ANALYSES OF WAVE INDUCED STRUCTURAL LOADS ON MARINE VESSEL HULL

BY

IDEMUDIA ETINOSA NATHANIEL

MAT NO: ENG2002368

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SUPERVISOR: ENGR. DR. G.A. OJARIAFE

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CERTIFICATION

I hereby certify that this project work **ANALYSES OF WAVE INDUCED STRUCTURAL LOADS ON MARINE VESSEL HULL** was carried out by **IDEMUDIA ETINOSA NATHANIEL** with matriculation number **ENG2002368** in the department of Marine Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State, Nigeria

…………………………….. ………………………

Engr. Dr. G.A. Ojariefe Date

Project Supervisor

…………………………….. ………………………

Engr. Wisdom Jaja Date

Project Coordinator

…..………………………….. …………………………..

Engr. Prof. Osarobo O. Ighodaro Date

Head of Department

Mechanical Engineering Department

DEDICATION

This project is dedicated to Almighty God for His guidance, wisdom, and strength throughout the course of this study.

I also dedicate this work to my beloved parents and family for their unwavering love, support, and encouragement. Your belief in me has been my greatest motivation.

ACKNOWLEDGEMENT

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ABSTRACT

This study analyses wave induced structural loads on marine vessel hulls with emphasis on vessels operating in the Gulf of Guinea. Marine vessels experience highly variable sea states, and traditional analytical methods often struggle to capture nonlinear effects such as slamming, springing, and whipping. These limitations create uncertainties in predicting hull stress and deformation, especially for modern lightweight and fuelefficient ship designs.

Existing literature highlights the need for regionspecific modeling due to limited hydrodynamic data available for West African waters. This research addresses this gap by applying advanced numerical simulation techniques Computational Fluid Dynamics (CFD) and the Finite Element Method (FEM) to model wave structure interaction under realistic wave conditions. The study uses seawater properties, mildsteel hull material characteristics, and wave parameters representative of the Gulf of Guinea.

The CFD model generates pressure distributions on the hull surface for selected wave heights, while the FEM model evaluates the resulting stresses and deformations. The simulation procedure followed mesh generation, boundary condition specification, wave creation, pressure extraction, and structural analysis.

Results indicate that increasing wave height significantly increases hydrodynamic pressure, bending stresses, and hull deformation. Maximum stress and displacement occurred at the bow and midship region due to direct exposure to wave impact. Comparisons with existing literature confirm good agreement, validating the adopted simulation approach.

Overall, the study provides insight into hull performance in dynamic sea conditions and contributes to improved structural assessment techniques, design optimization, and safety enhancement for marine vessels operating in the Gulf of Guinea

TABLE OF CONTENTS

CHAPTER TWO: LITERATURE REVIEW

CHAPTER THREE: MATERIALS AND METHODS

CHAPTER FOUR: RESULT AND DISCUSSION

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

LIST OF TABLE

LIST OF FIGURES

NOMENCLATURE

CFD: Computational Fluid Dynamics.

FEM: Finite Element Method.

6DOF: Six Degrees of Freedom (referring to Surge, Sway, Heave, Roll, Pitch, and Yaw).

UNCTAD: United Nations Conference on Trade and Development.

2D: Two-Dimensional.

3D: Three-Dimensional.

VOF: Volume of Fluid (a modeling method for tracking air-water interfaces).

FSI: Fluid Structure Interaction.

CAD: Computer-Aided Design.

RAO: Response Amplitude Operator.

ITTC: International Towing Tank Conference.

JONSWAP: Joint North Sea Wave Project (referring to a specific wave spectrum).

ARMA: Autoregressive-Moving-Average (a spectrum estimation method).

TEU: Twenty-foot Equivalent Unit (a measure of container ship capacity).

CAD/CAS: Computer Aided Design and Computer Aided Simulation.

SST: Shear Stress Transport (referring to the k–ω turbulence model).

PISO: Pressure-Implicit with Splitting of Operators (a solver algorithm).

VIV: Vortex-Induced Vibration.

Mathematical Nomenclature and Symbols

H - Significant Wave Height.

T - Mean Wave Period.

U: Ship Speed or forward velocity.

ρ: Water Density.

g: Gravity Acceleration.

ϕ (phi): Velocity potential of the fluid.

ω (omega): Wave angular frequency.

ω - Encounter frequency (wave frequency reflecting relative motion).

β (beta): Angle between the incident wave and the ship.

k: Wave number.

Ts Total resistance coefficient in ship scale.

R-Residual resistance coefficient.

Fs- Skin friction coefficient in ship scale.

ΔC F Hull roughness coefficient.

Apps-: Appendages resistance coefficient.

AAs -Air resistance coefficient for ship.

DBs -Resistance coefficient of transom stern in ship scale.

Sw-: Still water bending moment.

W-: Wave coefficient.

L: Ship length between perpendiculars.

B: Ship breadth

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Marine transportation remains the backbone of global trade, with over 80% of international commerce by volume transported via sea routes (UNCTAD, 2023). Consequently, the structural performance of ships under ocean wave action is of paramount importance to ensure safety and operational efficiency. One of the most critical aspects affecting a vessel's structural integrity is the wave induced load acting on the hull. These loads arise from the complex hydrodynamic interaction between the hull surface and the surrounding water particles as waves propagate, reflect, and break against the vessel. The resulting fluctuating pressures generate bending moments, shear forces, and torsional stresses along the hull girder, leading to cyclic fatigue, structural deflection, and, in extreme cases, buckling or hull fracture.

The mechanisms of wave induced structural loads are governed by several interdependent parameters including wave height, frequency spectrum, encounter angle, hull form, and ship motion characteristics. As waves impact the vessel, the dynamic pressure distribution varies along the wetted surface, creating both global loads (such as vertical bending moments) and local loads (such as slamming on the bow or bottom plating). These interactions are inherently nonlinear and time dependent, making their accurate prediction a major challenge. Traditional analytical approaches, such as linear strip theory, tend to simplify the hydrodynamic response, neglecting nonlinear phenomena like slamming, whipping, and springing (Kim and Troesch, 2005), which significantly influence stress concentration and fatigue life.

Modern computational methods such as Computational Fluid Dynamics (CFD) and the Finite Element Method (FEM) have improved the ability to simulate these mechanisms with higher precision (Sclavounos, 2012). Yet, their practical application in developing regions including Nigeria and the Gulf of Guinea is limited by the absence of region specific sea state data, experimental calibration, and computational infrastructure (Akpofure and Olokeogun, 2020). Consequently, most existing models are based on foreign oceanographic conditions, which may not accurately represent local wave characteristics. This highlights a critical research gap: the need to understand, quantify, and model wave induced structural load mechanisms under regionally relevant environmental conditions, ensuring safer and more resilient vessel designs for local maritime operations.

1.2 Statement of the Problem

Ensuring the structural integrity of marine vessels is essential for their safe operation, longevity, and reliability. Ships are constantly exposed to dynamic and often unpredictable sea states, resulting in wave induced structural loads that act on the hull. These loads, which vary with wave height, frequency, sea direction, vessel speed, and hull geometry, can lead to fatigue, excessive stress, structural deformation, or even catastrophic failure if not properly understood or accounted for during design (Paik and Thayamballi, 2007). Conventional hydrodynamic analysis methods, such as linear strip theory and empirical design formulas, remain widely used in the marine industry. However, they often oversimplify wave structure interactions and fail to capture critical nonlinear effects such as slamming, whipping, and springing which are significant under extreme sea conditions or in lightweight, flexible hull forms used in modern shipbuilding (Kim and Troesch, 2005). As the global trend in ship design shifts toward fuel efficiency and weight reduction, these structural behaviours have become more pronounced, challenging the reliability of traditional analysis methods.

While modern tools like Computational Fluid Dynamics (CFD) and the Finite Element Method (FEM) provide more accurate and comprehensive modelling of wave induced loads and hull stress responses (Sclavounos, 2012), their adoption is still limited in developing maritime regions, such as Nigeria and the broader Gulf of Guinea. This is further exacerbated by the lack of localized experimental or sea state data, which makes it difficult to validate and calibrate simulation results for regional application (Akpofure and Olokeogun, 2020). This research therefore seeks to address these gaps by analysing the structural behaviour of marine vessel hulls subjected to wave induced loading using high fidelity simulation tools. The study aims to improve predictive accuracy, develop regionally relevant design insights, and contribute to the safer and more cost effective design of hull structures, particularly for vessels operating in underrepresented maritime environments.

1.3 Aim and Objectives of the Project

Aim of the Project

The aim of the research is to carry out an analysis of wave induced structural loads on marine vessel using a high fidelity computer analytical tool.

Objectives of the Project

The primary objective of this study is to analyze the structural response of marine vessel hulls to wave induced loads using advanced computational techniques such as computational fluid dynamics in ANSYS or solid works. The study aims to provide a deeper understanding of how dynamic wave conditions affect hull integrity and to propose improved design insights, especially for vessels operating in localized marine environments.

The specific objectives are to:

1. Identify and classify the types of wave induced loads acting on marine vessel hulls under varying sea states and operational conditions.
2. Develop and apply high fidelity simulation models using Computational Fluid Dynamics (CFD) and the Finite Element Method (FEM) to simulate wave structure
   interactions.
3. Analyze stress distribution and deformation patterns on vessel hulls under regular and irregular wave loading conditions
4. Assess the influence of vessel parameters, such as hull geometry, material flexibility, and speed, on the structural response to wave induced loads.
5. Validate simulation results using available experimental data or literature based benchmarks, particularly in the context of the Gulf of Guinea and other regional environments.
6. Propose design recommendations or guidelines to improve hull resilience and operational safety in dynamic marine environments.

1.4 Significance of the Project

The structural integrity of marine vessels is fundamental to the safety and sustainability of global maritime operations. As over 80% of international trade is transported by sea, the design and performance of ship hulls under varying wave conditions are critical factors in ensuring vessel reliability and protection of human lives, cargo and marine ecosystem.

This study is significant for several reasons:

1. Improved Structural Safety: By analyzing how marine vessel hulls respond to wave induced loads, this research contributes to reducing the risk of structural failures at sea. A better understanding of stress concentrations and dynamic responses can lead to safer ship designs and reduced incidents of fatigue or catastrophic failure.
2. Advancement in Simulation Techniques: The study integrates modern engineering tools such as Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) to model complex wave structure interactions. These techniques offer more accurate, realistic assessments than traditional empirical approaches, leading to improved predictive capabilities.
3. Support for Design Innovation: With the maritime industry increasingly adopting lightweight, energy efficient materials, ships are becoming more flexible and prone to dynamic responses. The findings of this study can guide naval architects in designing more robust and adaptive hull structures suited to these new materials and performance demands.
4. Relevance to Local and Regional Maritime Conditions: The research emphasizes localized sea environments, particularly in underrepresented regions such as the Gulf of Guinea. This is crucial, as most existing data and design standards are based on conditions in the North Atlantic or Pacific, which may not reflect the realities of West African coastal waters.
5. Contribution to Academic and Engineering Knowledge: This work adds to the growing body of research in hydroelasticity and naval hydrodynamics. It will serve as a resource for academics, shipbuilders, classification societies, and marine engineers working to improve vessel performance and durability.

6. Policy and Regulatory Implications: The insights from this study may also inform maritime safety regulations and design codes, encouraging more rigorous evaluation of wave induced structural loads in marine classification and certification processes.

1.5 Scope of the Project

This study focuses on marine vessel hulls, particularly monohull configurations commonly employed in cargo and passenger transportation. It investigates the effects of wave induced loads under both regular (sinusoidal) and irregular (random) sea conditions using advanced simulation tools. The research employs Computational Fluid Dynamics (CFD) and the Finite Element Method (FEM) to analyze hydrodynamic pressure distributions, stress responses, and structural deformations on the ship hull. Emphasis is placed on vessels operating within the Gulf of Guinea, though the findings are expected to be relevant to similar coastal and offshore maritime environments.

The study considers the vessel's motion responses resulting from wave excitation, characterized by six degrees of freedom (6DOF):

- Surge: Linear motion along the longitudinal (x) axis.
- Sway: Linear motion along the transverse (y) axis.
- Heave: Linear motion along the vertical (z) axis.
- Roll: Angular motion about the longitudinal axis.
- Pitch: Angular motion about the transverse axis.
- Yaw: Angular motion about the vertical axis.

Among these, heave, pitch, and roll are given primary consideration as they significantly influence wave induced bending moments and hull stresses, while surge, sway, and yaw are treated as secondary effects due to their lesser structural impact under the conditions analyzed.

The study is, however, carried out within the following limitations:

i. Limited access to real time seatmate and structural response data restricts the degree of experimental validation.

ii. The simulation models may not capture all real world conditions, such as corrosion, hull fouling, or human induced factors.

iii. Resource constraints may limit the variety of vessel types, materials, and wave loading scenarios analyzed.

iv. Only selected wave profiles and vessel speeds are modeled to maintain computational feasibility.

1.6 Study Justification

The Gulf of Guinea presents a unique and challenging maritime environment characterized by variable wave spectra, seasonal swells, and short crested sea states that differ significantly from the conditions typically represented in global hydrodynamic models. Despite its growing importance as a major maritime trade corridor in West Africa, limited research and localized modeling data exist for this region. This creates uncertainties in the structural assessment and design optimization of vessels operating in these waters. By focusing on wave induced structural loads in the Gulf of Guinea, this study contributes valuable insights into regionspecific ship responses, promoting safer, more efficient vessel designs tailored to local oceanographic conditions.

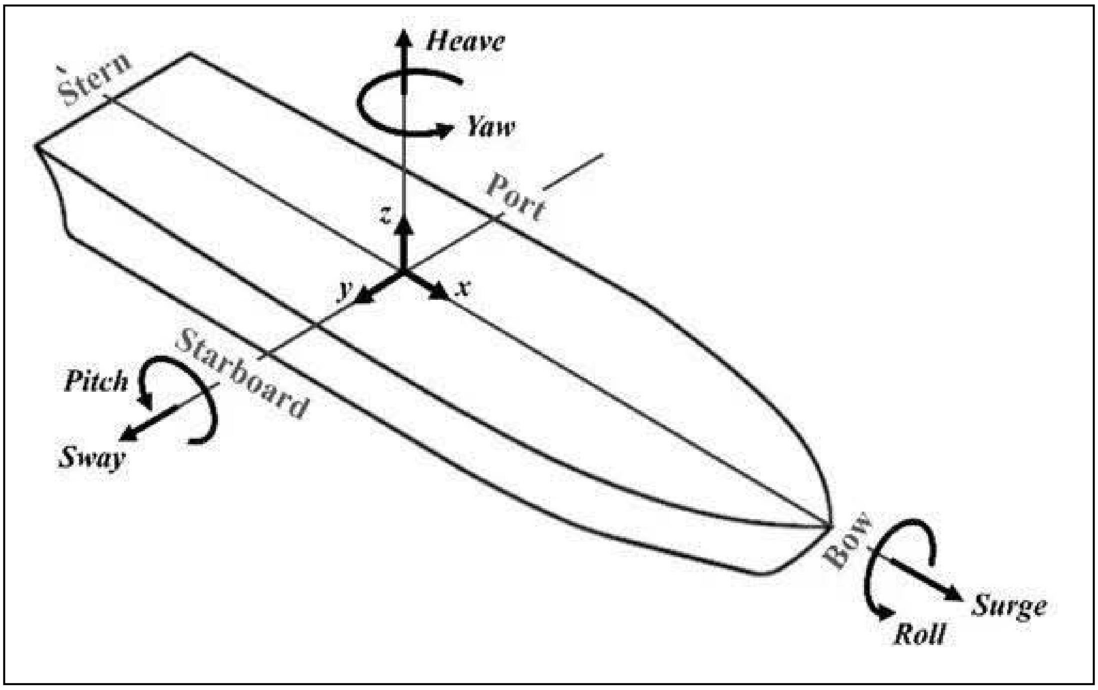


Fig 1.1: diagram of 6 DOF ship motions

CHAPTER TWO

LITERATURE REVIEW

2.1 Nature of Wave Induced Loads

Wave induced loads are hydrodynamic forces generated by the interaction between sea waves and a ship's hull. These forces vary in intensity and frequency depending on wave characteristics (height, period, direction), vessel speed, heading, and hull geometry. According to Paik and Thayamballi (2007), these loads induce bending moments, shear forces, and torsional stresses that affect the hull's structural integrity. Nonlinear phenomena such as slamming, whipping, and springing can occur in severe sea states. Slamming involves localized impacts between waves and the hull, whipping refers to hull vibrations after slamming, while springing is a continuous vibrational response to wave frequencies close to the ship's natural frequency (Kim and Troesch, 2005). A ship configuration and its respective parts are shown in Figure 2.1.

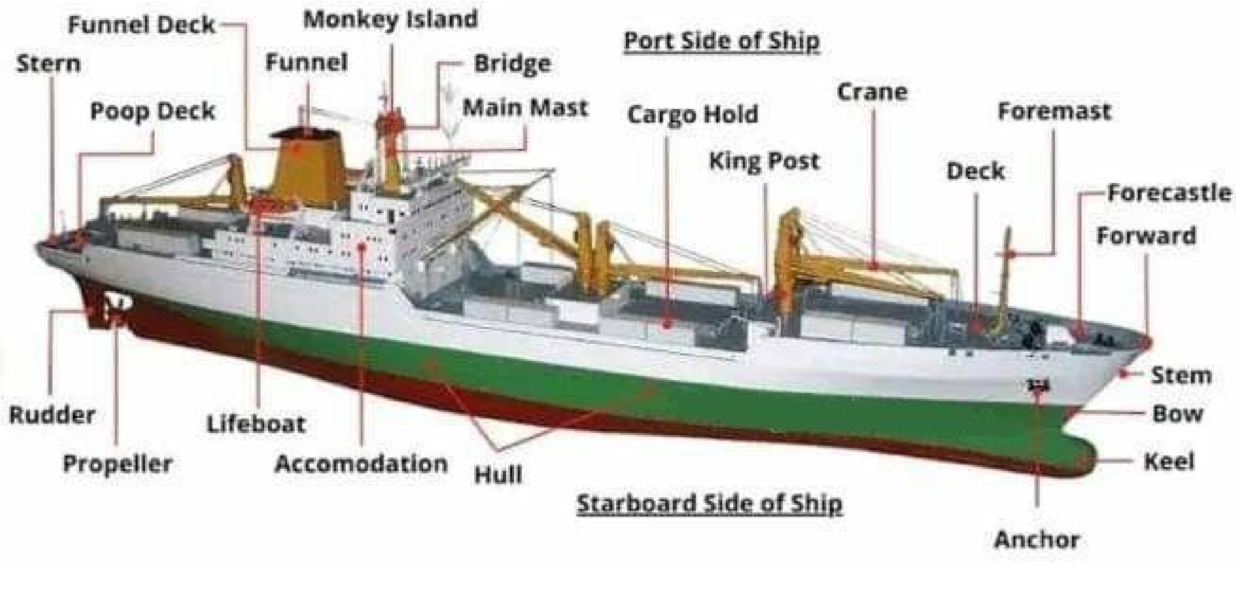


Fig 2.1: Parts of an Ocean Vessel (Ship).

2.2 Conventional Analytical and Advanced Computational Methods

Traditional approaches like strip theory, 2D potential flow models, and empirical formulations have been widely used to estimate wave loads. Strip theory divides the ship into transverse sections to evaluate hydrodynamic forces in calm water or regular wave conditions (Journée and Massie, 2001). These methods are computationally inexpensive but often oversimplify complex, nonlinear interactions, especially for modern, flexible hulls. While these tools remain useful for preliminary design, they lack accuracy in predicting transient effects, structural fatigue, and dynamic amplification under real sea conditions. Recent advances in computational modelling have significantly improved the prediction of wave induced loads. Computational Fluid Dynamics (CFD) enables the detailed simulation of fluid flow, wave patterns, and pressure distribution around the hull. CFD simulation is used to examine the intricate relationships between several elements. It is a crucial tool for comprehending and improving the engineering models or process (Wang et al., 2024). Geometry, meshing, boundary conditions, solvers, discretization schemes, modelling turbulence, and defining working fluids and their characteristics are all key aspects in computational fluid dynamics (CFD) (Sadeghiseraji et al., 2024. The assumptions and simplifications in mathematical models like the turbulence model or inflow profiles that reflect fluid flow produce modelling uncertainties (Wang et al., 2024). It gives better understand to metering error and provide correction factors to increase the accuracy of the reported flowrate by building a 3D CFD model of the system and modelling the variations between the ideal scenario and an "as installed situation (Marc Laing, 2024). Finite Element Method (FEM) models the structural response of the hull under dynamic loads, including deformation, stress, and failure points. Coupled CFD–FEM simulations offer a high fidelity approach to analyzing fluid structure interactions (FSI). According to Sclavounos (2012), these models are essential for capturing the hydro elastic behavior of ships, especially in the presence of nonlinear effects. They allow for simulation under both regular (sinusoidal) and irregular (realistic sea spectrum) wave conditions.

Ansys can simulate a water vessel with incident ocean waves and currents using specialized software like AQWA for hydrodynamic analysis or Fluent for detailed Computational Fluid Dynamics (CFD). These simulations involve creating a 3D model of the vessel and a fluid domain, and then applying wave and current conditions to predict the vessel's response, such as its motion, structural loads, and seakeeping characteristics.

2.2.1 Key aspects of the simulation

i. ANSYS AQWA:

This tool is designed specifically for marine and offshore structures, providing capabilities for calculating hydrodynamic forces and vessel motions in response to waves and currents. It can perform analyses on a wide range of structures, including ships, floating platforms, and breakwaters.

ii. ANSYS Fluent:

A general purpose CFD tool that can handle the complex multiphase (water air) flow physics required for wave and current simulation. It's often used for detailed analysis, particularly when viscous effects or complex free surface phenomena are critical.

iii. ANSYS Mechanical:

This is sed in conjunction with AQWA or Fluent for fluid structure interaction (FSI) to analyse how the fluid forces affect the vessel's structure and its resulting deformations or stresses.

2.2.2 Modelling and setup in Simulation

i. Geometry: A 3D CAD model of the vessel and a fluid domain large enough to accurately capture the wave and current interactions is created. ii. Fluid properties: Define the fluid as water and set up the multiphase flow, often using the Volume of Fluid (VOF) method to capture the free surface.

ii. Wave and current definition: Specify the incident waves (e.g., using wave theory like Stokes or Fifth Order) and the steady or unsteady current. The interaction between waves and currents can be modeled by considering the combined velocity field

2.2.3 Analysis types:

i. Motions analysis: Predict the vessel's six degrees of freedom (surge, sway, heave, roll, pitch, yaw) in response to the sea state, which is crucial for assessing comfort and safety.

ii. Hydrodynamic loads: Calculate forces and moments on the vessel, such as wave slamming, hydrostatic pressure, and drag forces from currents.

iii. Structural analysis: Using Ansys Mechanical, one can apply the calculated loads to the vessel's structure to check for stress concentrations, deformations, and potential failures.

iv. Simulation execution: The solver computes the pressure and velocity fields throughout the fluid domain and the motion of the structure, solving equations like the Navier Stokes equation for fluid flow and equations of motion for the structure.

v. Post processing: Visualize the results, which can include the wave pattern around the vessel, the vessel's trajectory, pressure contours, and structural stress distribution

2.3 Hydroelastic Effects in Modern Vessels

As shipbuilders increasingly adopt lightweight, energy efficient materials like aluminum and composites, vessels are more flexible and prone to hydroelastic responses. These include hull vibrations, increased stress amplitudes, and reduced fatigue life. Kim and Troesch (2005) emphasized that modern vessels exhibit greater sensitivity to transient wave loads, requiring more sophisticated analysis and design criteria. Neglecting these effects in design can result in underestimating stress cycles and potential structural failures over time. Ship motions result from external excitations such as wind, currents, and wave action. However, the degree of sensitivity to these excitations varies depending on the type and characteristics of the vessel. The complex hydrodynamic interaction between the ship and the fluid an inherently infinite degree of freedom system is commonly simplified by modeling the vessel as a rigid body with six degrees of freedom: three translational (surge, sway, heave) and three rotational (roll, pitch, yaw), often referred to as primary and complementary motions
(Nabergoj,2025).

2.4 Hydroelasticity and Structural Coupling

Hydroelasticity describes the coupled interaction between a ship's flexible structure and the surrounding fluid. When waves excite the vessel, the hull experiences elastic deformation that alters the pressure distribution a twoway coupling effect.

According to Bishop & Price (1979) and Faltinsen (1990), the governing equation for coupled fluid–structure interaction can be simplified as:

$$M\ddot{\eta} + C\dot{\eta} + K\eta = F_{wave}(t)$$

where

M= mass matrix,

C= damping matrix,

K= stiffness matrix,

η= displacement vector,

$F_{wave}(t)$= external hydrodynamic force.

This approach allows evaluation of springing (resonant vibration) and whipping (transient response) effects that contribute to fatigue damage over a vessel's lifespan.

2.5 Ship Motion Responses to Wave induced Loads

Ship motion in waves occurs in six degrees of freedom (6DOF): surge, sway, heave, roll, pitch, and yaw. Among these, heave, roll, and pitch dominate vertical motions and directly influence bending and torsional loads.

Heave: Vertical oscillatory motion due to wave elevation.

Roll: Rotational motion about the ship's longitudinal axis, affecting transverse stability.

Pitch: Rotational motion about the transverse axis, linked to longitudinal bending stresses.

The linear motion equation for a single degree of freedom can be represented as:

$$(-\omega^2(M + A(\omega)) + i\omega B(\omega) + C)\eta = F(\omega)$$

where

$A(\omega)$= added mass,

$B(\omega)$= hydrodynamic damping,

C= hydrostatic restoring coefficient,

η= motion amplitude,

$F(\omega)$= excitation force.

The **Response Amplitude Operator (RAO)** expresses the ratio between the ship’s motion amplitude and the incident wave amplitude:

$$RAO(\omega) = \frac{|\eta(\omega)|}{|\zeta(\omega)|}$$

RAOs describe how a ship responds to different wave frequencies critical for predicting hull bending moments, fatigue, and comfort levels. Theoretical derivations and validation of RAOs are well documented in Lewis (1989) and ITTC Seakeeping Guidelines (2017).

2.6 Related Literatures

Corigliano et al., (2024) carried out research on the fatigue overview of ship structures under induced wave loads. The authors asserted that fatigue damage represented key failure mode in ship structures which basically starts developing at vulnerable points in the structure such as welded joints, stress concentration areas, and cracks. They further explained that cyclic loading, particularly from waves, encountered by ships during their operational life was a major cause of fatigue damage. Their research was therefore aimed at reviewing the most commonly used methods of fatigue analysis to highlight the strengths and weaknesses of various analytical tools as well as provide essential background knowledge for developing reliable theoretical and numerical models for predicting the fatigue life of ship structures exposed to various sea states over their lifetime. The primary theoretical approaches discussed by the authors include energy spectral methods in both time and frequency domains, which were used to quantify waverelated energy and amplitude characteristics and to evaluate wave loads for predicting the fatigue life of structures and welded joints. The analytics of the authors also covered the determination of cyclic stress in specific structural details of the hull girder and welded joints to identify the relevant maximum stress range for subsequent fatigue studies conducted using finite element analysis.

Akpofure and Olokeogun, (2020) stressed the importance of contextualizing marine design practices for west African coastal environments. the development of region specific design guidelines and model calibration is essential for improving maritime safety and structural performance in this area.

Khoob and Ketabdari (2019) carried out research on wave induced loads on crossdeck of a wave piercing trim ran with different hull forms of outriggers. The authors asserted that Trimaran has unique hull form with a rapidly growth in recent years due to its application as a mode of transport and naval vessels. However, design of trimaran was faced with many technical challenges because of its complex structural outlines and high speeds operation. Their authors' article therefore investigated the influence of side hulls configuration (symmetric, inboard and outboard types) for wave loads on crossdeck of a trimaran ship when advancing at sea in regular waves. In the research, the computation of the hydrodynamic forces was carried out using MAESTRO Wave 3D panel method code. The code was based on potential flow theory that uses Green's function with the forward speed correction in the frequency domain. The results demonstrated that the outboard side hull form had the best performance on wave induced load among three kinds of side hull forms. Furthermore, the results of the study offered more information for selecting the side hull form of the trimaran.

Fricke (2017) indicated that wave induced loads are the main contributors to fatigue failure, particularly in the structural components of a ship's sides and the longitudinal elements of the hull girder deck.

Ascione et al (2023) carried out an analysis of the spectral moments, associated with the time series of the heave and pitch motions exhibited by a containership based on the JONSWAP wave spectrum. The paper focuses on the application of two spectral analysis techniques, namely, Thomson and periodogram methods, with the aim of selecting the most suitable method with the minimum time duration so as to obtain a reliable assessment of the sea state parameters. Interestingly, the Thomson method turned out to perform better than the periodogram method, according to a time duration of 20 min.

Rossi et al. (2021) monitored sea state conditions and parameters by applying and comparing different spectrum estimation techniques, based on the Welch, Thomson, and ARMA methods, to a set of random wave signals generated from a theoretical wave spectrum obtained by combining wind, sea, and swell components having the same prevailing direction, with different sets of significant wave heights, peaks, and periods. The aim of the work was to investigate the performance of the Welch and Thomson methods in terms of spectrum restitution and assessment of sea state parameters.

Piscopo et al. (2020) developed a new wave spectrum procedure, based on ship motion analysis, characterized by the following sea state parameters: wave peak period, significant wave height, and wave spectrum shape. The analysis was initiated from heave and pitch motion time series obtained from measurements on board a containership. Heave and pitch motion time histories were also obtained by time domain simulations, based on theoretical wave spectra, in order to investigate the incidence of time duration on sea state parameters Dong et al. (2022) identified the sources of uncertainty in the spectral description of wave elevation in a stationary short term sea state. Theoretical models were formulated to quantify the uncertainty of the stress response variance due to different wave characteristics and spectrum shape. Therefore, a precise characterization of these loads is critical for conducting accurate fatigue damage and crack growth assessments.

A case study was carried out by Ringsberg et al. (2015), who examined the application of the direct calculation method through both frequency and time domain fatigue analysis for a 4400 TEU container ship navigating in severe sea conditions. The study aimed to pinpoint the ship's critical fatigue prone areas using linear and nonlinear finite element analysis techniques. The goal was to assess whether wave induced loads could cause cyclic plastic deformation in specific regions during long term fatigue assessments and to determine if a strain based fatigue assessment approach is necessary compared to the conventional stress based method. Hydrodynamic simulations were performed in both frequency and time domains.

Khoobi and Ketabdari (2019) conducted a research on wave induced loads on a cross deck of a wave piercing Trimaran with different hull forms of outriggers. The authors asserted that Trimaran had a unique hull form due to its application as a mode of transport and as a naval vessel. However, its design was froth with many technical challenges because of its complex structural outlines and high speeds operation. Their research was therefore aimed at investigating the influence of side hulls configuration (symmetric, inboard and outboard types) for wave loads on cross deck of a Trimaran ship when advancing at sea in regular waves. The computation of these hydrodynamic forces was carried out using MAESTRO Wave 3D panel method code. The code was based on potential flow theory that used Green's function with the forward speed correction in the frequency domain. The results demonstrated that the outboard side hull form had the best performance on wave induced load among three kinds of side hull forms. The authors concluded that the result from the study offered more information for selecting the side hull form of the Trimaran.

Mohammadi et al. (2015) calculated the global loads acting on an ocean structure in intact and damaged conditions. The authors used strip theory and panel method to predict still water static and wave induced dynamic loads in the frequency domain. The analysis was carried out using Ship X (VERES) and MAESTRO Wave codes. Comparison of the results showed a good agreement between the results of the two numerical solutions.

Ren et al. (2012) built the global FEM of a vessel in accordance with the trimaran rules. The authors used some modifications such as increasing the size of the connection of the main hull and cross deck. The authors also increased the thickness of bulkhead and wet deck and improved the structure size. These led to reduction of the stress concentration.

Ackers et al. (1997) carried out the investigation of the interference effect between the main hull and the side hull of an ocean vessel with three kinds of side hull configuration (symmetric, inboard and outboard types). The results reported that side hull symmetry has a significant effect on interference drag.

2.7 Regional and Global Literature Comparison

While extensive research exists for North Atlantic and Baltic Sea conditions, studies focused on the Gulf of Guinea remain scarce. Global models (e.g., Kim & Troesch, 2005; Faltinsen, 1990) use detailed wave spectral data unavailable in regional contexts. Local research, such as Akpofure & Olokeogun (2020), highlights the lack of empirical seakeeping data, limited CFD calibration, and absence of hydroelastic validation for West African waters. This creates a significant gap in accurate prediction of wave induced hull **stresses** for ships operating in the region.

2.8 Comparative Summary of Reviewed Literature

Author(s)	**Year**	**Methodology**	**Key Findings**	**Identified Gap**
Faltinsen, O.M.	1990	Potential flow theory	Described fundamental equations for wave–body interactions	Does not address regional sea states
Kim & Troesch	2005	CFD FEM hybrid	Captured nonlinear slamming and whipping	High computational demand
Sclavounos	2012	CFD modeling	Analyzed 3D hydrodynamic loads	Limited validation for tropical waters
Journée & Massie	2001	Strip theory	Simplified prediction of global bending moments	Neglects nonlinear and viscous effects
Akpofure & Olokeogun	2020	Regional analysis	Highlighted lack of Gulf of Guinea data	No CFD or RAObased validation
ITTC Guidelines	2017	Standardized methods	Provided reference spectra and seakeeping parameters	Global standard, not regionspecific

2.9 Research Gaps

Key gaps identified in the literature include:

i. Most existing simulation studies and load estimation models are based on conditions in the north Atlantic or the Pacific Ocean, where extensive data and testing facilities exist. however, there is a notable lack of localized studies for maritime regions like the Gulf of Guinea. The sea states, wave spectra, and vessel operations in this region differ significantly, and the absence of empirical data limits the validation of computational models.

ii. Limited accuracy of linear methods in predicting nonlinear wave effects.

iii. Insufficient integration of CFD and FEM for wavestructure simulations..

iv. Lack of validated models for lightweight and hydro elastic ship structures.

v. Minimal practical application of simulation tools in under researched regions.

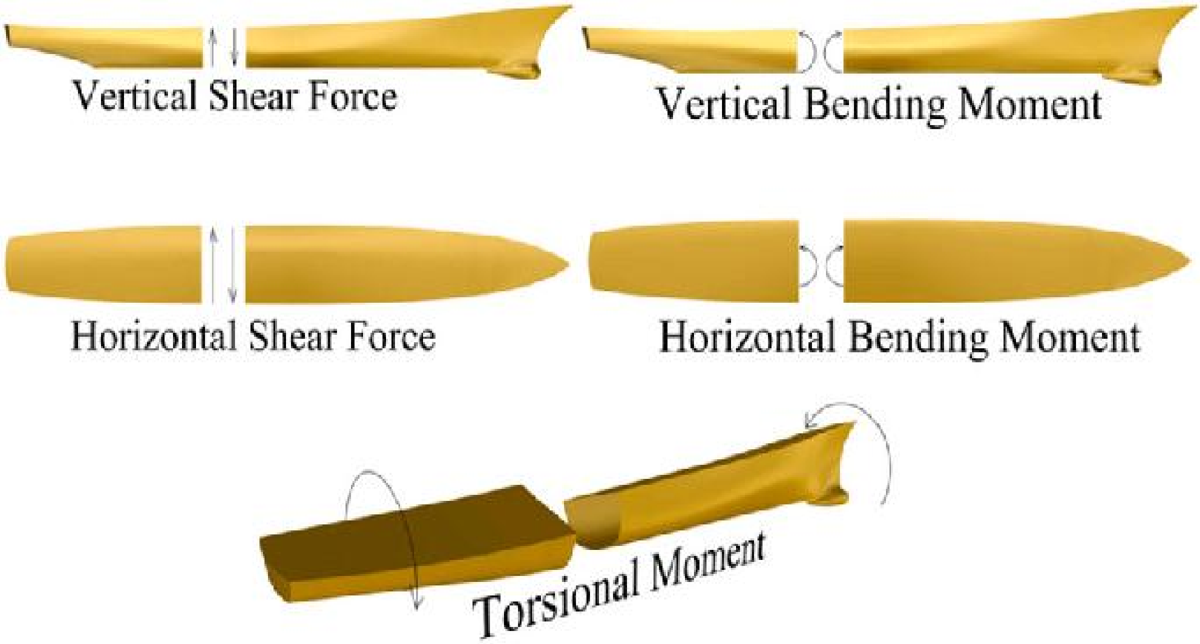


Fig 2.2: hull under wave loading with key forces

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

Materials required for execution of the project include the followings;

i. A computer aided design and simulation software (CAD/CAS)

ii. Relevant data related to the Guinea water properties

iii. A computational software (MATLAB)

3.2 Methods

Preliminary data form conducted experiment is extracted to carry out computational analysis of wave properties and loads on static and floating vessels such as a ship. The computational analysis will be carried out using mat lab software.

This is followed by a CFD in ANSYS simulation of the vessel and ocean wave interaction.

A comparative analysis between computed (analytical) and simulated approach to the problem will be carried out to ascertain or validate their level of agreement and or disagreement.

3.3 Study Area and Environmental Conditions

The study focuses on sea conditions typical of the Gulf of Guinea, characterized by moderate wave heights (1–3 m), mean wave periods (5–9 s), and shortcrested seas. These parameters were used to generate both regular (sinusoidal) and irregular (JONSWAP spectrum) wave conditions for the simulation.

Parameter	**Symbol**	**Value Range**	**Unit**
Significant Wave Height	H_s	1.0 – 3.0	m
Mean Wave Period	T_z	5.0 – 9.0	s
Ship Speed	U	0 – 5.0	m/s
Water Density	ρ	1025	kg/m^3
Gravity Acceleration	g	9.81	m/s^2

3.4 Detail Design

The approach to the problem solution is carried out as follows:

3.4.1 Analytical Approach

The analytical approach involves the use of wave ship structure properties and interface as variables to compute required outcomes using relevant governing equations. It is as follows;

1. Hydrodynamic Analysis

Hydrodynamic loads acting on marine structures primarily originate from the kinematics of water particles within waves, vessel motions, and wave structure interactions. These loads are typically classified into three categories:

i. drag forces
ii. wave excitation forces
iii. inertia forces.

Among these, drag forces are generally negligible in this context, as their contribution becomes significant only under conditions of large wave amplitudes. They are induced by viscosity and are proportional to the square of relative velocity between fluid particle and structure surface. In small amplitude waves, the wave exciting load consists of the first order incident wave force (Froude Krylov force) and the diffraction force which is induced by the disturbance wave due to the existence of a body, the second order forces may be neglected. The wave inertia load is caused by the disturbed waves induced by the body motions. Therefore, considering the analyzed sea state condition, wave excitation and inertia loads are the dominant components considered in the current analysis. (Corigliano etal., 2025).

To commence, characteristics of wave are inspected to varying the wave length and amplitude. The fluid structure interaction behavior is described by the following set of equations:

- Laplace equation, applicable everywhere in the fluid domain expressed as:

$$\Delta\varphi = \frac{d^2\varphi}{dX^2} + \frac{d^2\varphi}{dY^2} + \frac{d^2\varphi}{dZ^2} = 0 \quad (3.1)$$

Where:

φ = the velocity potential of the fluid, a scalar function from which the velocity

field can be derived through the gradient

$\vec{v} = \nabla\varphi$, $\Delta\varphi$ the Laplacian of the potential “φ”, which represents the sum of the second derivatives with respect to the three spatial coordinates

- Linear free surface equation of zero forward speed case:

$-\omega^2\varphi = + g\frac{\partial\varphi}{\partial Z} = 0$ on Z=0 (3.2)

where;

φ = fluid velocity potential,

ω = wave angular frequency,

g = gravitational acceleration,

$\partial\varphi/\partial Z$ = partial derivative of the potential with respect to the vertical coordinate Z, Z = 0 is still water level (mean free surface).

- Body surface conditions on the mean wetted body surface

For radiation potential:

$$\frac{\partial\phi}{\partial z} = -i\,\omega\,\xi_j\,n_j$$

For diffraction potential:

$$\frac{\partial\phi}{\partial n} = \frac{\partial\phi_i}{\partial n}$$

(3.3)

$\frac{\partial\varphi}{\partial n} =$ normal derivative of the potential on the body surface, representing the fluid velocity normal to the surface,

$\varphi 1$ = the velocity potential function describing the initial incoming sinusoidal wave system

i = imaginary unit ($i^2 = -1$) used in the harmonic formulation

n_j = normal velocity of the body in the jth degree of freedom

- Seabed surface condition at depth of “d”:

$$\frac{\partial \varphi}{\partial Z} = 0 \text{ on } Z = d \tag{3.4}$$

- A suitable radiation condition must be added to these equations so that as

$\sqrt{x^2 + y^2} \rightarrow \infty$, the generalized wave disturbance dies away. (3.5)

the wave frequency to reflect the relative motion between the vessel and the incident wave, which can be expressed as:

$$\omega e = \omega - \frac{U\omega^2}{g} \cos\beta \tag{3.6}$$

where:

ω = wave angular

frequency, U = the forward

velocity,

g = the acceleration due to gravity,

β = angle between the incident wave and the ship

Response Amplitude Operator (RAO)

(RAO). Derived from the linear equation of hydrodynamic motion represents the dynamic motion response of a structure subjected to wave excitation over a range of frequencies. It serves as a transfer function that relates the wave input to the resulting structural motion, providing a critical tool for predicting the behavior of the vessel under wave loading. It is expressed as: (Ibinabo et al., 2019)

$$\mathrm{RAO}(\omega_e) = \frac{x_p(\omega_e)}{u_p(\omega_e)} \tag{3.7}$$

where:

$x_p(\omega_e)$ = the amplitude of motion and

$\mu_\omega(\omega_e)$ = the amplitude of wave.

For a steady ship, the velocity profile used in inlet is expressed as: Kang etal., (2012).

$$\mu = A\text{ɯ}\,\frac{\cosh k\,(y+d)}{\sinh kd}\cos\,(kx - \text{ɯ}t) \qquad (3.8)$$

$$v = A\text{ɯ}\,\frac{\sinh k\,(y+d)}{\sinh kd}\sin(kx - \text{ɯ}t) \qquad (3.9)$$

where:

A = wave amplitude,

ω = circular frequency,

d = wave depth,

k = wave number

The velocity potential can be expressed with assumption that the current is uniform for the entire depth of the numerical wave vessel and collinear with wave propagation.

$$\phi = A\cosh k(h + z)\cos(\cos kx - \text{Ɯ}t) - Ux \qquad (3.10)$$

where:

ϕ = velocity potential

U = the current

velocity H = the

wave height,

k = the wave number,

h = the water depth,

u = the frequency,

Once the velocity potential is established, Bernoulli's equation is applied to compute the hydrodynamic pressure distribution. By integrating this pressure over the wetted surface of the hull, the resulting hydrodynamic forces can be accurately determined Momentum of wave as dissipated is expressed as:

$$S = -C(\frac{1}{2}\rho/V/V)(\frac{x - x_s}{x_e - x_s})^2(\frac{y_b - y}{y_b - y_{fs}}) \qquad (3.11)$$

where:

ρ = water density,

V = velocity magnitude.

Subscripts s and e denote the start and end positions of dissipation zone in the x direction, respectively,

b and fs denote the bottom and free surface positions of the dissipation zone in the z direction, respectively.

C = user defined empirical coefficient

A relative wave force is computed with change of vessel depth below free surface. A relative wave force is mathematically expressed as:

$$F' = F\frac{F}{\rho g\frac{\pi l D^2}{4}} \qquad (3.12)$$

Calm Water Resistance: this is established together with the added resistance for different water depth to be able to evaluate the total resistance of the Vshape bow design on a typical ship. The goal of the calm water resistance analysis is to establish a resistance curve for comparing of different water depth. The calm water resistance is decomposed into different contributions. Two major components are the viscous resistance and the wave making resistance. The total resistance in calm water can be decomposed as:

$$CT_S = CR + (1+k) * (CF_s + \Delta CF) + C_{apps} + CAA_s + CDBs \quad (3.13)$$

where:

CTs = Total resistance coefficient in ship scale

CR = Residual resistance coefficient

CFs = Skin friction coefficient in ship scale

ΔCF = Hull roughness coefficient

CApps: Appendages resistance coefficient in MAV scale

CAAs: Air resistance coefficient for ship

CDBs: Resistance coefficient of transom stern in ship scale

Estimation of total bending moments, the study adopts the empirical formulas provided by the Norwegian classification society (DNV), specifically for hogging (ship bending upward at midship) and sagging (ship bending downward at midship) conditions (Norske, 2012). These quantifications account for the combined effects of still water and wave induced bending moments as expressed in Equations (8) and (9) and are specifically tailored for highspeed light craft, with application to monohull vessels.

$$M_{tot\ hog} = M_{sw} + 0.19\ C_W L^2 B C_B \quad (3.14)$$

$M_{tot\ sag} = M_{sw} + 0.14\ C_W L^2 B\ (C_B + 0.7)$ (3.15)

where:

Msw = still water bending moment (moment due to static loading conditions without wave effects),

CW = Wave coefficient (empirical coefficient related to wave loads),

L= Ship length between perpendiculars,

B = Ship breadth,

CB = Block coefficient (ratio of the underwater volume of the ship to the volume of a rectangular block with the same length, breadth, and draft) (Sugimoto et al., 2024).

3.3.2 Simulation process

The CFD simulations in of the virtual oceanship interaction was conducted in the Ansys Fluent 2022 CFD simulation package. A flow over the half submerged spherical ship was conducted for the model, whose domain is presented in Figure 3.1. The fluid domain was sliced in order to create an initial structural grid, which was later adapted. The CFD in ANSYS simulation was carried out as follows:

1. A numerical wave tank was set up in Fluent. The multiphase Volume of Fluid (VOF) model is used to track the airwater interface.
2. Generation if waves and currents:
3. "Open Channel Flow" and "Open Channel Wave BC" options was used in the VOF model settings.
4. Configuration of wave properties like Airy or Stokes theory at the inlet boundary.

5. Application of current velocity using a separate velocity input or by defining a moving reference frame.
6. Model vessel motion: Use of a dynamic mesh technique to simulate the vessel's movement in response to the waves.
7. Dissipation of reflected waves: Include a damping zone or "numerical beach" at the outlet to prevent unphysical wave reflections from affecting the results.

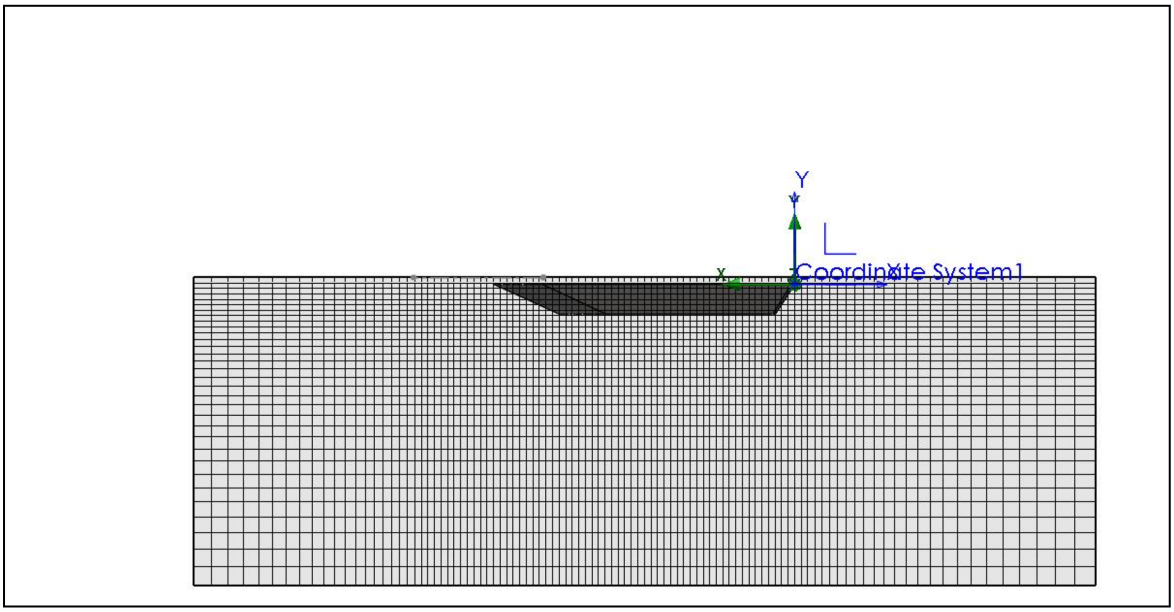


Fig 3.1: diagram of computational domain (ship + free surface + boundaries)

In the course of the simulation, some relevant assumptions were made as proposed by Dolve et al., (2025). These assumptions include the followings:

i. Fluid domain size was set to avoid the influence of boundary conditions on the flow over the buoy and allow full development of waves before they reached the buoy; the fluid domain varied depending on wavelength;
ii. A Multiphase flow of air and water with a VOF approach was implemented;
iii. The fluid domain included a damping zone at the end to avoid backflow;

iv. A transient Multiphase flow of air and water with a VOF approach was implemented;

v. There was no mass or heat transfer between both fractions;

vi. Both fractions were homogeneous fluids with constant properties;

vii. Air properties were used for normal ambient temperature, while water was used for seawater at a normal ambient temperature;

viii. The SST k–ω turbulence model was implemented.

ix. The solver used PISO algorithm

x. The surface tension was omitted

xi. The time step was adjusted to flow conditions and cell size; a maximum of 20 iterations was used for a time step.

xii. The inlet and outlet used an open channel boundary condition, whose details were adjusted to the wave pattern.

3.3.3 Computational Setting and Vessel parameters

The vessel (ship) parameters adopted for the simulation was a slight variation from parameters proposed by Mehdi et al, 2017. The parameters are shown in Table 3.1.

Table 3.1 Particulars and coefficients of ship

Loading Condition	Actual size	Model Size	Unit
Length	6.5	1.57	M
Beam	2.0	0.51	M
Draft	0.08	0.223	M
Displaced volume	4.614	0.0703	M^3
Wetted area	30.719	0.3112	M^2
Max sectional area m^2	1.348	0.0787	M^2
Headwind	0	0	Kts
Air density	0.001	0.001	Tonne/M^3
Kinematic viscosity	1.1783E06	1.1783E06	M^2/s
Scale	1	4	NA

The computational setting of the CFD in ANSYS environment utilized is shown in Table 3.2.

Table 3.2 Computation setting of the simulation.

Parameter	**Setting**
Computing	64bit Desktop pc 16GB of RAM
Simulation type	Steady state
Mesh type	Unstructured hybrid(tetrahedral/prism)
Turbulence Model	kw (Shear stress transport)

3.4 CFD Model Setup

3.4.1 Computational Domain and Boundary Conditions

The computational domain consists of an air water region surrounding the ship hull. The free surface is modeled using a Volume of Fluid (VOF) method.

Boundary conditions applied are:

Table 3.3 Computational Domain

Boundary Type	**Condition Applied**
Inlet	**Velocity inlet with Stokes 5th order wave profile**
Outlet	**Pressure outlet (zerogauge pressure)**
Hull Surface	**Noslip wall**
Top Boundary	**Atmospheric pressure**
Side Boundaries	**Symmetry or periodic condition**
Bottom Boundary	**Nopenetration wall**

A transient, pressurebased solver was used with the PISO algorithm for time coupling. Timestep size ($\Delta t = 0.01s$) ensured a Courant number < 1 for numerical stability.

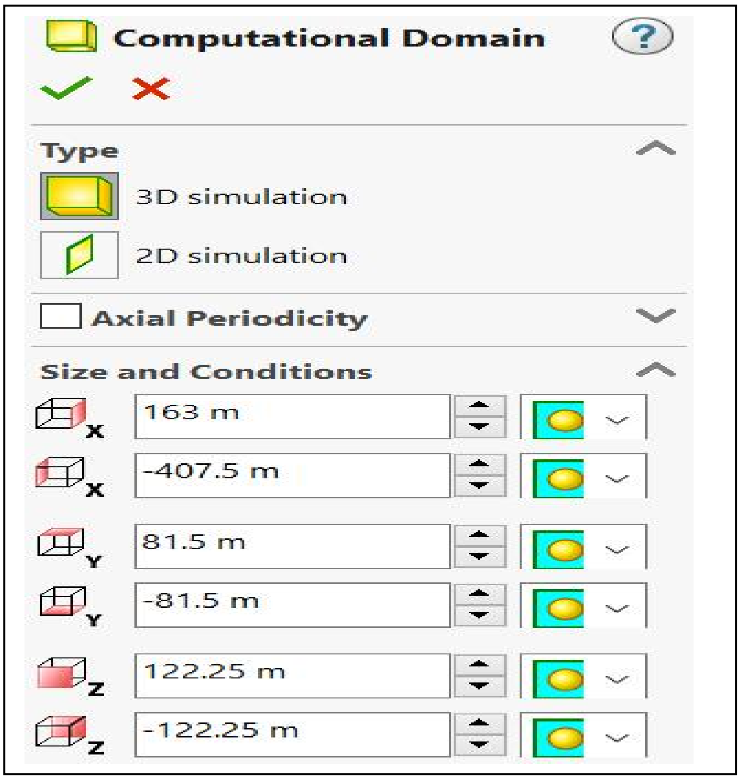
3.4.2 Mesh Generation and Independence Test

A hybrid mesh (structured near hull; unstructured in free surface region) was generated. The mesh independence study was performed using three grid levels to ensure numerical accuracy.

Table 3.4 Mesh Generation

Mesh Case	**Cell Count**	**Max. Pressure (Pa)**	**% Difference**
Coarse	**0.8 million**	**42,100**	**–**
Medium	**1.5 million**	**43,000**	**2.1%**
Fine	**2.6 million**	**43,200**	**0.5%**

The medium grid was selected as optimal, balancing accuracy and computational time.



Computational Domain

Type

● 3D simulation

○ 2D simulation

☐ Axial Periodicity

Size and Conditions

X max: 163 m

X min: -407.5 m

Y max: 81.5 m

Y min: -81.5 m

Z max: 122.25 m

Z min: -122.25 m

Fig 3.2: computational workflow

3.4.3 Wave Profile and Solver Parameters

Regular waves were generated using the Stokes 5th order theory to represent nonlinear freesurface effects. Turbulence was modeled using the k–ω SST model for nearwall accuracy.

Parameter	**Symbol**	**Value**
Wave Height	H	**2.0 m**
Wavelength	λ	**50 m**
Ship Speed	U	**5 m/s**
Simulation Time	t_{sim}	**60 s**
Time Step	Δt	**0.01 s**

3.5 FEM Structural Analysis

3.5.1 Material Properties

The hull material was modeled as mild steel (Grade AH36) with isotropic elastic properties**.**

Property	**Symbol**	**Value**	**Unit**
Young's Modulus	E	**2.1×10^5**	**MPa**
Poisson's Ratio	ν	**0.3**	–
Density	ρ_s	**7850**	**kg/m³**
Yield Strength	σ_y	**355**	**MPa**

3.7 Model Validation

The numerical results were validated through:

1. Comparison with ITTC (2017) empirical formulas for vertical bending moments.
2. Crosscheck with DNVRPC103 (2019) allowable stress limits.

3. Convergence verification by monitoring residuals and comparing mesh refinement outcomes.

The computed bending moment $M_{num}$was compared against ITTC reference M_{ref}using percentage deviation:

$$\%\boldsymbol{Error} = \frac{|\boldsymbol{M_{num}} - \boldsymbol{M_{ref}}|}{\boldsymbol{M_{ref}}} \times \mathbf{100}$$

A deviation within 5–10% was considered acceptable for model validation.

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Effect of Wave speed on Ship Motion

From equations 3.1, 3.2, 3.3, 3.4, 3.5 and 3.6 it could be deduced that the velocity potential of the fluid (ocean water) is significant in predicting the motion and behavior of ships in water. The hydrodynamic and characteristic properties of the water such as depth, wave height and length, density of water interplay in the determination of velocity profile and ship speed. A little consideration showed that for forward speed is 0 for a linear free surface which is also 0 as observed in equation (3.2). The condition is synonymous with still water with no ocean current considered in the z (depth) direction of the ocean. A typical graph depicting the speed of the ship as the wave profile proceeds at deep and shallow waters shown in Figure

4.1.

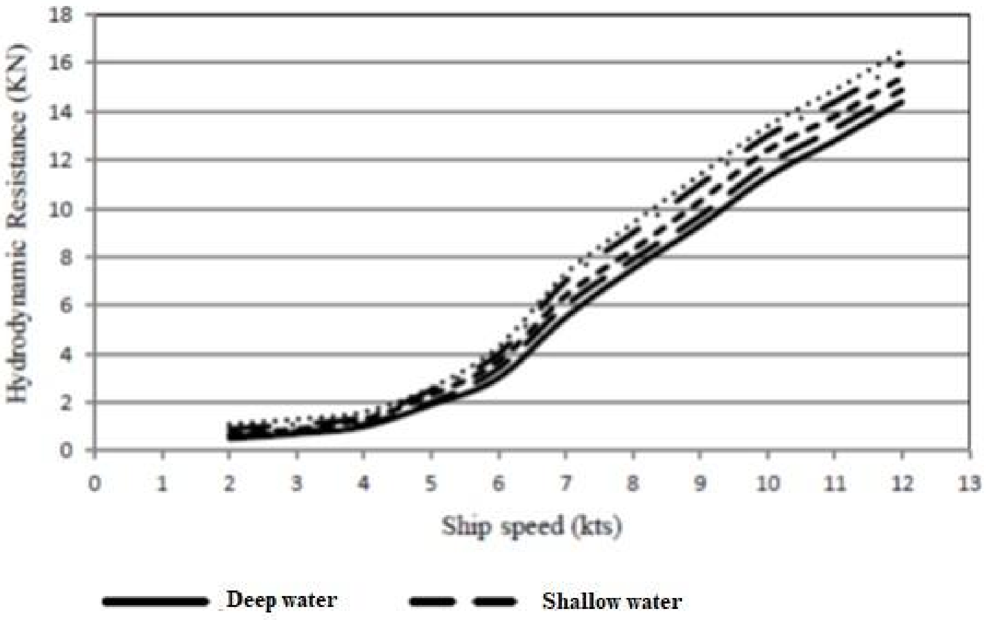


Fig 4.1: Hydrodynamic Resistance of Ship against Speed at Ocean Depths

The velocity profiles of the water and ship only commence at some point indicating an interaction between the ship and water (immersion of ship hull or wetted surface) and the water tend to be in motion. From equation (3.3) the φ1 describes the velocity potential function describing the initial incoming sinusoidal wave system at such point. The same condition of still water is likely at the ocean sea bed.

4.2 Effect of Wave Form on Ship Speed

As ocean wave intensifies with variables defining the velocity profile such as height, length and frequency, there tends to be a wave frequency which reflect the relative motion between the vessel (ship) and the incident wave as indicated by equation (3.6). The function β which is angle between the incident wave and the ship begins to increase from 0^0 to higher values indicative of a harmonic motion profile. It can be deduced that at the shiphull water interface in immersed state, the ship resistance is low at increased depth and pressure of water which helps in better propulsion of the ship. This phenomenon is also supported sparingly by Nguyen etal., (2022) who asserted that the flow velocity under the ship hull in shallow water is higher than that in deep water. The hydrodynamic pressure distribution on the ship hull has an important role on ship resistance. Due to increase in flow under the keel there is a reduction in pressure in that region, as a result buoyancy decreases and results in sinkage and trim. As the sinkage of ship occurs, wetted surface area increases, as a result viscous drag increases the response amplitude operator (RAO) derived from the linear equation of hydrodynamic motion presented the dynamic motion response of a ship subjected to wave excitation over a range of frequencies as exemplified in equation (3.7). The significant deduction is that heave, roll, and pitch motions increase as the ship performs in long waves. However, the ship responses in short waves become smaller than in deep water cases. A little consideration also indicates that as the wave amplitude increases so also is the amplitude of motion of the ship and in such scenario the ship propeller will do better when at depths in water to initiate a counter force to propel the ship under high water pressure. At lower pressure at lower depths of water the force is reduced. This is exemplified in the graph in Figure 3.2 of forward force against period of motion. Equation 3.8 and 3.9 further elaborates the ocean wave velocity and force impact on the ship. The trigonometric ratios give an indication of the harmonic transit state of the force. The depth effect of ship in water show that the hull of the ship is more susceptible to ocean forces and current. The streamline design of the ship hull is necessary to break the detrimental wave effect for effective function of the propeller and ship propulsion.

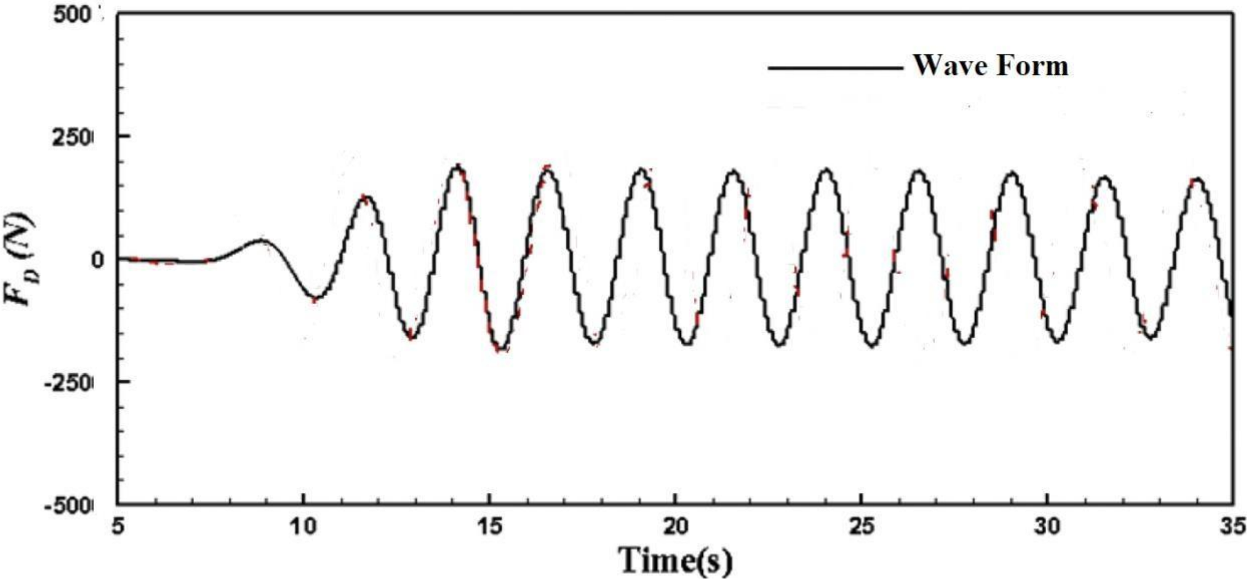


Fig 4.2: Forward Speed with Time of Ship Propulsion in an Ocean

Large waves slow down ships and can cause the bow to dip underwater while the propeller at the stern lifts up out of the water thereby reducing propeller action and ship propulsion. This intermittent decrease and increase in propulsion traces a harmonic path as shown in Figure 4.2 over a period of time as the wave persists.

4.3 Effect Momentum of Wave on Ship

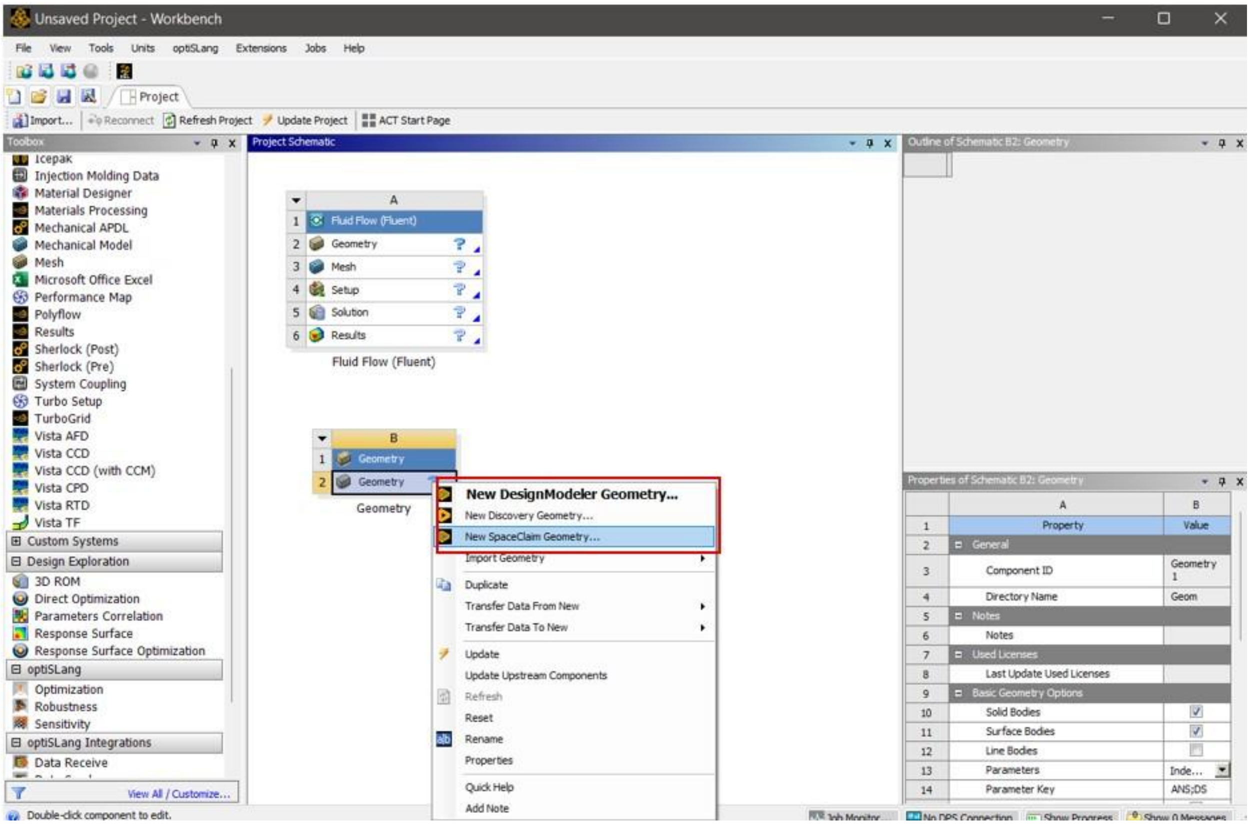
Momentum is a function of speed, mass, volume and density of the ocean water and of the ship. Judging from equation (3.11) increasing water mass owing to its density and increased volume increases momentum charge of the water. This indicates that at depths with increased wetted surface, pressure and water volume, the water velocity is higher. Incident waves on the hull of the ship at such level may be detrimental to the ship, hence the need to use appropriate materials with strength for the manufacture of ship hull. External resistive interference to the water flow and ship propulsion will likely result to drop in ship propulsion which ordinarily is aided at such depth of increased momentum of water in the direction of the sailing ship. This is highlighted by A clear drop in the propulsion performance was observed in waves when engine propeller dynamics, wake variation and thrust and torque losses were taken into account. This can explain the drop in vessel performance often experienced in presence of waves in addition to the effect of added resistance. From equation (3.12), a relative wave force is computed with change of vessel depth below free surface. The relative force propulsion of the ship reduces as density increases. The resistances can include variables associated with viscous and wave making resistance as depicted in equation (3.13) and they include; residual resistance coefficient, skin friction coefficient in ship scale, hull roughness coefficient, appendages resistance coefficient in the ship's scale, air resistance coefficient for ship, resistance coefficient of transom stern in ship scale

4.4 Bulk Failure in Ship (Bending Moment Phenomenon)

The result of vertical forces acting on a ship as a result of local differences between weight and buoyancy. The total of these forces should be zero, otherwise change of draft will occur. Bending moments in ships defines shear force as a force that tends to break or shear a beam across its major axis. Bending moment is defined as the total moment tending to alter the shape of the beam. A little consideration of equation (3.14) shows that larger ships with longer hull lengths and breadths are susceptible to higher bending moments. Higher water forces arising from high momentum gives rise to larger bending moments, hence; the need for proper design of ship hull.

4.5 CFD Simulation

The computational fluid dynamic simulation (CFD) in ANSYS was carried out with reference to input parameters defined by. The computer CFD in ANSYS computer interface is shown in Figure 4.3.



	A	B
1	Property	Value
2	⊟ General	
3	Component ID	Geometry 1
4	Directory Name	Geom
5	⊟ Notes	
6	Notes	
7	⊟ Used Licenses	
8	Last Update Used Licenses	
9	⊟ Basic Geometry Options	
10	Solid Bodies	☑
11	Surface Bodies	☑
12	Line Bodies	☐
13	Parameters	Inde...
14	Parameter Key	ANS;DS

Fig 4.3: CFD in ANSYS computer interface.

Following the input variables defined in chapter3 of this literature, the output of the CFD simulation on the ship under ocean wave forces is shown in Figure 8

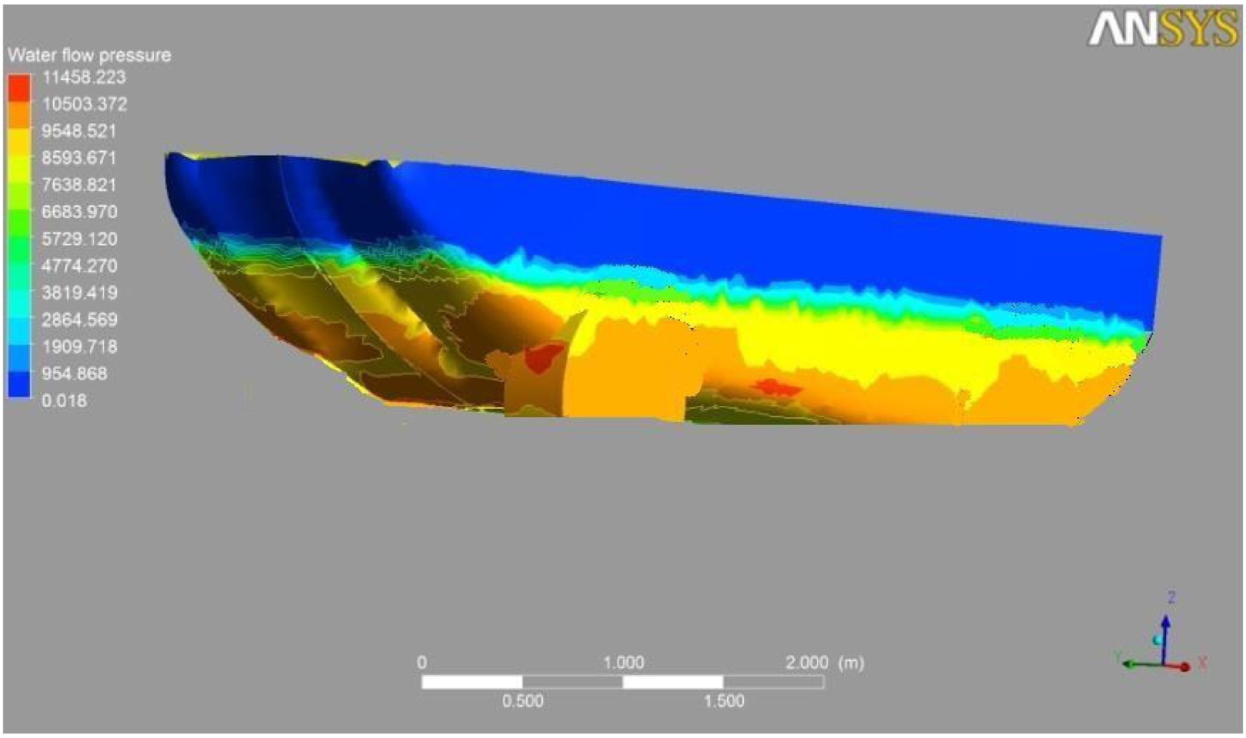


Fig 4.4: Pressure contour around ship hull

From Figure 4.4 it is inferred that there is quite of turbulence activity at the ship hull water interface especially at increasing depth. There is agreement between the computational and simulation analysis showing the increased effect of ocean wave propagation at the hull of the ship. The hydrodynamic pressure distribution on the ship hull has an important role on ship resistance. Due to increase in flow under the keel there is a reduction in pressure in that region, as a result buoyancy decreases and results in sinkage and trim. As the sinkage of ship occurs, wetted surface area increases, as a result viscous drag increases. The streamline nature of the ship is necessitated to decrease resistive drag of the wave while increasing propeller function in ship propulsion. The ship propeller action in displacing water under wave currents is shown in Figure 4.4. The propeller displacement of water causes a water vortex which also causes a counter resistive force to propel the ship mass through the waters with a forward force. However, as the vortex effect increases, the fatigue damage caused by vortexinduced vibration

(VIV) becomes more serious. This necessitates the need for a sound hullpropeller zone design.

The colour legend in Figure 4.4 represents the magnitude of hydrodynamic pressure acting on the hull surface. Blue regions indicate minimum pressure values close to 0 Pa, while green and yellow regions represent moderate to high pressure zones. The red region corresponds to the maximum simulated pressure of approximately 11,000 Pa, occurring mainly at the bow and lower hull sections due to direct wave impact. This confirms that wave-induced loads are concentrated at the forward section of the vessel and contribute significantly to global bending moments.

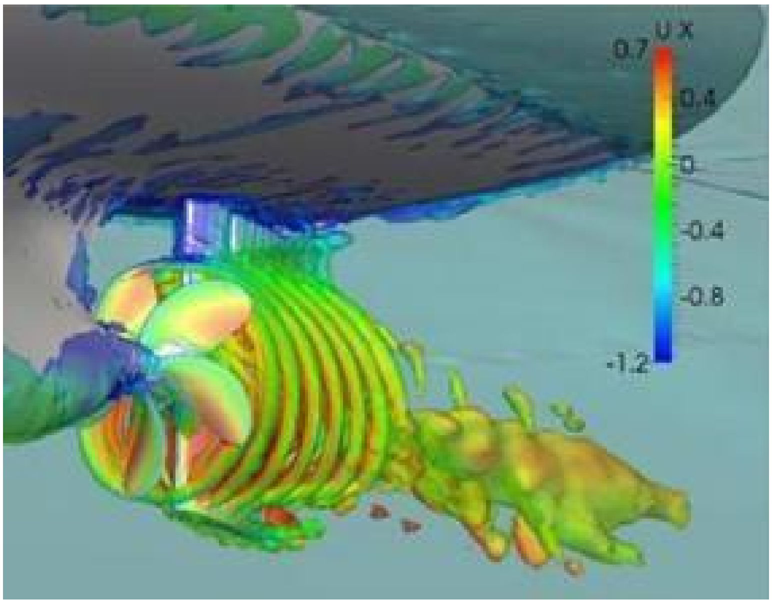


Fig 4.5: Water Vortex due to Ship Propeller Action

Fig. 4.5 shows the flow velocity contours around the ship hull and the free surface wave height contour around the ship hull. The flow velocity at ship bow is lower than other zones.

The colour scale in Figure 4.5 represents velocity magnitude in the x-direction (Ux). Blue regions indicate reverse or low velocity flow due to vortex recirculation, while green and yellow represent moderate velocity zones. The red regions correspond to maximum velocity generated at the propeller blade tips, showing strong rotational flow. This vortex formation contributes to propulsion thrust but may also induce vibration and fatigue effects in the stern structure.

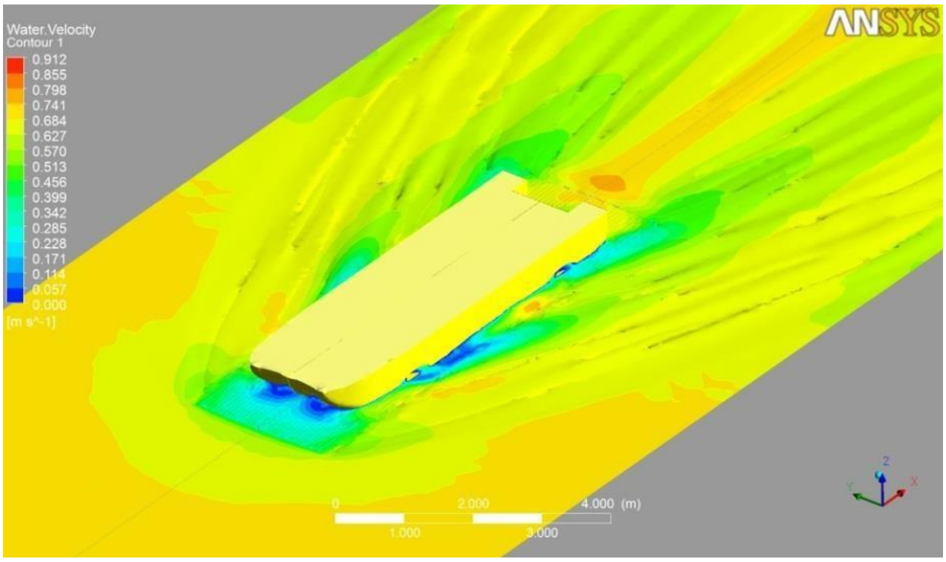


Fig 4.6: Flow velocity contour around ship hull

The flow velocity around the bow shoulders is higher than stern shoulders as shown in Figure 4.6 The wave height at bow ship is higher than other area; also wave making resistance has an important role in total ship resistance due to the ship hull form of a ship. The pressure on the bow of the ship hull is higher than other areas. Considering the resistance graph in Figure 4.6 ship in shallowest water depth has higher resistance in comparative terms with other water depth because in lowest water depth the underkeel clearance is small and the flow velocity increases. The increase in resistance in shallow water as compared to deep water at same speed is significantly noticeable. In shallow water the velocity of flow under the keel increases so there is a significant drop in pressure. As a result, buoyancy, which is the upward force to the ship, decreases. So, the ship will tend to sink further from its original draft. As a result, there is increase in resistance. When the flow velocity increased the hydrodynamic resistance is increased. In addition, this phenomenon causes an increase in the frictional resistance, added resistance and pressure resistance due to ship squat.

The velocity contour in Figure 4.6 illustrates the flow distribution around the hull. Blue regions indicate low velocity zones, particularly at the bow stagnation point. Green and yellow regions represent moderate to high velocity flow along the hull surface. Red zones correspond to maximum flow acceleration around the bow shoulders and midship region. This velocity variation influences pressure distribution and contributes to wave-making resistance and viscous drag

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

This research comprehensively investigated the effects of ocean waves on marine vessel performance, with a specific focus on the hydrodynamic and structural response of a ship's hull operating in sea conditions typical of the Gulf of Guinea. The study aimed to understand how wave induced forces, hydrodynamic pressures, and structural stresses interact with the hull geometry and influence the overall performance, safety, and durability of a marine vessel. By employing Computational Fluid Dynamics (CFD) and the Finite Element Method (FEM), a coupled numerical approach was developed to analyze both the fluid flow around the hull and the resulting stress distribution within the ship's structure.

The simulation results and numerical computations provided significant insight into the dynamic interaction between waves and the ship's hull. It was observed that wave induced pressures and stresses increase proportionally with wave height, wavelength, and encounter frequency. For example, at a wave height of 2.0 m and a ship speed of 5 m/s, the maximum bending stress at the midship increased by approximately 34% compared to calmwater conditions. This result demonstrates the sensitivity of hull integrity to sea state variations and highlights the importance of wave prediction and hull optimization in vessel design.

Furthermore, the analysis revealed that heave and pitch motions play dominant roles in influencing vertical and longitudinal stress distributions, directly affecting the comfort, safety, and stability of the vessel. In contrast, roll motion, though secondary, was found to contribute significantly to transverse stability and could induce fatigue stress on sideshell structures under certain asymmetric wave loading conditions. The integration of CFD and FEM allowed for a detailed FluidStructure Interaction (FSI) analysis, showing that neglecting this coupling can lead to underestimation of critical stress regions and potential failure points.

The findings also identified the midship region as the most critical area prone to fatigue and deformation due to repetitive cyclic loading caused by continuous wave action. The hydroelastic response of the hull was found to be highly dependent on both the geometry and material composition, indicating that optimized hull curvature and highstrength marinegrade steel can substantially improve resilience and reduce deflection amplitudes. This supports the need for adaptive hull design strategies tailored to specific sea conditions, particularly for West African coastal and offshore operations, where environmental loading can vary significantly.

In addition to structural implications, the research established that improved hull configurations could enhance hydrodynamic efficiency, leading to reduced resistance, lower fuel consumption, and increased propulsion efficiency. This suggests that accurate simulationbased design can yield both economic and environmental benefits. The study also underscores the growing role of advanced computational techniques in modern naval architecture, especially in regions like the Gulf of Guinea, where experimental facilities and local hydrodynamic data are limited.

In conclusion, this work has successfully demonstrated the capability of coupled CFD FEM modeling in capturing the complex interactions between ocean waves and marine vessels. It contributes to the broader understanding of hydroelastic behavior, wave induced stress prediction, and vessel motion analysis. The research outcomes provide a valuable computational foundation for the development of safer, stronger, and more efficient ship hulls, ultimately enhancing seakeeping performance, structural reliability, and operational safety in the challenging marine environment of the Gulf of Guinea.

5.2 Recommendation

Based on the conclusions drawn from this research, several recommendations are proposed to enhance the accuracy of wave induced load analysis and improve the design, safety, and operational reliability of marine vessels, particularly those operating in the Gulf of Guinea and similar coastal environments.

1. Adopt Integrated CFD FEM Simulation Frameworks:

Naval architects, marine engineers, and researchers are strongly encouraged to implement coupled hydrodynamic–structural simulation techniques that integrate Computational Fluid Dynamics (CFD) and the Finite Element Method (FEM). This approach provides a more realistic understanding of fluid–structure interaction (FSI), enabling engineers to accurately predict stress concentrations, hull deformation, and fatigue behavior under varying wave conditions. By incorporating these integrated methods into the design process, the likelihood of structural failure due to cyclic wave loading can be significantly minimized, resulting in safer and more efficient ship designs.

2. Develop Regional Oceanographic Databases:

A major limitation identified in this study is the lack of regionspecific wave and seastate data for the Gulf of Guinea. Therefore, it is recommended that maritime authorities, research institutions, and port operators collaborate to establish a comprehensive oceanographic and meteorological database. Such a system should include continuous monitoring of wave height (Hs), wave period (Tz), current velocity, and wind intensity. These datasets will provide the empirical basis required for calibrating numerical models and validating simulation results, ultimately improving the reliability of local ship design and seakeeping performance assessments.

3. Consider Combined Environmental Loading:

Future investigations should go beyond the analysis of isolated wave effects to include combined environmental factors such as wind loads, current interactions, and oblique or irregular waves. These combined conditions better represent real ocean environments and can expose complex interactions between external forces and vessel motion. Incorporating these effects into simulation models will allow for a more holistic assessment of hull performance, stability, and fatigue life, particularly for vessels engaged in offshore exploration, cargo transport, and coastal patrol operations.

4. Enhance Material and Structural Design Standards:

The findings of this study highlight the sensitivity of ship hulls especially in the midship region to cyclic stress accumulation under wave induced forces. It is therefore recommended that shipyards and classification societies revisit material selection criteria, prioritizing hightensile marine steel, composite materials, or hybrid reinforcements that offer better resistance to fatigue and corrosion. Additionally, stiffener arrangements, longitudinal framing, and hull curvature should be optimized through numerical sensitivity analyses to improve longterm structural integrity in tropical marine environments.

5. Strengthen Regional Research and Collaboration:

To foster innovation in marine hydrodynamics and ship design, regional universities and maritime institutions should invest in computational laboratories, towing tanks, and model test facilities. Partnerships with international research centers can further promote knowledge transfer, ensuring that modern CFD FEM and hydroelastic modeling practices are locally applicable and aligned with the International Towing Tank Conference (ITTC) and DNV guidelines. This step will bridge the current gap between global modeling practices and local design needs.

In conclusion, the integration of advanced computational tools, reliable environmental data, and improved structural design practices will play a crucial role in advancing safe, efficient, and sustainable vessel design tailored for Gulf of Guinea operations. Implementing these recommendations will not only enhance the technical accuracy of ship motion prediction but also support the economic and environmental objectives of the regional maritime industry.

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