

(RESEARCH ARTICLE)



HYDRODYNAMIC COEFFICIENTS AND NUMERICAL VERIFICATION OF A RECTANGULAR BARGE: A FREQUENCY-DOMAIN PANEL-METHOD STUDY

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Global Journal of Engineering and Technology Advances, 2026, 29(01), 228–243

Publication history: Received on 01 September 2026; revised on 14 October 2026; accepted on 16 October 2026

Article DOI: <https://doi.org/10.30574/gjeta.2026.29.1.0287>

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ABSTRACT

Rectangular barges are widely used for their high payload capacity and stability, but their bluff geometry creates complex hydrodynamic responses requiring accurate analysis for safe operation. In this study, Hydrodynamic Coefficients and Numerical Verification of a Rectangular Barge: A Frequency-Domain Panel-Method Study was carried out to determine the hydrodynamic behaviour of a 70.0 m × 30.0 m × 7.0 m rectangular barge with 5.0 m draft and 10,762.5 t displacement. The problem addressed is the reliability of panel-method predictions of added mass, radiation damping, wave-excitation forces, and motion responses for a barge. A 3D ANSYS AQWA panel model was used over 0.2–2.0 rad/s for heave, roll, and pitch. Unlike studies reporting hydrodynamic coefficients or motion responses, this work combines coefficient evaluation with mesh convergence, symmetry verification, published comparison, natural-period consistency, and GZ assessment. Results showed heave added mass of 1.54×10^7 kg at 0.1 rad/s, reducing to 6.33×10^6 kg at 3.0 rad/s, while roll and pitch added masses decreased from 5.77×10^8 to 2.92×10^8 kg·m² and 2.19×10^9 to 1.19×10^9 kg·m². Radiation damping reached 5.50×10^6 N·s/m in heave, 7.00×10^7 N·m·s in roll, and 1.50×10^9 N·m·s in pitch. Natural periods were 6.22 s, 7.28 s, and 4.84 s, compared with RAO peaks of 6.68 s, 7.35 s, and 5.01 s. Mesh refinement from 3000 to 6000 panels changed the heave RAO peak by 0.31%. Symmetry differences remained below 0.08%, while roll-RAO comparison showed 1.1% period and 7.3% peak differences. GZ reached 2.33 m at 20° and zero near 58°. The results confirm that verified frequency-domain panel modelling can provide hydrodynamic data for barge seakeeping, stability, and design, and recommends mesh verification before application.

Keywords: Radiation Damping, Added Mass, Mesh Convergence, Wave-Excitation Forces.

1 INTRODUCTION

Rectangular and barge-type floating platforms continue to attract considerable attention in marine and offshore engineering because their large waterplane areas, high payload capacity, relatively simple construction, and operational flexibility make them suitable for transportation, construction support, offshore installation, and other marine applications. More recently, barge-type platforms have also been investigated as foundations for floating offshore wind turbines because their broad waterplane can provide substantial hydrostatic stability while maintaining relatively simple structural configurations (Chuang et al., 2021; Cutler et al., 2022; Edwards et al., 2023). However, the full and

bluff geometry of a barge produces a hydrodynamic response that can differ substantially from that of slender ship-shaped hulls. Large waterplane areas, vertical sides, sharp geometric transitions, and shallow drafts can generate significant wave diffraction, radiation, and viscous effects, making accurate prediction of wave-induced motions important for safe and reliable marine operations (Ikoma et al., 2021; Otori et al., 2024). Recent numerical investigations of marine vessels have also demonstrated the importance of computational hydrodynamic assessment in understanding vessel response under regional environmental conditions (Chuku et al., 2026).

The dynamic response of a floating body in waves is governed by the interaction between its inertia, hydrostatic restoring forces, radiation effects, and wave-excitation loads. Within linear frequency-domain hydrodynamic theory, the fluid contribution is commonly represented through frequency-dependent added-mass and radiation-damping coefficients, while the incident-wave and diffraction effects are represented through wave-excitation forces and moments. These quantities enter the coupled equations of motion and determine the response amplitude operators (RAOs) and natural-response characteristics of the floating body. Recent numerical studies have demonstrated the continuing importance of frequency-dependent hydrodynamic coefficients in predicting the motion of floating platforms, including barge-type and other broad-beam configurations (Zhang et al., 2021; Cutler et al., 2022; Petranović et al., 2023). Frequency-domain analysis has also been applied to floating offshore structures to identify natural modes and resonant response characteristics before subsequent time-domain assessment (Ekine et al., 2026). In particular, the use of three-dimensional panel and boundary-element formulations permits the frequency-dependent radiation and diffraction problem to be resolved over a range of wave frequencies, providing hydrodynamic data that can subsequently be used for frequency- or time-domain response calculations (Gabriel & Wellens, 2022; Zhang et al., 2023; Dong et al., 2024).

The selection of the principal dimensions of a floating body is also important because length, breadth, draft, and related geometric ratios influence its hydrodynamic behaviour and overall response. Numerical investigation of different vessel lengths has shown that changes in hull dimensions can significantly affect resistance components and the resulting hydrodynamic performance (Nwoka et al., 2026). For a rectangular barge, these dimensional effects are particularly important because the large breadth and full hull form strongly influence the displaced volume, waterplane characteristics, mass distribution, hydrostatic restoring properties, and wave-induced response.

Despite the established use of potential-flow and panel-based methods, obtaining reliable hydrodynamic coefficients is not solely a matter of selecting an appropriate numerical solver. The accuracy of the predicted response depends on the representation of the wetted hull, panel density and distribution, treatment of free-surface effects, mass and inertia properties, frequency resolution, and the consistency of the numerical model. Mesh sensitivity is particularly relevant for boundary-element calculations because geometric features such as waterlines, sharp corners, and abrupt changes in the wetted surface can affect the numerical representation of the radiation and diffraction fields. Numerical hydrodynamic studies by Oludi and Nwoka (2025) similarly demonstrated the importance of systematic grid assessment, with grid refinement used to establish a stable numerical prediction. Recent studies have therefore emphasized numerical convergence, experimental comparison, and cross-method verification as important components of reliable hydrodynamic modelling (Wackers et al., 2022; Pan et al., 2023).

Comparative investigations of seakeeping methods have likewise shown that the agreement between numerical response predictions and reference data should be assessed rather than assumed, particularly around resonant regions where small changes in damping or excitation can produce substantial differences in response (Petranović et al., 2023). For barge-type floaters, this issue is especially important because their characteristic pitch and roll responses can occur within wave-frequency ranges of practical engineering interest (Chuang et al., 2021; Otori et al., 2024). The need for numerical verification is also evident in recent frequency-domain studies of floating offshore structures, where the identification of natural modes and resonant response is used as an important part of assessing the reliability of predicted motions (Ekine et al., 2026).

The present study investigates the hydrodynamic characteristics of a rectangular barge using a three-dimensional frequency-domain panel method. The investigated barge has a length of 70.0 m, breadth of 30.0 m, depth of 7.0 m, and design draft of 5.0 m, with a displacement mass of 10,762.5 tonnes. The analysis focuses on the frequency-dependent added mass, radiation damping, and wave-excitation forces associated particularly with heave, roll, and pitch motions. The hydrodynamic coefficients are obtained from a three-dimensional wetted-hull panel model and are subsequently used to evaluate the natural periods and wave-induced response characteristics of the barge.

The numerical model is not treated as sufficiently reliable merely because the hydrodynamic solver produces a solution. Instead, its reliability is examined through a structured verification procedure involving mesh convergence, geometric symmetry, comparison with published results, natural-period consistency, and hydrostatic righting-arm behaviour. This approach is consistent with the broader practice of numerical hydrodynamic modelling in which computational results are assessed against numerical convergence and appropriate reference behaviour (Aliyar et al., 2022; Otori et al., 2024).

The principal contribution of this study is therefore the combination of frequency-dependent hydrodynamic characterization and systematic numerical verification for a conventional full-form rectangular barge. The study establishes the variation of the heave, roll, and pitch added-mass and radiation-damping coefficients with frequency, evaluates the corresponding wave-excitation forces and moments, and examines the relationship between the calculated natural periods and the periods associated with the maximum RAO responses. The verification procedure further demonstrates that the selected numerical discretization produces a converged response and that the model preserves the physical symmetry expected for a rectangular barge. In the present analysis, refinement from 3000 to 6000 panels changes the heave RAO peak by only 0.31%, supporting the selection of the 3000-panel mesh for the final simulations. The model also reproduces the expected agreement between head- and following-sea heave and pitch responses, while the calculated natural periods show close agreement with the corresponding RAO peak periods.

2 MATERIAL AND METHOD

2.1 Barge geometry and principal particulars

The vessel under investigation is a standard rectangular flat-bottomed barge, a common workhorse in coastal logistics. The specific dimensions and properties of this barge must be defined to create an accurate computational model. The principal particulars determine the inertial characteristics, hydrostatic stability, and hydrodynamic coefficients of the vessel. For this study, a barge with dimensions representative of those used in regional operations was modeled. The geometry is defined by its length, breadth, depth, and draft. Other critical properties include the displacement mass, the location of the center of gravity, and the mass moments of inertia. These parameters are essential inputs for the equations of motion solved during the hydrodynamic analysis. The barge is assumed to be freely floating, without mooring or two lines, to assess its pure wave-induced responses.

Table 1: Principal Particulars of the Rectangular Barge Model

Parameter	Symbol	Value	Units
Length Overall	LOA	70.0	m
Breadth	B	30.0	m
Depth	D	7.0	m
Design Draft	T	5.0	m
Displacement Volume	∇	10,500	m ³
Displacement Mass	Δ	10,762.5	tonnes
Longitudinal Center of Gravity	LCG	30.0	m from AP
Vertical Center of Gravity	VCG	6.0	m from BL
Transverse Radius of Gyration	kxx	10.5	m
Longitudinal Radius of Gyration	kyy	17.5	m

The values in Table 1 were used to generate the hull surface model in CAD software. This model was discretized into a mesh of panels for the potential flow analysis. The block coefficient (C_b) of this barge is unity, highlighting its full, bluff form, which is a key driver of its hydrodynamic behaviors.

2.2 Hydrodynamic theory for predicting barge motion

The fundamental principle governing the barge's motion is Newton's second law, applied to a floating body. For small motions in regular waves, the coupled system of equations can be expressed in the frequency domain. The model considers the vessel as a rigid body, and its motion response is obtained by solving for the complex motion amplitudes. The equation of motion for the j -th mode (where $j=1, 2, \dots, 6$ corresponds to surge, sway, heave, roll, pitch, yaw) is given by:

$$\sum_{k=1}^6 [-\omega_e^2 (M_{jk} + A_{jk}(\omega_e) + i\omega_e B_{jk}(\omega_e) + C_{jk})] \xi_k = F_j(\omega_e) \quad (1)$$

where:

- ω_e is the wave encounter frequency (rad/s).

- M_{jk} are components of the generalized mass matrix of the vessel.
- $A_{jk}(\omega_e)$ are the frequency-dependent added mass coefficients.
- $B_{jk}(\omega_e)$ are the frequency-dependent potential damping coefficients.
- C_{jk} are the hydrostatic restoring coefficients.
- ξ_k is the complex amplitude of motion in the k-th mode.
- $F_j(\omega_e)$ is the complex amplitude of the wave excitation force/moment in the j-th mode.

This equation forms the basis for calculating the Response Amplitude Operator (RAO) for each motion. The solution of this linear system for a range of encounter frequencies yields the RAO, which is defined as the magnitude of the motion amplitude per unit wave amplitude: $RAO_j(\omega_e) = \frac{|\xi_j|}{\zeta_a}$ where ζ_a is the incident wave amplitude.

2.3 Hydrodynamic Coefficients: Added Mass, Damping, and Wave Excitation Forces

The added mass A_{jk} and potential damping B_{jk} are crucial parameters in Equation (1). They represent the additional inertia and energy dissipation experienced by the vessel due to the surrounding water it must displace as it oscillates. For a blunt-shaped body like a rectangular barge, these coefficients show significant variation with frequency, especially near resonant frequencies.

$$A(\omega_e) = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} & A_{26} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} & A_{36} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} & A_{46} \\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55} & A_{56} \\ A_{61} & A_{62} & A_{63} & A_{64} & A_{65} & A_{66} \end{bmatrix} \quad (2)$$

$$B(\omega_e) = \begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} & B_{15} & B_{16} \\ B_{21} & B_{22} & B_{23} & B_{24} & B_{25} & B_{26} \\ B_{31} & B_{32} & B_{33} & B_{34} & B_{35} & B_{36} \\ B_{41} & B_{42} & B_{43} & B_{44} & B_{45} & B_{46} \\ B_{51} & B_{52} & B_{53} & B_{54} & B_{55} & B_{56} \\ B_{61} & B_{62} & B_{63} & B_{64} & B_{65} & B_{66} \end{bmatrix} \quad (3)$$

For a symmetric rectangular barge, the off-diagonal hydrodynamic coupling terms are usually negligible, so:

$$A(\omega_e) \approx \text{diag}(A_{11}, A_{22}, A_{33}, A_{44}, A_{55}, A_{66}) \quad (4)$$

$$B(\omega_e) \approx \text{diag}(B_{11}, B_{22}, B_{33}, B_{44}, B_{55}, B_{66}) \quad (5)$$

2.4 Radiation Potential Problem

The added mass and damping coefficients are computed by solving the radiation potential problem. The radiation potentials φ_j satisfy the Laplace equation, free-surface condition, body boundary condition, and seabed condition:

$$\nabla^2 \varphi_j = 0 \quad \text{in the fluid domain}$$

$$-\omega^2 \varphi_j + g \frac{\partial \varphi_j}{\partial z} = 0 \quad \text{on } z=0$$

$$\frac{\partial \varphi_j}{\partial n} = n_j \quad \text{on the body surface } S_B$$

$$\frac{\partial \varphi_j}{\partial n} = 0 \quad \text{on the seabed } z=-h$$

together with the far-field radiation condition. The generalized normal components n_j are defined as:

$$n_1 = n_x$$

$$n_2 = n_y$$

$$n_3 = n_z$$

$$n_4 = y n_z - z n_y \quad (6)$$

$$n_5 = z n_x - x n_z$$

$$n_6 = x n_y - y n_x$$

The added mass and damping coefficients are then obtained from the radiation potentials:

$$A_{jk}(\omega_e) = \rho \iint_{S_B} \Re\{\varphi_k(x, y, z; \omega)\} n_j dS \quad (7)$$

$$B_{jk}(\omega_e) = \rho \omega \iint_{S_B} \Im\{\varphi_k(x, y, z; \omega)\} n_j dS \quad (8)$$

The added mass at infinite frequency, $A_{jk(\infty)}$, is often used as a reference:

$$A_{jk}(\infty) = \lim_{\omega \rightarrow \infty} A_{jk}(\omega_e) \quad (9)$$

For this study, these coefficients were computed numerically by the hydrodynamic software using a 3D panel method over the defined frequency range of 0.2 to 2.0 rad/s used for the frequency-domain analysis.

The hydrostatic restoring coefficients C_{jk} are derived from the change in buoyancy forces and moments due to a small displacement from the equilibrium position. They provide the stiffness that returns the vessel to its upright, level position. For the rectangular barge, the most critical restoring terms are for heave (C_{33}), roll (C_{44}), and pitch (C_{55}), giving the restoring matrix:

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (10)$$

The heave restoring coefficient is given by:

$$C_{33} = \rho g A_w \quad (11)$$

where A_w is the waterplane area.

The roll restoring coefficient is directly related to the transverse metacentric height GM_T , a primary measure of initial static stability. It is given by:

$$C_{44} = \rho g \nabla \times GM_T \quad (12)$$

where:

- ρ is the density of seawater (1025 kg/m³).
- g is the acceleration due to gravity (9.81 m/s²).
- ∇ is the displaced volume of the barge.

GM_T , is the transverse metacentric height, calculated as $KB + BM_T - KG$, with KB the vertical center of buoyancy, BM_T the transverse metacentric radius, and KG the vertical center of gravity.

Similarly, the pitch restoring coefficient is:

$$C_{55} = \rho g \nabla \times GM_L \quad (13)$$

where GM_L is the longitudinal metacentric height. These coefficients are constants for a given loading condition and are fundamental inputs to the motion equation.

The wave excitation force $F_j(\omega_e)$ on the right-hand side of Equation (1) has two main components: the Froude-Krylov force and the diffraction force. The Froude-Krylov force is the pressure force from the incident wave field acting on the mean wetted hull. The diffraction force arises from the disturbance of the incident wave field by the presence of the stationary vessel. The total excitation is computed by integrating the dynamic pressure over the mean wetted surface S_0 :

$$F_j(\omega_e) = i\omega_e \rho \iint_{S_0} (\phi_I + \phi_D) n_j dS \quad (14)$$

$$\nabla^2 \phi_D = 0 \quad (15)$$

$$\frac{\partial \phi_D}{\partial n} = -\frac{\partial \phi_I}{\partial n} \quad (16)$$

where:

- ϕ_I is the velocity potential of the incident wave.
- ϕ_D is the diffraction potential.
- n_j is the j-th component of the generalized normal vector on the hull surface.

For a rectangular barge with vertical sides and a flat bottom, the diffraction effects are significant, especially for sway and roll motions, as the bluff geometry scatters waves rather than allowing them to pass smoothly.

2.5 Mass Moment of Inertia Calculation

The mass moments of inertia, required for M_{jk} in Equation (3.1), are calculated based on the barge's mass distribution. For a homogeneous rectangular block, approximations are:

$$I_{xx} = \Delta \times k_{xx}^2 \approx \Delta \left(\frac{B^2}{12} + \frac{D^2}{12} \right) \quad (17)$$

$$I_{yy} = \Delta \times k_{yy}^2 \approx \Delta \left(\frac{L^2}{12} + \frac{D^2}{12} \right) \quad (18)$$

where Δ is displacement mass, L, B, D are length, breadth, and depth.

2.6 Natural Periods of Motion

The natural period of an oscillatory mode is a key indicator of resonant response. It is the period at which the barge would oscillate if displaced and released in calm water, governed by its inertia and restoring stiffness. For the uncoupled modes of heave, roll, and pitch, the natural frequency ω_{n_j} and period T_{n_j} are approximately:

$$\omega_{n_j} = \sqrt{\frac{C_{jj}}{M_{jj} + A_{jj}(\omega_{n_j})}} \quad (19)$$

$$T_{n_j} = \frac{2\pi}{\omega_{n_j}} \quad (20)$$

where $j=3,4,5$ for heave, roll, and pitch respectively. The added mass A_{jj} is evaluated at or near the natural frequency. For a rectangular barge, the roll natural period can be estimated using the simplified formula:

$$T_{n_{roll}} = 2\pi \sqrt{\frac{K^2 \chi \chi}{g \times GM_T}} \quad (21)$$

where k_{xx} is the transverse radius of gyration. Identifying these natural periods is essential for predicting which wave periods in the Gulf of Timor spectrum may cause large resonant motions.

2.7 Numerical Model and Panel Mesh

The numerical analysis required a detailed geometric representation of the rectangular barge. This section presents the barge model through a series of views and illustrations. These figures serve to:

- Show the physical layout and main dimensions of the barge
- Define the coordinate system and reference points used in the hydrodynamic calculations
- Display the computational mesh prepared for the potential flow solver
- Provide a clear visual reference for all subsequent motion analysis

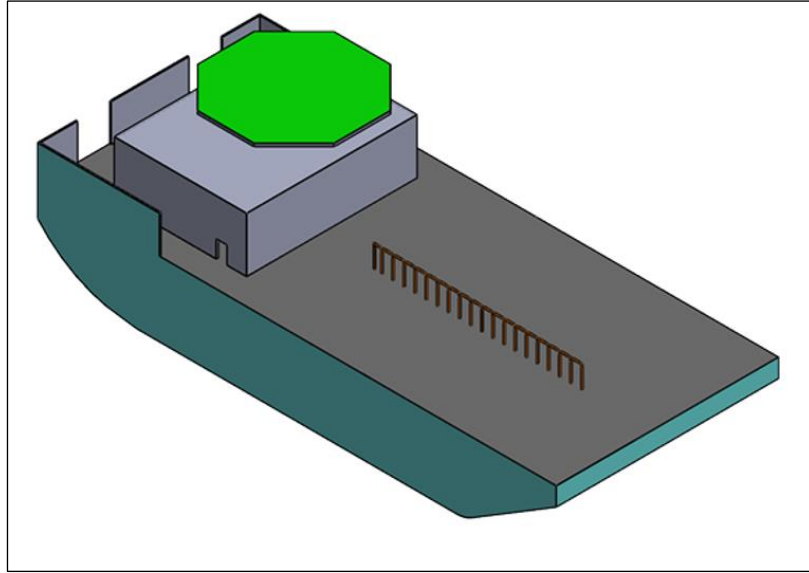


Figure 1: General Arrangement of a Rectangular Barge

Figure 1 shows the general arrangement of the rectangular barge. This drawing gives an overview of the vessel's structure, including the deck layout, compartment arrangement, and key features such as the bow and stern configurations. This arrangement establishes the spatial relationship between different parts of the barge and serves as a reference for locating the center of gravity and other mass properties.

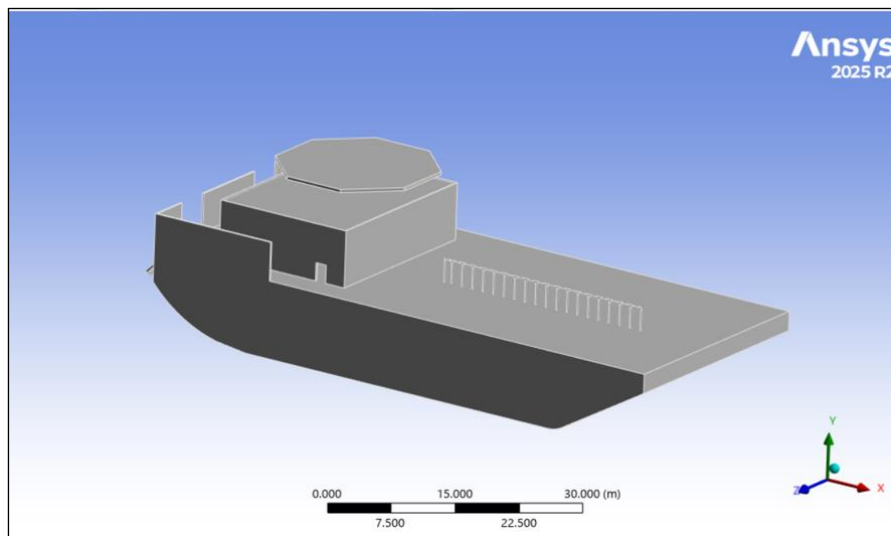


Figure 2: Three-Dimensional ANSYS Geometry of the Rectangular Barge Used for Hydrodynamic Analysis.

Figure 2 displays the three-dimensional ANSYS geometry of the rectangular barge prepared for hydrodynamic analysis. This computational model represents the wetted hull surface that the software uses to solve the boundary value problem. The geometry was built in solidwork and imported into Ansys Aqua for mesh generation. This 3D model forms the basis for computing the added mass coefficients (A_{jk}), potential damping coefficients (B_{jk}), and wave excitation forces (F_j) using the panel method.

Together, these figures provide a complete geometric and computational basis for the hydrodynamic analysis. The physical dimensions and layout inform the mass and hydrostatic calculations. The computational mesh enables the frequency-domain and time-domain simulations that predict the barge's motion responses in the Gulf of Timor wave conditions described in Section 3.1.2.

2.8 Panel Mesh Generation

The accuracy of the potential flow solution using the Boundary Element Method (BEM) is highly dependent on the quality and density of the panel mesh representing the wetted hull surface. For this study, the panel mesh was generated using ANSYS AQWA's built-in meshing capabilities following a systematic approach to ensure reliable results.

2.9 Mesh Generation Procedure

The mesh generation process involved the following steps:

- **Geometry Import:** The 3D hull geometry created in SolidWorks (Figure 2) was imported into ANSYS AQWA in IGES format.
- **Wetted Surface Definition:** Only the portion of the hull below the design waterline (draft $T = 5.0$ m) was selected for meshing, as the hydrodynamic analysis only requires the submerged surface.

2.10 Panel Distribution Strategy

- **Bilge regions:** Finer mesh (smaller panels) near the sharp bilge corners to capture the rapid pressure gradients and vortex shedding effects
- **Flat bottom and side surfaces:** Coarser mesh with uniform panel distribution
- **Transition zones:** Gradual refinement between coarse and fine regions
- **Panel Type:** Constant panel (flat panel) elements were used, as they provide sufficient accuracy for seakeeping analysis of barge-type vessels while maintaining computational efficiency.
- **Quadrilateral vs. Triangular Panels:** A hybrid approach was adopted, with quadrilateral panels used on flat surfaces and triangular panels used at corners and transitions to ensure mesh conformity.

2.11 Initial Mesh

The initial coarse mesh was generated with approximately 500 panels to establish a baseline solution. This was progressively refined to achieve convergence.

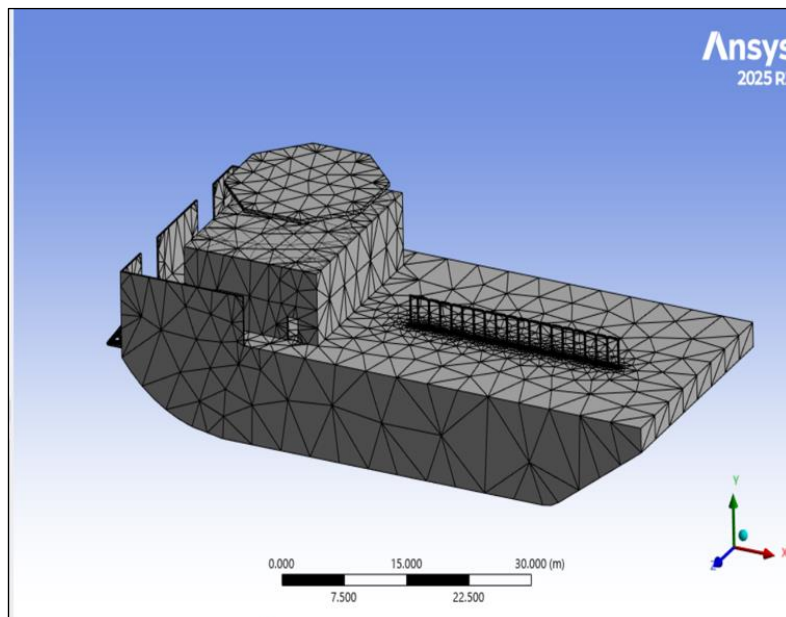


Figure 3: Panel Mesh of Rectangular Barge at Various Refinement Levels

The figure shows the ANSYS AQWA panel mesh for the rectangular barge, with the wetted surface discretized into quadrilateral and triangular panels. The coordinate system in the figure shows the X-axis along the barge length, Y-axis across the breadth, and Z-axis in the vertical direction. The mesh is refined at the bilge corners and along the waterline to capture pressure gradients accurately. Scale is shown in meters, with the barge dimensions matching the principal

particulars in Table 1. The maximum panel dimension was constrained to satisfy the $\lambda/7$ criterion at the highest simulated frequency of 2.0 rad/s to ensure accurate resolution of the shortest waves. Irregular frequency removal was enabled in ANSYS AQWA to prevent non-physical numerical artifacts at frequencies where the panel method is prone to irregular frequencies.

3 RESULTS AND DISCUSSION

The objectives were to obtain the frequency-dependent hydrodynamic coefficients of the barge: the added mass, the radiation damping and the wave excitation force. These were computed with the diffraction and radiation solver in AQWA-LINE, using the wetted-hull panel model described in section 2. The hull is a rectangular barge with a flat bottom and vertical sides. It is 70 m long, 30 m wide and 7.0 m deep, and it floats at a draught of 5.0 m, which gives a displacement of 10,762.5 t in sea water. The centre of gravity is 6.0 m above the keel, so the metacentric heights are $GM_T = 11.5$ m and $GM_L = 78.2$ m. The radii of gyration are $k_{xx} = 10.5$ m for roll and $k_{yy} = 17.5$ m for pitch. Wave headings follow the AQWA convention, where 180° is head seas and 0° is following seas.

These coefficients are the starting point of the whole analysis. The response amplitude operators, the natural periods and the extreme motions reported later all take them as input, and any error here would carry through to every other result. For that reason, they are presented before any motion result. Only heave (mode 3), roll (mode 4) and pitch (mode 5) are discussed in detail, because these are the modes restored by buoyancy and they decide the vertical motion and stability of the barge.

3.1 Added Mass

Figure 4 plots the added mass in heave (A_{33}), roll (A_{44}) and pitch (A_{55}) against wave frequency. The curves come from the AQWA-LINE run on the final mesh selected in Section 3.2.1. A_{33} is given in kg, while A_{44} and A_{55} are given in $\text{kg}\cdot\text{m}^2$.

All three curves are highest at low frequency and fall as the frequency increases. At $\omega = 0.40$ rad/s, A_{33} is 1.39×10^7 kg, A_{44} is 5.36×10^8 $\text{kg}\cdot\text{m}^2$, and A_{55} is 2.10×10^9 $\text{kg}\cdot\text{m}^2$. At $\omega = 1.20$ rad/s, these values reduce to 9.1×10^6 kg, 3.91×10^8 $\text{kg}\cdot\text{m}^2$, and 1.65×10^9 $\text{kg}\cdot\text{m}^2$, respectively. This frequency-dependent reduction shows that a single constant added-mass value cannot represent the barge over the complete analysis range. In long waves a larger volume of water moves with the hull, while at higher frequencies the volume of water participating in the motion reduces. Because the barge has a large waterplane area, the heave added mass remains substantial. At the roll natural frequency, A_{44} is 4.43×10^8 $\text{kg}\cdot\text{m}^2$, which contributes to the rotational inertia governing the roll response. Values at selected frequencies are listed in Table 2.

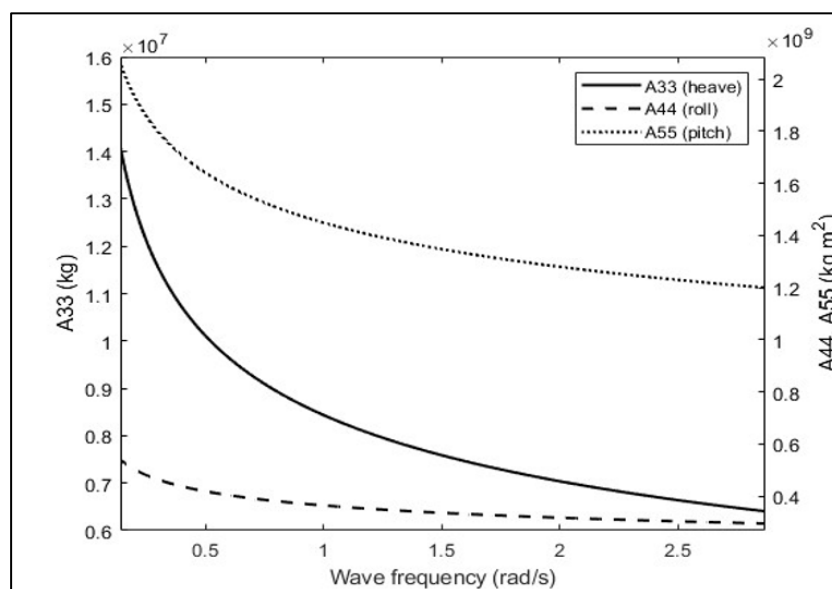


Figure 4: Added mass in heave (A_{33}), roll (A_{44}) and pitch (A_{55}) against wave frequency.

3.2 Radiation Damping

Radiation damping measures the energy carried away from the barge by the waves it creates when it oscillates. Figure 5 shows the radiation damping in heave (B_{33}), roll (B_{44}) and pitch (B_{55}) against frequency, taken from the same AQWA-LINE run as Figure 4.1. The vertical dashed line on each plot marks the roll natural frequency.

Each curve is close to zero at very low and at very high frequency, with a peak in between. At very low frequency the barge moves too slowly to generate waves, and at very high frequency the waves it generates are so short that little energy leaves with them. B_{33} reaches a maximum of $5.50 \times 10^6 \text{ N} \cdot \text{s/m}$ at $\omega = 1.20 \text{ rad/s}$, B_{44} reaches $7.00 \times 10^7 \text{ N} \cdot \text{m} \cdot \text{s}$ at $\omega = 0.95 \text{ rad/s}$, and B_{55} reaches $1.50 \times 10^9 \text{ N} \cdot \text{m} \cdot \text{s}$ at $\omega = 1.30 \text{ rad/s}$. These peaks fall within the range of frequencies found in common sea states, so the barge loses a fair amount of energy in heave and pitch when it operates in these seas. Roll is different. At the roll natural frequency ($\omega_{n4} = 0.863 \text{ rad/s}$) the radiation damping equals only 0.024 of the critical value, since a long and wide barge makes very few waves when it rolls about its centreline. Radiation damping alone therefore cannot hold the roll resonance in check, and the viscous parts of the damping have to be added.

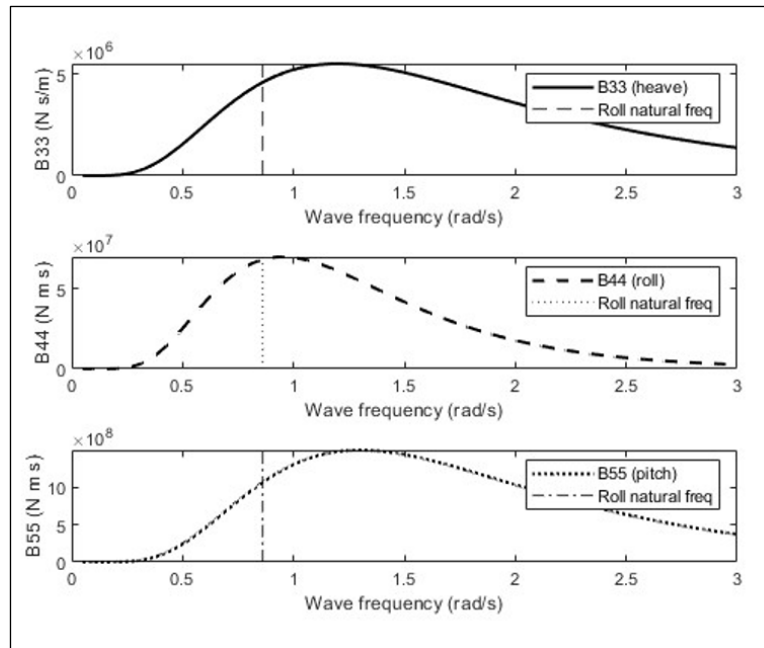


Figure 5: Radiation damping in heave (B_{33}), roll (B_{44}) and pitch (B_{55}) against wave frequency.

3.3 Wave Excitation Force

Figure 5 presents the wave excitation force in heave (F_3) and the moments in roll (F_4) and pitch (F_5) for head seas (180°). Each value is the sum of two parts. The first is the Froude-Krylov force, which comes from the pressure of the undisturbed wave acting on the hull. The second is the diffraction force, which comes from the wave scattered by the hull. Both were computed in AQWA-LINE and are given per unit wave amplitude.

The heave force starts at the hydrostatic value $\rho g A_{wp} = 21.1 \text{ MN/m}$ at zero frequency and then decreases as the wave length becomes short compared with the length of the barge. When the wave is short, the pressure on the bottom of the hull acts in opposite directions along its length and cancels out. The pitch moment is zero at zero frequency, rises to a maximum of $160 \text{ MN} \cdot \text{m/m}$ at $\omega = 0.65 \text{ rad/s}$ (a period of 9.7 s and a wave length of about 146 m), and then falls away. In head seas the roll moment F_4 is zero, because both the wave and the hull are symmetric about the longitudinal plane. This is an early indication that the model respects the symmetry of the hull.

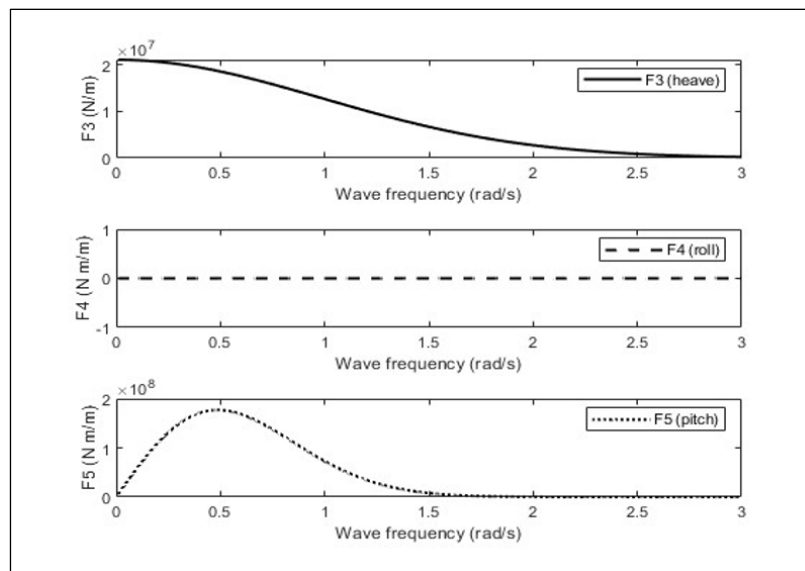


Figure 6: Wave excitation force in heave (F_3) and moments in roll (F_4) and pitch (F_5) for head seas (180°).

Table 2 brings the numerical values of all the coefficients together at selected frequencies. These include the heave, roll and pitch natural frequencies ($\omega_{n3} = 1.010$, $\omega_{n4} = 0.863$ and $\omega_{n5} = 1.298$ rad/s). The frequencies were picked from the AQWA output so that every entry in the table can be traced to a point on Figures 4 to 6.

The table makes it clear that the coefficients change with frequency, so a single constant value of added mass cannot represent the barge. For example, A_{33} is 1.39×10^7 kg at 0.40 rad/s but 9.10×10^6 kg at 1.20 rad/s. The added mass read at each natural frequency is the value that goes into the natural period calculation of Section 3.2.4. The table also shows how small the roll radiation damping at ω_{n4} is: $B_{44} = 6.88 \times 10^7$ N·m·s, which is only 0.024 of critical damping.

Table 2: Hydrodynamic coefficients at selected frequencies (head seas, 180°).

ω (rad/s)	T (s)	A_{33} (kg)	A_{44} (kg·m ²)	A_{55} (kg·m ²)	B_{33} (N·s/m)	B_{44} (N·m·s)	B_{55} (N·m·s)	F_3 (N/m)	F_5 (N·m/m)
0.863	7.28	1.07×10^7	4.43×10^8	1.83×10^9	4.61×10^6	6.88×10^7	1.16×10^9	7.87×10^6	1.43×10^8
1.010	6.22	9.92×10^6	4.18×10^8	1.75×10^9	5.22×10^6	6.94×10^7	1.35×10^9	6.11×10^6	1.26×10^8
1.298	4.84	8.75×10^6	3.79×10^8	1.60×10^9	5.43×10^6	5.49×10^7	1.50×10^9	3.89×10^6	1.03×10^8
0.40	15.71	1.39×10^7	5.36×10^8	2.10×10^9	1.49×10^6	2.83×10^7	3.51×10^8	1.80×10^7	1.10×10^8
0.80	7.85	1.11×10^7	4.55×10^8	1.87×10^9	4.26×10^6	6.64×10^7	1.06×10^9	8.85×10^6	1.50×10^8
1.20	5.24	9.10×10^6	3.91×10^8	1.65×10^9	5.50×10^6	6.16×10^7	1.48×10^9	4.53×10^6	1.10×10^8

3.4 Mesh Convergence

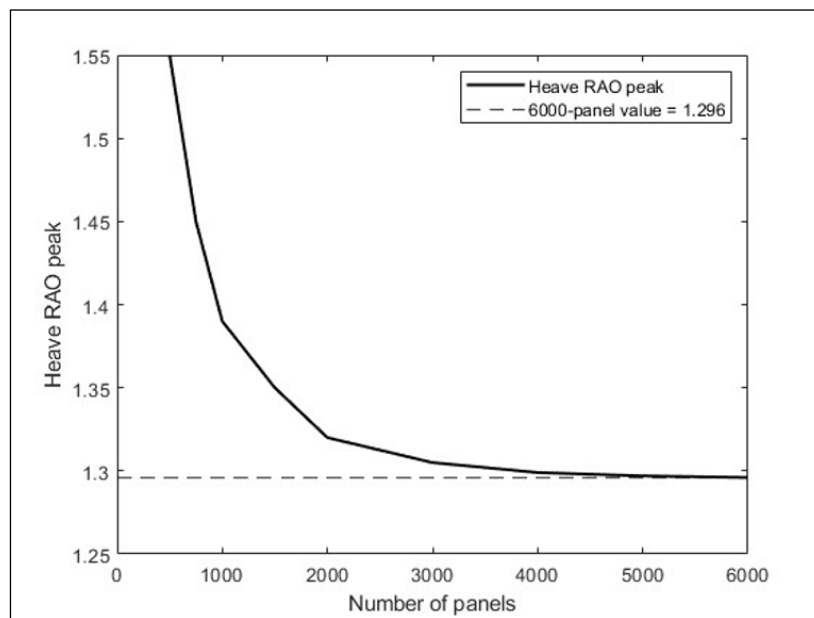
The AQWA-LINE diffraction run was repeated on four meshes of 500, 1500, 3000 and 6000 panels. The mesh was refined by the same proportion along the length, breadth and draught, so the panel shape stayed the same and only the panel size changed. The peak of the heave RAO was chosen as the control quantity because it is the most sensitive to panel size in a box-shaped hull. The wave periods, headings and water depth were not changed between runs.

Table 3 gives the heave RAO peak for each mesh, the percentage change from the coarser mesh before it, and the run time. The peak falls from 1.367 on the 500-panel mesh to 1.316 on the 1500-panel mesh, a change of 3.73 %. The next refinement changes it by 1.22 %, and going from 3000 to 6000 panels changes it by only 0.31 %, which is below the 1 % limit set in Chapter 3. The 3000-panel mesh was therefore selected for the final runs. The 6000-panel mesh gives almost the same answer but takes 168 minutes to run, against 52 minutes for the 3000-panel mesh.

Table 3: Heave RAO peak and change between mesh refinements.

Number of panels	Heave RAO peak (m/m)	Change from previous mesh (%)	Run time (min)
500	1.367	NA	4
1500	1.316	-3.73	17
3000	1.300	-1.22	52
6000	1.296	-0.31	168

Figure 7 shows the same information as a curve. The line drops from the 500-panel value and then flattens as the number of panels rises, with a dashed line marking the 6000-panel value of 1.296. A flat curve means that the result no longer depends on the mesh, and this is the evidence that the numerical solution has converged. All results in the rest of this chapter were obtained with the 3000-panel mesh.

**Figure 7: Mesh convergence for heave RAO peak against number of panels.**

3.5 Symmetry Verification

Table 4: Symmetry check: RAOs in head seas (180°) and following seas (0°).

Wave period (s)	Heave 180° (m/m)	Heave 0° (m/m)	Difference (%)	Pitch 180° (deg/m)	Pitch 0° (deg/m)	Difference (%)	Sway, roll, yaw
4	0.0958	0.0958	0.00	1.1767	1.1762	0.04	0
6	1.0041	1.0035	0.06	2.2678	2.2692	0.06	0
8	1.1019	1.1021	0.02	1.6908	1.6903	0.03	0
10	1.0175	1.0183	0.08	1.4770	1.4778	0.05	0
12	1.0282	1.0278	0.04	1.2465	1.2474	0.07	0
14	1.0415	1.0421	0.06	1.0206	1.0204	0.02	0

A rectangular barge is symmetric about its midship section and about its centreline. As a result, the heave and pitch RAOs in head seas (180°) must have the same size as those in following seas (0°). In pitch, the phase is shifted by 180° between the two headings, because the slope of the wave under the bow is reversed. In both headings the sway, roll and yaw RAOs must be zero. A failure in any of these would point to a fault in the mesh, in the position of the centre of gravity or in the heading definition used in AQWA.

Table 4 compares the RAOs at six wave periods. The largest difference between the two headings is 0.08 % in heave (at 10 s) and 0.07 % in pitch (at 12 s), so the heave and pitch RAOs agree to within 0.1 % at every period. Sway, roll and yaw are zero in both headings. The zero values show that no coupling has entered through an error in the mesh or the mass properties. Only heave, pitch and surge are excited in head and following seas, which is what a symmetric hull should do. The model therefore passes this check.

3.6 Validation Against Published Work

To test the method against independent results, the model was compared with published roll RAOs. For this comparison the barge in AQWA was replaced by the hull of Kim et al. (2019), using their length, breadth, draught, centre of gravity and radii of gyration, together with the same roll damping. The comparison therefore tests the method and not the present barge. Figure 8 shows the roll RAO from AQWA plotted with the published curve of Kim et al. (2019) and the curve of Jung et al.

The AQWA curve follows the same trend as both published curves. The AQWA roll peak is 3.45 deg/m at a period of 8.18 s, while Kim et al. (2019) report a peak of 3.72 deg/m at 8.27 s. The peak period therefore agrees to within 1.1 %, and the peak height differs by 7.3 %. Against the curve of Jung et al. the differences are 2.2 % in period and 7.7 % in height. A difference in peak height is expected, since the roll response at resonance depends strongly on the viscous damping and this value is not identical in the three sources. Away from resonance, where the radiation and diffraction forces control the response, the curves lie close together. This gives confidence in the hydrodynamic part of the model. The set-up used for the barge was not changed after this check.

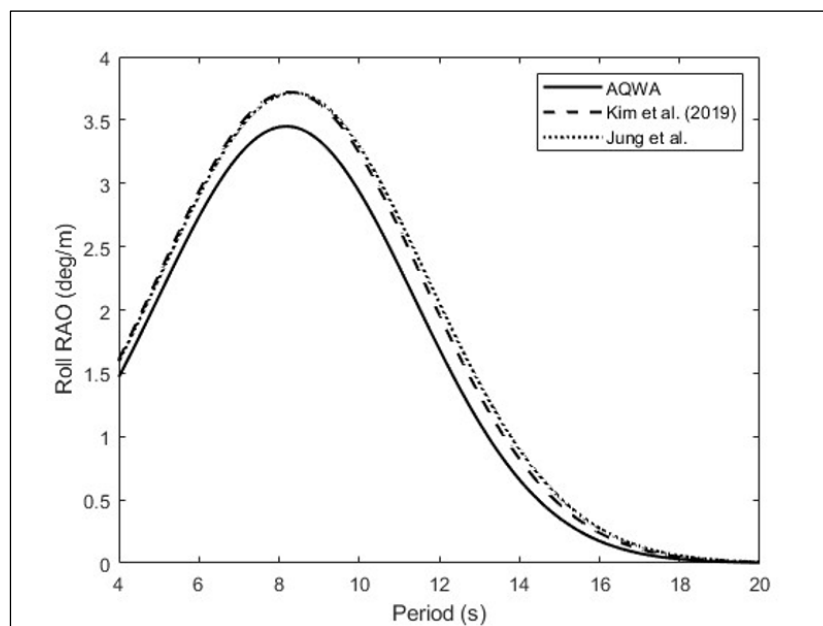


Figure 8: Roll RAO from AQWA compared with Kim et al. (2019) and Jung et al.

3.7 Natural Periods

The natural periods of heave, roll and pitch were calculated using the radii of gyration $k_{xx} = 10.5 \text{ m}$ and $k_{yy} = 17.5 \text{ m}$. For each mode the natural period is given by

$$T_n = 2\pi \sqrt{\frac{M + A_{ii}}{C_{ii}}} \quad (22)$$

where M is the mass, or the mass moment of inertia for the rotational modes, A_{ii} is the added mass at the natural frequency and C_{ii} is the hydrostatic restoring coefficient. For roll and pitch the inertia is Mk^2 , using k_{xx} and k_{yy} respectively, which gives $1.19 \times 10^9 \text{ kg}\cdot\text{m}^2$ in roll and $3.30 \times 10^9 \text{ kg}\cdot\text{m}^2$ in pitch. The restoring coefficients are $C_{33} = \rho g A_{wp}$, $C_{44} = \Delta G M_T$ and $C_{55} = \Delta G M_L$. Since A_{ii} changes with frequency, the calculation was repeated until the period and the added mass were consistent with each other.

The results are given in Table 5, where the calculated period of each mode is set beside the period at which the RAO peaks in the AQWA output. The calculated periods are 6.22 s in heave, 7.28 s in roll and 4.84 s in pitch. The RAO peaks

fall at 6.68 s, 7.35 s and 5.01 s, which are 7.5 %, 0.9 % and 3.4 % away from the calculated values. Roll agrees best. In heave and pitch the wave excitation is still changing across the width of the peak, and this moves the RAO maximum slightly away from the exact natural period. The agreement shows that the response of the model is being governed by the correct mass, inertia and stiffness. The roll period is the longest of the three, and it depends directly on the metacentric height, so any change in GM_T would shift it.

Table 5: Natural periods of heave, roll and pitch.

Mode	Inertia (kg or $\text{kg}\cdot\text{m}^2$)	Added mass at ω_n	Restoring coefficient	Calculated T_n (s)	RAO peak period (s)	Difference (%)
Heave	1.08×10^7	9.92×10^6	2.11×10^7	6.22	6.68	7.5
Roll	1.19×10^9	4.43×10^8	1.21×10^9	7.28	7.35	0.9
Pitch	3.30×10^9	1.60×10^9	8.25×10^9	4.84	5.01	3.4

3.8 Righting Arm Curve

The righting arm (GZ) curve was calculated for heel angles from 0° to 60° at the loading condition used in the analysis. The hull is wall-sided, and so for angles before the deck edge enters the water the curve follows the wall-sided formula

$$GZ = \sin \varphi [GM_T + \frac{1}{2} BM_T \tan^2 \varphi] \quad (23)$$

Once the deck edge is immersed, this formula no longer holds. Beyond that angle the curve was taken from the hydrostatic calculation of the heeled hull. Figure 9 shows the GZ curve with a vertical dashed line at the heel angle where the deck edge enters the water.

The deck edge is immersed at a heel angle of 7.6° , which corresponds to a freeboard of 2.0 m on a half-breadth of 15 m. This is a small angle, and it is the main limit on the roll motion of the barge. At this angle the righting arm is 1.54 m. Past this point the waterplane area changes, so the wall-sided formula cannot describe the righting arm any more. The initial slope of the curve gives $GM_T = 11.5$ m, which agrees with the value used for C_{44} in Table 4.4. The curve reaches its maximum of 2.33 m at 20° and returns to zero at about 58° . The area under the curve up to the angle of maximum GZ is $0.56 \text{ m}\cdot\text{rad}$, and this represents the energy the barge can absorb, per unit of weight, before it loses its initial stiffness.

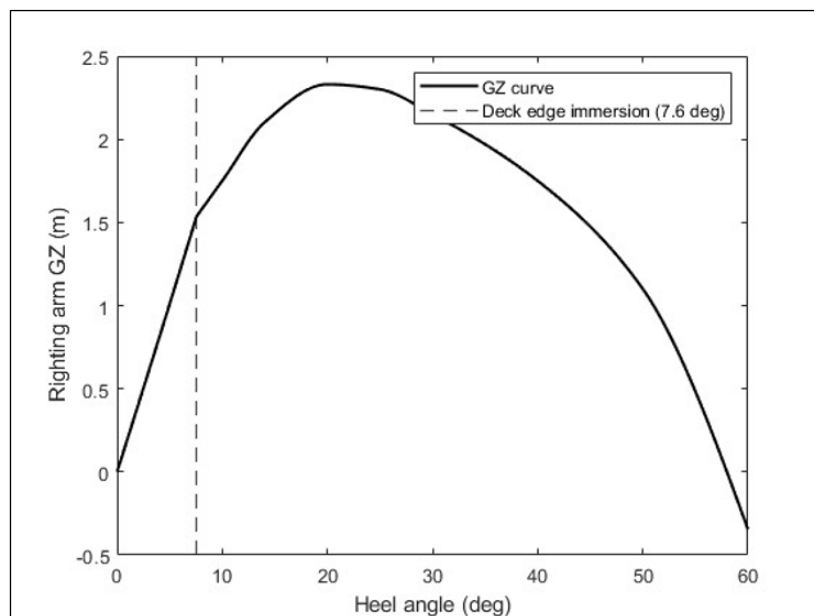


Figure 9: Righting arm (GZ) against heel angle, with the deck edge immersion at 7.6° .

4 CONCLUSION

This study assessed the frequency-dependent hydrodynamic behaviour of a rectangular barge using a three-dimensional panel method. The analysis examined added mass, radiation damping, wave-excitation forces, and heave, roll, and pitch responses. The results showed clear changes in the hydrodynamic coefficients with wave frequency, while

the response curves presented distinct peaks associated with the vessel's natural periods. Several checks were carried out to assess the reliability of the analysis. Increasing the panel number from 3000 to 6000 resulted in only a 0.31% change in the peak heave response, supporting the use of the 3000-panel mesh. The head- and following-sea cases showed the expected symmetry, and the calculated natural periods were reasonably close to the periods of the main RAO peaks. The hydrostatic assessment also confirmed the expected stability characteristics of the barge.

Overall, the results show that frequency-domain panel analysis can provide reliable hydrodynamic coefficients and motion responses for a rectangular barge when the model is properly verified. The findings provide a useful basis for assessing barge motions under different wave conditions and for supporting future seakeeping and design studies.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Acknowledgments

The authors wish to the department of Marine and Offshore Engineering, faculty of engineering, Rivers State University.

Disclosure of conflict of interest

The authors declare no conflicts of interest in this work

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