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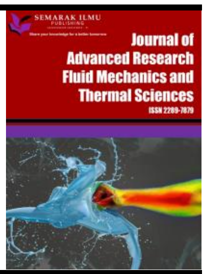

Comparative Investigation of Resistance Prediction for Surface Combatant Ship Model using CFD Modeling

Alaaeldeen Mohamed Elhadad Ahmed[1,*]

[1] Shipbuilding Engineering Department, Military Technical College, Cairo, Egypt

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ABSTRACT

The Multi-Mission Surface Combatant (MMSC) is a highly maneuverable combatant ship capable of littoral and open ocean operations. It was designed to confront modern maritime and economic security threats. The MMSC takes the proven capabilities of the littoral combat ship and the inherent flexibility of the Freedom-variant hull to meet the unique maritime requirements of international navies. Computational fluid dynamics (CFD) is applied to present a method to predict the resistance for new surface combatant ship. First, calculations for a typical benchmark DTMB 5415-24 model are carried out using three different mesh sizes for Froude numbers from 0.10 to 0.48 for the purpose of model validation by Star CCM$^+$. The numerical results are compared with the experimental data and the published CFD solutions in terms of wave field and resistance coefficients for accuracy of the solution parameters. Finally, the method is used to study the influence of Froude number variation on the total resistance and wave pattern for the new combatant ship model under the same conditions. Quantitative agreement between the numerical simulations has been observed. This demonstrates that our CFD model is capable of simulating the steady flow around a ship hull with an acceptable accuracy and thus can be used as a complementary tool to laboratory model tests for ship design and ship hydrodynamic research.

1. Introduction

Surface combatant are a significant sector in naval vessels that are built for surface warfare with their own weapons and armed forces. They are large, heavily armed surface ships, including various types of battleships, battlecruisers, cruisers, destroyers, frigates, and corvettes. They are primarily intended to engage with surface, and submerged targets by deploying weapons from the ship rather than by manned carried craft [1]. They can carry out other missions, including, counter-narcotics operations and maritime interdiction. The development of new military abilities to confront potential threats or upgrade the existing capabilities urged the design and construction of new naval warships.

* *Corresponding author.*
E-mail address: dr.aladdinahmed@gmail.com

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This study aims to introduce a flexible and applicable method to utilize CFD calculations to predict model resistance in the early design stage. CFD was applied to high performance hull form types to determine local flow details, optimize a given design, and select the most promising candidates for further testing [2].

Firstly, the free surface flow around the DTMB 5415-24 model was calculated on various Froude number cases and verified with the experimental data of the model. Furthermore, a numerical estimate of the effect of Froude number on wave pattern and total resistance for the new ship model was calculated and compared with confirmed validated data of the model [3].

In this paper, we introduce a method to estimate the hull model resistance and powering, as well as the flow field surrounding a new combatant hull model, by using the Star CCM+ as a primary step for production of a validated ship model in order to carry out additional experimental investigation in the towing tank [4,5].

2. Mathematical Model and Governing Equations

The incompressible, viscous turbulent flow field and two-phases (air and water) are governed by the RANS equations:

$$\frac{\partial Ui}{\partial xi} = 0 \tag{1}$$

$$\frac{\partial \mathrm{u_i}}{\partial \mathrm{t}} + \mathrm{u_i}\frac{\partial \mathrm{u_i}}{\partial \mathrm{x_j}} = -\frac{1}{\rho}\left(\frac{\partial \mathrm{P}}{\partial \mathrm{x_i}}\right) + \nu\frac{\partial^2 \mathrm{u_i}}{\partial \mathrm{x_j^2}} - \frac{\partial \overline{\mathrm{u_i'u_j'}}}{\partial \mathrm{x_j}}. \tag{2}$$

where i, j = 1, 2 and x_1, x_2 denote the horizontal and the vertical dimensions, respectively, u_1 and u_2 are the corresponding to the mean velocity components, $\overline{u_i'u_j'}$ defines the Reynolds stress component with u_i' being the fluctuating part of the velocity, p and ρ represents the dynamic pressure and the fluid density.

SST k-ω model was applied to compute the turbulent viscosity meanwhile the multiphase free-surface flow is simulated by the VOF method. Due to the Boussinesq approximation, the component of Reynolds stress was defined by a turbulent viscosity, ν_T, and the mean flow gradients as follows:

$$-\overline{u_i'u_j'} = \nu_T\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij} \tag{3}$$

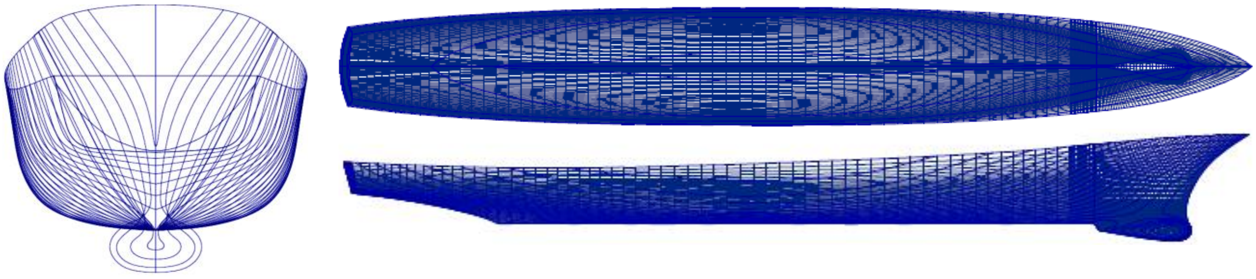
δ_{ij} and k are the Kronecker delta function, and turbulent kinetic energy respectively.

A three-dimensional numerical simulation was performed for the flow past the model [6]. The numerical simulations were predicted by a two-layer form, developed by Star CCM+ software. The fluid domain is partitioned into a finite number of cells, and the governing equations for fluid flow are then converted by a discretion process into algebraic form to be solved. Using a straightforward technique, the pressure and velocity fields were coupled [7,8].

3. Grid Generation, Solution Domain and Boundary Conditions

In this study, choosing a realistic hull model is a crucial step. A very well-known test model, surface combatant DTMB model 5415-24, is mathematically specified with an analytical description. This combatant hull is typically seen as a preferred test sample to verify a new numerical approach.

The combatant ship model's hull shape, grid structure, properties, and profile, which correspond to a scale of 24.824, are listed in Figure 1 and Table 1 [9].



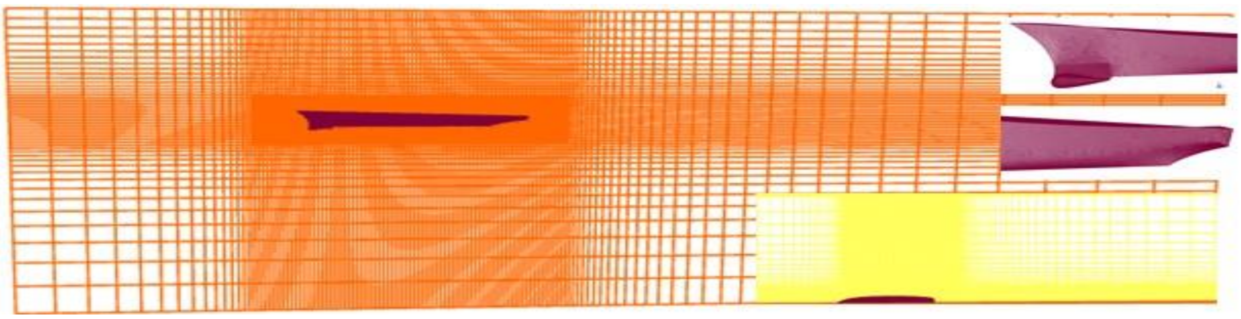
(a) (b)

Fig. 1. (a) Lines plan (b) Numerical grid of DTMB 5415-24 hull surface

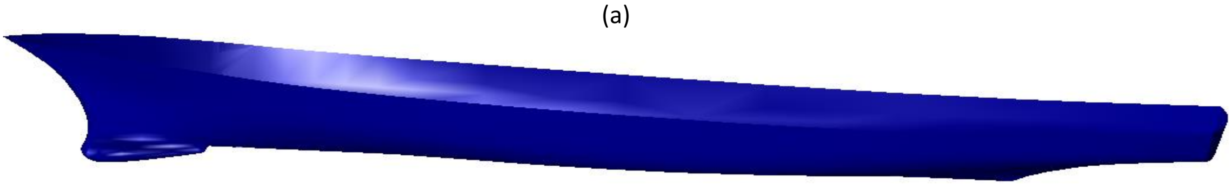
Table 1
Main particulars of DTMB #5415

L_{pp} (m)	5.72	LCG (m)	2.884
B (m)	0.760	VCG (m)	0.056
T (m)	0.248	Wetted Surface Area (S) (m^2)	4.786
Δ (tonne)	0.549	Block Coefficient (C_B)	0.506

The hull mesh domain is separated into the water and air zones with rectangular form. The x-axis is set up to point toward the bow, the y-axis to portside, and the z-axis is configured to point upward in the Cartesian coordinate system. The downstream and upstream limits are situated three and one hull length from the stern and bow, respectively [10]. The air zone is half a model length above the water's surface, while the water zone is one model length deep. Both zones' widths are assumed to be equal to one hull length. To create a structured multi-block grid, the domain volume is divided into several sub volumes [11,12]. The grids at the free surface and near the model are refined in order to get better resolution of free-surface elevation in the area of importance and improve the boundary layer approximation [13]. According to Figure 2, the minimum grid spacing of the hull wall is 1×10^{-3} L_{PP}.



(a)



(b)

Fig. 2. (a) Hull domain volume; (b) DTMB 5415-24 Model geometry

While the flow velocity is taken to be equal to the experimental velocity of the model, the inlet and outlet boundary conditions upstream and downstream are taken as velocity inlet and pressure-outlet with an open channel, respectively [14]. On all surfaces, a no-slip wall boundary requirement is applied. The symmetric plane invokes the symmetry requirement. Froude numbers ranging from 0.1 to 0.48 were separately computed for various cases. The time step is $\Delta t = 0.0001$ s [15].

A new model ship moving forward was simulated in the current investigation. According to ship sisters used by ITTC, a contemporary naval combatant surface ship with no bulbous bow was chosen as a recommended model for CFD validation for resistance and propulsion. Table 2 and Figure 3 and Figure 4 exhibit the main attributes and primary dimensions of this model. Water density is 999.8 kg/m^3.

Table 2
Characteristics of hull model

Description	Units	Dimensions	Description	Units	Dimensions
Length between PP.	L_{pp} (m)	5.72	wetted Surface Area	S (m^2)	4.998
maximum breadth	B (m)	0.911	volume of displacement	∇ (m^3)	0.571
maximum draft	T (m)	0.235	block coefficient	C_B	0.465
Longitudinal CG	LCG (m)	2.258	kinematic Viscosity	(m^2 /sec)	1.2845*10-6

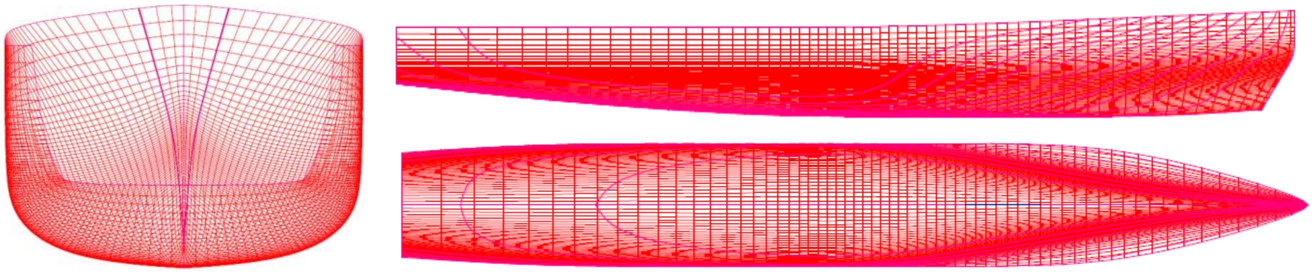


Fig. 3. Lines plan of the hull model

Fig. 4. 3 D hull model

The new model's resistance was calculated using different grid sizes using the same mesh, boundary conditions, and solution methodologies as the well-known DTMB 5415-24, and Star CCM+ results were compared to ensure competency with CFD theory [16].

Three main processes are necessary for a CFD solution: processing, problem analysis, and post-processing of the outcomes [17]. In our work, the suitable mesh production is combined with the development of the hull geometry as the solution. Figure 5 and Figure 6 depict the locations of the ship models in relation to the different limits of the solution domain as well as an overall view of the mesh surrounding the ship model [18]. For the flow computations, half of the new model according to the hull symmetry was employed. Three mesh sizes were investigated in this study; the total number of elements for coarse, medium, and fine grids, respectively, were 0.92, 1.37, and 1.97 M.

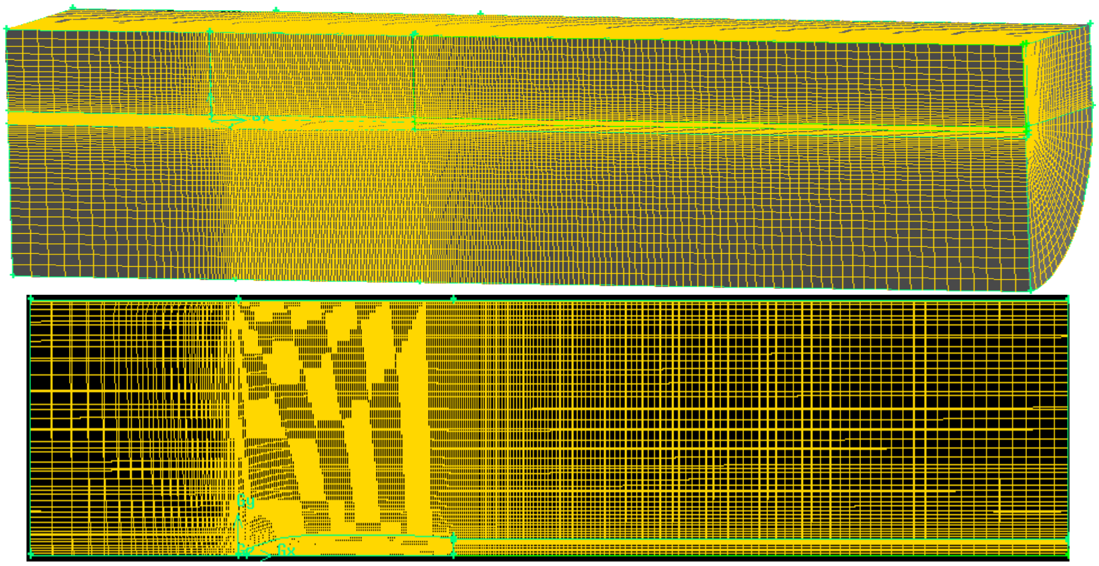
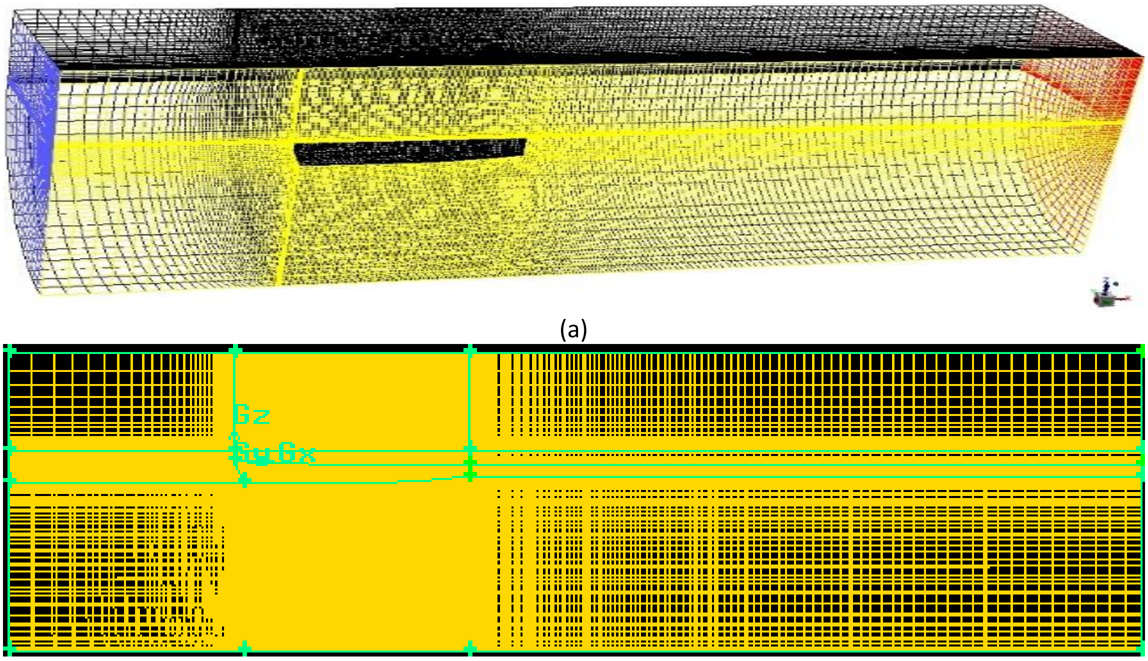


Fig. 5. Hull meshed domain volume



(a)

(b)

Fig. 6. (a) Solution domain (b) Overall view of the mesh around the model ship

In this study, the Reynolds-averaged Naiver-Stokes (RANS) equations are solved using the finite-volume method on hybrid structured grids using the Star CCM+. Gravity effects must be included in boundary conditions because the motion of the free-surface is controlled by gravitational and inertial forces. The computations make use of the SST k-ω with conventional coefficients. Monitoring the residuals of continuity, velocity, turbulence, volume fraction, and drag force allows for the assessment of the solution's convergence. The residual convergence criterion was taken as $1e^{-07}$ [19,20].

4. Resistance Calculations

The DTMB 5415-24 total resistance was estimated. The experimental results from the ITTC and towing tank experiments, which are mentioned in Figure 7, were compared with the results for the three grids that are performed for different Froude numbers ranging from 0.10 to 0.48 [21,22]. The numerical calculation results of ship resistance with automatic running attitude adjustment are displayed in Figure 8. The discrepancy between calculations and experiment findings is determined to be in good agreement, with an error of less than 4% where the difference is:

$$\Delta R_T\% = (R_T^{StarCCM+} - R_T^{exp}) / R_T^{exp}. \quad (5)$$

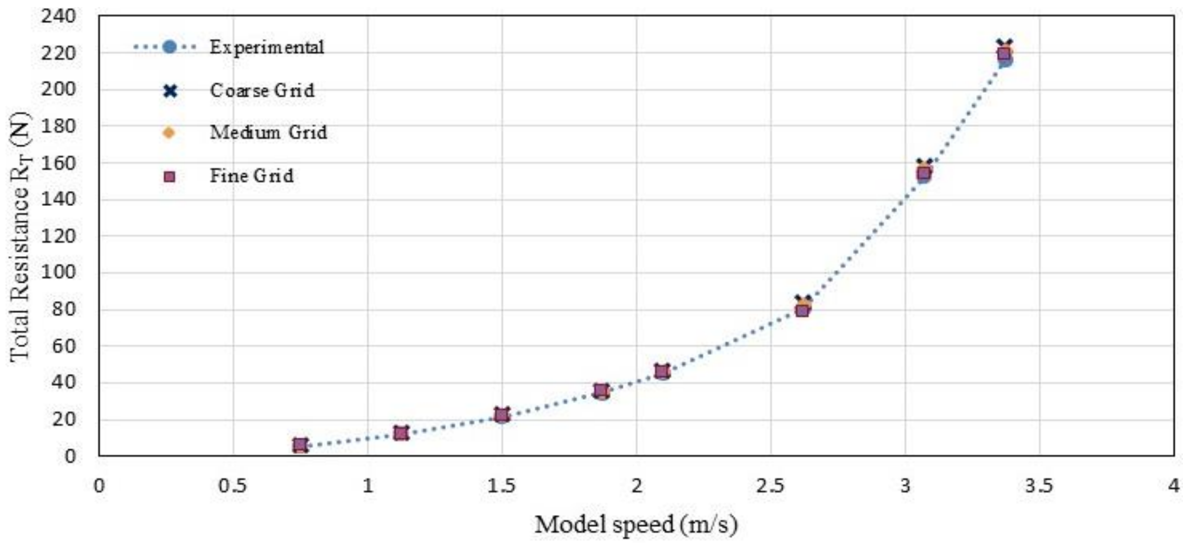


Fig. 7. Resistance curve for DTMB 5415-24 comparing three different sized grids

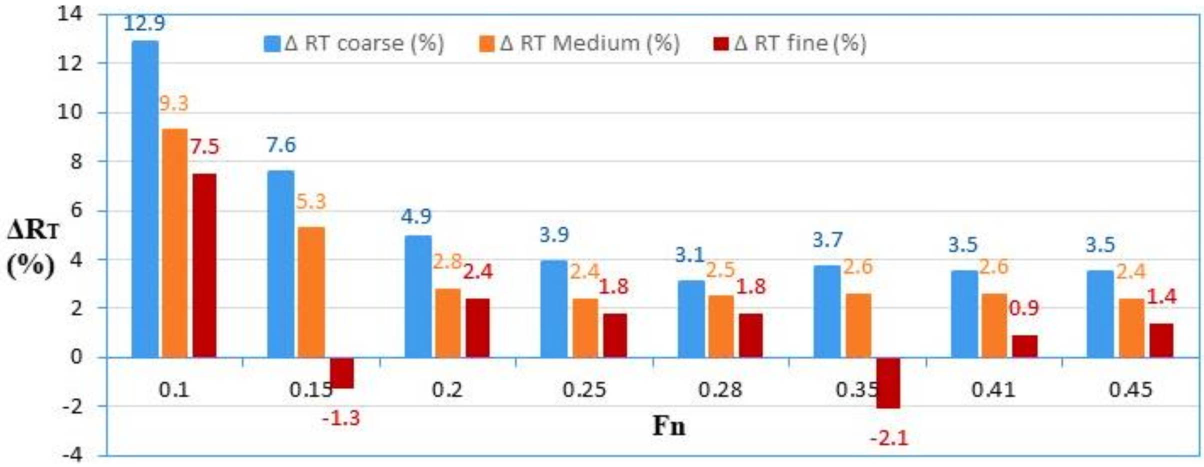


Fig. 8. The comparison of experimental and CFD results for DTMB 5415-24

In light of the mesh generation method's applicability and the close agreement between the numerical predictions, it can be concluded that resistance prediction can be accomplished using the entire numerical scheme. The results for the coarse and medium grids are quite similar, and the difference between the medium and fine grids is comparatively bigger but still tolerably acceptable. As a result, the fine grid fits the computations best and produces the most relevant results. The same mesh generation technique may also be used to evaluate the hydrodynamic performances of the new combatant ship model with no bulbous bow using Star CCM+.

A second phase involved utilizing CFD to determine the new combatant ship model's resistance in comparison to Froude numbers ranging from 0.10 to 0.48 under identical conditions, as illustrated in Figure 9 where the values were compared also to Maxsurf results. The total and residual resistance at Fn 0.45 and the total and frictional resistance coefficients (C_{TM} and C_F) for the estimated data are shown in Figure 10 and Figure 11 respectively. For Three different mesh sizes were employed in the CFD mesh analysis to assess the hydrodynamic performances. To evaluate the convergence of the solution, the calculated drag on the hull was noted and plotted. The differences = (medium - coarse) / (fine - medium), where $0 < \varepsilon < 1$ are minor and acceptable, also in very close agreement with the results of the coarse, medium, and fine grids, as in Table 3 [23].

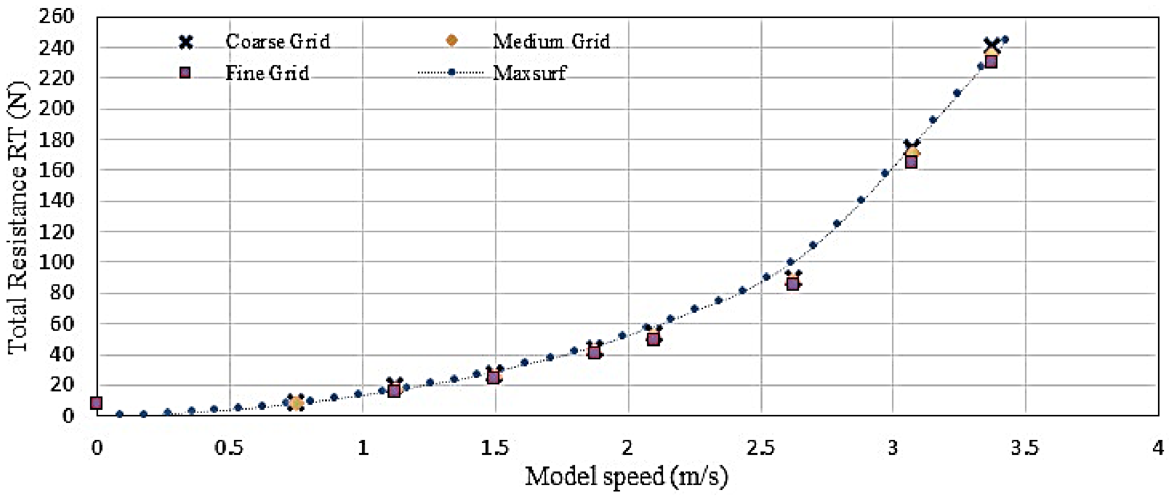


Fig. 9. Resistance curve for new combatant hull model at three different sized grids

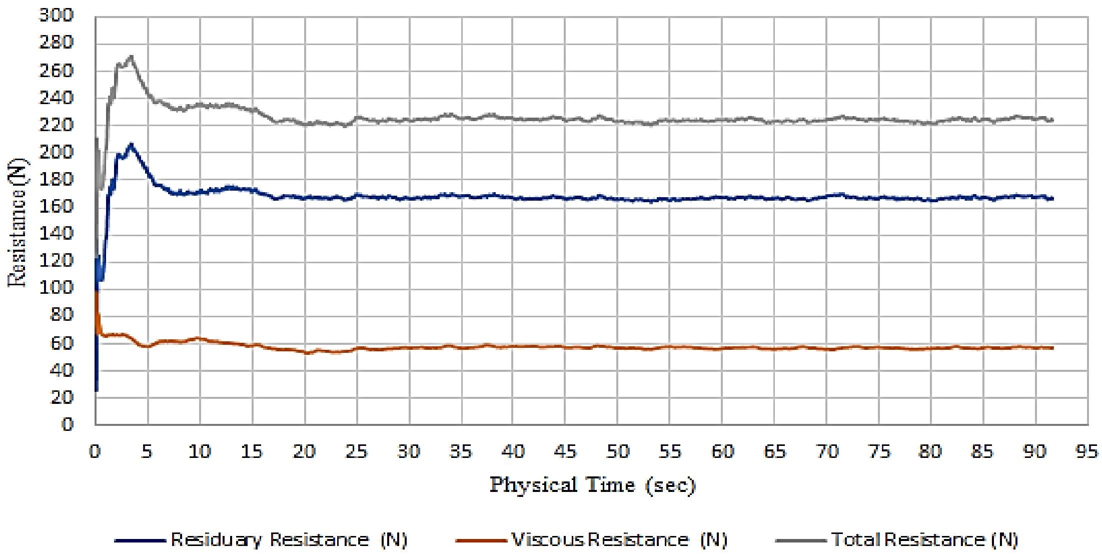


Fig. 10. Resistance plot for new combatant hull model at Fn 0.45 at fine grid

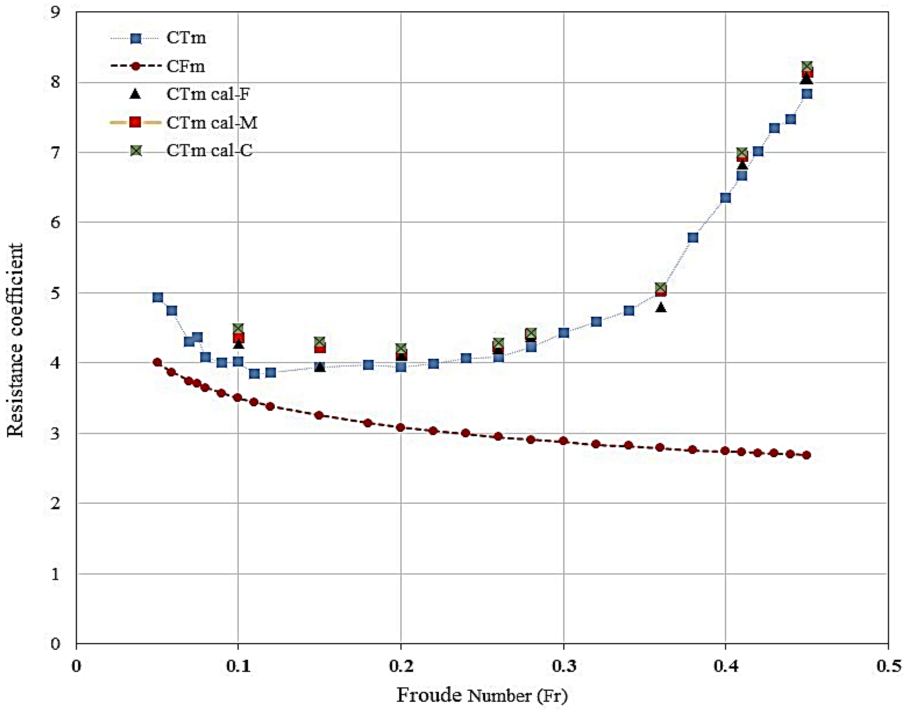


Fig. 11. The curves of total and frictional resistance coefficients C_{TM} and C_{FM}

Table 3
The CFD results for new combatant ship model

F_n	0.10	0.15	0.20	0.25	0.28	0.35	0.41	0.45
R_T (N) (C)	9.12	19.65	27.1	44.12	53.89	89.34	175.15	240.65
R_T (N)(M)	8.56	17.47	26.32	42.15	51.66	87.45	170.35	235.26
R_T (N) (F)	7.32	15.25	24.68	40.12	49.33	85.55	165.19	229.75
Difference ε	0.45161	0.98198	0.47561	0.97044	0.95708	0.99474	0.93023	0.97822

In order to evaluate a mesh generation method under the same conditions and find a method to evaluate the combatant ship resistance calculations, the numerical predictions of DTMB 5415-24 and the new hull model without bulbous bow are compared in this work as illustrated in Figure 12.

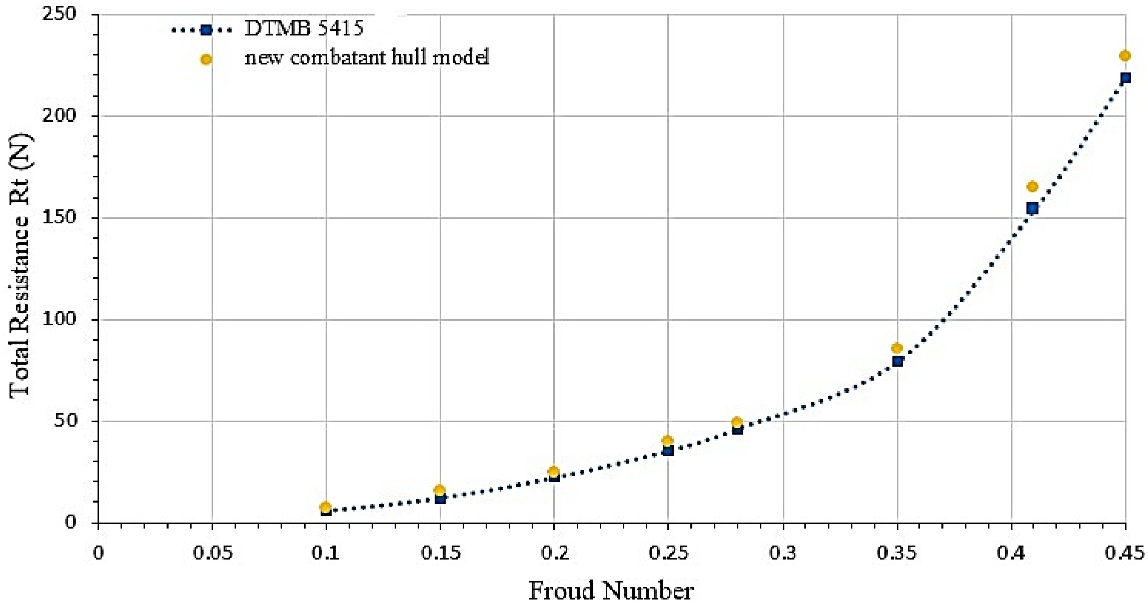


Fig. 12. Resistance results of the two hull models

The difference in total resistance between the two hulls is often acceptable for mesh investigation. The grid's results show excellent agreement. The expected resistance differs only slightly and by the same order of magnitude. As a result, the total numerical approach can be used to predict resistance.

Since convergent results are produced as the mesh size decreases, the fine grid is the one that will be used for the other hulls based on the grid results. It also fits the computation and displays the most relevant results. Finally, Figure 13 and Figure 14 illustrate the contours for the free surface wave for the two hull models at various Froude numbers.

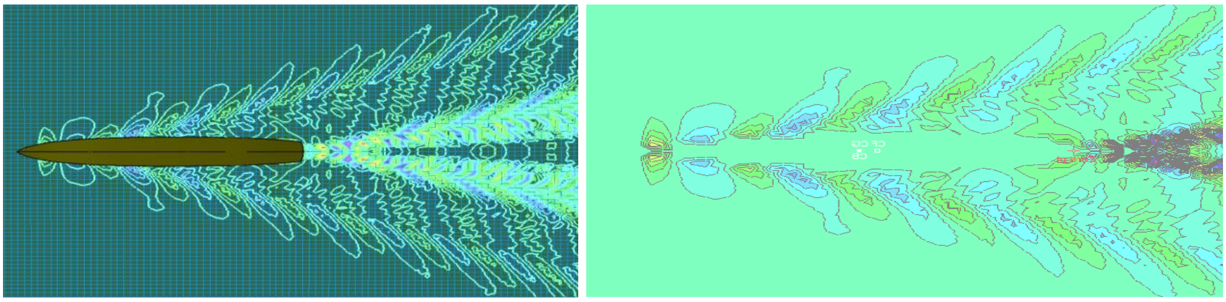


Fig. 13. Free surface wave contours for DTMB 5415-24 at Fn = 0.38 - coarse grid

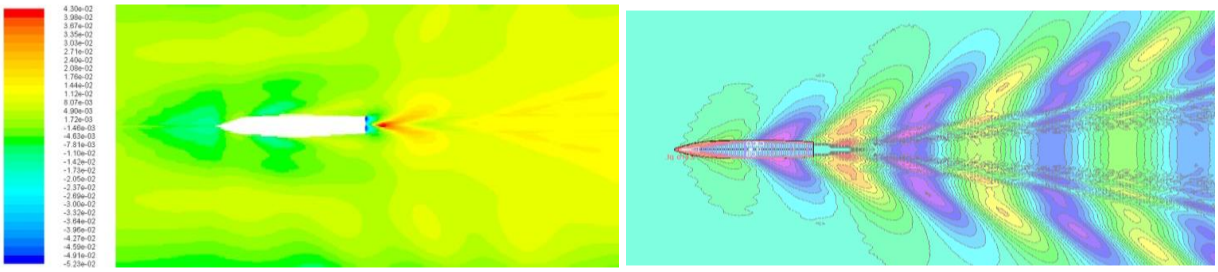


Fig. 14. Free surface wave contours for at Fn = 0.40 - medium grid

5. Conclusion

An important portion of the current data set has been cross-validated using DTMB experimental results, with extremely positive results. The hull simulations for DTMB 5415-24 are within acceptable accuracy according to extensive comparisons between Star CCM+ calculations and the ITTC and experimental results. The method used is also acceptable, and the mesh generation method can be used to estimate the hydrodynamic performances for the model on the new combatant ship.

The fine grid is adapted to the calculation and shows the most appropriate results. The resistance calculations of the new combatant ship exhibited better performance than the DTMB under the same conditions by providing better hydrodynamic performances. The new hull model provides a promising test model for experimental investigation.

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