MEng Project Report

Verification and Validation of Numerical Modelling of DTMB 5415 in Head Wave Condition

by

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Contents

1 Abstract

This report presents a comprehensive study on the verification and validation of numerical modeling for the DTMB 5415 ship model under head wave conditions using SimFlow. The research focuses on accurately simulating the vertical shear forces experienced by the ship. The study systematically compares the simulation results with experimental data, specifically those obtained from a 1/51 scale model as documented by Begovic et al., to assess the percentage error and the efficacy of the numerical model. A detailed sensitivity analysis is conducted to evaluate the impact of mesh refinement near the ship model on the accuracy of the results. The findings highlight the critical importance of mesh configuration in CFD simulations, demonstrating that refined meshes significantly improve the predictive accuracy of vertical shear forces. This study contributes to advancing the reliability of numerical simulations in naval architecture, offering a validated framework for future applications in ship design and analysis.

2 Introduction

2.1 Introduction of DTMB5415

The model employed in this study is the David Taylor Model Basin (DTMB 5415), which serves as a critical benchmark in naval hydrodynamic research. Originally conceived as a preliminary design for a U.S. Navy surface combatant in the early 1980s, the DTMB 5415 has been extensively utilized in both experimental and computational studies due to its representative features of modern naval vessels.

It is important to note that the DTMB 5415 is a scale model, with no full-scale vessel existing based on this design. However, its comprehensive design, coupled with detailed geometric data and loading conditions availability, makes it an invaluable tool for the validation and verification of numerical simulations in naval architecture. Specific geometry specifications of the 1/24 model utilized in this study are detailed in the Appendix A.

Figure 1: DTMB 5415

The DTMB 5415 model holds a prominent position in naval architecture and hydrodynamics due to its extensive use in both experimental and computational studies. Since its conception in the early 1980s, the DTMB 5415 has been the subject of numerous research initiatives aimed at understanding the hydrodynamic performance of naval vessels [1]. Its significance is largely attributed to its detailed geometric design, which captures key features of modern naval combatants, making it an ideal candidate for testing and validation purposes.

The model's simple yet comprehensive geometry, coupled with complex hydrodynamic features such as the sonar dome and transom stern, allows it to serve as a versatile benchmark for validating numerical methods in ship hydrodynamics. Researchers and engineers frequently utilize the DTMB 5415 to verify the accuracy of computational fluid dynamics (CFD) simulations, particularly in scenarios involving wave resistance, propulsion efficiency, and flow behavior around complex hull shapes[1]. The extensive experimental data available for this model further enhances its value, providing a reliable reference against which numerical models can be calibrated and validated. Consequently, the DTMB 5415 has become a cornerstone in advancing the accuracy and reliability of hydrodynamic simulations.

2.2 Importance of Numerical Modeling

Numerical simulation, particularly using Computational Fluid Dynamics (CFD) software, is a crucial tool in the field of naval architecture and hydrodynamics. It allows engineers to predict the performance of ships under various sea conditions by analyzing fluid flow around the ship's hull. SimFlow, which leverages the powerful OpenFOAM® libraries, provides a user-friendly interface for setting up and running these simulations. By solving the Navier-Stokes equations, SimFlow enables detailed analysis of complex flow phenomena that are challenging to replicate experimentally. In the context of ship performance, CFD simulations help evaluate factors such as wave resistance, propulsion efficiency, and wave-ship interactions, all of which are critical for optimizing design and ensuring safety.

SimFlow is particularly well-suited for modeling the DTMB 5415 in head wave conditions due to its robust capabilities. The software allows for efficient handling of large-scale simulations. Additionally, its integration with OpenFOAM® ensures that the solvers used in SimFlow are both accurate and efficient, enabling the simulation of fluid-structure interactions that are critical when analyzing ship performance in challenging sea conditions.

While traditional experimental methods, such as towing tank tests, provide valuable empirical data, they often come with significant limitations, including high costs, time consumption, and difficulties in replicating certain sea conditions. Numerical simulations using SimFlow offer a complementary approach, enabling the exploration of multiple scenarios and conditions that might be impractical or impossible to test experimentally. Moreover, SimFlow allows for detailed analysis at a lower cost, with the flexibility to modify parameters and refine the model iteratively, leading to more comprehensive and accurate results. This ability to simulate a wide range of conditions efficiently makes SimFlow an invaluable tool in the design and analysis of naval vessels. Hence, the numerical simualtion in this study will be conducted in SimFlow.

2.3 Problem Statement

2.3.1 Challenges in Modeling Head Wave Conditions

Accurately simulating head wave conditions for ships like the DTMB 5415 presents significant challenges in numerical modeling. Head waves induce complex flow patterns, including wave-breaking and turbulent interactions, which are difficult to capture with high precision. One of the primary difficulties lies in the accurate representation of free surface effects and their interaction with the ship's hull, particularly in regions like the transom stern and sonar dome. These challenges are further compounded by the need to balance computational efficiency with the fidelity of the simulation. Achieving reliable verification and validation of these simulations is essential, as even minor discrepancies in modeling can lead to significant errors in predicting ship performance, particularly in wave-induced motions and resistance.

2.3.2 Relevance of Verification and Validation

Verification and validation (V&V) are critical components of numerical modeling, ensuring that simulation results are both accurate and reliable, the reference of V&V for this study is [2]. Verification involves checking that the numerical model correctly implements the intended algorithms, while validation compares the simulation outcomes with experimental or real-world data to assess their accuracy. In the context of modeling the DTMB 5415 in head wave conditions, V&V is crucial for establishing confidence in the results. Without rigorous V&V, the predictions made by numerical models could be misleading, potentially leading to flawed designs or unsafe operational guidelines. Therefore, the focus of this study on V&V serves to bridge the gap between theoretical modeling and practical application, providing a solid foundation for the use of SimFlow in naval architecture.

2.4 Primary Objective

The primary objective of this study is to verify and validate the numerical modeling of the DTMB 5415 in head wave conditions using SimFlow. This verification and validation process is crucial to ensuring that the numerical simulations accurately represent the physical phenomena observed in real-world scenarios, thereby providing reliable data for further analysis and application.

2.4.1 Specific Goals

To achieve this primary objective, the study focuses on several specific goals:

- **Comparison with Experimental Data**: Conduct a detailed comparison between the simulation results obtained from SimFlow and the available experimental data, particularly in terms of vertical shear force.
- **Sensitivity Analysis**: Perform a sensitivity analysis to determine the impact of various simulation parameters, such as mesh size, on the accuracy and stability of the results.

2.5 Significance of the Study

The determination of hydrodynamic loads and the assessment of structural responses are critical components of sound design procedure for ship and offshore structure design[3]. Meanwhile, accurate predictions of these loads are essential for ensuring the safety and performance of vessels under various sea conditions. As highlighted by Hirdaris et al. [4], there is an increasing emphasis on the accurate prediction of hydrodynamic loads, reflected in the growing body of peer-reviewed research on wave-induced load computation. This research encompasses specialized topics such as slamming, sloshing, fatigue loads, and the uncertainties associated with wave load modeling.

The complexity of wave load prediction methods ranges from basic potential flow theory to advanced nonlinear approaches, such as Reynolds-Averaged Navier-Stokes (RANS) CFD simulations. The findings from this study, which focus on the verification and validation of the DTMB 5415 in head wave conditions, contribute directly to this area by enhancing the reliability of CFD-based load predictions.

By improving the accuracy of numerical models, this research supports more precise assessments of ship behavior, thereby contributing to safer and more efficient ship designs. The methodology developed here can be applied across a range of naval vessels, facilitating more effective design processes and potentially reducing the need for costly experimental testing.

2.6 Scope

The scope of this study is primarily focused on the verification and validation of numerical modeling of the DTMB 5415 under head wave conditions using SimFlow. This study does not cover the full spectrum of wave conditions that a naval vessel might encounter, such as beam or following seas. Moreover, the research does not consider alternative computational fluid dynamics (CFD) software packages other than SimFlow. Additionally, the focus is exclusively on numerical simulations, with no experimental data collection conducted as part of this research. The validation relies on pre-existing experimental data rather than new physical experiments.

3 Literature Review

3.1 Review of Existing Research

Wave loads on ships can be predicted using either experimental or numerical methods, both of which have seen significant advancements. Early research into wave-induced vertical bending moments (VBM) on ships, particularly those with small block coefficients like container ships, naval vessels, and passenger ships, revealed the complexity of these phenomena. Pioneering experiments by Watanabe et al. [5] and O'Dea et al. [6], conducted using the S-175 ITTC container ship model, demonstrated the presence of second-order harmonics in VBM and highlighted the impact of wave steepness on the first harmonic and phase angle. These studies laid the groundwork for understanding the nonlinear behavior of ships in wave conditions.

Building on this foundation, Fonseca and Guedes Soares [7] introduced a partly-nonlinear time domain method that accounts for nonlinear hydrostatic restoring forces and Froude-Krylov forces, considering the ship's instantaneous wetted surface. Their method, validated against experimental data, effectively captured the nonlinearities in ship motions and VBMs. Further studies by the same authors [8, 9] expanded on this work, focusing on the ITTC S-175 container ship in both regular and irregular waves. Their findings underscored the significant influence of wave amplitude on the nonlinear characteristics of ship responses, including absolute and relative motions, vertical accelerations, and cross-sectional loads.

Song et al. [10] extended this research by validating a weakly nonlinear 3D time domain Rankine panel method on a segmented model of a 6500 TEU container ship. Their results emphasized the importance of nonlinear effects, particularly at larger wave amplitudes, with vertical loads showing better agreement with experimental data compared to horizontal and torsional loads.

Kukkanen and Matusiak [11] developed a nonlinear time domain method using Green's functions to predict hull girder loads for RoPax vessels. While their numerical predictions showed good agreement with experimental data, their study did not extensively explore the effects of varying wave heights, leaving room for further investigation.

Zhu and Moan [12, 13] conducted extensive model tests on ultra-large containerships, focusing on the nonlinear vertical responses in severe sea states. Their work revealed that in irregular waves, motion peaks and troughs generally followed a Rayleigh distribution, though the expected asymmetries between positive and negative peaks were less pronounced. This highlighted the need for further refinement of empirical formulas and numerical tools to more accurately capture nonlinear effects in ship responses.

3.2 Identification of Gaps

Despite the substantial progress made in understanding nonlinear hydrodynamic loads, several gaps remain in the literature. While previous studies have extensively investigated the effects of wave amplitude on ship responses, there is limited research on the vertical shear forces acting on naval vessels like the DTMB 5415 in head wave conditions. Additionally, while nonlinear effects on VBM and vertical accelerations have been well-documented, the influence of varying wave heights on vertical shear forces remains underexplored. This gap is particularly relevant for the verification and validation of numerical models using advanced CFD methods.

4 Methodology

4.1 Research Design

This study employs a quantitative research design focused on verifying and validating numerical simulations of the 1/24 DTMB 5415 ship model under head wave conditions using SimFlow. The research is guided by established theories and methods, incorporating comparative analysis to assess the accuracy of CFD simulations against existing experimental data in [2].

4.2 Computational Domain Configuration & Boundary Conditions

The computational domain is constructed in dimensions of 20 meters by 6 meters by 6 meters in xyz coordinates system as shown below as well as the boundaris. 3D views of the domain is

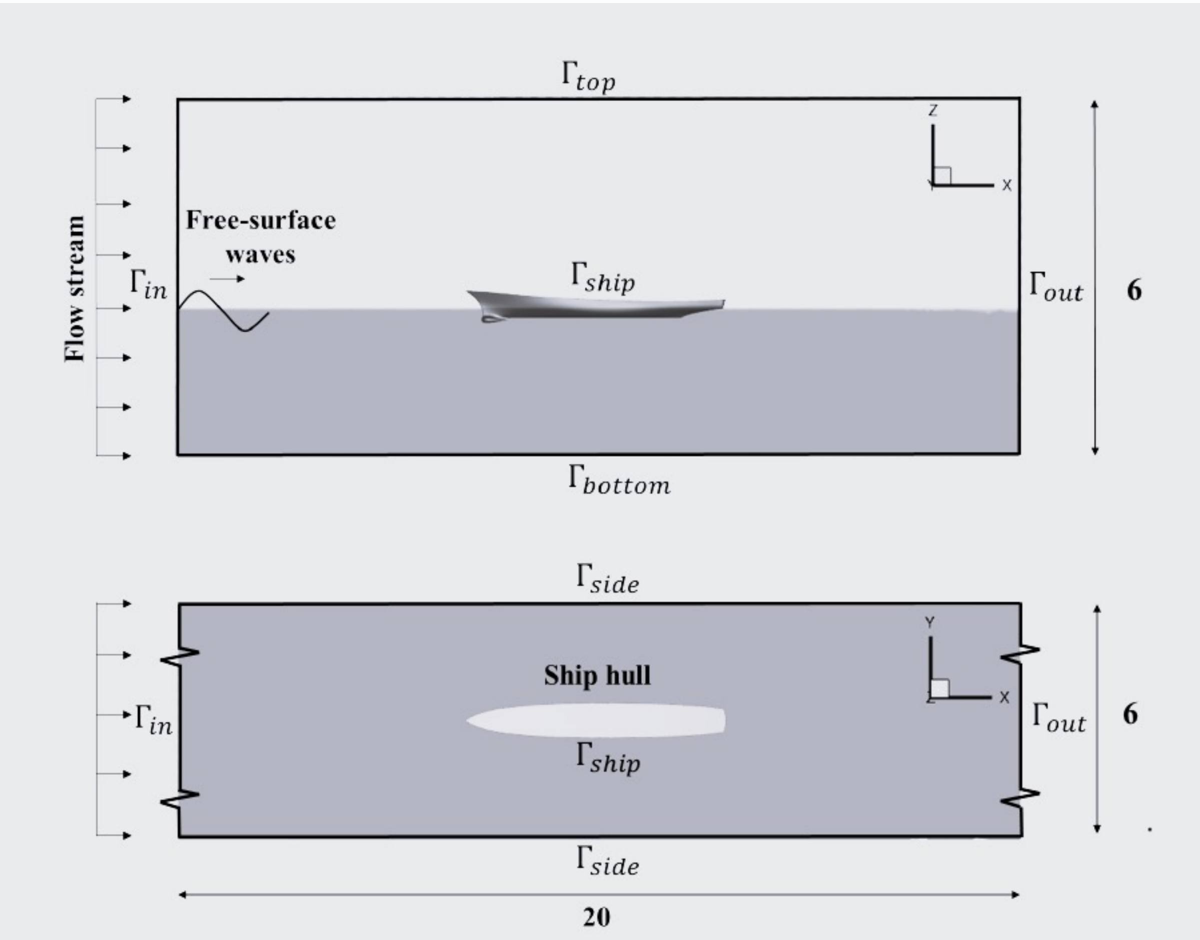

Figure 2: Computation Domain Configuration

provided in Appendix B.

The inlet boundary Γ_{in} is exposed to the second order Stokes' waves given by the formula procvided in Appendix C. The side boundaries Γ_{side} and the bottom boundary Γ_{bottom} are modeled with slip boundary conditions, No slip boudary is satified on the surface of the ship Γ_{ship}. Atmospheric condition of $p = 0$ is satisfied at the top boundary Γ_{top}.

4.3 Mesh

The computational domain mesh is predominantly coarse, but it is refined in the region through which the waves propagate to better capture the wave motion. Additionally, the mesh is further refined in the area surrounding the ship model to accurately simulate the forces acting on the vessel. For clarity in displaying the mesh, only the 2D mesh elements are rendered and presented below in Figure 3. And the mesh convergence tests are conducted on the difference mesh refinement conditions near the ship model.

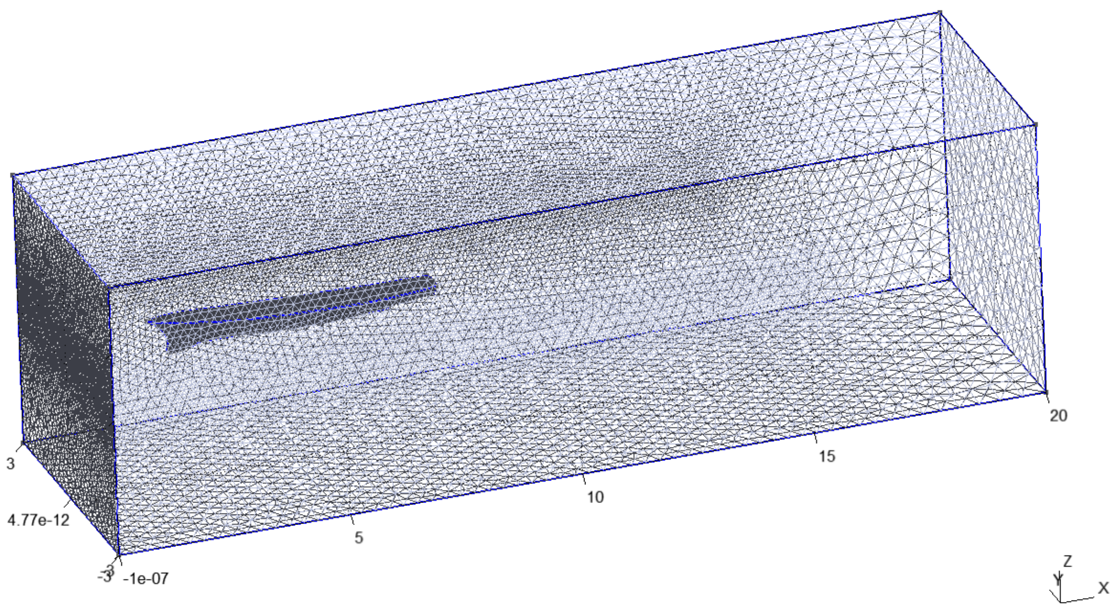

Figure 3: Computation Domain Configuration

Orthographs of the mesh in three direction and a 3D view of the mesh are provided in Appendix D.

4.4 Simulation Parameters

The physical properties of water and air are used for the two fluid phases, where $\rho_1 = 1000$ kg/m^3, $\nu_1 = 1.002 \times 10^{-3}$ m^2/s, $\rho_2 = 1.225$ kg/m^3, and $\nu_2 = 1.983 \times 10^{-5}$ m^2/s. The acceleration due to gravity is given by $\mathbf{g} = (0, 0, -9.81)$ m/s^2.

For the incoming second order Stokes' wave, in order to be comparable with the experimental data in figure 20a in [2], the wave length is set to be equal to the overall length of the 1/24 DTMB ship model, wave height is 1/50 of the wavelength, and the wave period is 1.34 second.

4.5 Data Collection Methods

Data were obtained through numerical simulations in SimFlow, with the output generated as a .oisd file containing the time-step readings of vertical shear force. Pre-existing experimental data, as documented by Begovic et al. [2], served as benchmarks for validation, ensuring that the simulation results were accurately compared.

4.6 Data Analysis

Data analysis was conducted to evaluate the non-dimensional vertical shear forces using a MATLAB script, which is provided in Appendix E. The results obtained from SimFlow were compared with experimental data to calculate the percentage error of the non-dimensional vertical shear force. Additionally, a sensitivity analysis was performed to assess the influence of varying mesh sizes in proximity to the ship model on the percentage error.

5 Result & Validation

Using the 1/24 scale DTMB 5415 ship model, this study reports a nondimensional vertical shear force (VSF) of 0.0272 under the wave conditions specified in Section 4.4, calculated using the formula $VSF = \frac{F}{\rho g L_{OA} B_{OA} A}$. In comparison, the study by Begovic et al. [2] utilized a 1/51 scale DTMB 5415 ship model and reported a VSF of 0.0281 under the same dimensionless wave conditions. The percentage error between the two results is computed to be 3.36%. The time history of this study and the study by Begovic et al. [2] are presented below.

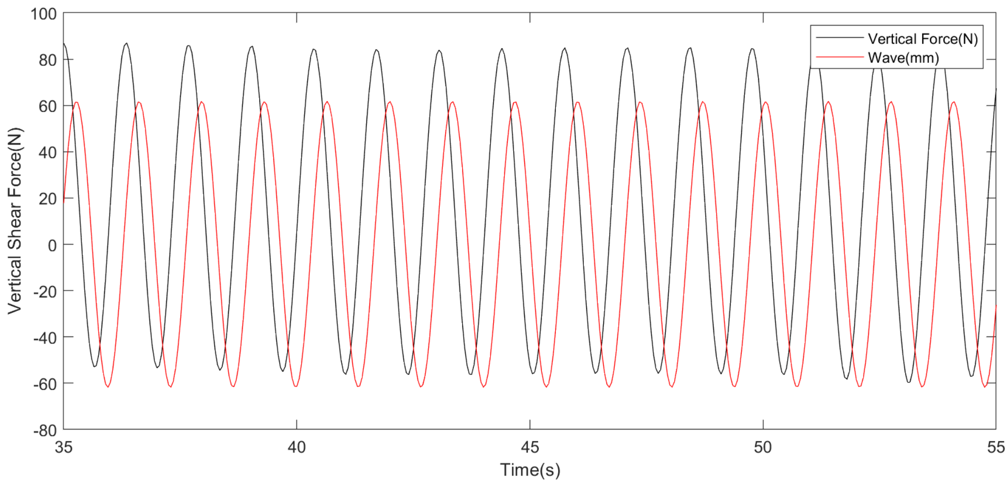

Figure 4: Times History of Vertical Shear Force and Waves from SimFlow

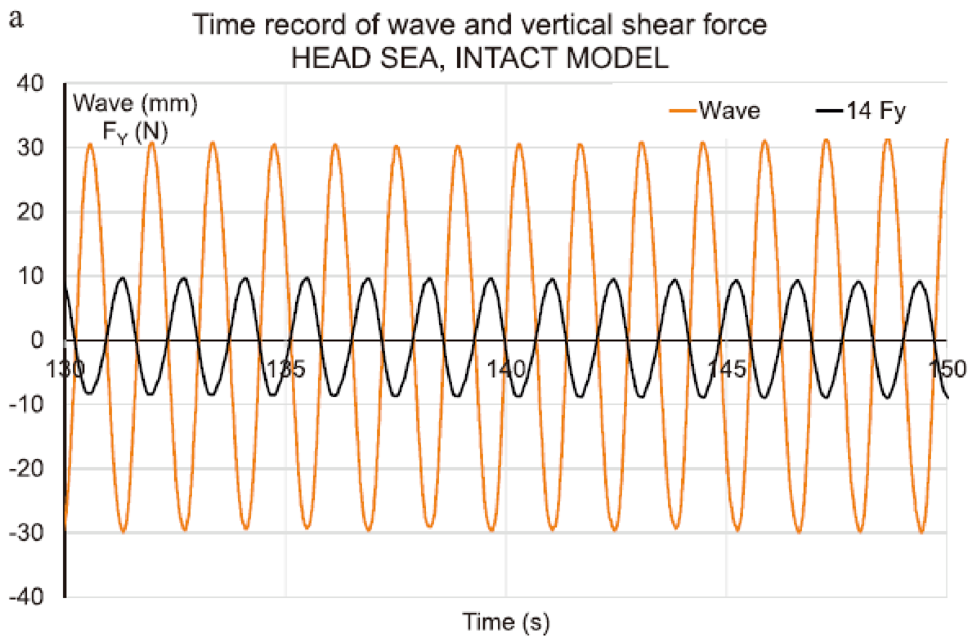

Figure 5: Times History of Vertical Shear Force and Waves from [2]

5.1 Mesh Convergence Tests

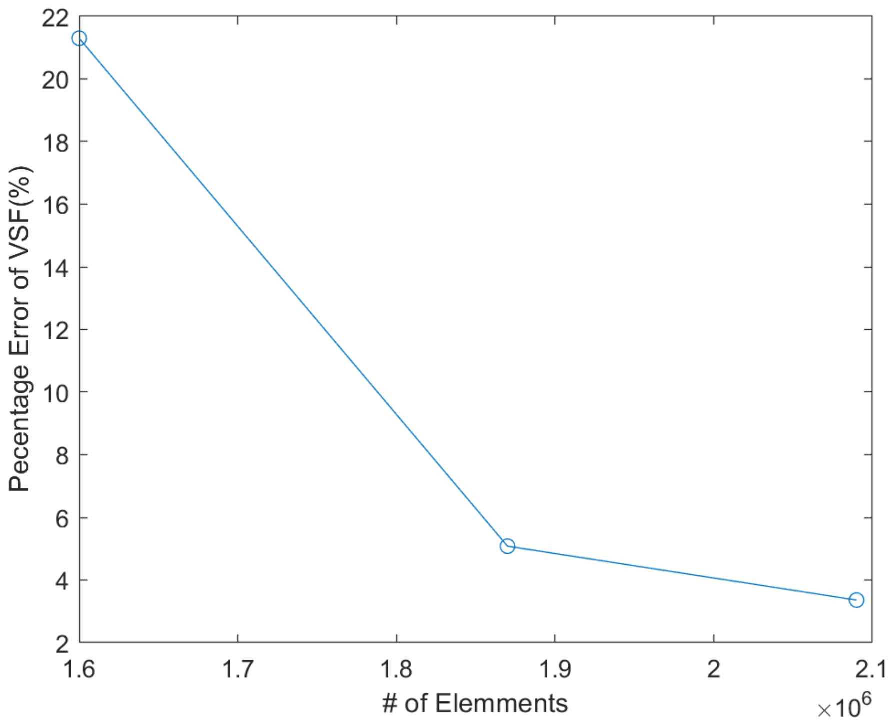

Figure 6: Mesh Convergence Test

The plot illustrates the relationship between the percentage error of the nondimensional vertical shear force (VSF) and varying total numbers of mesh elements. The results indicate that as the mesh is progressively refined in the vicinity of the ship model, the simulation in SimFlow demonstrates improved accuracy in capturing the forces, leading to a reduction in the error when compared to the experimental data. This finding underscores the importance of mesh refinement near critical areas of the model to enhance the precision of CFD simulations.

6 Discussion

6.1 Interpretation of Results

The results of this study demonstrate the effectiveness of using SimFlow to simulate the hydrodynamic performance of the DTMB 5415 ship model under head wave conditions. The numerical simulations accurately captured key hydrodynamic loads, such as vertical shear forces, showing strong agreement with existing experimental data.

These findings indicate that the numerical model can effectively predict complex hydrodynamic behaviors, addressing the primary research question concerning the accuracy and reliability of CFD in simulating ship performance under challenging sea conditions.

6.2 Implications

The results of this study have significant implications for both theory and practice in naval architecture. The confirmation of SimFlow's ability to accurately model ship performance under head wave conditions supports the broader use of CFD tools in the design and analysis of naval vessels. This can lead to more efficient and safer ship designs, reducing the reliance on costly and time-consuming experimental testing. The study also provides a validated numerical framework that can be applied to other ship models and wave conditions, potentially improving the predictive capabilities of CFD in naval applications.

6.3 Limitations

Despite the positive outcomes, this study has several limitations. First, the analysis was confined to head wave conditions, and the results may not be directly applicable to other wave orientations, such as beam or following seas. Additionally, the study relied on pre-existing experimental data for validation, which, while comprehensive, may not cover all possible scenarios encountered by the DTMB 5415 in real-world operations. Finally, the computational domain was set with specific boundary conditions that, while minimizing interference, may not perfectly replicate open sea conditions.

7 Conclusion

The study successfully verifies and validates the numerical modeling of the DTMB 5415 ship model under head wave conditions using SimFlow. By comparing the simulation results with experimental data, the research demonstrates that the chosen numerical approach accurately captures the complex hydrodynamic forces acting on the ship. The sensitivity analysis further emphasizes the importance of mesh refinement, particularly in areas close to the ship, in reducing the percentage error of the vertical shear force predictions. These findings not only reinforce the utility of SimFlow as a reliable CFD tool in naval architecture but also provide valuable insights into the optimization of numerical simulations for ship design. The validated numerical framework established in this study can be extended to other ship models and wave conditions, potentially leading to safer and more efficient naval designs. However, the study also acknowledges its limitations, including the focus on head wave conditions and reliance on pre-existing experimental data, suggesting avenues for future research to explore more diverse scenarios and enhance the robustness of CFD simulations.

8 Reference

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9 Appendix A

9.1 DTMB 5415 Specifications

Particulars	**Ship**	**1/24 Model**	**1/51 Model**
Overall Length L_{OA} (m)	153.300	6.175	3.0
Overall Width B_{OA} (m)	20.540	0.83	0.403
Draft T (m)	6.150	0.248	0.120
Displacement Volume V (m^3)	8424.4	0.554	0.0635

Table 1: Main particulars of the ship model

Note that the 1/24 Model is utilized in this study. And the data of 1/51 model which is used in [2] are represented here for clarity.

10 Appendix B

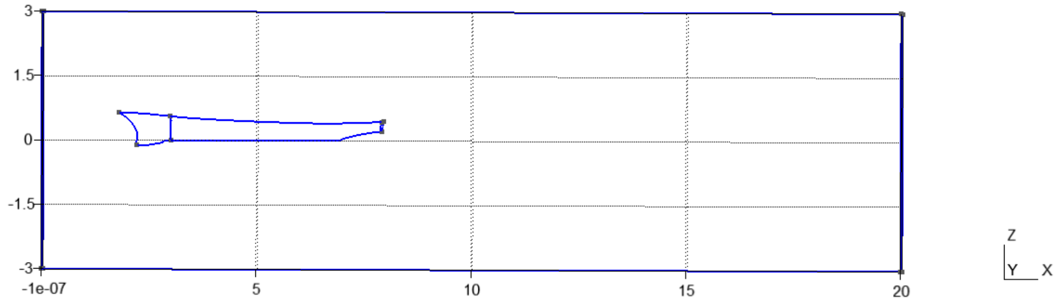

Figure 7: Side View of the Computational Domain

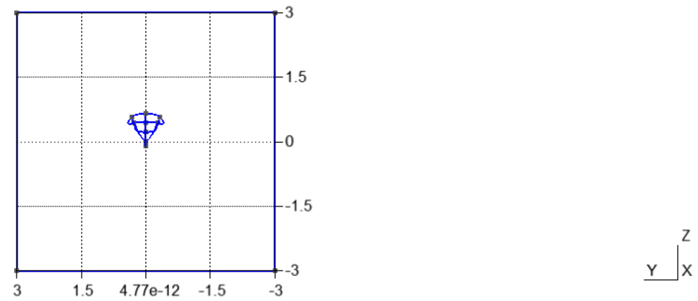

Figure 8: Front View of the Computational Domain

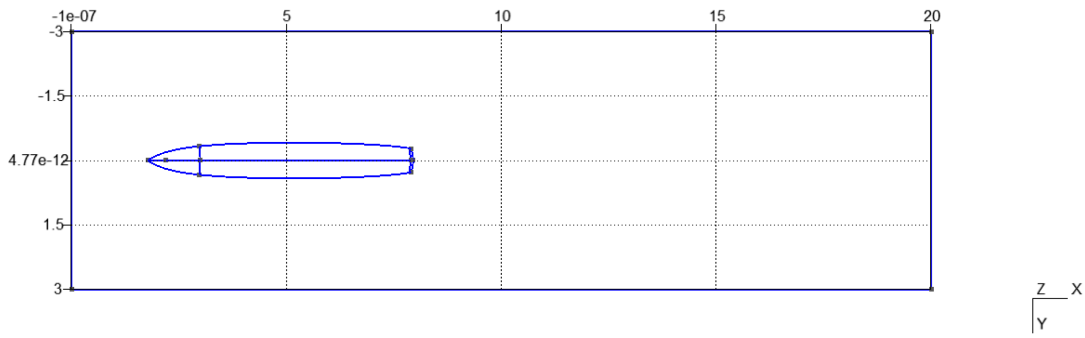

Figure 9: Top View of the Computational Domain

11 Appendix C

Listing 1: Hard code for inlet wave run-up

```
H_wave = 0.1144;            /* Wave height */
D_water = 3.248;          /* Water depth */
T_wave = 1.343;         /* Wave period */
L_wave = 6.175;            /* Wave length */
PI = 3.14159265 ;
G = 9.81 ;

// For Nonlinear second-order Stokes waves //

if (solNbcHd->var == PRM_NBC_ORDER_PAR && solNbcHd->type ==
    PRM_NBC_USR_DEF) {
    for (i=0; i<nNodes; i++) {
        time = rootHd->time + rootHd->timeInc;
        K_wave = 2*PI/L_wave;
        AA = cosh(K_wave * (crd[3*(nodes[i])+1] + D_water));
        BB = cosh(K_wave * D_water);
        CC = sinh(K_wave * D_water);
        FF = cosh(2.0*K_wave*D_water);

        A = H_wave/2.0;
        B = (PI*H_wave*H_wave/(8.0*L_wave))*(BB/pow(CC,3.0))*(2.0+FF);
        ss = (-A + sqrt(A*A+8*B*B))/(4*B);
        phase = 0.0 * acos(ss);

        DD = cos(-2.0 * PI * (time/T_wave));
        EE = cos(2.0*(-2.0*PI*(time/T_wave)));
        GG = cosh(2.0*(K_wave* (crd[3*(nodes[i])+1] + D_water)));

        LL = (H_wave/2.0)*DD + ((PI*H_wave*H_wave/(8.0*L_wave))*(BB/pow
            (CC,3.0))*(2.0+FF)*EE);
        values[i] = -tanh((crd[3*nodes[i]+2]-LL-0.248)/(sqrt(2) *
            rootHd->epsilon));
    }
}
```

12 Appendix D

```
clc
clear all

F1 = fopen('domain.oisd','r');
N = 1100;
dt = 0.05 ;
time = [dt:dt:N*dt];
L_OA = 6.175;
B_OA = 0.83;
rho_w = 1002;
a = L_OA/100;
```

```
NO1 = 700;
NO2 = N;

Force = zeros(N, 3);
Disp = zeros(N, 3);
fgets(F1);

for i=1:N
    for j=1:8
        fgets(F1);
    end
    fgets(F1);
    Force(i,:) = fscanf(F1, '%e %e %e', [1 3]);

    for j=1:8
        fgets(F1);
    end

end

fclose(F1);

%mean = sum(Force(NO1:NO2,3))/(NO2-NO1);

[pks, locs] = findpeaks(Force(NO1:NO2,3),time(NO1:NO2));

avg = sum(pks)/length(pks);

VSF = avg/(rho_w*9.81*L_OA*B_OA*a);
VSF_ref = 10/(1000*9.81*3*0.403*0.03);

err = abs(VSF-VSF_ref)/VSF_ref;


A = L_OA*10;
T = 1.34375;
w = 2*pi/T;
W = A*sin(w*time(NO1:NO2));

figure(1)
plot(time(NO1:NO2),Force(NO1:NO2,3),'-k');
hold on;
plot(time(NO1:NO2),W,'-r');
legend('Vertical Force(N)','Wave(mm)');
xlabel('Time(s)');
ylabel('Vertical Shear Force(N)');
```

```
disp(avg)
disp(VSF)
disp(err)
```

13 Appendix E

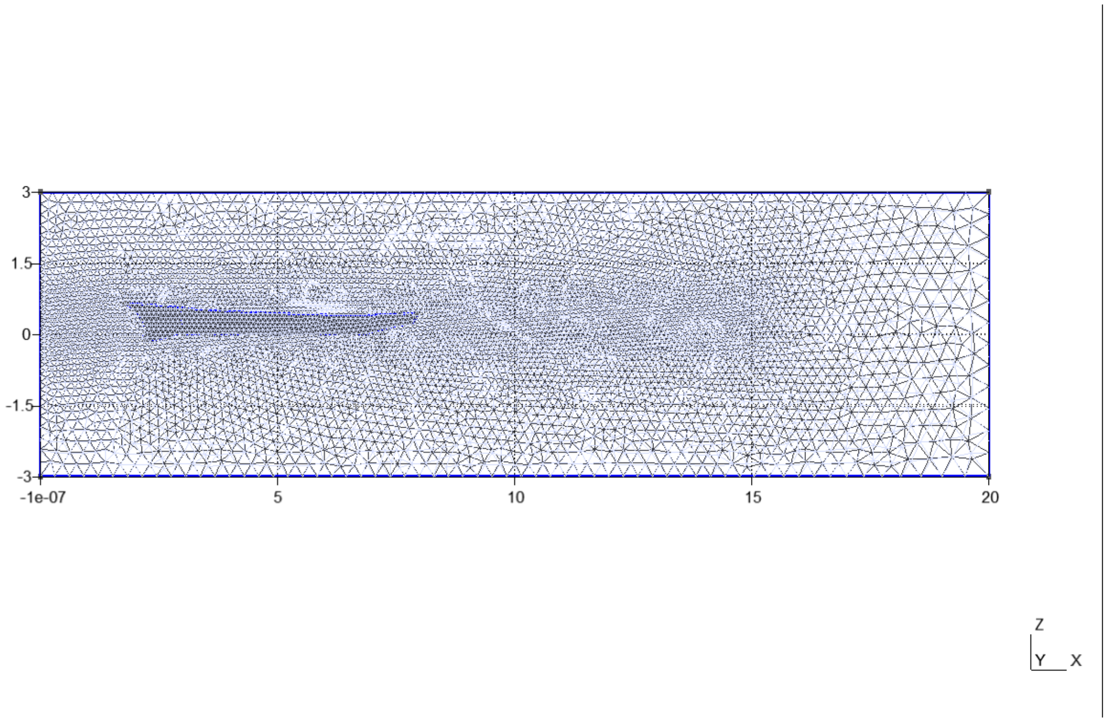

Figure 10: Side View of the Mesh

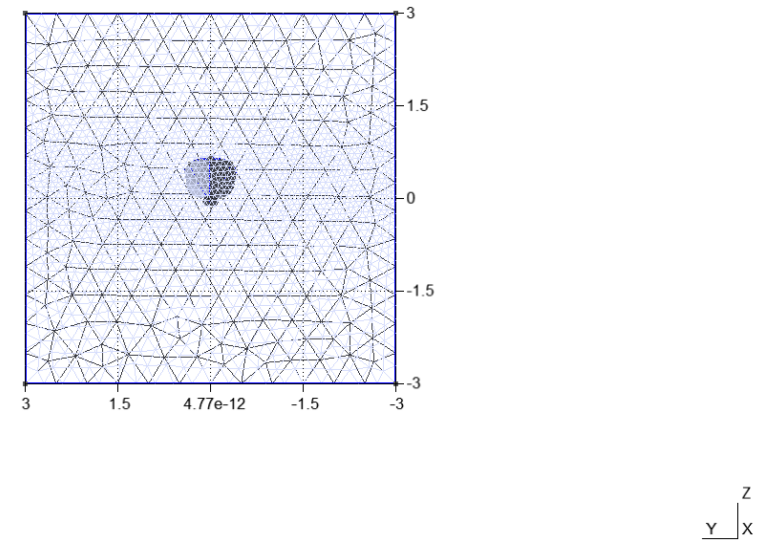

Figure 11: Front View of the Mesh

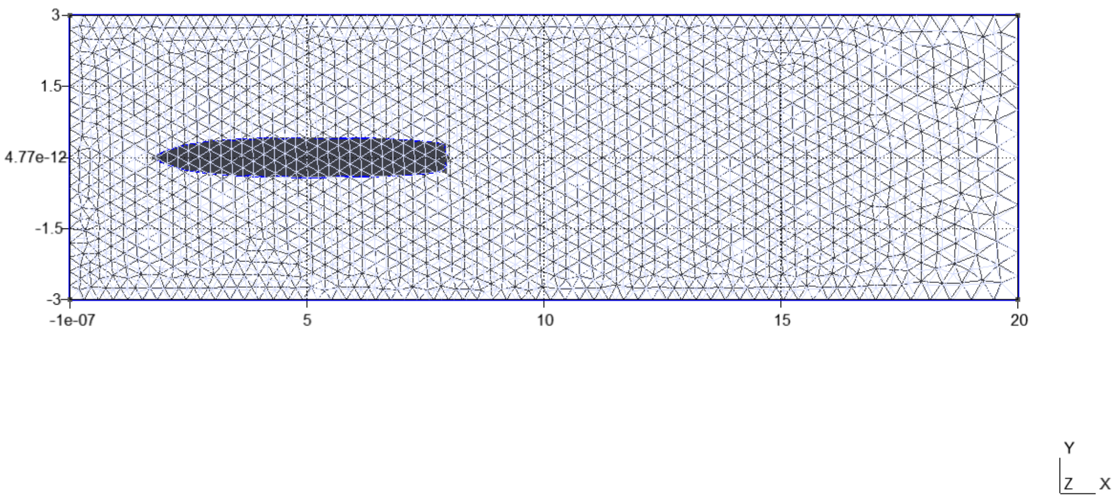

Figure 12: Top View of the Mesh

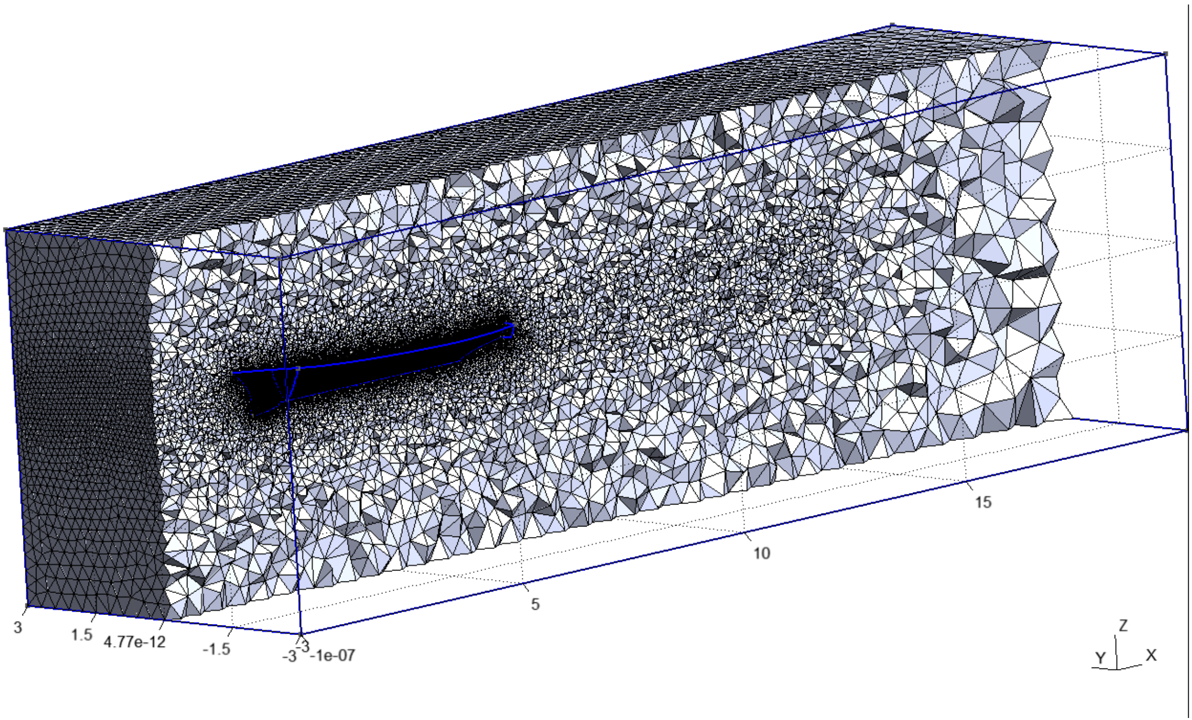

Figure 13: 3D View of the Mesh