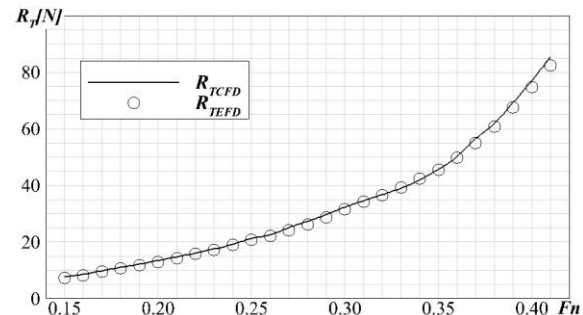
Figure 18. Comparison of calculated and measured resistance (IIHR).

Experimental measurements for the 7500 tdw chemical tank were conducted in the ICEPRONAV basin for five speed range of 1.592 to 1.82 m/s, corresponding to Froude numbers ranging from 0.214 to 0.245. The results of the experiments were reported by [3]. The extrapolation of the experimental data has been done by the ITTC 78 method, which allows form factor ((1+k)=1.3) and the wave resistance coefficient to be determined. For the CFD-EFD comparative study, the potential free-flow flow around the model in the case of the vessel moving in calm water was calculated for a series of five Froude numbers ranging from 0.214 to 0.245. Figure 19 shows the values of the wave coefficients calculated (continuous line) and measured (circle symbol) and the coefficient of residual resistance (triangle symbol).
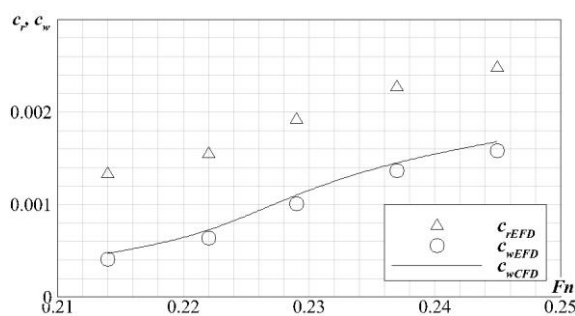

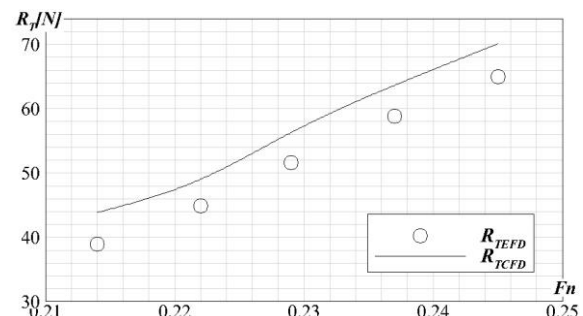**Figure 19.** Comparison of calculated and measured wave resistance coefficients.

Figure 20. Comparison of total resistances measured and calculated.

It can be noticed that there is a good correlation between calculated and measured wave coefficients. Moreover, the numerically determined curve of the curve closely follows the experimental one, and each slope change of the experimental curve was accurately captured. The comparative analysis of the results reveals that the differences between the measured and calculated drag resistance are maintained almost constant over the curve length and are between 7-11%, figure 20.

3. Conclusions

In this chapter, the experimental and numerical data for qualitative and quantitative validation of the numerical solution for nonlinear potential flow with free surface were discussed. The experimental tests led to the clarification of flow characteristics in the bow and stern region. This contributed to the understanding of the interdependence between the ship shape, the speed of the ship and the phenomena accompanying the flow. Furthermore, experimental results were used to validate the numerical method. For consistent validation, comparisons of global and local parameters were made. From the analysis of the comparisons made study it was found that the numerical results are in good correlation with the experimental data for Froude numbers ranging from 0.15 to 0.40 and the nonlinear calculation method is able to reproduce the most important characteristics of the wave system obtained in experimental tests. Wave phases were well estimated, but differences in amplitude may appear. However, their shortcomings will not influence the comparative study of different ship shapes if the same paneling of the free surface is used. In the range of Froude numbers, between 0.15-0.40, the percentage difference between the calculated and measured resistances was between -0.76 and 11%. By synthesizing the validations made in the four studied cases, we can conclude that there is a satisfactory concordance between theoretical and experimental data, which confirms the accuracy of the calculation program.

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