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Simulation of a Container Vessel Using Boundary Element Method for the Computation of Hydrodynamic Pressure and Forces

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ABSTRACT: This study presents a comprehensive analysis of the hydrodynamic behavior of a containership under varying wave conditions using the Boundary Element Method (BEM). The hydrodynamic pressure distribution, as derived from BEM simulations, highlights critical pressure zones on the vessel's hull, with maximum pressures reaching approximately 160 N/mm² near the bow. These high-pressure regions, caused by direct wave impacts, emphasize the structural vulnerability to fatigue, underscoring the need for reinforced designs in areas subjected to repeated loading. Additionally, the pressure mapping reveals patterns that align with expected wave-induced behaviors, validating the effectiveness of the BEM in capturing critical load distributions. The analysis also investigates wave excitation forces and diffraction/Froude-Krylov forces across six motion modes (surge, sway, heave, roll, pitch, and yaw). Translational modes exhibit peak forces of up to 8000 N at low wave frequencies (~0.1 Hz), while rotational modes encounter forces as high as 10^8 N, particularly in roll and pitch. These findings highlight the influence of wave characteristics, such as frequency and angle, on vessel stability and structural stress. The results provide valuable insights for vessel design and operational planning, advocating for enhanced stabilization systems, optimized structural reinforcements, and improved cargo placement strategies to ensure safety, performance, and longevity under various sea conditions.

KEYWORDS: Hydrodynamic Pressure; Hydrodynamic force; Boundary Element Method; Boundary Conditions

INTRODUCTIONThe maritime industry is pivotal in global trade, with container vessels playing a crucial role in the transportation of goods across the world's oceans. Understanding the hydrodynamic forces acting on these vessels is essential for ensuring their structural integrity, operational efficiency, and safety. Accurate computation of these forces aids in the design and optimization of container ships, contributing to their performance and reliability in various sea states.

The Boundary Element Method (BEM) is a powerful numerical technique used to solve problems involving fluid flow around structures, particularly in the context of hydrodynamics. This method has gained prominence due to its efficiency in handling infinite domains, such as open sea environments, and its ability to provide precise solutions with relatively fewer computational resources compared to other numerical methods like the Finite Element Method (FEM) or Finite Difference Method (FDM) [1];[2]. BEM is particularly suited for the simulation of container vessels because it simplifies the complex interactions between the vessel's hull and the surrounding water by focusing on the boundaries of the problem domain. This boundary-focused approach reduces the dimensionality of the problem, allowing for efficient computation of hydrodynamic forces such as wave-induced loads, added mass, and damping coefficients [3]; [4].

One of the primary challenges in simulating container vessels involves accurately modeling the complex geometries of ship hulls and predicting their interactions with varying wave conditions. BEM addresses these challenges by employing integral equations that relate the unknowns on the boundary to known quantities, thus enabling precise modeling of the hull's response to wave action [5].

The hydrodynamic analysis of container vessels using BEM involves several critical steps. First, the geometry of the vessel's hull is defined and discretized into boundary elements. Then, the boundary conditions are applied, representing the physical constraints and interactions between the hull and water. The hydrodynamic forces are computed by solving the resulting system of equations, providing insights into the vessel's behavior under different sea states ([6]; [7]). Recent advancements in computational capabilities and software tools have further enhanced the application of BEM in maritime engineering. These advancements allow for more detailed simulations and the inclusion of complex factors such as non-linear wave effects and interactions between multiple vessels or floating structures ([8]; [9]).

The simulation of container vessels using the Boundary Element Method is a vital tool in maritime engineering. It enables accurate computation of hydrodynamic forces, contributing to the design, safety, and efficiency of these critical assets in global trade. As the industry continues to evolve, the integration of advanced numerical techniques like BEM will remain essential in addressing the complex challenges associated with marine vessel hydrodynamics.

II Importance of Hydrodynamic Forces Simulation or Calculations for Container Vessels

Hydrodynamic forces simulation is crucial for ensuring the structural integrity and safety of container vessels. These forces, including wave-induced loads, added mass, and damping forces, significantly impact the ship's hull and structural components. By accurately simulating these forces, engineers can design and reinforce ship structures to withstand the harsh marine environment, preventing structural failures and ensuring the safety of the vessel and its cargo [3]; [7].

Simulating hydrodynamic forces enables the optimization of container vessel designs. Accurate hydrodynamic simulations help optimize hull shapes and configurations, leading to improved fuel efficiency, reduced resistance, and enhanced speed. This optimization is essential for reducing operational costs and minimizing the environmental impact of maritime transportation [5]; [4].

Hydrodynamic simulations play a vital role in evaluating the stability and seakeeping characteristics of container vessels. These simulations help predict the vessel's response to waves, including motions such as pitching, rolling, and heaving. By accurately predicting these motions, engineers can design ships that maintain stability and comfort for the crew and cargo, even in rough sea conditions, preventing accidents and ensuring smooth operation [9].

Effective load management on container vessels requires an understanding of the distribution of hydrodynamic forces. Accurate simulations allow for the determination of optimal loading conditions, ensuring that the vessel remains balanced and operates efficiently. This is important for preventing overloading or uneven loading, which can compromise the vessel's stability and safety [6]; [8].

Hydrodynamic force simulations are essential for meeting maritime regulations and standards set by classification societies. Compliance with these regulations is mandatory for obtaining certification and permits to operate. Accurate simulations help shipbuilders and operators meet these standards, ensuring legal compliance and facilitating international trade [1].

Simulating hydrodynamic forces helps predict the long-term durability and maintenance needs of container vessels. These forces contribute to fatigue and wear on the ship's hull and components. By accurately assessing these effects, maintenance schedules can be planned, and necessary reinforcements can be made, extending the vessel's lifespan and reducing downtime [2].

I.

I. Methodology for Computing Hydrodynamic Pressure and Forces on Container Vessels Using Boundary Element Method

The Boundary Element Method (BEM) is employed to compute hydrodynamic forces on container vessels. This method is chosen due to its efficiency in solving problems related to fluid-structure interactions. The process involves the following steps: defining the geometry, setting up the boundary conditions, discretizing the boundaries, solving the boundary integral equations, and post-processing the results.

Steps in BEM Analysis

1. Geometry Definition
   i. Define the geometry of the container vessel's hull using CAD software or existing hull forms. Ensure the geometric model accurately represents the hull shape and features.
2. Boundary Conditions

Apply boundary conditions to the vessel. These include:

i. Free surface boundary conditions to account for the water surface.
ii. Symmetry conditions if applicable.
iii. Far-field conditions to simulate the infinite domain of the fluid.

3. Discretization

Discretize the hull surface into boundary elements (panels). This involves breaking down the surface into small, manageable elements where the boundary integral equations can be applied. Common discretization techniques include:

i. Triangular to Quadrilateral elements.

4. **Formulation of Boundary Integral Equations**

Formulate the boundary integral equations based on potential flow theory. These equations relate the velocity potential and its normal derivative on the boundary elements. The typical boundary integral equation for the potential flow is:

Potential flow Equation

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

∇^2 Laplace operator, representing the sum of the second partial derivatives with respect to spatial coordinates. $\emptyset$ Velocity potential function, which describes the potential flow in an inviscid, incompressible fluid.

Bernoulli’s Equation

$$\frac{\partial \emptyset}{\partial t} + \frac{1}{2}(\nabla \emptyset)^2 + \frac{p}{\rho} + gz = 0 \qquad (2)$$

$\frac{\partial \emptyset}{\partial t}$: Temporal derivative of the velocity potential, $\frac{1}{2}(\nabla \emptyset)^2$: Kinetic energy term per unit mass,

p: Pressure field in the fluid, ρ: Fluid density, g: Acceleration due to gravity, z: Elevation above a reference level.

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Boundary Integral Equation

$$\emptyset(x) = \int_S \left[\frac{\emptyset(y)\frac{\partial G(x,y)}{\partial n} - G(x,y)\frac{\partial \emptyset(y)}{\partial n}}{x-y}\right] dS \qquad (3)$$

x: Field point where the potential is being evaluated, y: Source point on the boundary, s: Boundary surface over which the integration is performed, $\frac{\partial G(x,y)}{\partial n}$: Normal derivative of the Green's function, $G(x,y)$: Green's function representing the influence of a source at y on the potential at x, $\frac{\partial \emptyset(y)}{\partial n}$: Normal derivative of the potential function on the boundary. Hydrodynamic Pressure

$$P = -\rho\left(\frac{\partial \emptyset}{\partial t} + \frac{1}{2}\nabla\emptyset . \nabla\emptyset\right) \qquad (4)$$

P: Pressure at a point in the fluid, $\frac{1}{2}\nabla\emptyset . \nabla\emptyset$: Kinetic energy per unit mass in the fluid Hydrodynamic Force Integrate the pressure over the hull surface to obtain the total force and moment:

$$F = \int_s P . n . dS \qquad (5)$$

F: Hydrodynamic force exerted by the fluid, P: Pressure field, n: Normal vector to the surface, dS: Differential surface element over which the integration is performed. Hydrodynamic Moment

$$M = \int_s r \times (P . n) dS \qquad (6)$$

M: Hydrodynamic moment exerted by the fluid, r: Position vector from a reference point to the surface element, p: Pressure field, n: Normal vector to the surface, dS: Differential surface element over which the integration is performed.

5. Solution of the System of Equations

Solve the system of linear equations resulting from the discretization of the boundary integral equations using numerical techniques such as Gaussian elimination or iterative solvers.

6. Post-Processing

i. Analyze the computed hydrodynamic forces and visualize the results. This includes:
    i. Contour plots of the velocity potential.
    ii. Time-domain responses of the vessel to wave excitations.
    iii. Frequency response analysis.

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Table 1: Principal Dimension of Container Ship B178 [10]

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

V. CONCLUSION

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

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at its widest point and affecting its stability and cargo capacity. The Hull Depth (D) is 16.34 meters, which is the vertical distance from the bottom of the hull to the main deck and influences buoyancy and cargo hold volume.

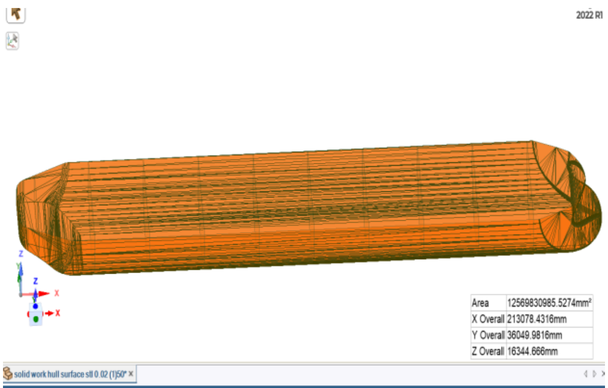

Figure 1: Full Scale Model with Ten Bulkhead and 20mm Thickness

Figure 1 represents a 3D geometric model of a container ship hull, likely created in SolidWorks and exported as a surface model. This model, with its detailed geometry and mesh structure, is suitable for hydrodynamic analysis using the Boundary Element Method (BEM). The key geometric parameters provided, including overall dimensions (X: 213.08m, Y: 36.05m, Z: 16.34m) and the surface area (1256.98309855274m²), are crucial for calculating hydrodynamic pressures and forces.

In the BEM framework, the surface of the hull is discretized into elements where boundary conditions, such as the incident wave potential, are applied. The high level of detail in this model ensures accurate representation of the hull's shape, which is critical for computing wave-induced pressures and forces. The model's longitudinal symmetry and smooth hull curvature are advantageous for reducing numerical errors in BEM calculations.

IV Results and Discussion

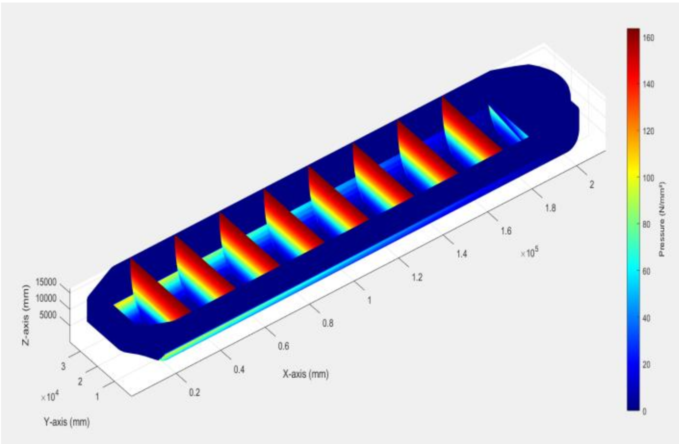

Figure 2: Full Scale Model Pressure Mapping

The hydrodynamic pressure mapping on the container vessel, as illustrated in the figure, highlights the interaction of wave forces with the hull surface. The pressure distribution, represented by a gradient from blue (low pressure) to red (high pressure), identifies critical high-pressure zones, especially near the bow and along the vessel's sides, which face direct wave impacts. Notably, the maximum pressure reaches approximately 160 N/mm² at the bow, where incoming waves exert the greatest energy. These high-pressure

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areas are structurally significant, as repeated wave impacts in these regions can induce fatigue, requiring reinforcements to prevent potential structural failures. Operationally, understanding this pressure distribution aids in optimal cargo placement, ensuring sensitive cargo is positioned in low-pressure zones and heavy loads are strategically balanced to mitigate impact stresses.

From a design and maintenance perspective, the data underscores the importance of reinforcing the bow and sides to handle the stresses caused by concentrated wave forces, especially during prolonged rough seas. This mapping also supports predictive simulations, enabling engineers to assess vessel response across various sea states and proactively address potential fatigue issues. By incorporating these insights into the vessel's design and operational strategies, safety, structural integrity, and longevity can be significantly enhanced.

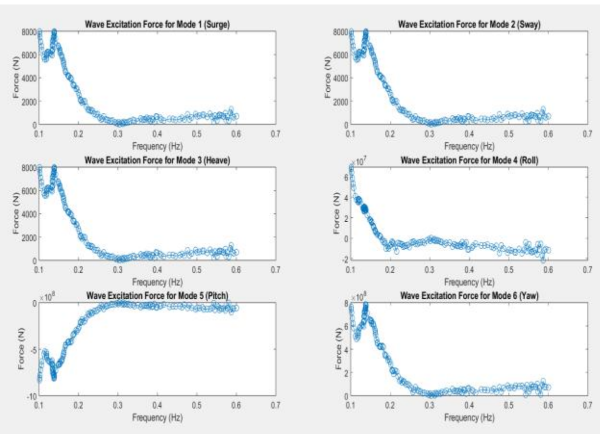

Figure 3: Wave Excitation Force against Frequencies for Six Mode

Wave excitation forces across the vessel's six motion modes (surge, sway, heave, roll, pitch, and yaw) highlight how wave interactions at specific frequencies impact motion and structural stress. Translational modes (surge, sway, and heave) experience sharp peaks in excitation forces around 0.1 Hz, with maximum values near 8000 N, indicating that long-wavelength waves generate substantial forces. These forces significantly influence the vessel's forward, lateral, and vertical stability, requiring design considerations to handle low-frequency wave effects effectively. Similarly, high forces in rotational modes like roll (10^7 N at 0.2 Hz), pitch (10^8 N at 0.1–0.2 Hz), and yaw (10^8 N at 0.1 Hz) underline the importance of stabilization systems to counteract wave-induced rotational motions and protect structural integrity.

These findings pinpoint the critical frequencies where wave forces pose the highest risk, guiding design and operational strategies for improved vessel safety and stability. Reinforcements in key structural areas, effective dampening systems for roll and pitch, and robust directional control mechanisms for yaw are crucial to mitigate these wave-induced stresses. Addressing these challenges ensures the vessel can operate safely and maintain stability under various sea conditions, enhancing performance and longevity.

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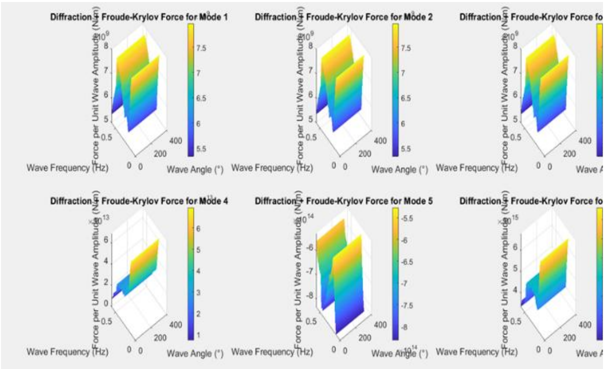

Figure 4: Diffraction and Froude-Krylov Force for the Six Mode

The diffraction and Froude-Krylov forces acting on the vessel's six modes—surge, sway, heave, roll, pitch, and yaw—illustrate how wave-induced forces vary with wave frequency and angle. In Mode 1 (Surge), forces reach approximately 9 N/m at low frequencies (0–200 Hz) and broad wave angles, emphasizing the influence of wave direction on surge forces. Mode 2 (Sway) experiences similar force magnitudes, peaking at 8 N/m in low-frequency conditions, reflecting strong lateral forces that challenge vessel stability. For Mode 3 (Heave), forces also peak around 9 N/m, significantly affecting vertical motion and highlighting the need for structural reinforcements to minimize discomfort and maintain stability during vertical accelerations caused by wave interactions.

Modes involving rotational motion exhibit higher force magnitudes. In Mode 4 (Roll), forces rise to 13 N/m, demonstrating the susceptibility to wave-induced rolling, which can compromise vessel stability in severe conditions. Mode 5 (Pitch) experiences extremely high forces, up to 10^14N/m, indicating substantial rotational stress along the longitudinal axis, requiring reinforced bow and stern areas to mitigate risks like bow slamming. Mode 6 (Yaw) records the highest forces, peaking at 10^15N/m, underlining the critical impact of wave direction on the vessel's directional stability. These findings are crucial for vessel design, pointing to the importance of stabilizing mechanisms and strategic reinforcements to handle wave-induced forces while ensuring stability and operational safety under varying sea conditions.

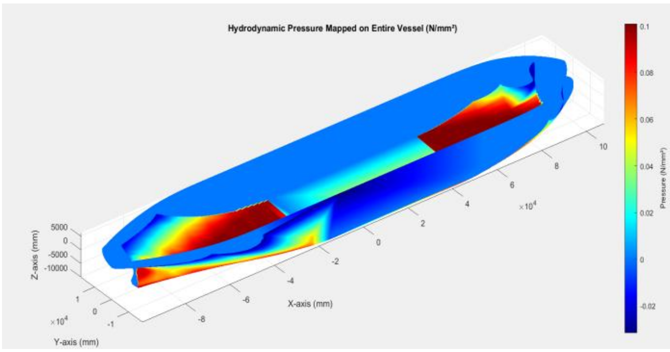

Figure 5: Hydrodynamic Pressure for Validation

The MATLAB code hydrodynamic pressure Figure 5 compares the hydrodynamic pressure on the container vessel using MATLAB's Boundary Element Method (BEM) and ANSYS Aqwa hydrodynamic pressure Figure 6. MATLAB results show a pressure range from approximately -0.02 N/mm² to 0.1 N/mm², while ANSYS Aqwa results, converted to the same units, range from -0.0105 N/mm² to 0.0141 N/mm². This

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alignment in the order of magnitude demonstrates consistency between the two methods. Both models exhibit similar pressure distribution patterns, with higher pressures observed at the bow and stern and a gradient along the vessel's length, indicating typical hydrodynamic behavior under wave impacts. Despite differences in color scales and minor numerical variations, the consistent pressure distribution reinforces the validity of the MATLAB BEM model.

The simulations were conducted under comparable conditions, including wave frequency, wave angle, and amplitude, ensuring the validity of the comparison. While slight discrepancies in peak values exist, these can be attributed to differences in mesh resolution, solver settings, or discretization methods between MATLAB BEM and ANSYS Aqwa. The overall agreement between the models confirms that MATLAB's BEM approach effectively replicates hydrodynamic pressure distribution on the vessel, providing reliable results comparable to those from a commercial software like ANSYS Aqwa. Further refinements, such as increasing mesh resolution, could help minimize these discrepancies and enhance the accuracy of the MATLAB model.

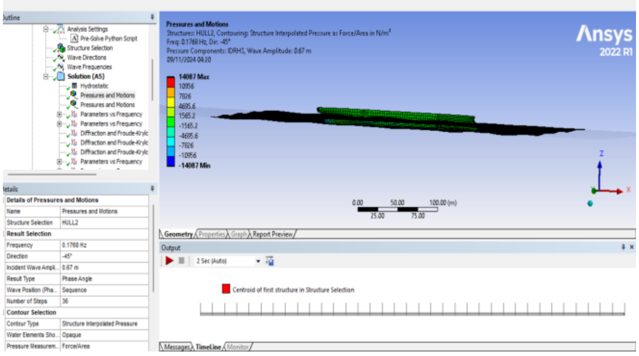

Figure 6: ANSYS Validation ofHydrodynamic Pressure

I. Conclusions

The results from the hydrodynamic analysis highlight critical insights into the interaction between wave forces and the container vessel, providing valuable guidance for design, operation, and maintenance. Figure 2 emphasizes the significance of hydrodynamic pressure mapping, revealing maximum pressures of approximately 160 N/mm² concentrated at the bow and vessel sides. These high-pressure zones, subjected to repeated wave impacts, demand structural reinforcements to mitigate fatigue and potential failures. This information supports optimal cargo placement strategies, ensuring sensitive cargo is safeguarded and loads are balanced to reduce stress. Additionally, predictive simulations based on this mapping can enhance vessel longevity and operational safety under rough sea conditions.

Figures 3 and 4 focus on wave excitation forces and diffraction/Froude-Krylov forces, respectively, across the vessel's six motion modes. Translational modes (surge, sway, heave) exhibit peak forces of up to 8000 N at critical low-frequency ranges (~0.1 Hz), while rotational modes (roll, pitch, yaw) experience forces as high as 10^7 -10^8N at specific frequencies and wave angles. These forces underscore the need for stabilization systems and reinforcements to address motion-induced stresses and ensure structural integrity. The diffraction and Froude-Krylov force analysis further highlights how low frequencies and broad wave angles amplify forces in all modes, particularly in surge (9 N/m), sway (8 N/m), and roll (13 N/m). Incorporating these findings into vessel design, such as reinforcing critical areas and optimizing stabilization and control systems, ensures enhanced performance, safety, and resilience across various operational conditions.

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