MEng Project Report

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

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August 9, 2024

Contents

1 Abstract

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.

Notably, the hull geometry of the DTMB 5415 includes a sonar dome and a transom stern, making it an ideal subject for hydrodynamic analysis, particularly in wave resistance and propulsion efficiency contexts. Propulsion is provided by twin open-water propellers, driven by shafts supported by struts—further enhancing the model's relevance in studying fluid flow and propulsion mechanisms interactions.

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 hull geometry, along with relevant loading conditions and operating speeds, are detailed in subsequent sections of this report and in the Appendix.

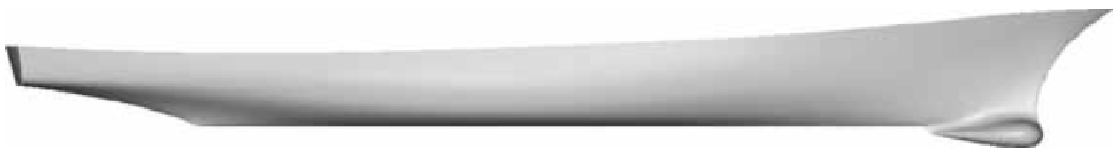

Figure 1: DTMB 5415

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), has become an indispensable tool in the field of naval architecture and hydrodynamics. CFD allows for the detailed analysis of fluid flow around ship hulls, enabling engineers to predict performance under various sea conditions. By solving the Navier-Stokes equations, CFD provides insights into complex flow phenomena that are difficult to capture experimentally. In the context of ship performance, numerical simulations help in evaluating resistance, propulsion efficiency, and wave-ship interactions, which are critical for optimizing design and ensuring safety.

ANSYS Fluent is one of the most advanced CFD tools available for simulating fluid dynamics in complex geometries, such as those found in ship hulls like the DTMB 5415. Fluent's robust turbulence models, including the k-ω SST model, are well-suited for capturing the intricate flow patterns around the sonar dome and transom stern. Additionally, ANSYS Fluent offers powerful solvers that efficiently handle large-scale simulations, including those involving free surface flows and fluid-structure interactions, which are essential when modeling the DTMB 5415 in head wave conditions.

While traditional experimental methods, such as towing tank tests, provide valuable data, they are often limited by cost, time, and the difficulty of replicating certain sea conditions. Numerical simulations using tools like ANSYS Fluent offer a complementary approach, enabling the exploration of multiple scenarios and conditions that might be impractical or impossible to test experimentally. Furthermore, CFD 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.

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 CFD tools like ANSYS Fluent 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 ANSYS Fluent. 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 ANSYS Fluent and the available experimental data, particularly in terms of vetical 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

2.5.1 Impact on Naval Design and Analysis

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 ANSYS Fluent. This research is confined to exploring specific aspects of hydrodynamic performance, such as wave resistance, ship motion, and the impact of turbulence models on simulation accuracy. The study is limited to using Reynolds-Averaged Navier-Stokes (RANS) based simulations and does not extend to other numerical methods like Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS). Additionally, the parameters under investigation include mesh density, time step size, and the selection of turbulence models. The analysis is also constrained to head wave conditions, deliberately excluding other wave orientations like beam or following waves.

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 ANSYS Fluent, nor does it explore other advanced numerical techniques outside the RANS framework. 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.

3.3 Theoretical Framework

This study builds on the established experimental research by focusing on the vertical shear force on the DTMB 5415 ship model, utilizing the finite element method (FEM) within ANSYS Fluent. The theoretical framework involves applying RANS-based simulations to predict the nonlinear hydrodynamic loads, incorporating the lessons learned from previous experimental and numerical studies. By addressing the identified gaps, this research aims to enhance the accuracy and reliability of numerical predictions, thereby contributing to the broader field of naval architecture and hydrodynamics.

4 Methodology

4.1 Research Design

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

4.2 Computational Domain Configuration

The computational domain for the simulations was configured to accurately represent the physical environment in which the DTMB 5415 operates under head wave conditions. The domain was discretized using a structured/unstructured mesh (choose the one you used), with a finer mesh density applied near the hull surface and in regions of expected high flow gradients, such as the bow wave and wake regions. The boundaries of the domain were set at sufficient distances from the ship to minimize the influence of boundary conditions on the simulation results. The wave generation was implemented using a specific wave theory (e.g., linear, second-order Stokes), and absorbing boundary conditions were applied to prevent wave reflection at the domain limits.

4.3 Simulation Parameters

Key parameters for the simulations were carefully chosen to reflect realistic operating conditions for the DTMB 5415. The turbulence model used in the simulations was the k-ω SST model, known for its robustness in predicting turbulent flows around ship hulls. The time step size was selected based on the Courant-Friedrichs-Lewy (CFL) condition to ensure numerical stability while capturing the dynamics of the flow. Additionally, the simulations were run until steady-state conditions were achieved, or until a sufficient number of wave encounters were simulated to capture the periodic nature of the wave loads on the ship.

4.4 Data Collection Methods

Data were obtained through numerical simulations in ANSYS Fluent, using input parameters based on the DTMB 5415's geometric and hydrodynamic characteristics. Pre-existing experimental data served as benchmarks for validation, ensuring that the simulation results could be effectively compared.

4.5 Data Analysis

Data analysis involved evaluating key hydrodynamic responses such as vertical shear forces and bending moments. The results from ANSYS Fluent were compared with experimental data to determine accuracy, and a sensitivity analysis was conducted to assess the impact of different simulation parameters, including mesh density and time step size.

5 Discussion

As a seciton of the HARP project, this work facilitates developing innovative tools for predicting underwater vessel noise during the design phase. It will identify potential noise sources, such as on-board machinery and propeller noise. Enhanced design models are anticipated to assist the industry in adopting ‘quiet’ technologies for the next generation of ships, ensuring they maintain safety, productivity, and environmental performance.

6 Future Work

This work has only completed the first step of the scope stated in the methodology section. The future work is to replace the DTMB ship model with BURNSi model and conduct test using the set-up mentioned above.

7 Conclusion

8 Reference

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9 Appendix

9.1 DTMB 5415 Specifications

Particulars	**Ship**	**Model**
Overall Length L_{OA} (m)	153.300	3.0
Overall Width B_{OA} (m)	20.540	0.403
Draft T (m)	6.150	0.120
Displacement Volume V (m^3)	8424.4	0.0635

Table 1: Main particulars of the ship model

9.2 3D Mesh