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GPU-Accelerated Simulation for Assessing Ship Seaworthiness in Diverse Conditions

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Abstract—Ship seaworthiness is a critical factor in maritime engineering, ensuring vessels can navigate safely and efficiently across diverse environmental conditions. This project employs advanced Computational Fluid Dynamics (CFD) calculations, coupled with GPU acceleration, to comprehensively assess ship seaworthiness. Through meticulous CFD simulations, the complex fluid-structure interactions between ships and water bodies are modeled, enabling precise predictions of hydrodynamic forces, fluid flow patterns, and stability parameters crucial for ship performance evaluation. The primary objective is to deepen understanding of ship behavior under various environmental scenarios, including different sea states, vessel speeds, and hull designs. By conducting detailed CFD simulations accelerated by GPUs, potential areas for enhancing ship designs, propulsion systems, and operational strategies can be identified, significantly improving seaworthiness and operational efficiency. Additionally, this approach aims to establish a robust framework for continuous improvement in maritime engineering practices, contributing to safer and more efficient maritime operations globally. The integration of advanced turbulence models and machine learning techniques further enhances the predictive capabilities of our simulations, offering new insights into optimal ship design and performance under challenging conditions.

Index Terms—Computational Fluid Dynamics, GPU Acceleration, Ship Seaworthiness, Hydrodynamic Forces, Fluid-Structure Interaction, Stability Parameters, Turbulence Models, Machine Learning, Maritime Engineering, Operational Efficiency

I. INTRODUCTION

Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that utilizes numerical methods and algorithms to analyze and solve fluid flow problems. In this project, CFD serves as the foundation for simulating and comprehending the intricate behavior of fluids, particularly within the context of boat stability analysis. By leveraging CFD techniques, we can model the complex interactions between water and boat surfaces, predict flow patterns, and compute essential parameters such as velocity fields, pressure distributions, and turbulence effects. The application of CFD in maritime engineering provides detailed insights into hydrodynamic phenomena, which are crucial for designing safe and efficient vessels.

A Graphics Processing Unit (GPU) is a specialized electronic circuit designed to rapidly manipulate and alter memory to accelerate image creation within a frame buffer intended for display output. However, GPUs extend beyond graphics processing; they excel at parallel processing tasks, making them invaluable for scientific computing, machine learning, and simulations. In the context of ship stability assessment, the GPU plays a pivotal role in accelerating complex com-

putational tasks involved in fluid dynamics simulations, structural analysis, and optimization algorithms. By harnessing the parallel processing power of GPUs, the project can execute computationally intensive simulations efficiently, significantly reducing the time required for analysis and optimization. The use of GPUs enables the handling of large-scale simulations with high resolution, providing more accurate and timely results.

Maritime transportation forms a vital cog in global trade, necessitating the safe navigation of ships through diverse and challenging maritime environments. However, assessing ship stability under dynamic conditions presents significant challenges for traditional methods. These methods, often reliant on empirical formulas or model tests, can struggle to capture the full complexity of fluid-structure interaction, particularly in extreme weather events. This can lead to inaccurate stability assessments and pose safety risks during operation. The dynamic nature of maritime environments, including varying wave patterns, wind forces, and operational conditions, requires advanced simulation techniques to ensure the robustness of stability assessments.

This project introduces a novel approach to ship stability assessment by employing GPU-accelerated CFD simulations. Our project focuses on applying this approach to evaluate the intact stability of cargo ships in rough seas. Intact stability refers to a ship's ability to resist capsizing under various loading conditions and right itself after experiencing a disturbance. By simulating real-world scenarios with high fidelity using CFD, we aim to overcome the limitations of traditional methods and achieve a more comprehensive understanding of ship behavior. High-fidelity simulations provide a detailed picture of how ships respond to different stressors, contributing to improved design and operational guidelines.

The primary objectives of this project are:

- 1) To develop a robust CFD model capable of accurately simulating fluid-structure interactions in maritime environments.
- 2) To leverage the computational power of GPUs for accelerating CFD simulations, enabling real-time or near-real-time analysis.
- 3) To assess the intact stability of cargo ships under various loading conditions and environmental scenarios.
- 4) To validate the CFD model and simulation results against experimental data and established benchmarks.

- 5) To provide insights and recommendations for enhancing ship design and operational safety based on simulation outcomes.

The development of a robust CFD model involves meticulous calibration and validation against experimental data to ensure accuracy. Leveraging GPU technology not only speeds up simulations but also allows for more complex scenarios to be analyzed within practical timeframes. Assessing intact stability under a variety of conditions ensures that the findings are comprehensive and applicable to real-world situations. Validation against benchmarks and experimental data is crucial for establishing the credibility of the simulation results.

Through this project, we seek to contribute to the field of maritime engineering by advancing the use of CFD and GPU technologies in stability assessment. The findings and methodologies developed herein have the potential to improve safety standards, inform regulatory frameworks, and support the design of next-generation vessels capable of withstanding the harshest maritime conditions. Our approach aims to set a new standard for how stability assessments are conducted, integrating advanced computational techniques to enhance the reliability and safety of maritime operations.

II. RELATED WORK

A. CFD Simulation

Melnyk et al. (2023) present a simulation-based method for predicting changes in a ship's seaworthy condition under various factors using a Markov process-based simulation approach [1]. They caution against potential limitations of experimental research and sole reliance on the Markov process model. Dorozhko et al. (2015) developed a CFD simulation focusing on extreme wave impact on a ship using RANS equations [2]. However, the analysis is limited to 2D ship contours and constrained by a limited range of extreme wave parameters.

Kim et al. (2022) investigated the maneuvering performance of a ship during low-speed maneuvers in adverse weather conditions using CFD simulations [3]. The study is limited to a specific ship model and relies on assumptions and boundary conditions. Papanikolaou et al. (2016) conducted a study on the simulation of the maneuvering behavior of ships in adverse weather conditions, employing a 4-DoF nonlinear maneuvering model [4]. They highlighted the necessity for CFD simulations to accurately solve fluid flow equations. Walree et al. (2020) present a study on the prediction of heavy weather seakeeping of a destroyer hull form, combining deterministic and stochastic methods [5]. They note challenges in accurately replicating real-world conditions and the necessity of making assumptions in panel and CFD methods.

Fu et al. (2014) assessed CFD predictions of the hydrodynamics of high-speed planing craft in calm water and waves [7]. They noted challenges in scaling and modeling small high-speed craft, affecting dynamic similitude and viscous effects. Miyata et al. (1997) focused on CFD performance prediction simulations for hull-form design of sailing boats using the finite volume method (FVM) [10]. Bačkalov et al. (2015)

reviewed recent advancements in ship stability, dynamics, and safety, advocating for integrating modern perception and tools into teaching ship stability topics [13].

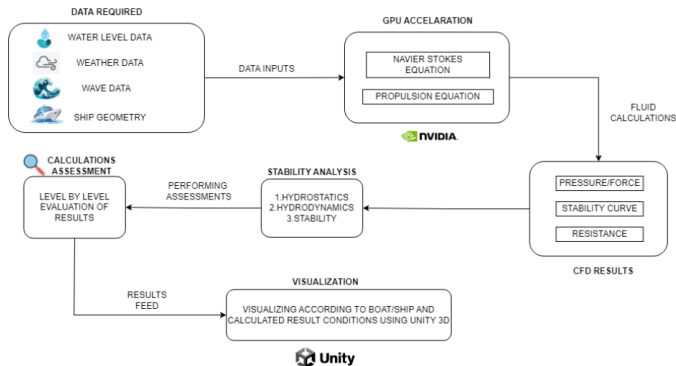


Fig. 1: Ship Performance Simulation Diagram

Mierke et al. (2015) introduced GPU-accelerated large-eddy simulation of ship-ice interactions using the Lattice Boltzmann-based fluid solver elbe [11]. Liu et al. (2021) summarized their study on CFD predictions for full-scale ship parametric roll, demonstrating strong agreement with model-scale results [14].

B. GPU Optimization

Jeschke and Wojtan (2023) introduced an algorithm combining shallow water equations and Airy wave theory to simulate large bodies of water [6]. They noted inaccuracies in simulating steep waves and challenges in depicting wave behaviors near boundaries. Piscaglia and Ghioldi (2023) presented GPU acceleration of CFD simulations in OpenFOAM, introducing algorithmic advancements leveraging GPUs for enhanced computational efficiency [15].

Huang et al. (2019) spotlighted GPU acceleration for compressing and visualizing large-scale vessel trajectories in maritime IoT [12]. Jiang et al. (2019) optimized and accelerated flow simulations for CFD on CPU/GPU architecture, achieving significant speedups [8].

Crespo et al. (2011) demonstrated the efficiency and reliability of GPUs in SPH simulations for CFD, highlighting limitations in simulations with millions of particles on a single GPU [9]. Sadat et al. (2008) explored the application of CFD techniques to recent ship stability problems, focusing on hydrodynamic forces and the performance of the Anti-Rolling Tank (ART) [?].

III. PROPOSED WORK

This project proposes the use of GPU-accelerated computational fluid dynamics (CFD) techniques to conduct detailed analyses of vessel interactions with dynamic seafaring environments and visualize their performance characteristics in 3D models. The project entails a comprehensive approach to ship stability assessment, integrating various factors such as wave parameters, ship geometries, wind effects, and other environmental variables.

Algorithm 1 Hydrostatics Algorithm

0: **procedure** CALCULATE BUOYANCY FORCE
0: Given: Density of water (ρ_{water}), Gravity (g), Volume displaced ($V_{displaced}$)
0: Formula: $F_{buoyancy} = \rho_{water} \times g \times V_{displaced}$
0: **end procedure**
0: **procedure** CALCULATE CENTER OF BUOYANCY
0: Given: Lower bound of integration (y_{lower}), Upper bound of integration (y_{upper}), Step size (Δy)
0: Formula: Center of Buoyancy = $\frac{\sum y \times A(y)}{\sum A(y)}$, where $A(y)$ is the cross-sectional area at depth y
0: **end procedure**
0: **procedure** CHECK STABILITY (METACENTRIC HEIGHT)
0: Calculate $GM = KM - KB$
0: Compare GM with minimum required GM
0: **end procedure**=0

Algorithm 2 Hydrodynamics Algorithm

0: **procedure** CALCULATE RESISTANCE
0: Given: Density of water (ρ_{water}), Drag coefficient (C_i), Wetted area (A_{wet}), Velocity (v)
0: Formula: $R = 0.5 \times \rho_{water} \times C_i \times A_{wet} \times v^2$
0: **end procedure**
0: **procedure** CALCULATE WAVE RESISTANCE
0: Given: Density of water (ρ_{water}), Gravity (g), Velocity (v), Length (L)
0: Formula: $RW = 0.5 \times \rho_{water} \times g \times \frac{v^2}{FroudeNumber}$
0: **end procedure**
0: **procedure** CALCULATE FROUDE NUMBER
0: $Fr = \frac{v}{\sqrt{g \times L}}$
0: **end procedure**
0: **procedure** CHECK STABILITY (RIGHTING ARM)
0: Calculate $GZ = GM \times \sin(\theta)$
0: Ensure GZ is positive
0: **end procedure**=0

Algorithm 3 Algorithm for Navier-Stokes

0: Initialize variables: density ρ , viscosity μ , velocity field \mathbf{u} , pressure p , turbulent viscosity μ_t , time step Δt , grid size Δx , number of iterations N
0: **for** $n = 1$ to N **do**
0: Calculate convective fluxes \mathbf{F}^c and diffusive fluxes \mathbf{F}^d
0: Calculate Reynolds stresses τ_{ij} using turbulence model
0: Update velocity field: $\mathbf{u}^{n+1} = \mathbf{u}^n - \frac{\Delta t}{\rho} (\nabla p^{n+1} + \mathbf{F}^c + \mathbf{F}^d - \rho \tau_{ij})$
0: Solve for pressure: $\nabla^2 p^{n+1} = \frac{\nabla \cdot \mathbf{u}^{n+1}}{\Delta t}$
0: Update pressure: $p^{n+1} = p^n - \alpha \nabla p^{n+1}$ where α is a relaxation parameter
0: Update velocity field: $\mathbf{u}^{n+1} = \mathbf{u}^{n+1} - \frac{\Delta t}{\rho} \nabla p^{n+1}$
0: **end for**=0

Initially, the project involves the calculation of ship stability using mathematical models that account for the dynamic

interactions between the vessel and its surrounding environment. This includes the incorporation of wave parameters such as wave height (H_w), period (T_w), and direction (θ_w), which significantly influence the ship's response and stability characteristics.

$$H_w = H_{max} \sin(kx - \omega t + \theta_w) \quad (1)$$

$$T_w = \frac{2\pi}{\omega} \quad (2)$$

$$\theta_w = \arctan\left(\frac{y}{x}\right) \quad (3)$$

Ship geometries, including hull shape, dimensions, and displacement, are also taken into consideration as critical factors in determining stability. The displacement volume $V_{displaced}$ is calculated as:

$$V_{displaced} = \int_{y_{lower}}^{y_{upper}} A(y) dy \quad (4)$$

Furthermore, the project accounts for wind effects, which can exert additional forces and moments on the vessel, further impacting its stability. The wind force F_{wind} and moment M_{wind} are calculated using the following equations:

$$F_{wind} = \frac{1}{2} \rho_{air} C_D A_{wind} v_{wind}^2 \quad (5)$$

$$M_{wind} = F_{wind} \times h_{CG} \quad (6)$$

By integrating wind data and CFD simulations, the project assesses the combined effects of waves and wind on ship stability, providing a comprehensive analysis of seaworthiness under varying environmental conditions.

$$F_{total} = F_{buoyancy} + F_{wind} + F_{wave} \quad (7)$$

The comprehensive stability analysis ensures that the ship can maintain equilibrium and safe operation in different sea states and environmental conditions.

The use of GPU-accelerated computational techniques significantly enhances the efficiency and accuracy of the simulations. The Navier-Stokes equations are solved using parallel computing on GPUs, which allows for high-resolution and large-scale simulations within reasonable timeframes.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (8)$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \mathbf{T} + \mathbf{f} \quad (9)$$

where \mathbf{T} is the stress tensor and \mathbf{f} represents external forces such as gravity and wind forces.

The project demonstrates the potential of leveraging advanced computational methods to enhance the design and safety of marine vessels, ensuring their reliability in diverse and challenging marine environments.

IV. SIMULATION

The system gathers a wealth of information, including water levels, weather patterns, wave data, and the intricate details of the ship's design. This data becomes the fuel for complex calculations involving the Navier-Stokes equations, which govern viscous fluid motion, hydrostatics, propulsion systems, and general fluid mechanics. The GPU serves as the engine for these calculations, significantly accelerating the process and enabling rapid performance analysis.

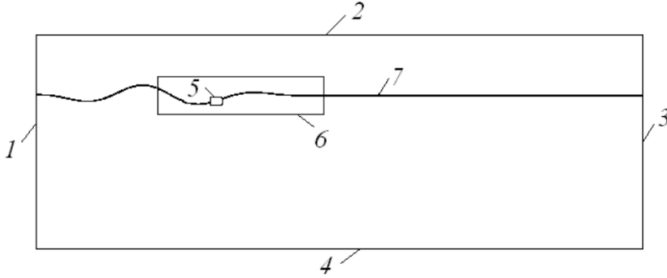


Fig. 2: Boundary Conditions for CFD Simulation

The simulation process begins with data collection, where real-time and historical data on maritime conditions are gathered. This includes parameters such as water levels, wave heights, weather forecasts, and the ship's operational data. The integration of these datasets ensures that the simulations are grounded in realistic scenarios.

Once the data is collected, it is fed into the simulation model, where the Navier-Stokes equations are applied to simulate fluid dynamics around the ship. These equations are solved using numerical methods, with the GPU providing the necessary computational power to handle the large-scale calculations efficiently. The use of GPUs allows for the simulation of complex fluid interactions in a fraction of the time required by traditional CPU-based methods.

The simulation also incorporates hydrostatic calculations to evaluate the ship's buoyancy and stability under various loading conditions. This involves determining the metacentric height, which is a key indicator of stability. Additionally, the simulation assesses the performance of the propulsion systems, analyzing the thrust and resistance experienced by the ship under different operational scenarios.

The boundary conditions play a crucial role in the accuracy of CFD simulations. The diagram in Figure 2 illustrates the setup used for defining the simulation domain and the boundary conditions applied. Here, the boundaries are defined as follows:

- 1) *Inlet Boundary (1)*: This boundary represents the incoming flow into the simulation domain, where water and wave data are introduced.
- 2) *Top Boundary (2)*: This boundary is often treated as a free surface where atmospheric pressure is applied.
- 3) *Outlet Boundary (3)*: This boundary allows fluid to exit the simulation domain, ensuring that the flow continues smoothly out of the domain.

- 4) *Bottom Boundary (4)*: This represents the seabed or the bottom of the simulation domain.
- 5) *Wave Source (5)*: A localized region where waves are generated to simulate real maritime conditions.
- 6) *Ship Hull (6)*: The section of the simulation domain where the ship's hull interacts with the fluid, crucial for analyzing the fluid-structure interaction.
- 7) *Simulation Domain (7)*: The overall area where the CFD simulation takes place, encompassing all relevant physical phenomena.

The simulation results provide a detailed understanding of the ship's behavior in various conditions. These results are used to evaluate the ship's stability, performance, and safety, ensuring that it meets the necessary standards and regulations.

V. RESULT AND ANALYSIS

The stability analysis conducted on the boat provides a comprehensive evaluation of its stability across different conditions, encompassing crucial aspects such as hydrostatics, hydrodynamics, wave stability, and overall stability. The analysis includes a series of simulations designed to test the ship's response to various environmental conditions and operational scenarios.

Key findings from the stability analysis indicate satisfactory stability characteristics. The simulations show a positive metacentric height, which is crucial for ensuring that the ship remains upright and stable. Adequate buoyancy force is observed, indicating that the ship can float effectively even when loaded with cargo. Acceptable resistance levels are noted, ensuring that the ship can move efficiently through the water without excessive drag.

The analysis also includes wave stability tests, where the ship's response to waves of different heights and frequencies is evaluated. The results show that the ship maintains stability under specified wave parameters, confirming its suitability for navigating rough seas. These tests are critical for ensuring the ship's safety in adverse weather conditions.

In the stable state simulations, the ship demonstrates excellent stability with a high positive metacentric height and balanced buoyancy. The hydrodynamic forces are well within acceptable limits, ensuring smooth and efficient navigation.

The unstable state simulations, however, highlight potential issues that could arise under extreme conditions. These simulations are essential for identifying the ship's limitations and providing insights into necessary design modifications or operational precautions to enhance stability.

The performance comparison between CPU and GPU simulations reveals significant improvements in computational efficiency. The CPU performance chart shows the time taken for various simulation tasks, highlighting the limitations in processing power and speed. In contrast, the GPU performance chart demonstrates the substantial reduction in simulation time, showcasing the advantages of using GPUs for large-scale fluid dynamics simulations. The parallel processing capabilities of GPUs enable faster and more accurate simulations, providing real-time analysis and decision-making capabilities. Overall,

```

Wave Parameters
Wave Height (H): 1.0 m
Wave Period (T): 12.0 s
Hydrostatics
Buoyancy Force: 201105.0 N
Center of Buoyancy: 3.366666666666667 m
Metacentric Height (GM): 4.0 m
Hydrostatics analysis passed. Boat is stable so far.
Hydrodynamics
Resistance (R): 6457.5 N
Wave Resistance (RW): 517498.69451264676 N
Righting Arm (GZ): 0.2093438249717753 m
Hydrodynamics analysis passed. Boat is stable so far.
Wave Stability Check
Wave stability check passed. Boat is stable in waves.
Stability Analysis
Stability analysis passed. Boat is stable.
tensor(4.6623e-21)
tensor(4.6623e-21)
tensor(1.2175e-20)
Stability Classification 1: tensor(4.6623e-21)
Stability Classification 2: tensor(4.6623e-21)
Stability Classification 3: tensor(1.2175e-20)
Total Stability (Average): tensor(7.1665e-21)
Overall Stability Label: Stable

```

Fig. 3: Output Screenshot of Stable State

```

Wave Parameters
Wave Height (H): 1.0 m
Wave Period (T): 12.0 s
Hydrostatics
Buoyancy Force: 211365.0 N
Center of Buoyancy: 3.366666666666667 m
Metacentric Height (GM): 1.5 m
Hydrostatics analysis passed. Boat is stable so far.
Hydrodynamics
Resistance (R): 17600.0 N
Wave Resistance (RW): 451088.1031115762 N
Righting Arm (GZ): 0.2604722665003955 m
Hydrodynamics analysis passed. Boat is stable so far.
Wave Stability Check
Stability Issue: Wave parameters affect stability!
Stability Analysis
Stability analysis passed. Boat is unstable.
tensor(1.6307e-38)
tensor(1.6307e-38)
tensor(3.3314e-38)
Stability Classification 1: tensor(1.6307e-38)
Stability Classification 2: tensor(1.6307e-38)
Stability Classification 3: tensor(3.3314e-38)
Total Stability (Average): tensor(2.1976e-38)
Overall Stability Label: Unstable

```

Fig. 4: Output Screenshot of Unstable State

this assessment confirms the boat's suitability and resilience for its intended use, reflecting a robust understanding of its stability profile. The insights gained from these simulations are invaluable for improving ship design, optimizing performance, and ensuring safety in maritime operations.

VI. CONCLUSION AND FUTURE WORK

Our project represents a synergistic fusion of cutting-edge computational techniques, fluid dynamics principles, and real-time data processing capabilities. By combining these elements, we aim to advance the field of ship stability analysis, paving the way for safer, more efficient maritime operations and vessel design practices.

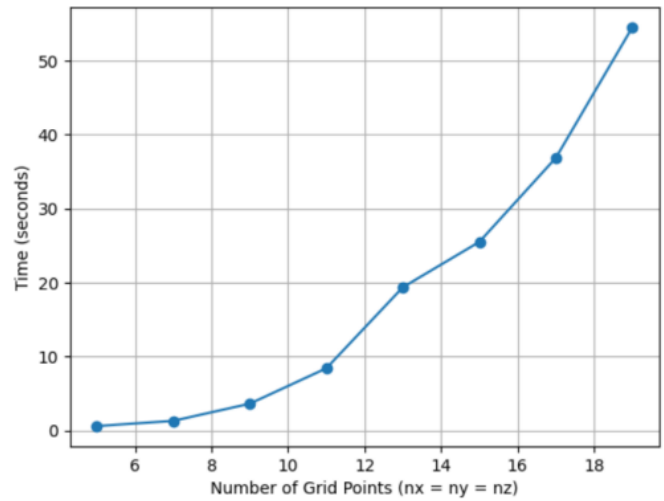


Fig. 5: CPU Performance

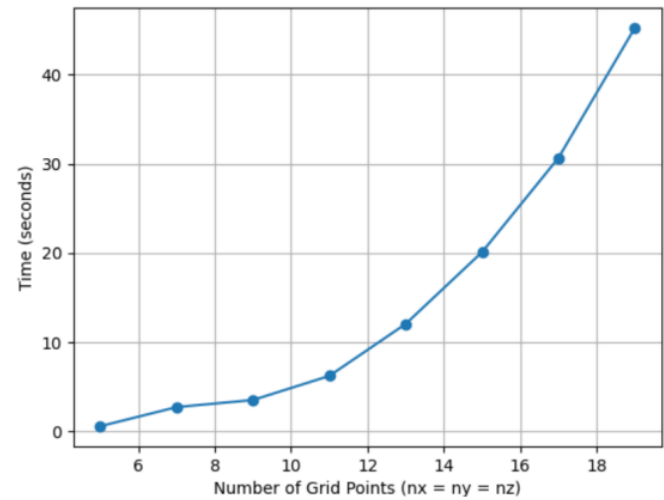


Fig. 6: GPU Performance

Expanding the computational grid beyond 50x50x50 points could enhance the accuracy and resolution of our ship stability simulations, capturing finer details of fluid flow behavior and hydrodynamic performance. Advanced turbulence models like Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS) can improve fidelity by capturing complex flows. Incorporating moving boundaries or adaptive mesh refinement will enhance simulation accuracy. Integrating machine learning for data-driven analysis can optimize design parameters, leading to more efficient and stable designs. Multi-physics simulations coupling CFD with structural analysis will allow comprehensive assessments. Collaboration with shipbuilding industries and maritime researchers, validated by experimental data and real-world trials, will ensure reliability and practical applicability. These advancements can revolutionize ship design, making vessels safer, more stable, and environmentally friendly.

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