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VERIFICATION AND VALIDATION STUDY FOR THE TOTAL SHIP RESISTANCE OF THE DTMB 5415 SHIP MODEL

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ABSTRACT

The present study describes the viscous flow simulation of the bare hull ship resistance of the DTMB 5415 model ship. The study includes computations for ship resistance as well as free-surface and sinkage and trim prediction for three different Froude numbers. Computations are performed using the ISIS-CFD solver included in Fine^{TM}/Marine software available under the NUMECA suite where the discretization in space is based on finite volume method using unstructured grid. The Reynolds Average Navier-Stokes equations are numerically solved in a quasi-static approach where the turbulence is modeled by making use of the k-ω SST model. Four different computational grids were generated for performing a verification and validation study based on Richardson extrapolation method. Results are compared with the benchmark experimental data provided in the Gothenburg workshop on CFD in ship hydrodynamics in 2010. Validation of the numerical results shows a reasonable agreement with the experimental data.

Keywords: CFD, ship resistance, free-surface flow, RANSE, verification and validation.

1. INTRODUCTION

Due to the availability of a wide range of commercial CFD software and the great development in computational capabilities that resulted lately in the High Performance Computations, CFD started to be considered as one of the robust and reliable tools that can be used to solve flow problems in all the industrial fields. A great development is recorded in the past two decades for CFD in ship hydrodynamics, especially when the problem of concern is a classical resistance problem. A satisfying level of accuracy was recorded in the past two conferences on the Workshop on CFD in Ship Hydrodynamics organized in Gothenburg 2010 [1] and Tokyo 2015 [2]. Although the results for CFD might seem promising in some cases, yet verification and validation of results are essential to know how much these results can be reliable.

The current study presents a simple ship resistance simulation for a complicated geometry and relatively fast ship, the DTMB bare hull, as a primary step for further investigation that will be carried by the author in the very near future which will include the fully appended ship resistance of the same particular hull and the motion characteristics in regular waves. The paper includes a focused analysis of the results obtained by the solver to investigate their accuracy. The verification study is based on a simple generalized Richardson Extrapolation method, following the same procedures proposed in [3] and in accordance with the requirements of the International Towing Tank Conference [4].

The DTMB 5415 ship model, which was conceived as a preliminary design for a Navy surface combatant 1980 [5], is used for this particular investigation. The hull geometry includes both a sonar dome and transom stern. No full-scale ship exists. The model is depicted in Fig. 1 and the main particulars are provided in Table 1.

Fig. 1. DTMB 5415 geometry

Table 1. Main particulars of the DTMB model 5415

Main Particulars	Value
L_{pp} [m]	5.719
L_{wl} [m]	5.726
B_m [m]	0.768
T [m]	0.248
Displacement [m^3]	0.554
Block Coefficient C_B	0.507
Mid-ship section coefficient C_M.	0.821

2. NUMERICAL METHOD

The computations are performed using the ISIS-CFD solver available by Fine™/Marine commercial software provided under the NUMECA suite. The solver is based on the finite volume method to provide a spatial discretization for the governing equation to solve the Reynolds averaged Navier-Stokes equations in a global approach [6]. Closure to the turbulence is achieved by making use of the *k-ω SST* model. The free surface is captured within an air-water interface based on the volume of fluid approach.

The computational domain is of a rectangular shape, whose length is five times the ship length, breadth is two times the ship length and height is two times the ship length. Taking an advantage of the geometrical symmetry, only a half of the ship is used for the computations, as depicted in Fig. 2.

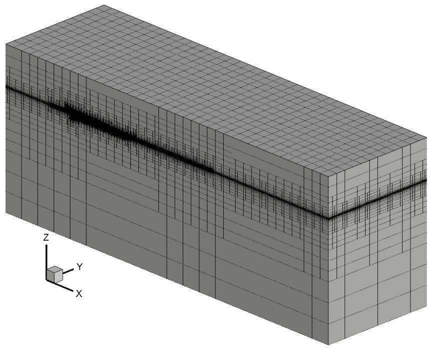

Fig. 2. Computational domain

The boundary conditions imposed are as follows: the far-field condition is set for the downstream, which is located at three times the ship length, for the lateral boundary and for the upstream. The pressure is prescribed on the top which is located at half ship length from the still water level and on the bottom, as shown in Fig. 3. The wall is treated in two different methods; wall modeled simulation where a wall function is applied with a first layer distance from the wall y^+=30 and wall resolved simulation setting y^+ less than unity., while the slip is applied on the deck, supposing that it remains in the air during the computation, therefore the viscous effect can be neglected.

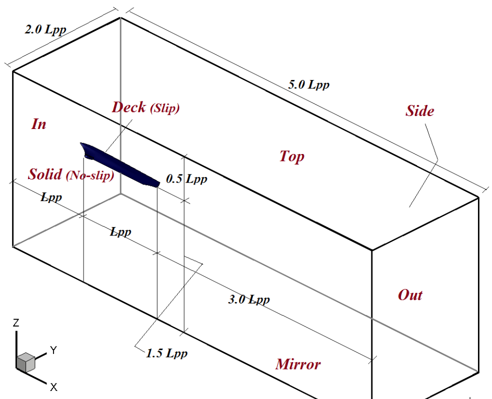

Fig. 3. Domain dimensions and boundary conditions

The flow is accelerated through a quasi-static approach within a time-span corresponding to the following relationship between the length of the ship and the ship inflow velocity as:

$$T_{acc}=2.0L_{pp}/U_{\infty} \qquad (1)$$

Computations are performed for 30 seconds using 10 iterations per time step. The integration in time is done based on a second order convergence criteria using combined upwind scheme and centered scheme.

The computational grids are generated by using the HEXPRESS automatic grid generator included in the Fine^{TM}/Marine software. Unstructured grids with hexahedral elements are created by imposing restrictions for the discretization parameters. These restrictions are essential to ensure the grid similarity for a successful Richardson Extrapolation.

For the grid convergence study, four different grids were generated. The total numbers of grid cells are summarized for every computation condition in Table 2 with a grid refinement ratio approximately equals to 1.5. The WM in Table 2 refers to the wall model condition, while the WR refers to the wall resolved condition. M1 and M4 refer to the finest and the coarsest mesh respectively.

Table 2. Number of grid cells expressed in millions of cells

Computational case	M1	M2	M3	M4
WM	9.85	6.74	4.31	2.91
WR	16.55	10.17	6.81	4.34

A special refinement is applied on the free-surface to capture the wave pattern. A cell size of 2% of the wave length is set in the x and y-direction and 0.1% L_{pp} in the z-direction. Fig. 4 shows the computational grids. Fig. 4 (a) shows the coarsest mesh configuration, while Fig. 4 (b) shows the finest grid and Fig. 4 (c) shows the refinement on the free-surface.

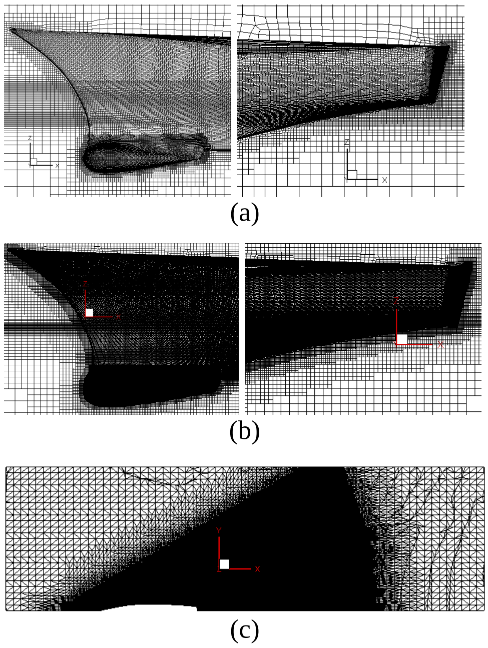

Fig. 4. Grid configuration: (a)- coarse mesh, (b)- fine mesh and (c)- free-surface mesh.

3. RESULTS AND DISCUSSION

The simulation solutions are split into three categories, i.e. the ship resistance, sinkage and trim and free-surface topology. They will be distinctly discussed in the following subsections.

3.1. RESISTANCE

Two sets of results for ship resistance computations are presented in this section. The first is concerned with the computations of the total ship resistance at three different velocities corresponding to Fn=0.1, 0.28 and 0.41. In these particular computations, only wall modeled approach is used. The second focuses on the effect of wall treatment on the results. This is computed only for the design velocity where Fn=0.28. The total ship resistance results for the first set of computations are drawn in Fig. 5. The results show a better accuracy level for the finest grid compared to the others, as expected.

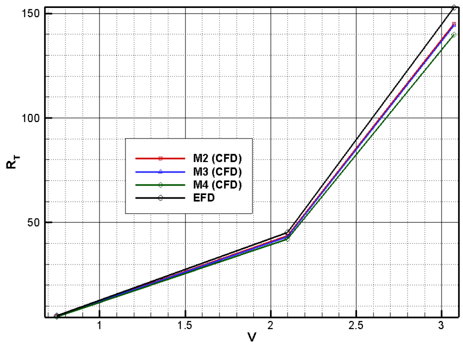

Fig. 5. Total resistance curve versus ship velocity comparison between CFD and EFD [7]

The error range and the parameters for the grid convergence study are tabulated in Table 3, where, ε_{12} is referring to solution change between grids M1 and M2, U_i is the iterative uncertainty rising from the iterative errors, P_g is the order of accuracy for a certain grid, $P_{g,th}$ is the theoretical order of accuracy for a certain grid which is dependent of the order of the convergence criteria, i.e. $P_{g,th}$=2.0 for a second order convergence criteria, U_g is the grid uncertainty established based on the grid errors, S_1 is the CFD value computed on the finest grid M1, U_D is the data uncertainty which is related to the error in the measured results and finally the U_V is the validation uncertainty which is used as an error limit to validate the computed results.

Table 3. Verification and validation parameters for the total resistance computations

Parameter	Fn		
	0.1	0.28	0.41
ε_{12}/S_1	1.5E-03	1.4E-03	5.4E-03
Ui/ε_{12}	0.0187	0.0148	0.058
$P_g/P_{g,th}$	0.855	0.76	1.67
$U_g\%S_1$	1.5	1.7	3.1
$S_1\%D$	3.84	3.23	5.02
$U_D\%D$	1.32	0.64	0.61
$U_V\%$	1.98	2.88	3.012

The verification study of the computed results shows a monotonic convergence. The difference between the CFD results between S_1 & S_2 is not significant; this resulted in the low grid order ratio. The iteration errors are not significant compared to the grid error for Fn=0.1 and 0.28, while for Fn=0.41 is relatively higher, this explains the high error in the computed value. This might require an extra computation on a finer grid to enhance the quality of the solution.

From the validation point of view, the study shows that the results exceeded the validation level U_V. This again imposes the need for a further investigation, though the values for Fn=0.28 can be validated within the U_V level if the factor of safety method imposed by Roache in [8] is used. Nevertheless, the error range for Fn=0.1 and 0.28 is still within a considerably accepted level, while for Fn=0.41 the error is within 5%, a value that is considerably high.

The wall treatment study shows a better accordance with the test results especially for the wall resolved case and for the finest grids in both cases, the error range compared to the EFD results is plotted against the total number of grid cells in Fig. 6.

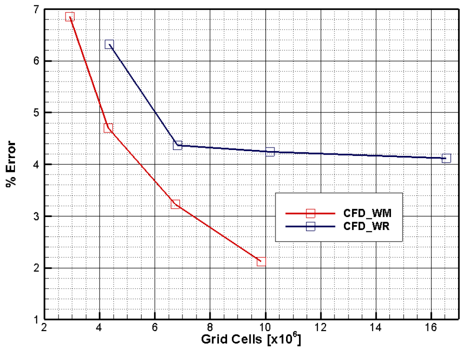

Fig. 6. Error in the total resistance computed for Fn=0.28 based on the wall condition

The error range is between 2.12 to 6.86 for the wall modeled method, while it ranges between 4.12 and 6.32 for the wall resolved. The figure shows a slight change in the error value between the solutions in the wall resolved for the three finest grids.

The convergence study for the wall treatment cases is tabulated in Table 4. The verification results showed monotonic convergence. Iteration errors seem to be slightly more significant in the wall resolved computations, while it seems to be less significant in the wall modeled ones. This might be related to the effect of turbulence in the boundary layer. The grid uncertainty is less significant for the wall resolved model in the first computational case. The reason behind this is related to the low difference ε between the computed values in the finest three grids.

Table 4. Verification and validation parameters for Fn=0.28 based on the wall treatment condition

Parameter	Wall modeled		Wall resolved	
	Mesh 1-3	Mesh 2-4	Mesh 1-3	Mesh 2-4
ε_{12}/S_1	1.13 E-03	1.4 E-03	1.3 E-03	1.38 E-03
Ui/ε_{12}	0.0104	0.015	0.031	0.025
$P_q/P_{q,th}$	0.68	0.76	1.05	1.87
$U_q\%S_1$	1.8	1.7	0.9	1.8
$S_1\%D$	2.12	3.23	4.12	4.24
$U_D\%D$	0.64	0.64	0.64	0.64
$U_V\%$	2.35	2.88	4.23	3.39

Comparing the error in the computed results with the verification uncertainty level U_V shows that the validation is achieved for only the finest grids in both approaches; either the wall modeled or wall resolved. Nevertheless, it did not achieve the U_V level in the other case due to the wide difference between the solutions, especially for the wall resolved approach.

Overall, the analysis of the results obtained in this study cannot withdraw a clear conclusion due to the fluctuation of the validation process between the two cases. An extra case might be necessary to help understanding more efficiently the convergence behavior.

3.2. SINKAGE AND TRIM

Sinkage and trim results showed a slightly minor effect of the wall treatment on the results. The detailed results and the corresponding error for every case are tabulated in Table 5.

Table 5. Sinkage and trim results

Sinkage					
Fn	EFD	CFD			
		M1	M2	M3	M4
0.1	0.174 E-03	N.A.	0.168 E-03	0.165 E-03	0.157 E-03
E%D			3.4	5.17	9.77
0.28 WM	1.82 E-03	1.83 E-03	1.83 E-03	1.835 E-03	1.84 E-03
E%D		0.55	0.55	0.82	1.1
0.28 WR		1.835 E-03	1.836 E-03	1.836 E-03	1.853 E-03
E%D		0.82	0.87	0.87	1.81
0.41	4.7 E-03	N.A.	4.28 E-03	4.16 E-03	4.15 E-03
E%D			8.9	11.4	11.7
Trim					
0.1	0.018	N.A.	0.0175	0.017	0.0163
E%D			2.8	7.7	9.4
0.28 WM	0.108	0.110	0.1107	0.113	0.113
E%D		1.85	2.5	4.63	4.63
0.28 WR		0.112	0.112	0.113	0.117
E%D		3.7	3.7	4.62	8.33
0.41	0.421	N.A.	0.416	0.415	0.396
E%D			1.18	1.42	5.94

For the sinkage solution, a high level of error is found for Fn=0.41 which is about 11.7. This may require a future investigation on a finer grid to understand the reason for this deviation. Another high value is recorded for the sinkage on the coarsest mesh of Fn=0.1; this could be related to refinement criteria for the free-surface which was chosen based on a higher Froude number, this tends to under predict the wave accurately, as it will be discussed later in the free-surface results. This under prediction of the wave magnitude fore and aft the ship changes the values for sinkage and trim based on which the results are computed.

As far as the trim solution is concerned, the accuracy of the solver is better compared to the sinkage results. Yet, the error range for Fn=0.1 case is quite significant. A special investigation is also required for the wall resolved case of the coarsest grids.

3.3. FREE-SURFACE FLOW

One of the most important issues in ship hydrodynamics is the free-surface geometry since it influences directly the wetted surface area of the ship based on which the ship resistance is calculated. Besides, errors in computed wave profiles may determine misleading judgments concerning other phenomena related to the flow, such as the wave breaking, trim and sinkage, stability and so on. For a validation reason, a comparison between the computed free-surface and the measured one is given in the following only for the Fn=0.28 case. Results are compared for the finest mesh against the towing results obtained in both [7] and [9]. Fig. 7 shows the free-surface topology comparison between computed results and test results.

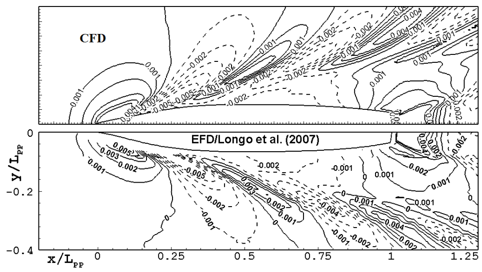

Fig. 7. Comparison between the free-surface shape computed for Fn=0.28 at T=30 sec and measured [9]

It is worth mentioning that the computed free-surface reveals not only a slight phase shift in respect to the measured elevation near the forward perpendicular and near the aft shoulders, but also a difference in the height of the crest fore and the trough aft. Seemingly this fact can be related to the insufficient number of cells used there, a fact which possibly suggest a higher grid refinement in that area. Obviously, this fact may be easily noticed in Fig. 8 which bears out a comparison between the computed and measured [9] wave cut at y/L_{pp}=0.082.

Similarly, comparisons between the wave cuts made at a distance of y/L_{PP}=0.172 is brought into focus in Fig. 9. The comparisons reveal a reasonable agreement of the computed solution with the experimental data [9], although the abovementioned phase shift and peak and trough deviation are still present.

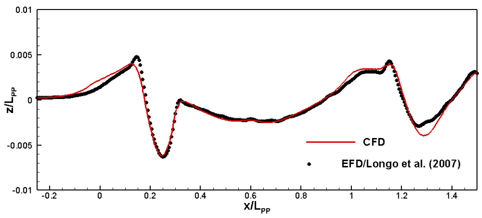

Fig. 8. Comparison between the wave elevation at y/L_{pp}=0.082 computed at T=30 sec and measured [9]

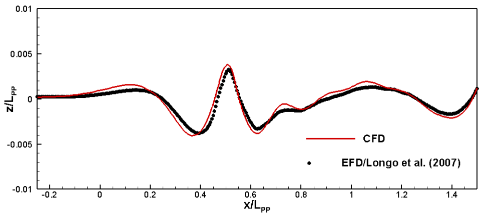

Fig. 9. Comparison between the wave elevation at y/L_{pp}=0.172 computed at T=30 sec and measured [9]

4. CONCLUDING REMARKS

The verification and validation study presented in this paper was performed on the ship resistance prediction of the DTMB 5415 ship model with a length between perpendiculars equals to 5.72 m. The simulation is performed for three different inflow velocity corresponding to Fn=0.1, 0.28 and 0.41 with two degrees of freedom considered in this computation including sinkage and trim. A special focus on the effect of the wall treatment is also presented only for the design velocity corresponding to Fn=0.28. For the same velocity, the free-surface is studied and compared with the tank test results.

Ship resistance computations were performed and presented in two different categories depending on the scope of the computations. The total ship resistance was computed for three different inflow velocities and compared with the tank test results revealing reasonable agreement with an error range between 3.84 and 5.02% compared to the tank test results. Consequently, the verification and validation study based on Richardson Extrapolation was performed and revealed the need of another computation on a finer grid to withdraw a clear conclusion about the success of the verification process. Validation of results showed that the computation error exceeded the verification level. Yet, the validation of the design velocity errors could reach the verification level if the factor of safety approach is applied.

The comparison of results for Fn=0.28 based on the wall condition was also presented and compared to the test results showing a reasonable agreement with an error range between 2.12 and 6.8 %. Verification and validation study based on the obtained results was conducted and showed that the error in the finest grids was less than the verification level in both case studies where the wall is either modelled or resolved. However, the error in the coarsest study exceeded the verification level. This returns us to the same conclusion that an extra fine mesh study might be necessary to judge the computations behaviour.

Sinkage and trim results showed a fluctuating behaviour from the accuracy point of view. The range of error was between 0.55 and 11.7 for sinkage, a fact that requires a special investigation to enhance the computation accuracy. On the other hand, the trim error range was between 1.18 and 9.4%. The high value is registered for the lowest Froude number where the numerical scheme might suffer accuracy to predict the minor changes in the flow for such low Froude numbers.

Free-surface flow comparison between the computed results and the measured free-surface showed a reasonable agreement in predicting the wave pattern. Yet, a phase shift in the wave profile is noticed with a slight change in the wave amplitude at the forward perpendicular and nearby the stern shoulders. This requires a special refinement of the mesh in that area.

Overall, the computed results seem to be promising for ship resistance computations and free-surface prediction. On the other hand, some predicted results for sinkage and trim seem to be unsatisfying and require accuracy enhancement. For the sake of drawing a clear conclusion about the convergence study, a further investigation seems to be necessary, especially if the results are going to be used as a foundation for the fully appended hull resistance for the same ship model.

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