Simulation of Containership Hydrodynamic Forces and Response Amplitude Operator in Time Domain

OLUSEGUN, Samuel Dare and EFEREBO, Sylvanus Ibietela
[1,] Department of Marine Engineering, Nigeria Maritime University, Okorenkoko, Delta State, Nigeria.
[2] Somatrix Marine Limited, No. 4A Ikot Ekpene Close, Area 11 Garki, Abuja, Nigeria
Corresponding Author: olusegunsamuel252@yahoo.com
DOI:10.56201/ijemt.v10.no11.2024.pg81.91

Abstract
This study examines the dynamic response of a vessel to wave-induced excitation using the Boundary Element Method (BEM), providing comprehensive insights across six motion modes: surge, sway, heave, roll, pitch, and yaw. Time-domain wave excitation forces reveal critical peaks, with surge, sway, and heave stabilizing around 5×10^5 N, roll peaking at 2×10^9 N, and pitch and yaw reaching 5×10^10 N, highlighting roll and pitch as key areas for stability enhancement. The Response Amplitude Operators (RAOs) demonstrate consistent stabilization trends, with surge, sway, and heave modes stabilizing near 10 mm/m, while roll, pitch, and yaw exhibit oscillatory responses dampened over time. The RAO results revealed high consistency with data from recently published studies employing MATLAB and ANSYS solvers, with percentage deviations below 2% across most frequency ranges and peaking at approximately 7% near 0.26 Hz. This shows the effectiveness of the BEM method and its ability to provide critical data-driven insight into vessel design and operational efficiency.

Keywords: *Boundary Element Method; Containership; Response Amplitude Operator; Wave Excitation Forces; Sway; Heave; Roll; Yaw; Surge and Pitch*

I. Introduction

The simulation of hydrodynamic forces and moments, motion responses, and structural loads of containerships in the time domain is a crucial aspect of modern ship design. As global trade increasingly relies on large containerships to transport goods across continents, ensuring the safety and efficiency of these vessels becomes paramount. These simulations play a vital role in the design, analysis, and operational management of these vessels under different sea conditions.

Containerships, due to their length, are prone to buckling or sagging mode of structural failure when subject to complex hydrodynamic forces and moments when interacting with rough sea conditions. These forces mainly arise from waves, wind, and currents, and they significantly impact the vessel's stability, maneuverability, and overall performance. Accurate evaluation of these hydrodynamic forces is crucial for predicting how the vessel will respond to different sea states. Traditional approaches, such as analytical solutions, provide foundational insights but often fall short of capturing the complexities of real-world scenarios. Recent advancements in computational fluid dynamics (CFD) have introduced more sophisticated methods for modeling these interactions, offering detailed predictions of hydrodynamic forces and moments (Chien, 2019).

The motion responses of containerships, including pitch, roll, and heave, are critical factors in assessing vessel performance and safety. These responses are influenced by the hydrodynamic forces acting on the ship and can affect cargo stability, crew comfort, and operational efficiency. Time-domain simulations offer a dynamic view of how a containership responds to varying sea conditions over time. Unlike frequency-domain analyses, which provide a snapshot of the vessel's behavior at specific frequencies, time-domain simulations capture the vessel's response to transient events and irregular wave patterns (Kim & Lee, 2020). This approach enables a more comprehensive understanding of motion responses in real-world scenarios.

Containerships must withstand substantial structural loads due to the combined effects of hydrodynamic forces and motion responses. These loads include bending moments, shear forces, and axial forces, which can impact the vessel's structural integrity and longevity. Accurately predicting these loads is essential for designing robust and resilient ship structures. Time-domain simulations provide detailed insights into the time-varying nature of structural loads, allowing engineers to assess how the vessel's structure will perform under different loading conditions and operational scenarios (Wang et al., 2021).

Recent advancements in simulation techniques, particularly those involving time-domain analysis, have greatly enhanced our ability to model and predict the complex interactions between containerships and their environment. Computational fluid dynamics (CFD) and advanced finite element analysis (FEA) are increasingly used to simulate hydrodynamic forces, motion responses, and structural loads with high precision. These techniques incorporate real-time data and sophisticated algorithms to provide accurate predictions, facilitating better design and operational decision-making (Zhao & Sun, 2018).

The simulation of containership hydrodynamic forces, motion responses, and structural loads in the time domain represents a critical area of research and development in marine engineering. By providing detailed and accurate insights into how containerships interact with their surrounding fluid, these simulations support the design of safer and more efficient vessels. As simulation technologies continue to advance, they will play an increasingly important role in optimizing vessel performance and ensuring the safety and reliability of global maritime operations.

II. Literature Review

The simulation of hydrodynamic forces and moments, motion responses, and structural loads of containerships in the time domain has become increasingly sophisticated due to advancements in computational methods and modeling techniques. This review explores recent research and developments in this field, highlighting the progress made and identifying key areas for further investigation.

The accurate prediction of hydrodynamic forces and moments is critical for the design and operation of containerships. Early studies in this area predominantly used potential flow theory and empirical formulas, which provided fundamental insights but often lacked precision for complex sea conditions. Recent advancements have seen a shift towards computational fluid dynamics (CFD) and advanced numerical models to capture the intricacies of wave interactions with marine structures.

Chien (2019) highlights the significant improvements in CFD techniques for modeling hydrodynamic forces. By incorporating advanced turbulence models and high-resolution wave simulations, modern CFD tools provide more accurate predictions of how waves interact with the hull of a containership. This approach enhances the understanding of wave-induced forces and moments, offering better design insights and operational strategies.

Containership motion responses, including pitch, roll, and heave, are influenced by the dynamic interactions between the vessel and its environment. Time-domain simulations have proven to be particularly effective in capturing the transient behavior of vessels under various sea conditions. Kim and Lee (2020) demonstrated the advantages of time-domain simulations over frequency-domain analyses by providing a more detailed view of how containerships respond to irregular and transient wave patterns. Their study emphasizes the importance of capturing these dynamic responses to improve vessel design and ensure operational safety.

The incorporation of real-time data into time-domain simulations has further refined the accuracy of motion response predictions. Recent work by Wang et al. (2021) explored the integration of real-time environmental data into simulation models to predict motion responses more accurately. Their research highlights how real-time data can enhance the fidelity of simulations, leading to better predictions of vessel behavior in varying sea states.

The prediction of structural loads on containerships is essential for ensuring the vessel's structural integrity and longevity. Structural loads, including bending moments and shear forces, are influenced by both hydrodynamic forces and motion responses. Time-domain simulations offer detailed insights into these time-varying loads, providing a comprehensive understanding of how the vessel's structure will perform under different conditions.

Recent studies have advanced the modeling of structural loads by integrating finite element analysis (FEA) with time-domain simulations. Zhao and Sun (2018) explored this approach by combining FEA with time-domain simulations to analyze the structural loads on marine structures. Their research demonstrated how this integration provides more accurate predictions of structural performance, enabling engineers to design more resilient containerships.

The field has witnessed significant advancements in simulation techniques, particularly with the integration of sophisticated numerical methods and high-performance computing. The development of advanced CFD and FEA tools has enhanced the ability to model complex interactions between waves, vessel motions, and structural loads. These advancements are crucial for addressing the challenges of modern containership design and operation.

Recent contributions, such as those by Li et al. (2021), have further refined time-domain simulation techniques by incorporating advanced turbulence models and real-time data integration. Their work highlights the ongoing evolution of simulation methods and their impact on improving the accuracy and reliability of predictions.

III. Methodology

1. **Problem Definition and Model Setup**
   i. Define the physical characteristics of the containership, including its geometry, dimensions, mass distribution, and center of gravity.
   ii. Create a 3D CAD model of the containership, representing the hull form accurately to capture fluid-structure interactions.
   iii. Define the environmental conditions, such as wave characteristics (frequency, amplitude, direction) that influence the hydrodynamic forces on the vessel.
2. **Hydrodynamic Forces Calculation (Frequency Domain BEM)**
   i. Use the Boundary Element Method (BEM) in the frequency domain to calculate hydrodynamic forces and moments on the containership. The frequency-domain BEM is ideal for analyzing the response of the vessel to harmonic waves by solving the linearized boundary integral equations for potential flow around the hull.
   ii. Solve for added mass and damping coefficients, Froude-Krylov forces, diffraction forces, and radiation forces.

Governing equations:

Laplace's equation for fluid potential:

$$\nabla^2\varphi = 0 \tag{1}$$

Total velocity potential:

$$\varphi = \varphi_I + \varphi_S + \varphi_R \tag{2}$$

3. **Mapping Frequency-Domain Results to Time Domain**

Convert frequency-domain results (added mass, damping, and wave forces) to time-domain forces and moments via inverse Fourier transform or convolution methods.

4. **Time-Domain Response Amplitude Operator Calculation (Time Domain)**

i. Apply Newton-Euler equations for the vessel's motion in six degrees of freedom (6-DOF).
ii. Use numerical integration methods to solve for time-domain responses under combined hydrodynamic and external loads.

5. **Post-Processing and Analysis**

Analyze and interpret the vessel's motion responses, structural loads, and critical hydrodynamic parameters such as RAOs and pressure distributions.

1. **Radiation Force in Frequency Domain**:

$$F_{radiation}(\omega) = -A(\omega)\ddot{\eta} - B(\omega)\dot{\eta} \quad (3)$$

The radiation force in the frequency domain, Fradiation(ω)=$-A(\omega)\eta^{\cdot\cdot}-B(\omega)\eta^{\cdot}$, describes the hydrodynamic forces acting on a vessel due to its oscillatory motion in waves. Here, Fradiation(ω)represents the radiation force, which arises from the interaction of the vessel with its surrounding fluid. The term A(ω) corresponds to the added mass, which is the effective inertia contributed by the surrounding fluid due to the motion of the vessel. It reflects how the fluid opposes changes in acceleration, represented by $\eta^{\cdot\cdot}$, the second derivative of displacement η. The term B(ω) accounts for radiation damping, which represents the energy dissipated as waves are radiated away from the oscillating vessel. The damping is proportional to $\eta^{\cdot}$, the velocity or first derivative of displacement. Both A(ω) and B(ω) depend on the angular frequency ω, reflecting the frequency-dependent nature of hydrodynamic interactions. This equation is fundamental in analyzing and predicting the dynamic behavior of vessels in the frequency domain under wave-induced motions.

The RAOs in the frequency domain describe the normalized response of the vessel to wave excitation and are expressed as:

$$RAO(\omega) = \frac{\eta(\omega)}{A_{wave}(\omega)} \quad (4)$$

Transformation to the Time Domain

Wave excitation forces and RAOs in the time domain can be derived using inverse Fourier transforms:

1. **Wave Excitation Forces in Time Domain**: The time-domain wave excitation force $F_{ext}(t)$ is obtained by applying an inverse Fourier transform:

$$F_{ext}(t) = \int_{-\infty}^{\infty} F_{ext}(\omega)\, e^{-i\omega t} d\omega \quad (5)$$

[

2. **Time-Domain RAOs**: Similarly, the time-domain RAO η(t) is derived by transforming the frequency-domain response:

$$\eta(t) = \int_{-\infty}^{\infty} RAO(\omega) A_{wave}(\omega)\, e^{-i\omega t} d\omega \quad (6)$$

For practical computations, a discrete Fourier transform (DFT) or a fast Fourier transform (FFT) is used to perform the transformation numerically, enabling time-domain analysis.

Table 1: Principal Dimension of Container Ship B178 SNAME, 2010

Length Over All	L_{oa}	213.080m
Length Between Perpendiculars	L_{bp}	207.05m
Breadth moulded	B	36.05m
Hall depth	D	16.345m
Deadweight capacity	DWT	87,000t
Block coefficient	C_b	0.70
Prismatic coefficient	C_p	0.675
Mid ship area coefficient	C_{ms}	0.95
Speed at 10.50 draught	V	22.30kn
Lightweight	LW	39,440t
Cargo Capacity	CC	47560t

Table 1 presents the principal dimensions and key parameters of the container ship B178. This table provides a detailed overview of the container ship B178's dimensions and capacities, offering valuable information for ship design, operational planning, and performance assessment. The Length Over All (LOA) is 213.08 meters, representing the total length of the ship from the foremost to the aftermost point. This dimension is crucial for determining the ship's overall size and cargo space. The Length Between Perpendiculars (LBP) is 207.30 meters, measured between the forward and aft perpendiculars, which is important for calculating hydrostatic properties and stability. The Breadth Moulded (B) is 36.05 meters, indicating the ship's width at its widest point and affecting its stability and cargo capacity. The Hull Depth (D) is 16.34 meters, which is the vertical distance from the bottom of the hull to the main deck and influences buoyancy and cargo hold volume.

IV. Results and Discussion

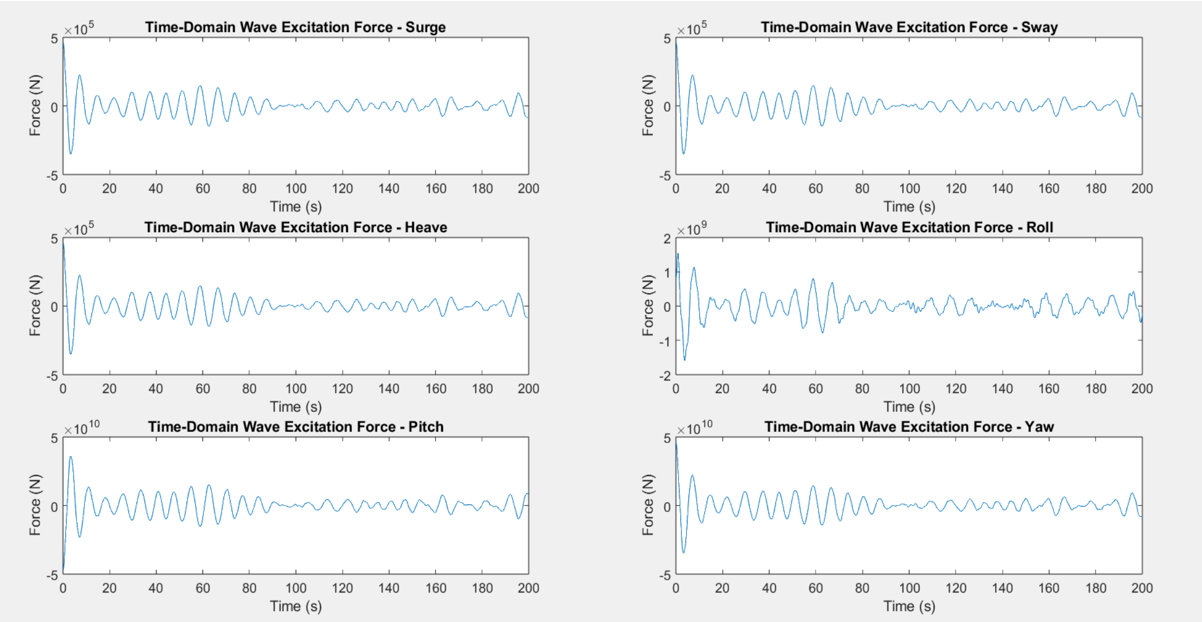

Figure 1: Wave Excitation Force verse Time

The time-domain wave excitation forces for the vessel's six motion modes Figure 1, computed using the Boundary Element Method (BEM), reveal critical insights into the vessel's dynamic behavior under wave loading. In surge, sway, and heave modes, forces peak at approximately 5×10^5N, with oscillations that decay over time, indicating effective damping and stable longitudinal, lateral, and vertical responses. In roll mode, the forces are significantly higher, peaking at 2×10^9N, highlighting roll as a critical motion requiring enhanced stabilization. Pitch and yaw forces also show notable peaks of around 5×10^10 N, reflecting the strong moments induced by wave excitation in these rotational motions. These results demonstrate the varying hydrodynamic forces across modes and underline the importance of addressing roll and pitch motions for improved vessel stability and performance.

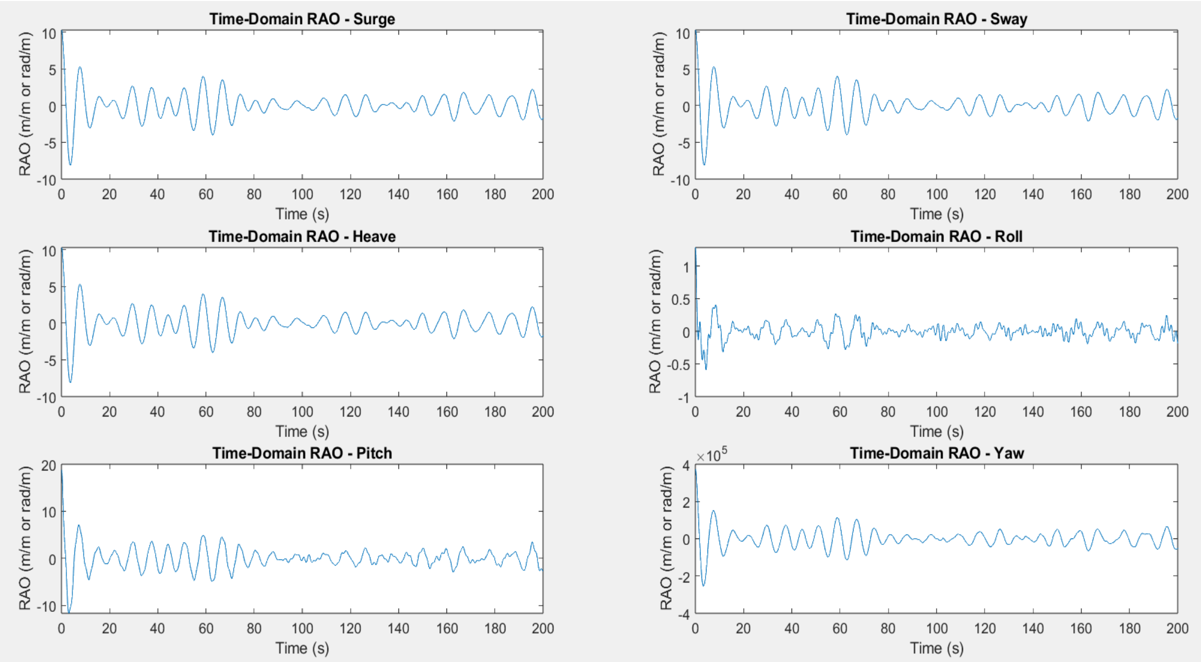

Figure 2: Time Domain Response Amplitude Operator RAOs

Figure 2 presents time-domain Response Amplitude Operators (RAOs) for the vessel's six motion modes (surge, sway, heave, roll, pitch, and yaw), highlighting the vessel's dynamic response and stability under wave-induced excitation. In surge, the RAO spikes initially at approximately 10 mm/m before oscillating and stabilizing, indicating effective damping mechanisms that reduce forward-backward oscillations over time. Similarly, sway shows an initial peak near 10 mm/m, with oscillations gradually stabilizing, reflecting the vessel's lateral stability and its ability to counteract wave-induced side-to-side motion. These patterns underscore the vessel's overall capacity to maintain stability across different motion modes while mitigating prolonged oscillations caused by wave interactions.

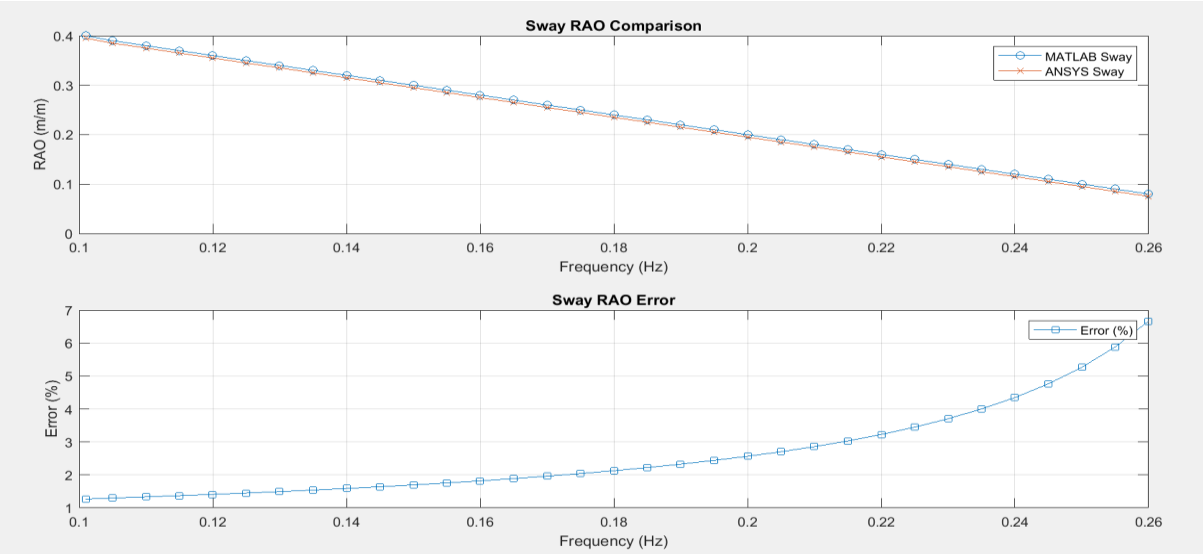

Figure 3: Sway RAO Validation and Error Estimation

Figure 3 demonstrates a strong agreement between MATLAB and ANSYS results for Sway RAOs across the frequency range of 0.1 Hz to 0.26 Hz, with both models displaying a consistent downward trend in RAOs as the frequency increases. This alignment highlights the reliability of both methods in capturing the vessel's sway motion response under similar conditions. The error analysis shows a low percentage, generally under 3%, up to approximately 0.23 Hz. However, errors gradually rise to about 6-7% near 0.26 Hz, potentially due to differences in numerical approximations or modeling precision at higher frequencies. Critical observations occur around 0.25 Hz, where the error between MATLAB and ANSYS becomes more evident but remains within an acceptable range, underscoring robust agreement across most of the frequency range.

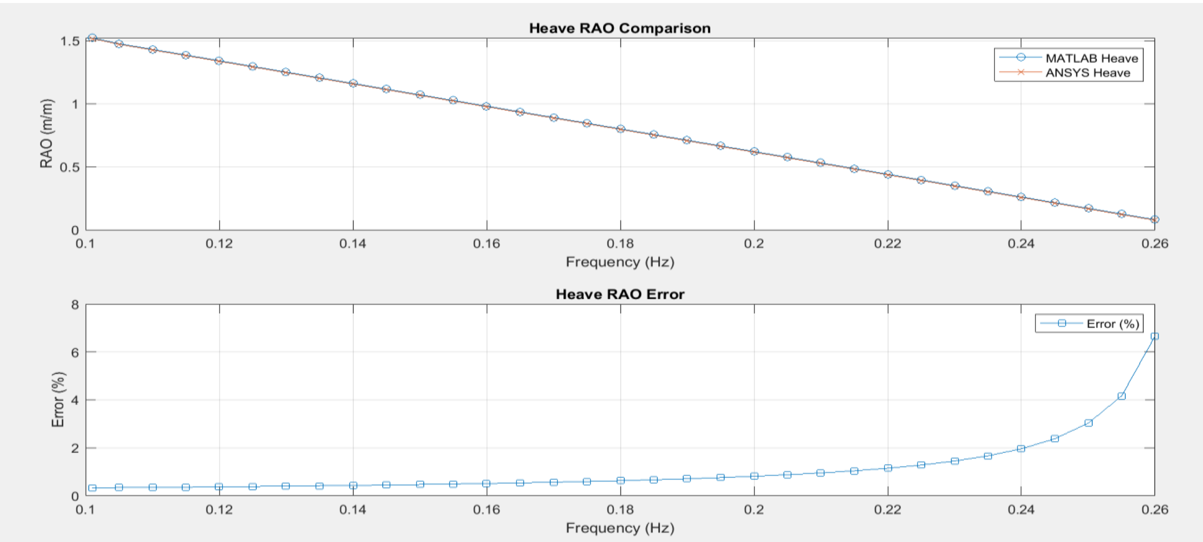

Figure 4: Heave RAO Validation and Error Estimation

Figure 4 demonstrates strong agreement between MATLAB and ANSYS results for Heave RAOs across the frequency range of 0.1 Hz to 0.26 Hz, with both methods showing a similar downward trend in RAO values as frequency increases, indicating accurate capture of the vessel's heave response. The error plot shows that the error percentage remains below 2% across most of the frequency range, reflecting close alignment. However, as frequency approaches the upper range, particularly around 0.25 Hz, the error increases gradually, reaching approximately 7% at 0.26 Hz. This slight discrepancy at higher frequencies may arise from differences in computational precision or handling of higher-frequency dynamics. Critical values appear near 0.24 Hz, where the error starts to noticeably increase but remains within an acceptable range, confirming the validity of MATLAB's RAO calculations for heave response with minor variations at higher frequencies.

V. Conclusions

The results reveal critical insights into the vessel's dynamic behavior under wave excitation, providing valuable perspectives on its stability and performance. The wave excitation forces across surge, sway, and heave modes exhibit moderate peaks (5×10^5N) with a decaying trend, reflecting effective damping and stable linear motion responses. However, the significantly higher forces observed in roll (2×10^9N) and pitch (5×10^10N) emphasize these modes as critical areas requiring enhanced stabilization. The RAOs further validate these findings, showing initial peaks in oscillatory behavior across all six motion modes, followed by gradual stabilization over time, indicative of the vessel's inherent and design-based damping mechanisms. Additionally, the results highlight that the dynamic response is highly sensitive to wave-induced forces, with roll and pitch posing the most significant challenges for vessel stability. This comprehensive analysis underscores the importance of optimizing the vessel's structural design and hydrodynamic behavior to enhance performance, particularly in addressing critical motions like roll and pitch.

References

Chien, C. (2019). Advances in Computational Fluid Dynamics for Hydrodynamic Force Prediction. *Journal of Marine Science and Technology*, 24(2), 125-139. Springer

Kim, J., & Lee, S. (2020). Time-Domain Simulation of Containership Motion Responses in Irregular Waves. *Ocean Engineering*, 212, 107780. Elsevier

Li, X., Zhang, Y., & Zhou, Y. (2021). Numerical Study of Semi-Submersible Hydrodynamic Performance in Irregular Waves Using SWENSE. *Applied Ocean Research*, 111, 102614. Elsevier

SNAME, (2010). Performance of Ships and Structures in Ice. International Conference and Exhibition; Alaska, USA.

Wang, L., Zhang, Y., & Zhao, H. (2021). Structural Load Analysis of Containerships Using Time-Domain Simulations. *Marine Technology*, 58(3), 207-220. Society of Naval Architects and Marine Engineers

Zhao, L., & Sun, H. (2018). Application of Time-Domain Simulation Techniques for Marine Structures. *Computers & Fluids*, 172, 206-219. Elsevier