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Hydrodynamic Analysis and Performance Evaluation of a Ship in Irregular Sea Conditions

Ofohaorji, Noble. N.[a], Orji, Charles U.[ab], Dick, Ibitoru F.[b] and Adah, Elekpa[b]
[a]NNPC/SPDC-JV Centre of Excellence for Marine and Offshore Engineering, Rivers State University, Port Harcourt, Nigeria.
[b]Department of Marine Engineering, Faculty of Engineering, Rivers State University, Nkpolu-Oroworukwo, Port Harcourt, Nigeria.
Corresponding author's email: noble.fupre@gmail.com.

ABSTRACT
The maritime industry, a critical global trade facilitator, necessitates the movement of goods and passengers across the world's oceans. Ships, the backbone of this industry, encounter diverse environmental conditions, from calm waters to tumultuous seas. Among these challenges, irregular sea conditions have gained increasing attention among naval architects, marine engineers, and safety regulators. The extremes in ship motions and loads, induced by severe sea states, pose a significant threat to ship and cargo safety. This study focuses on the hydrodynamic response of a ship in irregular sea conditions, with a particular emphasis on vertical plane motions (heave, pitch, and roll). The approach involves the generation of irregular wave scenarios based on wave spectral models, employing computer-aided design and ANSYS software. Time-domain simulations offer a nuanced perspective on the ship's dynamic behavior. It concentrates on long-crested wave scenarios and considers three specific spectral models; Pierson-Moskowitz, Bretschneider, and JONSWAP. The study refrains from examining structural or material aspects of ship design and omits the consideration of viscous effects. The most extreme vertical responses were observed under the Pierson-Moskowitz Sea state to be -0.44291m heave and 0.68986° pitch during the simulation time of 300s, whilst JONSWAP resulted in the most extreme roll motion of 3.69873e-3°. The methodology and results provide critical insights for naval architects, marine engineers, and safety regulators as they navigate the complexities of irregular sea conditions. This research emphasizes the impact of wave spectra on ship behavior, bridging the theoretical and practical aspects of maritime operations in ship hydrodynamics.

KEYWORDS: Irregular Waves, Motion Response, Potential Flow Theory, Time-domain Analysis, Wave Spectral Model.

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1.0 INTRODUCTION

The maritime industry, a linchpin of global commerce, grapples with significant challenges when navigating irregular sea conditions characterized by unpredictable and severe wave patterns. Ships, indispensable to this industry, traverse diverse environmental conditions, from placid waters to turbulent seas. Among these challenges, irregular sea conditions, marked by unpredictable and severe wave patterns, have emerged as significant threats to ship and cargo safety. The complexity of real-world ocean waves, their nonlinearity, and the absence of full-scale measurements in extreme sea states make the field challenging to navigate (Oberhagemann *et al*., 2012). As a response, the simulation of irregular waves has become pivotal for enhancing safety and operational efficiency (Zaraphonitis *et al*., 2016).

Early research in naval architecture focused on ship performance in calm waters. However, similar work by Weinblum and Denis (1950) shifted the focus to understanding the complex interplay between ships and waves. Ships inherently maintain a mean forward velocity, and their oscillatory movements in the presence of waves overlap with a steady flow environment. This raises questions about the steady-state problem, which is of considerable interest, notably in calculating wave resistance in calm waters.

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In cases where both the ship's unsteady movements and the wave characteristics are of small amplitudes, systematic perturbation techniques become applicable, yielding leading-order solutions that are linear in these modest amplitudes. The surrounding seaway can be deconstructed into individual components, each characterized by unidirectional and sinusoidal attributes. In the jargon of this field, however, spectral analysis first applied to ship motions by Denis and Pierson (1953) provided the first insights into this methodology and made the study of ship motions in regular waves applicable to an irregular seaway.

Faltisen (1990) laid the foundational principles for comprehending the complex dynamics of ship motion. This work elucidated the importance of considering the intricate interplay between a vessel's design, the dynamic forces of irregular waves, and the resultant motion characteristics. Advancements in naval architecture and marine engineering have leveraged cutting-edge computational tools and methodologies for in-depth exploration of hydrodynamic modeling and response prediction, significantly enhancing the precision of predicting ship motion in irregular sea conditions (Jiao & Tezdogan, 2023). Utilizing advanced numerical techniques such as Computational Fluid Dynamics (CFD) and potential flow theory, researchers have simulated and modeled intricate hydrodynamic interactions between vessels and irregular waves (Kim & Tezdogan, 2022). These simulations have improved the understanding of ship behavior, encompassing responses like pitch, roll, and heave, especially in the challenging and unpredictable conditions of irregular seas.

Oceanography inherently involves the study of irregular waves, characterized by a non-uniform series fluctuating in height, length, and breadth, forming unsteady and unreliable sequences. Goda (1985) describes this as a random phenomenon, emphasizing the continuous variability in wave dimensions. Contrary to a constant progression of identical waves, the sea surface, or gravity waves, exhibits waves of varying heights and periods, moving in distinct directions. Particularly in wind waves, irregularities in direction, amplitude, and frequency prevent a deterministic description of surface elevation. Recognizing the inherent randomness of surface elevation is crucial before analysis, necessitating a proper understanding of sea surface characteristics. Two approaches to represent wind waves' irregular nature are through the wave energy spectrum and statistical probability distributions of single wave characteristics. Larsén *et al.* (2015) explored a statistical methodology for extreme wave estimation. Spectra descriptions are vital for studying wave characteristics in marine structures, considering the spectrum as the sum of wave parameters produced by events separated in space, time, or both. While the sea surface spectrum lacks a specific mathematical form, empirical expressions, such as the modified Pierson-Moskowitz model for "Fully Developed Sea" and the JONSWAP model for fetch limited "Developing Sea," have been widely accepted and used for decades. Sun *et al.*, (2023) investigated the motion response of Floating, Production, Storage, and Offloading (FPSO) vessels, which play a critical role in offshore oil and gas operations. Guo *et al.* (2016) statistically analyzed how ships respond to extreme sea conditions. The study delved into the statistical characterization of ship motions, forces, and structural responses under extreme sea states.

Currently, the irregular waves can be primarily classified into two categories: long-crested waves and short-crested waves. The main difference between them is in whether multi-directional factors are taken into consideration. Short-crested waves, due to their directional spreading, result in a more complex motion response in structures compared to long-crested waves (Jiao *et al.*, 2019a). Hua (2000) conducted a study on the strong nonlinear rolling

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performance of ships in random waves using the long-crested irregular wave based on linear theory. Carrica *et al.* (2006; 2008) investigated the motion response of a ship with speed in long-crested irregular waves based on the Bretschneider spectrum, using the Reynolds-averaged Navier-Stokes equations based on the computational fluid dynamics (CFD) method. Using the three-dimensional time-domain hydroelasticity theory, Jiao *et al.* (2019b) considered the Froud–Krylov nonlinear effect to predict ship motion and wave loads in long-crested irregular waves.

However, conventional research about the interaction between structures and irregular waves typically relies on a specific wave spectrum for simulation. It often neglects the impact of irregular waves generated under various wave spectra on structural motion. This paper seeks to address this gap by presenting a comprehensive methodology employing time-domain analysis to assess a ship's motion response under varying wave spectra with the following specific objectives, to:

(i) Generate a 3D model of a typical ship geometry using computer-aided design (CAD) software.
(ii) conduct time domain simulations to capture the ship's motion and response over a specific period, providing insights into the ship's dynamic behaviour.
(iii) visualize and analyse the simulation results, providing a comprehensive assessment of the ship's response to irregular sea conditions.
(iv) assess the ship's performance and stability in response to varying wave spectra and identify potential areas for improvement in design or operational practices.

The research is grounded in well-established principles of naval architecture and marine engineering and aims to improve ship safety, performance, and sustainability.

2.0 MATERIALS AND METHODS

2.1 Materials

The hull modeling for the vessel was accomplished using SolidWorks. SolidWorks is a 3D computer-aided design (CAD) software developed by Dassault Systemes. It is widely used in engineering and design to create 3D models, simulate physical properties, and produce detailed technical drawings. ANSYS, a renowned engineering analysis and simulation software suite was used to simulate hydrodynamic aspects. ANSYS is designed with multiple interactive programs that can operate independently or be integrated with other software for concurrent analysis using the ANSYS Workbench tool. In this research, ANSYS Workbench unites Aqwa Hydrodynamic Diffraction, utilized for modeling sea conditions and fluid flow analysis around the vessel, with Aqwa Hydrodynamic Response, applied for investigating the vessel's responses. This amalgamation of tools within the Workbench suite catalyzes the vessel's comprehensive hydrodynamic analysis and performance evaluation.

2.2 Methods

Analyzing and understanding a vessel's hydrodynamic response can be done numerically or through computational simulations in a frequency or time domain. In this study, responses are analyzed in the time domain using computational simulations. The flow field for this paper is governed by the Potential flow theory. The governing equations will be developed in the following sections.

2.2.1 Coordinate System

Consider the motion of a freely floating body in waves, as shown in Figure 1. A floating body has six degrees of freedom. Completely defining the ship's motion requires considering movements in all these modes. The motions are defined as movements of the center of gravity of the ship and rotations about a set of orthogonal axes through the center of gravity, O. These are space

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axes moving with the mean forward speed of the ship but otherwise fixed in space.

In this context, the body-fixed frame plays a crucial role. This frame is rigidly attached to the ship's structure and moves in tandem with the ship's motion. It serves as the reference frame for describing the ship's internal dynamics, the forces acting upon it, and the moments influencing its behavior. Regarding the body-fixed frame, the x-axis aligns with the ship's centerline, the y-axis with the ship's beam, and the z-axis is oriented vertically.

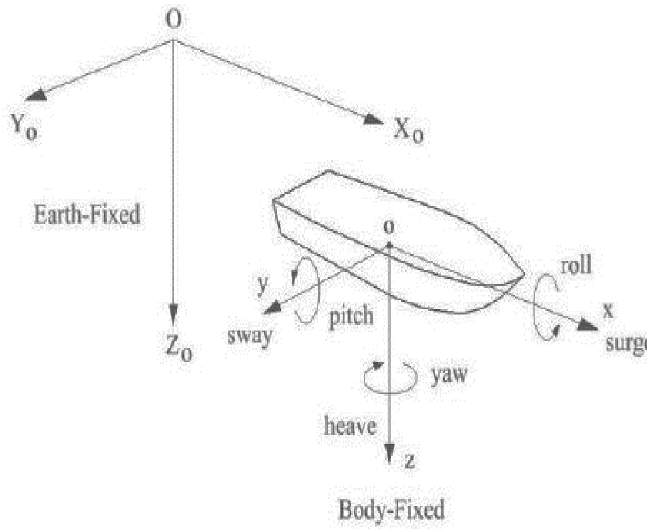

Figure 1: Coordinate System (*By Marco-Altosole*)

2.2.2 Potential Flow Theory

The problem for any water wave theory is determining the velocity potential, ϕ about the fluid region. The potential function, $\phi(x, z, t)$, can defined as a continuous function that satisfies the basic laws of fluid mechanics: conservation of mass and momentum, assuming incompressible, inviscid, and irrotational flow. There is a vector identity that states for any scalar, ϕ

$$\nabla \times \nabla\phi = 0 \tag{1}$$

for irrotational flow,

$$\nabla \times \vec{V} = 0 \tag{2}$$

Therefore,

$$\vec{V} = \nabla\phi \tag{3}$$

where $\phi = \phi(x, y, z, t)$ is the velocity potential function. Such that the components of velocity in Cartesian coordinates, as functions of space and time, are:

$$u = \frac{\partial\phi}{dx}, v = \frac{\partial\phi}{dy} \text{ and } w = \frac{\partial\phi}{dz} \tag{4}$$

2.2.2.1 Wave Velocity Potential

The profile of a simple wave with a small steepness looks like a sine or a cosine and the motion of a water particle in a wave depends on the distance below the still water level. This is the reason the wave potential is written as

$$\phi(x, z, t) = P(z) \cdot \sin(kx - \omega t) \tag{5}$$

In which $P(z)$ is an unknown function of z,
Wave number, $k = 2\pi/\lambda$,
Wave frequency, $\omega = 2\pi/T$,
λ is the wavelength,
T is the wave period,
t is time,
x is the direction of wave propagation, and
z is the vertical coordinate.

The velocity potential must satisfy the following conditions:

(i) The Laplace or continuity equation
(ii) Seabed boundary condition
(iii) Free surface dynamic boundary condition
(iv) Free surface kinematic boundary condition

The complete development of these conditions and the Dispersion relationship has been done extensively in several works of literature and can be found in Journee and Massie (2001), hence not repeated here.

2.2.2.2 Laplace Equation

The Laplace equation is often used to describe the velocity potential field. The velocity potential, ϕ is a scalar field that, when differentiated, provides the components of the velocity field in the fluid. The Laplace equation

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is solved for the velocity potential to determine the flow around a ship's hull and to calculate hydrodynamic quantities such as pressure distributions, added mass, and damping coefficients. Applying this condition, the wave potential can be given as:

$$\phi(x,z,t) = (C_1e^{kz} + C_2e^{-kz})\sin(kx - \omega t) \tag{6}$$

Where: C_1, C_2 are undetermined constraints.

2.2.2.3 Seabed Boundary Condition

The seabed boundary condition refers to the condition or constraints that exist at the interface between the water and the seabed (ocean floor) when modeling the behavior of a ship or any other floating or submerged structure. This boundary condition is essential for accurately simulating how a ship interacts with the seabed or underlying surface. The vertical velocity of water particles at the seabed is zero (no-leak condition), hence the velocity potential becomes:

$$\phi(x,z,t) = C \cdot \cosh[k(h+z)]\sin(kx - \omega t) \tag{7}$$

Where: h is the water depth.

2.2.2.4 Free Surface Dynamic Boundary Condition

This boundary condition is essential for modeling the dynamics of a free surface, which is a boundary where the fluid's surface is exposed to the atmosphere, i.e., $z = \zeta$(vertical displacement). At the free surface, there is a continuity of pressure between the fluid inside and the air or the atmosphere outside. This means that the pressure at the free surface is the same as the atmospheric pressure. Hence the velocity potential becomes:

$$\phi = \frac{\zeta_a g}{\omega} \cdot \frac{\cosh[k(h+z)]}{\cosh kh}\sin(kx - \omega t) \tag{8}$$

In deep water with $h \to \infty$ (short waves), the wave potential becomes:

$$\phi = \frac{\zeta_a g}{\omega} e^{kz}\sin(kx - \omega t) \tag{9}$$

Where: ζ_a is the wave amplitude, and

g is the acceleration due to gravity.

2.2.2.5 Free Surface Kinematic Boundary Condition

This refers to the conditions that describe the behavior of the free surface of a fluid, such as water, as it interacts with the surrounding environment. At the free surface, there is a continuity of velocity, which means that the velocity of the fluid at the free surface must be continuous with the velocity of the fluid in the region just below the surface. Hence the vertical velocity at the free surface is given as:

$$\frac{\partial \zeta}{\partial t} + \frac{1}{g} \cdot \frac{\partial^2 \phi}{\partial t^2} = 0 \qquad \text{for } z = 0 \tag{10}$$

Since $z = \zeta$, then, $\frac{\partial z}{\partial t} + \frac{1}{g} \cdot \frac{\partial^2 \phi}{\partial t^2} = 0$ for $z = 0$ (11)

Equation (11) is otherwise known as The Cauchy-Poisson Condition.

2.2.3 Dispersion Relationship

It is a fundamental concept in wave mechanics, and it is used to characterize how waves propagate in different media. This relationship gives the applicability of the velocity potential in deep water. It is given as:

$$\omega^2 = kg \cdot \tanh(kh) \tag{12}$$

for deep water, $\tanh(kh) \to 1$,
hence $\omega^2 = kg$ (13)

2.2.4 Motion Equations

The elastic deformation caused by wave action on the structure is minor compared to the geometric scale of the structure itself in actual engineering. At present, the structure is regarded as a rigid body when studying the hydrodynamic problems of the structure. Then, the equation of motion of the structure can be expressed as:

$$[M + A]\ddot{x} + [D]\dot{x} + [C]x = F_o \tag{14}$$

where, $[M]$ is the mass matrix of the structure; $[A]$ is the added mass matrix; $[D]$ is the damping

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matrix; $[C]$ is the stiffness matrix; F_o is the total fluid force of the structure, respectively. The comprehensive development of the motion equations and the expressions for the hydrodynamic coefficients can be found in (Lewis ed., 1989) hence not repeated here.

2.2.5 Motion Response System

A harmonic load system produces a harmonic response. Since the equation of motion of the ship is a harmonic one in the form:

$$(M + A)\ddot{x} + D\dot{x} + Cx = F_o \sin \omega t \quad (15)$$

The response will also be a harmonic one, hence the response becomes:

$$x = X_o \sin(\omega t - \theta) \quad (16)$$

Where: X_o = motion amplitude
θ = phase angle

Taking derivative of x

$$\dot{x} = \omega X_o \cos(\omega t - \theta) \quad (17)$$

$$\ddot{x} = -\omega^2 X_o \sin(\omega t - \theta) \quad (18)$$

Ignoring A for simplification, equation (14) becomes:

$$-M\omega^2 X_o \sin(\omega t - \theta) + D\omega X_o \cos(\omega t - \theta) + CX_o \sin(\omega t - \theta) = F_o \sin \omega t \quad (19)$$

$$X_o = \frac{F_o}{(-M\omega^2 + C)\cos\theta + D\omega \sin\theta} \quad (20)$$

$$X_o = \frac{F_o}{\sqrt{(-M\omega^2 + C)^2 + (D\omega)^2}} \quad (21)$$

This is the response of the system, and for a spring mass damper system, the response can be derived in terms of the system's natural frequency, ω_n, damping factor, η, and frequency ratio, λ.

Natural frequency $\omega_n = (\frac{C}{M})^{\frac{1}{2}}$
Damping coefficient $D = 2M\omega_n\eta$
Frequency ratio $\lambda = \frac{\omega}{\omega_n}$

$$X_o = \frac{F_o/C}{\sqrt{(1-\lambda^2)^2 + (2\eta\lambda)^2}} \quad (22)$$

X_o is the motion response amplitude.

2.2.6 Ship Modelling

The ship geometry modeling must accurately account for the hull's shape and structural intricacies of the real ship. In this research, a cargo vessel is utilized with the principal parameters outlined in Table 1 for analysis.

Table 1: Principal parameters of the cargo ship

Notation (unit)	Item	Value
L_{pp} (m)	Length between perpendiculars	175.0
B (m)	Beam	25.4
T (m)	Draft	9.5

2.2.7 Spectral Analysis

In the spectral analysis theory, the motion and load responses of ships in irregular waves are the linear outputs of incident waves. Thus, ship response spectrum in long-crested irregular waves can be obtained by:

$$S_R = S_{(\omega)} \times [RAO]^2 \quad (23)$$

Where: S_R is the Ship response spectrum, and
$S_{(\omega)}$ = Spectrum

2.2.7.1 Pierson-Moskowitz Spectrum

Pierson and Moskowitz (1964) proposed a new formula for an energy spectrum distribution of a wind-generated sea state. Commonly known as the P-M spectral model, it was developed for fully developed seas in the Northern Atlantic Ocean generated by local winds, and it has been found to be ideal in representing a severe storm wave in seakeeping analysis. The P-M spectral model is written as:

$$S_{(\omega)} = \frac{124}{{T_z}^4} H_s \omega^2 \exp\left[-\frac{496}{{T_z}^4}\omega^{-4}\right] \quad (24)$$

Where: $S_{(\omega)}$ = Spectrum

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H_s = Significant wave height
T_z = Zero up-crossing period
ω = Wave frequency

2.2.7.2 Bretschneider Spectrum

To overcome the limitation of fully developed seas, a two-parameter spectrum was developed. This spectrum can be used for sea states of varying severity from developing to decaying by allowing the user to specify the modal frequency and significant wave height. Based on the assumption that the spectrum is narrow-banded, and the individual wave height and wave period follow the Rayleigh distribution, Bretschneider (1959, 1969) derived the following form of the spectral model:

$$S_{(\omega)} = 0.1687 H_s{}^2 \frac{\omega_m{}^4}{\omega^5} \exp\left[-0.675\left(\frac{\omega_m}{\omega}\right)^4\right] \quad (25)$$

Where: $\omega_m = \frac{2\pi}{T_s}$ = Modal frequency
T_s = Significant wave period

According to the Bretschneider spectral model, it can be shown that:

$$T_s = 0.946 T_0$$

Where T_0 is the Peak period.

2.2.7.3 JONSWAP (Hs) Spectrum

The JONSWAP (Joint North Sea Wave Project) spectrum can consider the imbalance of energy flow in the wave system (for instance, when seas are not fully developed). Energy imbalance is always the case when there is a high wind speed. Parameterization of the classic form of the JONSWAP spectrum (using fetch and wind speed) was undertaken by Houmb & Overvik (1976). The JONSWAP wave spectrum is used to describe typical winter storm waves of the North Sea. The spectral ordinate at a frequency is given by:

$$S_\omega = 0.0749 H_s{}^2 T_z (T_z\omega)^{-5} \exp\left[-0.4567 (T_z\omega)^{-4}\right](3.3)^{\gamma} \quad (26)$$

Where: $\gamma = \exp\left[-\left(\frac{1.286 T_z \omega - 1}{2C^2}\right)^2\right]$

$C = 0.07$ for $\omega \le \omega_0$
$\tau = 0.09$ for $\omega > \omega_0$

$$\omega_0 = \frac{5.24}{T_1}$$

$$T_1 = \frac{1.287 T_z}{1.199}$$

2.2.8 Numerical Development using ANSYS.

2.2.8.1 Geometry Import

The numerical model used in this research is intentionally simplified, encompassing solely the hull's geometry while excluding appendages. This simplification is a deliberate choice made to create an optimized representation for investigating seakeeping phenomena in a controlled and focused manner. By concentrating on the essential geometry of the hull, the model allows for a precise and efficient exploration of the ship's dynamic responses in irregular sea conditions, aligning with the specific objectives of this study.

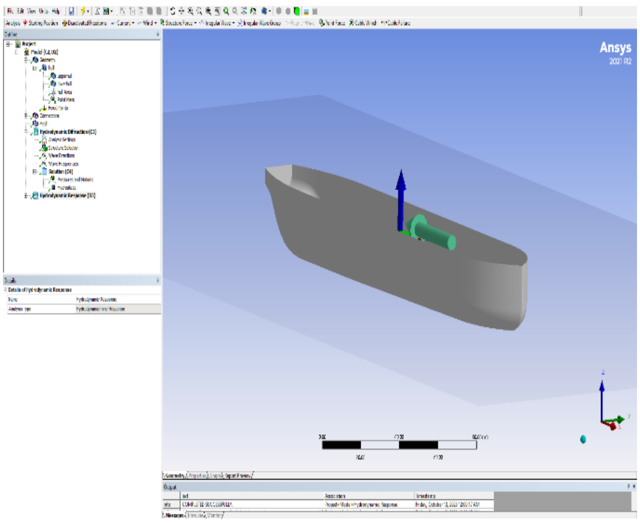

Figure 2: Imported Geometry

2.2.8.2 Meshing

The "all triangles method" was selected as the preferred meshing technique. This choice was motivated by its remarkable adaptability, enabling the accurate representation of complex shapes without the need for excessive mesh refinement. Additionally, the preference for

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Computational Fluid Dynamics (CFD) physics was evident in the simulation setup. CFD excels in managing irregular and intricate geometries, making it especially suited for simulating the flow around ships' hulls, propellers, and other intricate components. The meshing process was efficiently executed using the Fluent solver, which is equipped with advanced meshing tools and robust geometry handling features. These capabilities empower users to create and manipulate complex mesh structures with precision and ease.

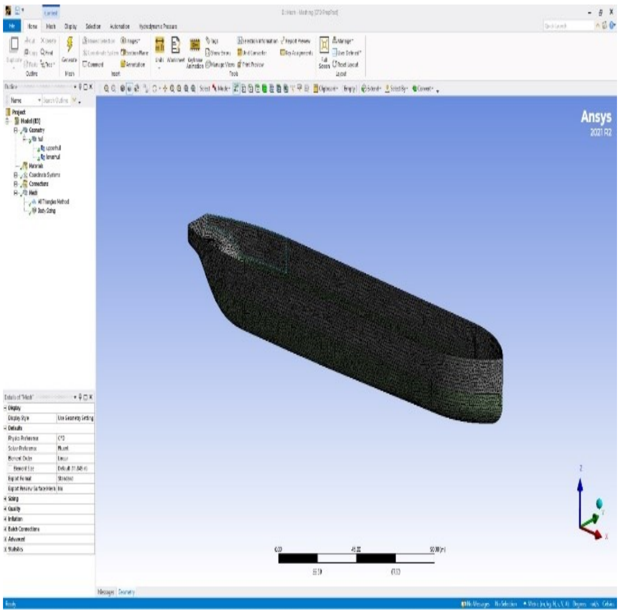

Figure 3: Meshed Geometry

2.2.8.3 Free Running Simulation

The ship's hull is placed within a computational representation of real-world fluid flow conditions, accurately mirroring the complexities of a maritime setting. Importantly, during this phase, no external forces or control inputs are artificially applied to the ship model. This enables the ship to respond autonomously to the intricate hydrodynamic forces imparted by the surrounding water, akin to its behavior in the open sea. Ensuring accurate and detailed results, the simulation employs advanced time integration techniques. This approach allows us to meticulously progress through the analysis in small temporal increments. At each time step, the solver computes and updates the flow variables, resulting in a comprehensive and precise evaluation of the ship's responses under diverse fluid flow conditions.

3.0 RESULTS AND DISCUSSION

3.1 Time-Domain Analysis

In this study, the impact of spectral models on ship responses is investigated by predicting ship motion under various wave states. The time history of the ship's response in heave, pitch, and roll degrees of freedom are compared and analyzed under different sea conditions idealized by the chosen spectral models. The goal is to identify the modes of extreme motions experienced by the ship.

3.1.1 Heave Motion Analysis

Figure 4 presents the time history curves of the ship heave motion response under three wave spectra at the incident angle of 180 degrees. The simulation time is 300s. This visualization offers a comprehensive depiction of the ship's adaptive behavior as it navigates through varying wave spectra.

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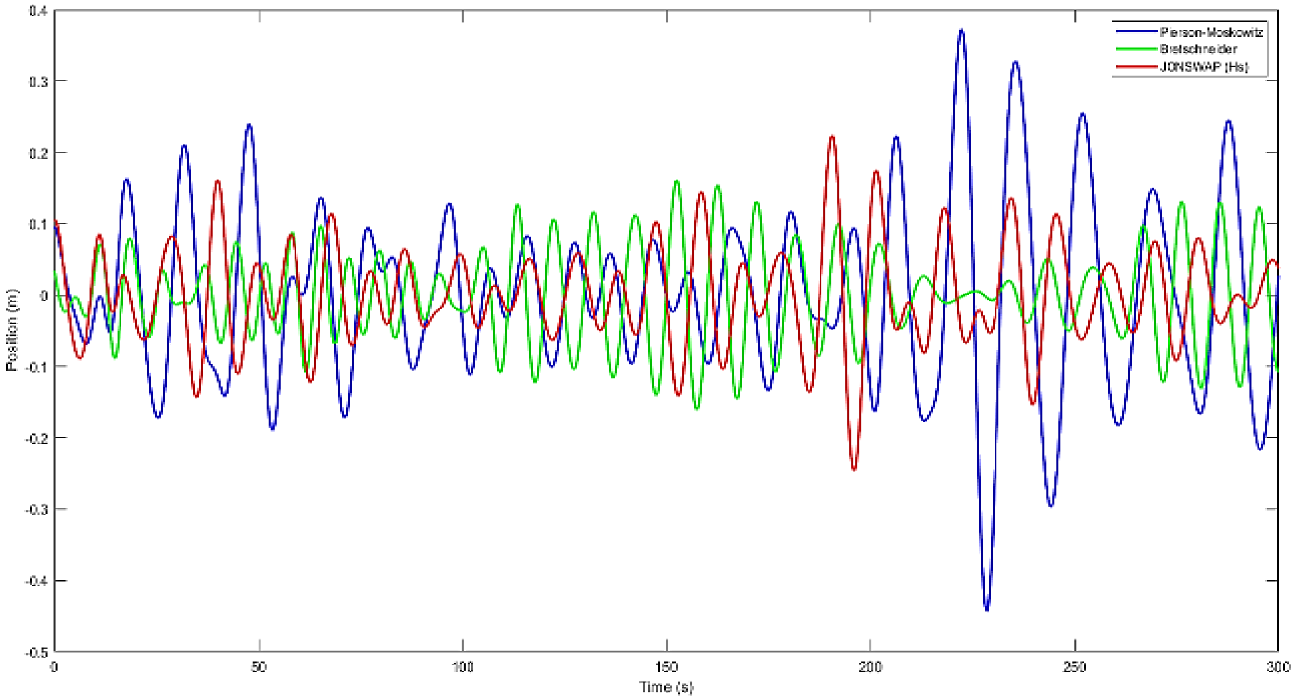

Figure 4: Heave motion responses

Analysis of the results in Figure 4 reveals distinct ship responses under different spectral models, shedding light on the ship's behavior concerning amplitudes, periodicity, and phase changes, with potential implications for slamming events. Notably, the ship encounters the most pronounced vertical displacement under the Pierson-Moskowitz (P-M) spectral model. Initially, it follows a predictable pattern, maintaining stable heave motion. However, a sudden and drastic deviation in the response indicates a severe wind-generated storm, potentially raising concerns about slamming occurrences that could impact the ship's safety, crew, and cargo. Conversely, when subjected to the Bretschneider spectrum, the ship's heave motion demonstrates a controlled and predictable pattern with discernible periodicity and amplitude variations. This stable response profile reduces the risk of slamming incidents and facilitates smoother onboard operations and cargo stability. In contrast, the JONSWAP (Hs) spectrum results in a highly irregular ship response, resembling the behavior observed under the P-M model in terms of amplitude changes and phase variability. While this spectrum introduces smaller displacements, the erratic nature of the ship's motion may still pose challenges, including the possibility of slamming events under certain conditions.

These findings underscore the critical role of wave spectra selection in influencing ship behavior and safety in irregular sea conditions, with specific attention to the potential for slamming events. The Pierson-Moskowitz spectrum's potential for extreme and unpredictable responses, marked by drastic amplitude and phase changes, highlights the importance of careful consideration in ship design and operational planning to mitigate slamming risks. Conversely, the Bretschneider spectrum demonstrates potential benefits in terms of stability, reducing the likelihood of slamming, while the JONSWAP spectrum introduces unique challenges with its irregular but less extreme motion characteristics.

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These observations provide valuable insights for maritime professionals, enabling them to make informed decisions regarding ship responses in varying wave spectra and the potential implications for slamming events. These insights contribute to the development of safety protocols and design enhancements, particularly in regions where slamming events may pose a significant threat to maritime operations.

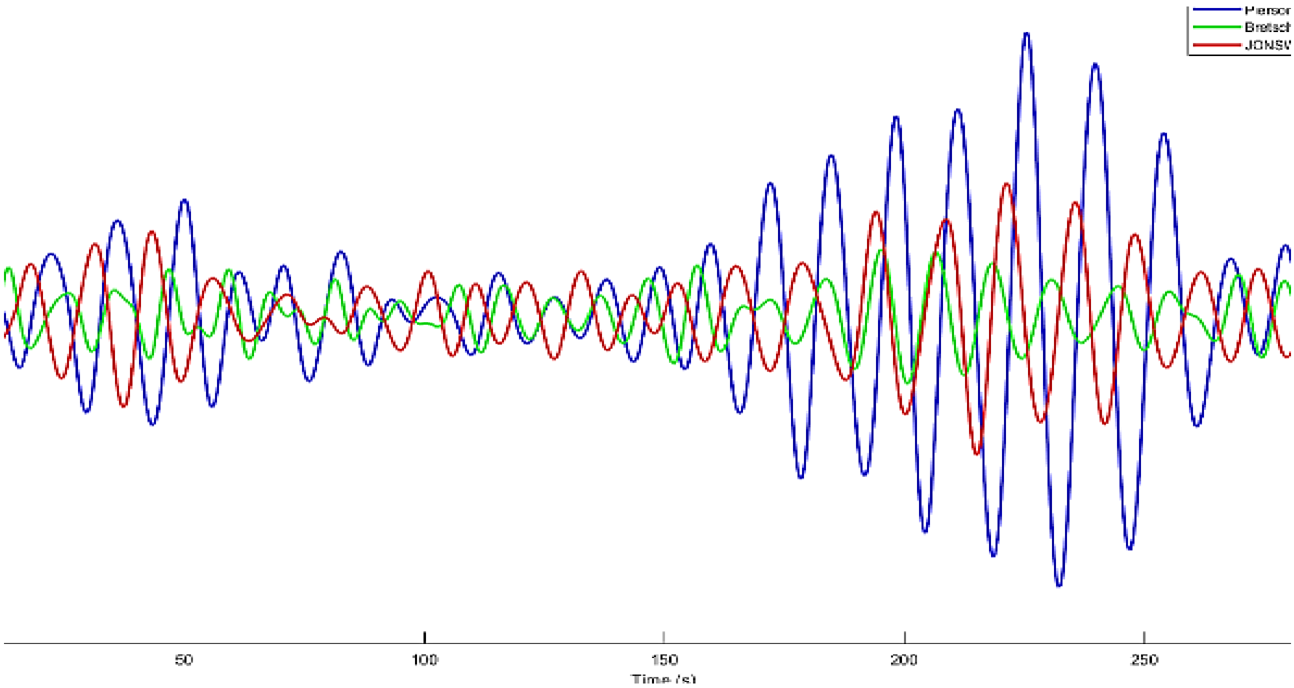

Figure 5: Pitch motion responses

3.1.2 Pitch Motion Analysis

Examining the ship's pitch motion response in irregular sea conditions entails a detailed assessment of its angular rotation about the transverse axis, with measurements recorded in degrees. This investigation provides an understanding of how the ship responds to varying wave conditions, focusing on the dynamic behavior of its bow and stern as they oscillate up and down while the vessel remains parallel to the horizon. This motion is important to understand in the context of ship stability.

Figure 5 illustrates the distinct response disparities among the three different spectral models.

Notably, the Pierson-Moskowitz (P-M) wave model emerges as the most challenging, inducing pronounced and potentially discomforting pitching of the ship. Excessive pitch motion in such conditions can have detrimental effects, leading to passenger and crew discomfort, seasickness, and operational challenges. The P-M model serves as a stark reminder of the volatile nature of irregular sea conditions, underlining the importance of engineering considerations in ship design and operations. Conversely, the Bretschneider wave model provides a more stable scenario, with the ship exhibiting minimal degrees of rotation during the simulation. This relative stability offers tangible engineering advantages, ensuring a smoother and more predictable sailing experience. It minimizes the stresses on the ship's structure and systems, optimizing both passenger comfort and cargo safety. The JONSWAP wave model, while displaying a degree of regularity in pitch motion, stands as an intriguing middle ground. It offers engineering benefits by streamlining the ship's pitching prediction, simplifying the planning of onboard activities, and cargo securing. This analysis underscores the profound impact of

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wave spectra selection on pitch motion—a critical engineering concern. Ship designers and operators must carefully deliberate their choice of wave models, as they significantly influence the ship's behavior and structural integrity in irregular sea conditions. In doing so, they can enhance both passenger and crew well-being and ensure the safety and stability of the vessel.

3.1.3 Roll Motion Analysis

The evaluation of roll motion in ship dynamics centers on the precise measurement of angular rotation about the vessel's longitudinal axis often quantified in degrees. Roll motion is a critical parameter for engineers and naval architects as it is the most critical ship motion of all six modes, and it directly influences a ship's stability, seakeeping ability, and passenger comfort, particularly when navigating through the challenging conditions of irregular seas. This analysis offers a detailed examination of how the ship responds to various wave spectra, shedding light on its dynamic behavior and stability performance. Engineers rely on this data to assess the ship's ability to withstand severe rolling, which is vital for maintaining safe and comfortable conditions on board and safeguarding cargo during transit.
Figure 6 shows the range of roll motions of the ship under the three spectral models being considered, each bearing unique and consequential engineering implications.

Under the Bretschneider wave model, the ship's response characterizes a scenario of minimal roll motions sustained throughout the simulation period. This outcome is emblematic of smooth and stable sailing conditions, marking a pivotal improvement in passenger comfort, cargo security, and overall onboard safety. The consistent, subdued rolling is a testament to the vessel's inherent stability, underscoring the advantages of selecting wave spectra that effectively mitigate the potential for extreme rolling. In stark contrast, both the Pierson-Moskowitz (P-M) and JONSWAP models share a common trajectory in their time histories. Initially, these models display limited roll motions during the early phases of simulation. However, as time advances, a discernible surge in both amplitude and period of roll motions becomes apparent, reaching peak levels under the JONSWAP wave model. This amplification of roll motion, notably pronounced in the JONSWAP model, places a spotlight on the engineering challenges associated with severe rolling. It poses a range of concerns, including the hindrance of onboard operations, the potential for seasickness among passengers and crew, and the jeopardy of cargo stability (Vessel Motion Effects on Crew, 2015). The salient notoriety of roll motions lies in their capacity to instigate ship capsize, facilitate the onset of resonance conditions, and induce the shifting and toppling of objects within the vessel. Considering these engineering insights, ship designers and operators are prompted to conscientiously weigh the influence of wave spectra selection on roll motion dynamics, with a paramount focus on preserving the stability and safety of their vessels when navigating irregular sea conditions.

3.1.4 Overall Spectral Response Analysis

The spectral response analysis reveals significant insights into the ship's performance in irregular sea conditions, emphasizing the extremes in heave, pitch, and roll motions and showing that the motion amplitude of the ship under the three selected spectra is related to the wave type and sea conditions to a certain extent (Sun *et al.,* 2023). Notably, the Pierson-Moskowitz (P-M) wave spectrum consistently results in the most extreme values across all but one degree of freedom. Table 2 presents the extreme values recorded in each degree of freedom across the three different spectral models.

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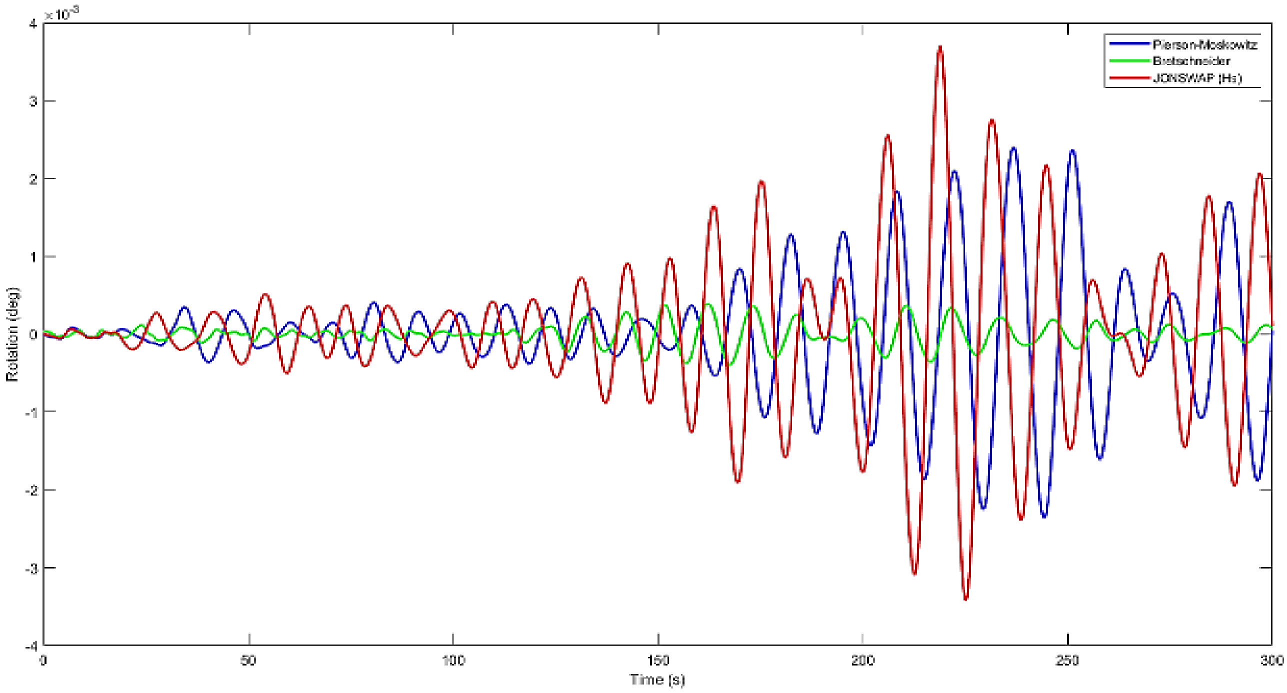

Fig. 6 Roll motion responses

Table 2: Spectral response maximum values

Motion mode (unit)	Pierson-Moskowitz	JONSWAP (Hs)	Brethsneider	Maximum
Heave (m)	-0.44291	-0.24554	0.16064	P-M
Pitch (deg)	0.68986	-0.33899	-0.1651	P-M
Roll (deg)	2.40287e-3	3.69873e-3	-3.9693e-4	JS(HS)

In Table 2, the P-M model stands out with the most pronounced vertical displacements in heave motion, underscoring its potential for discomfort, seasickness, and risk to onboard operations. The Negative heave motion occurs when the ship moves downward from its equilibrium position, or when the ship sinks below the still water level. This can have several implications for the ship's performance, stability, and safety (Zaraphonitis *et al.*, 2016). Some of the possible effects are:

(i) Negative heave motion can increase the hydrostatic pressure on the ship's hull, which can cause structural deformation or damage, especially if the ship is not designed to withstand such loads.
(ii) Negative heave motion can also reduce the ship's buoyancy, which can affect its stability and trim. If the ship's center of gravity is too high or the metacentric height is too low, the ship may become unstable and capsize.
(iii) Negative heave motion can also increase the ship's resistance, which can reduce its speed and fuel efficiency. This can have economic and environmental consequences for the ship's operation.
(iv) Negative heave motion can also affect the ship's comfort and operability, as it

can cause motion sickness, fatigue, and stress for the crew and passengers. It can also interfere with the ship's navigation, communication, and cargo handling systems.

Considering pitch motion, the P-M spectrum again takes the lead, displaying the most extreme angular rotations. These high pitch angles can disrupt operations and threaten the well-being of passengers and crew. Finally, in the domain of roll motion, the JONSWAP wave model exhibits the most extreme values which agree with published research evidence in industry experience that the JONSWAP model influences the most significant effect on Roll motions of the vessel compared to its Pitch motions (Sun *et al.,* 2023). The abrupt and extensive roll motions in this model present challenges related to ship capsize, resonance, and cargo stability.

These findings emphasize the importance of wave spectrum selection and its direct impact on ship behavior in irregular sea conditions (Colwell, 2005; Crossland *et al.*, 2007). Engineers and maritime professionals must weigh the trade-offs between predictability, stability, and extremeness when designing ships and planning voyages in dynamic maritime environments.

4.0 CONCLUSION

This research underscores the critical role of wave spectrum selection in determining a ship's behavior in irregular sea conditions. The approach included a 3D ship model development, irregular wave simulations, time domain analysis, data visualization, and ship performance assessment. The significance of the results lies in their practical implications for ship design, safety, and passenger comfort. While challenges exist, the findings align with existing knowledge highlighting the need for further exploration in this field. As the maritime industry continues to evolve, understanding and optimizing ship responses in unpredictable seas remain a central concern for naval architects and marine engineers.

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