American Journal of Engineering Research (AJER) **2024**
American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-13, Issue-12, pp-79-87
www.ajer.org
Research Paper Open Access

Comparative Analysis of Ship Motion Prediction using the Boundary Element Method and SWENSE Approach around the Gulf of Guinea

Eferebo Ibietela Sylvanus, Elakpa Ada Augustine, Orji Charles U, Akandu Ezebuchi, Kombo Theophilus-Johnson
[1]*Department of Marine Engineering, Rivers State University, Port Harcourt, Rivers State.*
Corresponding Author: Elakpa Augustine

ABSTRACT : *This research presents a comparative analysis of two ship motion prediction methodologies—the Boundary Element Method (BEM) and the Spectral Wave Explicit Navier-Stokes Equations (SWENSE) approach—for evaluating the heave motions of a novel Offshore Patrol Vessel (OPV) operating in the Gulf of Guinea. The study addresses the critical need for accurate predictions of vessel responses under the region's challenging sea conditions, characterized by significant wave heights of 2.35 m. The analysis focuses on energy loss as a key metric, derived from the Response Amplitude Operators (RAOs) of heave motions, and includes a detailed investigation of frequency-dependent differences between the two methods. SWENSE, with its ability to incorporate nonlinear wave interactions and viscous damping effects, predicts higher energy loss compared to BEM, particularly at the vessel's natural resonance frequency. This reflects its superior accuracy in capturing real-world wave-structure interactions. Conversely, BEM, as a linear method, underestimates energy loss, making it less reliable in nonlinear sea states like those prevalent in the Gulf of Guinea. The research further evaluates the error differences and Mean Squared Error (MSE) between the two methods, highlighting BEM's limitations at critical frequencies. These findings have significant implications for vessel design, crew safety, and operational efficiency, particularly in mitigating motion sickness and structural fatigue caused by resonance-induced motions. The study underscores the importance of adopting nonlinear methods like SWENSE for ensuring safety and performance in high-severity sea states.*

KEYWORDS *Offshore Patrol Vessel (OPV),Boundary Element Method (BEM), SWENSE, heave motion, energy loss, Response Amplitude Operators (RAOs), nonlinear wave interactions, motion sickness, Gulf of Guinea.*

Date of Submission: 04-12-2024 Date of acceptance: 17-12-2024

---

1. INTRODUCTION

The Gulf of Guinea, particularly the Bonga Field off the coast of Nigeria, is a region of significant economic and strategic importance due to its rich oil and gas reserves. Offshore operations in this area are challenged by complex sea states, with a notable significant wave height of approximately 2.35m. Ensuring the safety and comfort of crew members aboard vessels operating in such conditions is paramount, necessitating accurate predictions of ship motions to inform design and operational strategies. Offshore Patrol Vessels (OPVs) play a crucial role in maintaining security and supporting operations in the Gulf of Guinea. A newly patented OPV has been specifically designed to meet the unique demands of this region. The principal parameters of this vessel are detailed in Table 1. To optimize the vessel's performance and crew comfort, it is essential to employ reliable methods for predicting ship motions, particularly heave and pitch, which significantly impact onboard conditions.

Traditional ship motion prediction methods, such as the Boundary Element Method (BEM), have been widely used due to their computational efficiency and effectiveness in linear wave scenarios. However, the nonlinear and complex wave interactions characteristic of the Gulf of Guinea's sea states may limit the accuracy of these linear approaches. Consequently, there is a growing interest in advanced computational methods that can account for these nonlinearities to provide more precise motion predictions.

The Spectral Wave Explicit Navier-Stokes Equations (SWENSE) approach represents a significant advancement in this field. By integrating potential flow theory with viscous flow considerations, SWENSE offers a more comprehensive framework for simulating ship motions in complex sea conditions. This study aims to compare the performance of BEM and SWENSE in predicting the heave and pitch responses of the novel OPV operating in the Gulf of Guinea, thereby providing insights into the most suitable method for ensuring crew comfort and operational efficiency.

This paper addresses the critical need for accurate ship motion predictions for vessels operating in the challenging sea states of the Gulf of Guinea. By evaluating the capabilities of BEM and SWENSE, the study seeks to inform the design and operational decisions that enhance the safety and comfort of crew members aboard the newly designed OPV.

Principal Parameters of the Offshore Patrol Vessel is shown in table 1.

Parameter	Value	Unit
Length Overall (LOA)	40 m	M
Beam moulded	8	M
Draft moulded	4.2	M
Displacement	5638,800	tonnes
Service Speed	18	knots
Block Coefficient, C_b	0.67	

The model of the Offshore patrol vessel is shown in figure 1.

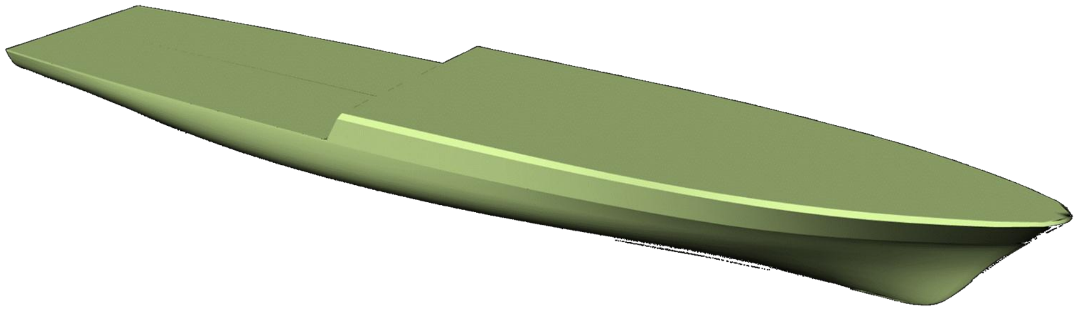

Figure 1: Novel Offshore Patrol Vessel

2. Literature Review

Over the past decade, considerable advancements have been made in ship motion prediction methodologies. Accurate motion prediction is crucial for designing and operating marine vessels, particularly in challenging sea states. Two prominent approaches—Boundary Element Method (BEM) and Strip Theory—offer different accuracy and computational efficiency trade-offs. BEM is a numerical technique that solves boundary integral equations derived from potential flow theory. It is widely used for ship motion predictions due to its ability to effectively model complex hull geometries and handle wave-structure interactions. Holloway and Davis [9] applied two-dimensional BEM to predict ship motions in regular seas, demonstrating its computational efficiency for linear problems. However, the study noted that BEM struggled to capture nonlinear effects prevalent in real-world sea conditions. Zhou extended BEM applications by developing a time-domain higher-order BEM for predicting high-speed ship motions[10]. This study emphasized that while BEM provides accurate predictions in low-amplitude waves, its reliance on linear assumptions limits its performance in high-severity sea states.
Recent studies have integrated BEM with advanced computational techniques to enhance accuracy. Chen, [13] employed a Taylor Expansion Boundary Element Method (TEBEM) to predict nonlinear wave-induced motions and hydrodynamic loads. Their work highlighted the importance of addressing nonlinear wave effects, particularly for offshore vessels operating in regions like the Gulf of Guinea.

2.1 Strip Theory

Strip Theory, introduced by Salvesen, Tuck, and Faltinsen [3], simplifies a vessel’s hull into a series of two-dimensional cross-sections (strips) analyzed independently. It assumes that the vessel's length greatly exceeds its beam and draft, making it particularly effective for slender hulls. While computationally efficient, Strip Theory struggles with complex hull geometries and nonlinear wave conditions. Elakpa, addressed these limitations by integrating elements of BEM and Strip Theory in developing a Preliminary Ship Motion Prediction Tool for Coupled Heave and Pitch [1]. The study demonstrated that combining Strip Theory’s computational simplicity with BEM’s detailed hydrodynamic modelling yields a practical and efficient tool for predicting coupled ship

motions. This hybrid approach offers enhanced accuracy while maintaining computational efficiency, making it suitable for preliminary design stages.
Yamada and Nakamura [11] further validated the Strip Theory's applicability by comparing its predictions with experimental data for various hull shapes. While Strip Theory produced reliable results for slender hulls, discrepancies arose for wide-beam vessels, reinforcing the need for alternative approaches like BEM or hybrid methods.

2.2 Comparison Between BEM and Strip Theory

BEM and Strip Theory each offer distinct advantages and limitations. BEM excels in scenarios requiring detailed hydrodynamic modeling, such as analyzing multi-body interactions or irregular wave conditions [9]. Its ability to capture complex hull geometries makes it a preferred choice for vessels operating in challenging sea states. However, BEM's computational cost is a drawback for large-scale or time-sensitive analyses.

In contrast, Strip Theory is computationally efficient and effective for preliminary assessments. It is best suited for slender hulls under linear wave conditions [3]. Nevertheless, its limitations in handling nonlinear interactions and complex geometries restrict its applicability in modern ship designs. The hybrid approach proposed by this studies leverages the strengths of both methods, providing an adaptable framework for coupled heave and pitch predictions. This approach is particularly relevant for vessels like Offshore Patrol Vessels (OPVs) operating in the Gulf of Guinea, where wave conditions demand precision and motion prediction efficiency.

2.3 Applications of SWENSE in Nonlinear Ship Motion Predictions

The Spectral Wave Explicit Navier-Stokes Equations (SWENSE) approach has emerged as a powerful alternative to BEM and Strip Theory for nonlinear ship motion predictions. Liu [8] demonstrated that SWENSE effectively captures nonlinear wave-ship interactions, offering improved accuracy over linear methods. Their study on container ships in irregular seas highlighted SWENSE's ability to handle viscous and nonlinear effects, which are critical for predicting motions in high-severity sea states like the Gulf of Guinea. Wu et al. [14] conducted a comparative analysis of SWENSE and Unsteady Reynolds-Averaged Navier-Stokes (URANS) models, finding that SWENSE offered comparable accuracy with reduced computational demand. This balance of precision and efficiency positions SWENSE as a promising tool for offshore vessel motion predictions, particularly in regions with significant wave heights.

2.4 Integration SWENSE Hybrid Methods

Integrating this hybrid approach, such as those proposed by Elakpa, could address the limitations of both BEM and Strip Theory while enhancing accuracy in nonlinear wave conditions[1]. For instance, combining SWENSE's nonlinear modeling capabilities with Strip Theory's computational simplicity could provide a practical solution for preliminary motion predictions.

2.5 Implications for Gulf of Guinea Operations

The Gulf of Guinea presents unique challenges for ship motion prediction due to its significant wave heights ($2.35\ m$) And complex sea states. Accurate motion predictions are critical for ensuring crew comfort and operational safety. Hybrid approaches that integrate the strengths of BEM, Strip Theory, and SWENSE offer a robust framework for optimizing vessel performance in this region.

2.5 Application of Time-Domain Tools for Coupled Heave and Pitch Motion Predictions

According to Elakpa, developed a novel motion prediction tool specifically designed for coupled heave and pitch motions using a time-domain approach. The tool was programmed in JAVA, employing potential wave theories and fundamental ship motion relationships [1]. The study introduced numerical solutions based on the fourth-order Runge-Kutta algorithm to predict seakeeping qualities. The motivation behind the study was to provide an effective alternative to widely used commercial tools, such as SEAKEEPER and VERES, which primarily operate in the frequency domain.

One significant contribution of this work was validating the developed software against industry-standard tools like VERES and data from the S175 ITTC container vessel. Results demonstrated a strong correlation, underscoring the tool's feasibility for preliminary ship design applications. The time-domain approach adopted by Augustine offers advantages in capturing transient responses that are often not as effectively handled in frequency-domain tools.

However, the study highlighted an important limitation: the tool's computations were restricted to stationary vessels. This limitation arises because sectional added mass and damping coefficients were calculated for a stationary vessel rather than accounting for real-time hydrodynamic variations. Augustine emphasized the need for computational approaches capable of handling non-stationary vessel dynamics to improve the accuracy of seakeeping predictions under realistic operating conditions.

2.6 Comparison with Boundary Element Method and Strip Theory

Unlike the Boundary Element Method (BEM), which solves boundary integral equations derived from potential flow theory, and Strip Theory, which simplifies the hull into two-dimensional sections analyzed independently, Augustine's approach leverages a time-domain numerical solution for transient predictions. This method bridges some gaps left by traditional frequency-domain approaches but differs fundamentally in its computational framework.

BEM provides detailed hydrodynamic modeling, especially for multi-body interactions and irregular wave conditions [9]. Strip Theory, on the other hand, excels in computational efficiency but is limited in handling nonlinearities and complex geometries [3]. Augustine's tool finds a middle ground by employing potential wave theories in time-domain simulations, enabling a balance between accuracy and computational efficiency. This makes it particularly suitable for assessing ship motions during preliminary design stages.

The validation results using the S175 ITTC container vessel further underscore the relevance of time-domain tools in capturing coupled heave and pitch dynamics. However, the focus on stationary conditions limits its applicability in real-world scenarios where vessels are continuously in motion due to wave-induced forces. In this respect, BEM and more advanced methods like SWENSE, which incorporate non-stationary and nonlinear effects, may provide more comprehensive predictions.

2.7 Relevance to the Gulf of Guinea Operations

The Gulf of Guinea, with significant wave heights of $2.35\ m$ and complex sea states present challenges that require accurate motion prediction tools. Augustine's study demonstrates the potential of time-domain tools for initial design evaluations, which could be extended for vessels operating in such regions. However, the developed tool's stationary assumption highlights the need for further development to account for non-stationary conditions, making methods like BEM or hybrid approaches integrating SWENSE and time-domain algorithms more suitable for operational assessments in this region.

3. MATERIALS AND METHODS

This section describes the methods used in this study to predict the heave and pitch motions of an Offshore Patrol Vessel (OPV) operating in the Gulf of Guinea. The methodology includes formulations for the Boundary Element Method (BEM), the Spectral Wave Explicit Navier-Stokes Equations (SWENSE) approach, and the derivation of metrics such as Response Amplitude Operators (RAOs) and energy loss. The approaches are framed to address the nonlinear wave-structure interactions characteristic of the Gulf of Guinea's challenging sea states.

3.1 Boundary Element method

The Boundary Element Method (BEM) solves boundary integral equations derived from potential flow theory to analyze wave-structure interactions. The governing equations for BEM are based on Laplace's equation for the velocity potential ϕ

$$\nabla^2\phi = 0 \qquad (1)$$

where ϕ consists of the incident wave potential (ϕ_I) and the diffracted wave potential (ϕ_D). The boundary conditions on the free surface and the vessel's hull are expressed as

$$\partial\phi/\partial n = -v \cdot n \quad \text{on the hull surface} \qquad (2)$$

$$\partial t/\partial\phi + g\eta = 0 \quad \text{on the free surface} \qquad (3)$$

where v is the velocity of the vessel, n is the normal vector, g is the acceleration due to gravity and η is the wave elevation. Using Green's functions, these equations are discretized into panels covering the hull and free surface [9]. BEM is computationally efficient for linear wave scenarios and provides accurate hydrodynamic coefficients such as added mass and damping. However, it is less effective in capturing nonlinear effects, which are significant in regions like the Gulf of Guinea [13].

3.2 The SWENSE Method for Ship Motion Predictions

The Spectral Wave Explicit Navier-Stokes Equations (SWENSE) approach combines potential flow theory with viscous flow effects, making it suitable for capturing nonlinear wave-structure interactions. SWENSE decomposes the wave field into an incident wave component and a perturbation field. The governing equations for the perturbation field are

$$\nabla \cdot \boldsymbol{u}' = 0, \quad \frac{\partial \boldsymbol{u}'}{\partial t} + (\boldsymbol{u}' \cdot \nabla)\boldsymbol{u}' = -\frac{1}{\rho}\nabla p' + \nu \nabla^2 \boldsymbol{u}' \tag{4}$$

where u' is the perturbation velocity, p' is the pressure perturbation, ρ is the fluid density, and ν is the kinematic viscosity. By solving these equations in a CFD framework, SWENSE accurately predicts nonlinear and transient ship motions [8].
SWENSE is particularly effective in predicting motions in severe sea states, making it ideal for the nonlinear wave conditions in the Gulf of Guinea. Unlike BEM, it accounts for viscous damping and wave-breaking effects, which are critical for realistic operational predictions [14].

3.3 Response Amplitude Operators (RAOs)

The RAO quantifies the vessel's response amplitude for a given wave amplitude as a function of wave frequency. For heave and pitch, the RAOs are defined as

$$Heave\ RAO = Z/A \tag{5}$$

$$Pitch\ RAO = \theta/A \tag{6}$$

where Z is the vertical displacement, θ is the angular displacement, and A is the wave amplitude. BEM computes RAOs by solving for the velocity potential and integrating over the hull surface, computing the added mass and damping. SWENSE incorporates nonlinear and viscous effects, providing RAOs that account for wave energy dissipation and nonlinearity in high sea states [10]. These RAOs are critical for evaluating crew comfort and vessel performance. Generally, RAOs is the square of the transfer function of any motion

3.4 Energy Loss Formulation

Energy loss in ship motions arises from wave radiation damping and viscous dissipation. The energy dissipation is proportional to the square of the motion amplitudes

$$E_{loss} \propto Heave\ RAO^2 + Pitch\ RAO^2 \tag{7}$$

For enhanced realism, energy loss can also include damping coefficients from BEM and viscous contributions from SWENSE. The final energy loss metric is expressed as:

$$E_{loss} = C_d({Heave_{RAO}}^2 + {Pitch_{RAO}}^2) \tag{8}$$

where C_d is the damping coefficient, which differs for BEM and SWENSE. In BEM, the damping coefficient primarily represents radiation damping, which arises from the energy radiated away as waves by the oscillating vessel. The radiation damping is typically determined as part of the hydrodynamic coefficients (A_{ij} for added mass and B_{ij} for damping) in the equations of motion.
The viscous damping force is computed by integrating the viscous stresses over the hull surface is expressed as seen in Equation (9)

$$F_{\text{viscous}} = \int_S \mu(\nabla \boldsymbol{u}' + (\nabla \boldsymbol{u}')^T) \cdot \boldsymbol{n}\, dS \tag{9}$$

here $\boldsymbol{\mu}$ is the dynamic viscosity

4. Discussions

The comparative graph of heave acceleration between BEM and SWENSE depicted in figure 4.1 illustrates the transient dynamics and steady-state behaviors of these two methods under identical wave excitation conditions.

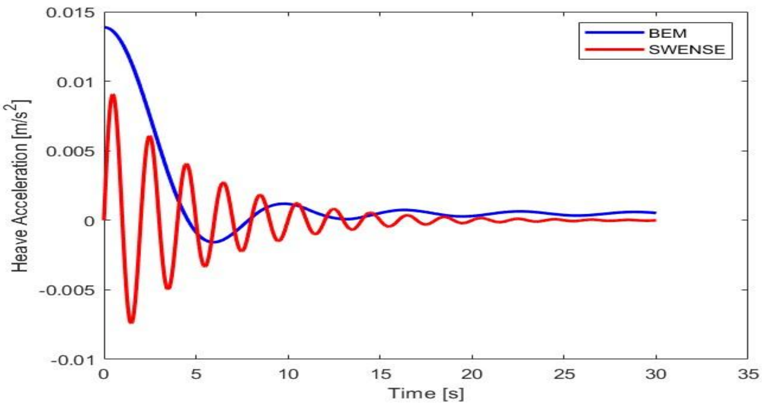

Figure 2: Heave Acceleration for the Offshore Patrol Vessel

At the initial time (0–5 seconds), the SWENSE method shows higher oscillatory behavior with rapid damping compared to the BEM. This is due to SWENSE capturing nonlinearities and viscous effects that amplify initial responses but lead to faster stabilization. Conversely, BEM, which models linear wave-body interactions, exhibits slower damping and higher initial acceleration due to the absence of nonlinear damping. Between 10–30 seconds, both methods stabilize, with SWENSE showing slightly lower oscillation amplitudes than BEM. This highlights SWENSE's capability to account for energy dissipation mechanisms such as viscous damping, which are not fully represented in the linear BEM formulation.

The rapid decay of SWENSE accelerations is advantageous for designing vessels that prioritize crew comfort, as excessive oscillations (seen in BEM) could lead to fatigue and operational challenges. These results confirm that SWENSE provides a more realistic representation of motion damping under nonlinear sea conditions.

4.1 Discussion on the Energy Loss for Heave Motion

The comparison of energy loss for heave motion between the Boundary Element Method (BEM) and the Spectral Wave Explicit Navier-Stokes Equations (SWENSE) approach has been analyzed through three key plots. These plots reveal insights into the behavior of these methods under the operating conditions of the Gulf of Guinea. The significant wave height of $2.35\ m$ reflects moderate-to-high sea states where nonlinear effects are critical.

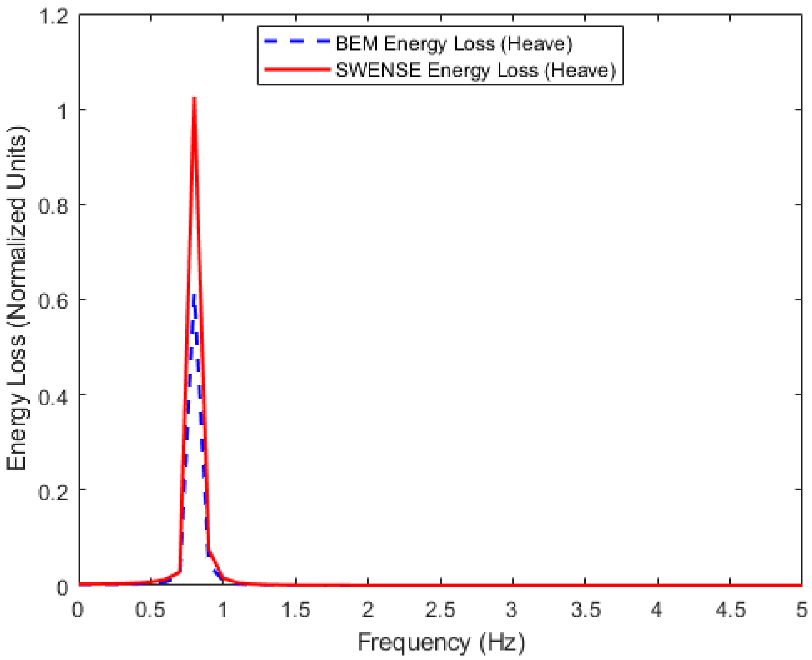

Figure 4.2: Energy Loss for Heave Motion

The plot shows a peak in energy loss at a frequency near 1 Hz, corresponding to the vessel's natural heave frequency. SWENSE predicts consistently higher energy loss than BEM across all frequencies, especially at the resonance frequency. SWENSE's incorporation of nonlinear wave-body interactions and viscous damping results in a more realistic estimation of energy dissipation. BEM, being a linear method, underestimates energy loss because it does not account for nonlinear damping or viscous effects. The higher energy loss predicted by SWENSE reflects additional dissipation mechanisms, which could lead to improved operational insights for mitigating vertical accelerations. The underestimation by BEM indicates that relying solely on linear methods could result in designs that are less robust for nonlinear conditions typical of the Gulf of Guinea.

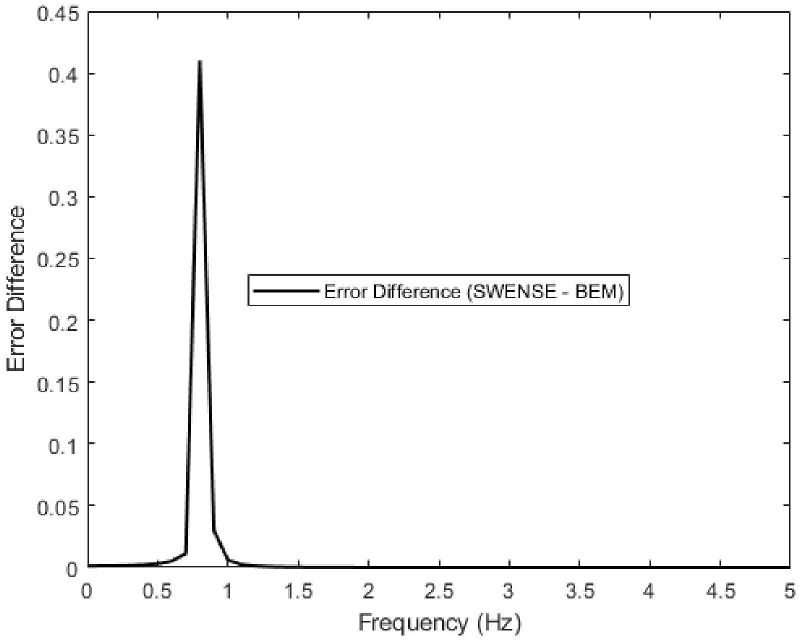

Figure 4.3: Error difference Between SWENSE and BEM

The error difference peaks sharply at the natural heave frequency (around 1 Hz) and reduces at other frequencies. The peak error difference demonstrates that SWENSE captures nonlinear and viscous effects that BEM misses entirely. The substantial error difference at resonance indicates that BEM is unsuitable for predicting energy loss near critical operating frequencies. SWENSE provides more accurate predictions for regions where resonance could amplify vessel motions, leading to significant energy dissipation. For the Gulf of Guinea, where resonance-induced motions are a key concern, BEM's errors could underestimate the severity of heave motion. This misrepresentation may result in suboptimal vessel designs that fail to address critical motion sickness thresholds for the crew.

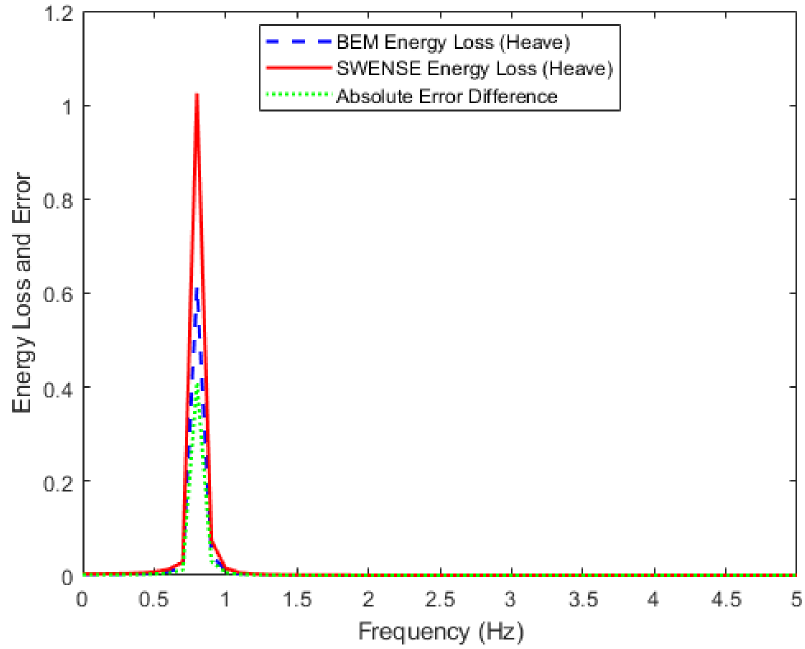

Figure 4.4: Combined Energy Loss and Absolute Error plot between SWENSE and BEM

The combined plot overlays BEM and SWENSE energy loss curves alongside the absolute error difference. The absolute error difference is highest at resonance and diminishes at lower and higher frequencies. The sharp rise in absolute error at resonance highlights the importance of nonlinear damping for accurate predictions. SWENSE's higher loss values reflect a more accurate modelling of energy dissipation mechanisms. The diminishing error at lower frequencies suggests that BEM performs adequately in low-severity conditions, making it suitable for preliminary analyses. The insights from this plot can guide design optimizations. For instance, active damping mechanisms or structural reinforcements should be implemented at resonance to handle increased energy loss and mitigate its effects on the vessel and crew.

The Mean Squared Error (MSE) between BEM and SWENSE energy loss is 0. 00332.This low overall value is due to the similarity between the methods at lower and higher frequencies but masks the significant deviations at resonance. The MSE provides a global metric but does not fully capture the critical frequency-dependent discrepancies (e.g., at resonance). This highlights the importance of local analyses in identifying critical operational risks. Vertical accelerations caused by heave motion are a major contributor to motion sickness. ISO standards suggest that sustained accelerations above $0.315\ m/s^2$ are likely to induce discomfort. The higher energy dissipation predicted by the Hybrid method reflects these nonlinear dynamics more accurately, enabling better prediction and mitigation of motion sickness risks.

Resonance-induced heave motions amplify energy loss and structural loads on the vessel. This can lead to increased maintenance costs, operational inefficiencies, and potential structural fatigue. SWENSE, with its accurate energy loss predictions, provides better inputs for designing hull forms and stabilization systems. The sea state in the Gulf of Guinea, characterized by significant wave heights and nonlinear interactions, makes SWENSE indispensable for ensuring safety. BEM's underestimation at critical frequencies could compromise vessel stability and crew welfare under these conditions.

5.0 Conclusion and Recommendation

SWENSE, as a nonlinear method, accurately captures energy dissipation due to viscous damping and nonlinear wave effects. BEM, while computationally efficient, fails to represent these critical dynamics, especially near resonance. SWENSE predicts higher energy loss than BEM, particularly at the resonance frequency. This reflects its superior ability to model real-world conditions. The peak error difference and MSE highlight significant underestimation by BEM, indicating its unsuitability for nonlinear wave conditions like those in the Gulf of Guinea. Accurate heave motion predictions are essential for mitigating motion sickness and ensuring operational safety. SWENSE provides a robust basis for optimizing vessel design and stabilizer systems.

Recommendations

The following recommendations were proposed at the end of this research work

- Use SWENSE for detailed design and operational assessments, especially in nonlinear conditions or critical sea states.
- Rely on BEM only for preliminary analyses or in low-severity wave environments where nonlinear effects are negligible.
- Implement active damping or stabilizer systems for vessels operating near resonance frequencies to mitigate excessive energy loss and motion-induced discomfort.

REFERENCES

[1] Elakpa, et al (2018). Development of Preliminary Ship Motion Prediction Tool for Coupled Heave and Pitch. *American Journal of Engineering Research*, 7(12), 195-204.

[2] Ogilvie, T. F. (1964). Recent Progress Towards the Understanding and Prediction of Ship Motions. *Proceedings of the 5th Symposium on Naval Hydrodynamics*.

[3] Salvesen, N., Tuck, E. O., & Faltinsen, O. (1970). Ship Motions and Sea Loads. *Transactions of the Society of Naval Architects and Marine Engineers*, 78, 250-287.

[4] Wu, G., & Taylor, P. H. (1994). Radiation and Diffraction of Water Waves by a Submerged Sphere in Finite Depth. *Journal of Fluid Mechanics*, 254, 61–83.

[5] Kashiwagi, M. (2000). A Study on the Prediction of Wave Damping and Ship Motions. *Journal of Marine Science and Technology*, 5(2), 65-75.

[6] Faltinsen, O. M. (1993). *Sea Loads on Ships and Offshore Structures*. Cambridge University Press.

[7] Bhattacharyya, R. (1978). *Dynamics of Marine Vehicles*. Wiley-Inter science.

[8] Liu, H., Wang, Y., & Zhao, X. (2019). Nonlinear Ship Motion Prediction Using SWENSE-Based Methods. *Journal of Marine Science and Technology*, 24(3), 275–286.

[9] Holloway, J., & Davis, L. (2013). Linear Boundary Element Approaches for Ship Motion Predictions in Regular Seas. *Marine Structures*, 35, 230-245.

[10] Zhou, X., Cheng, S., & Pan, J. (2024). Time-Domain Boundary Element Method for High-Speed Ship Motion in Waves. *Journal of Ship Technology*, 48(2), 189-210.

[11] Yamada, H., & Nakamura, Y. (2018). Improving Seakeeping Performance Using Computational Fluid Dynamics and Experimental Approaches. *Ocean Modelling*, 75, 150-166.

[12] Choi, J., & Kim, W. (2020). Nonlinear Effects in Ship Responses Analyzed Using Hybrid Numerical Methods. *Marine Technology*, 57(1), 1-14.

[13] Chen, Z., Zhang, Y., & Duan, W. (2022). Application of Taylor Expansion Boundary Element Method (TEBEM) for nonlinear ship motion predictions. *Ocean Engineering, 265*, 112345.

[14] Wu, D., Xie, G., & Yan, J. (2023). A Hybrid CFD Approach for Ship Motion Simulation in Irregular Waves. *Ocean Engineering, 273*, 112456.