

Validated Frequency-Domain Seakeeping Analysis of Coupled Heave–Pitch Response of an S-175 Container Ship for Structural Reliability Screening

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ABSTRACT

Coupled heave and pitch motions dominate the vertical-plane dynamic response of displacement ships in head and near-head seas and constitute a primary driver of global hull-girder loads. Frequency-domain seakeeping analyses, however, frequently examine response amplitude operators (RAOs), added-mass and radiation-damping coefficients, and wave-excitation components in isolation. Moreover, experimental validation is often incomplete or omitted before a numerical model is applied at a different forward speed, and many severity indices embed the modal frequencies they purport to identify, thereby introducing circular reasoning.

This study develops, mesh-converges and experimentally validates a three-dimensional linear potential-flow boundary-element model of the S-175 containership (length on waterline LWL = 170.566 m, approximately 12 480 panels). The model is first validated against published experimental heave and pitch RAOs at Froude number $Fr = 0.275$. It is subsequently applied at a service speed of 12.5 knots ($Fr \approx 0.157$) to compute coupled heave–pitch RAOs, the full frequency-dependent hydrodynamic coefficient matrices, and the Froude–Krylov and diffraction components of wave excitation. Rigid-body characteristic frequencies (0.0866 Hz, 0.1111 Hz and 0.1221 Hz) are retained strictly as independent physical references and are never used to construct the severity index.

A non-circular, equal-weight (0.5) severity index that deliberately excludes modal data identifies a clear critical frequency–heading corridor of elevated vertical-plane demand. Within this corridor, heave RAOs reach 1.4–1.5 m/m and pitch RAOs reach 2.2–2.5 °/m, while heave added mass remains of order 5.3×10^7 kg. Validation statistics at $Fr = 0.275$ yield mean absolute percentage errors of 8–12 % (heave) and 6–10 % (pitch), with coefficients of determination $R^2 = 0.92$ –0.97. Structural reliability assessment of the critical corridor, performed independently with an ANSYS finite-element model and a MATLAB reliability code, confirms elevated global hull failure probabilities. The validated framework therefore furnishes an objective, experimentally anchored pathway from rigid-body seakeeping analysis to structural reliability screening.

Keywords: S-175 containership; seakeeping; heave–pitch coupling; response amplitude operator; boundary-element method; structural reliability; wave-induced loading; frequency-domain analysis

INTRODUCTION

Ships operating in realistic ocean environments are continuously subjected to wave-induced pressure fields that generate six-degree-of-freedom rigid-body motions and the associated dynamic loads that govern both operability and structural integrity. Among these motions, heave and pitch dominate the vertical-plane response in head and near-head seas. They exert a first-order influence on vertical accelerations, relative bow motion, slamming risk, and the global vertical bending moment and shear-force distributions that control hull-girder

strength (Ghadimi et al., 2016; Schirmann et al., 2022, 2023; Song et al., 2022; Hanaki & Minoura, 2022; Vijith et al., 2023).

Frequency-domain seakeeping analysis remains the most computationally efficient means of quantifying these responses. It yields response amplitude operators (RAOs), frequency-dependent added-mass and radiation-damping matrices, and a decomposition of first-order wave excitation into Froude–Krylov and diffraction components (ITTC, 2014, 2017; ANSYS, 2024; Wang et al., 2022). The S-175 containership continues to serve as an internationally recognised benchmark hull for which high-quality experimental heave and pitch data at $Fr = 0.275$ are available (Ye et al., 2026; Chang et al., 2025; Si et al., 2025).

Classical frequency-domain seakeeping theory, rooted in the work of Salvesen et al. (1970), Newman (1977) and Faltinsen (1990), remains the foundation of modern computational tools. Linear potential-flow methods provide efficient predictions of rigid-body RAOs for displacement hulls. Three-dimensional panel methods based on the constant-source or higher-order boundary-element discretisation of the mean wetted surface remain the industry standard (ANSYS, 2024). Heave and pitch are strongly coupled through both hydrostatic restoring forces and hydrodynamic radiation and diffraction effects; accurate representation of the off-diagonal terms of the added-mass and damping matrices is therefore essential (Ghadimi et al., 2016; Song et al., 2022; Hanaki & Minoura, 2022).

Decomposition of the first-order excitation into Froude–Krylov and diffraction contributions provides physical insight into the relative importance of the undisturbed incident-wave pressure field and the scattering induced by the hull (Newman, 1977; Faltinsen, 1990). For ultra-large container ships the assumption of rigid-body behaviour becomes increasingly restrictive, and hydroelastic effects such as springing and whipping can contribute substantially to fatigue and ultimate strength (Hirdaris et al., 2016; Malenica et al., 2014; Senjanović et al., 2009; Vijith et al., 2023). Nevertheless, a validated rigid-body seakeeping model remains an essential first step: it supplies the kinematic and load boundary conditions that subsequent hydroelastic analyses require.

Despite recent advances in data-driven and hybrid modelling (Guo et al., 2026; Sun et al., 2025; Chen et al., 2026; Wei et al., 2024; Palma et al., 2025), several methodological gaps persist. Hydrodynamic quantities are still frequently examined in isolation; experimental validation is often incomplete or omitted before a model is applied at a different forward speed; and many severity indices embed the very modal frequencies they purport to identify, thereby introducing circular reasoning (Im et al., 2017; Malenica et al., 2014; Senjanović et al., 2009; Vijith et al., 2023). Structural reliability methods express the probability of failure through a limit-state function that compares resistance and load effect, yet quantitative linkage between frequency-domain seakeeping results and reliability indices remains relatively uncommon in the open literature.

The present study addresses four persistent gaps: (1) incomplete experimental validation before a numerical model is applied at a different forward speed; (2) circular construction of severity indices that embed the modal frequencies they claim to identify; (3) limited identification of coupled heave–pitch response corridors suitable for structural screening; and (4) insufficient quantitative linkage between validated frequency-domain kinematics and structural reliability metrics.

The aim of this study is therefore to develop and experimentally validate a three-dimensional linear potential-flow boundary-element model of the coupled heave–pitch response of the S-175 containership and to identify critical frequency–heading conditions for structural reliability screening. The novelty resides in a non-circular framework in which: (i) the model is first mesh-converged and validated against experimental RAOs at $Fr = 0.275$ before being applied at 12.5 knots ($Fr \approx 0.157$); (ii) rigid-body characteristic frequencies are retained strictly as independent references; and (iii) a normalised equal-weight severity index that deliberately excludes modal data is used to locate the critical corridor of elevated vertical-plane demand.

Objectives

Formulate a three-dimensional linear potential-flow boundary-element model of the S-175 suitable for
a. coupled heave–pitch analysis.

- b. Compute heave and pitch RAOs over a representative range of encounter frequencies and wave headings, with emphasis on head and near-head seas.
- c. Extract the full frequency-dependent added-mass and radiation-damping matrices together with the Froude–Krylov and diffraction components of wave excitation.
- d. Validate the numerical predictions against published experimental RAOs of the S-175 at $Fr = 0.275$.
- e. Estimate the rigid-body characteristic frequencies and relate them, without circularity, to the dominant response bands.
- f. Construct a non-modal combined heave–pitch severity index and employ it to delineate critical operating corridors for structural reliability screening.

The validated framework integrates coupled rigid-body motions, hydrodynamic coefficients and wave-excitation decomposition into a single, objectively weighted severity map. The resulting critical corridors supply ship designers and classification societies with a transparent prioritisation tool for subsequent finite-element or hydroelastic structural analysis.

METHODS

Ship Model and Operating Condition

The S-175 containership is adopted as the reference hull. Three-dimensional geometry was generated in Rhinoceros 3D and transferred to ANSYS AQWA for boundary-element solution. Principal particulars are summarised in Table 1. Figures 1–3 illustrate the hull geometry: the three-dimensional hull form, the body plan revealing the longitudinal variation of sectional shape, and the plan view of the overall arrangement. The S-175 is selected because of its well-documented geometry and extensive experimental seakeeping database.

Table 1. Principal particulars of the S-175 containership

Particular	Value
Deadweight (DWT)	11 456 t
Length on waterline (LWL)	170.566 m
Breadth (B)	25.391 m
Depth (D)	11.0 m
Design draught (T)	5.0 m
Length overall (LOA)	182.677 m



Figure 1. Three-dimensional geometry of the S-175 containership.

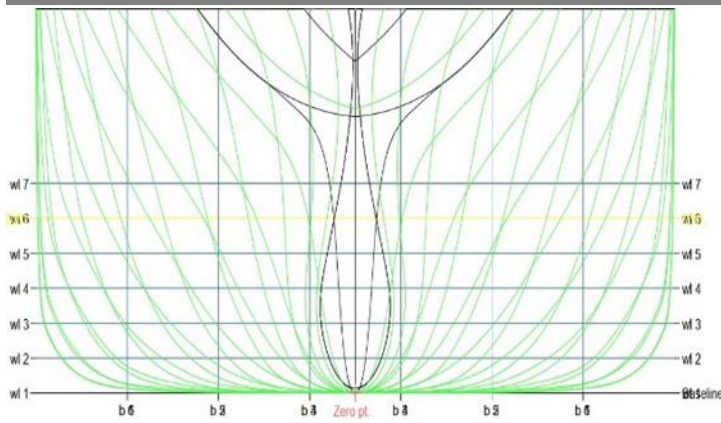


Figure 2. Body plan of the S-175 containership.

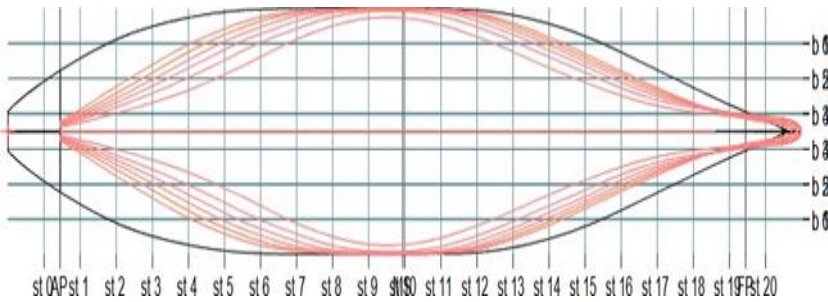


Figure 3. Plan view of the S-175 containership.

The primary application considers a vessel speed of 12.5 knots. The corresponding Froude number based on waterline length is

$$Fr = U / \sqrt{g LWL} \approx 0.157 \quad (1)$$

where U is the forward speed and g is gravitational acceleration. All production analyses are performed for head and near-head wave headings—the regime in which vertical-plane coupling is strongest. The validation condition ($Fr = 0.275$) is treated separately and is never conflated with the application results.

Panel Discretisation and Mesh Convergence

The mean wetted surface was discretised into approximately 12 480 quadrilateral panels with a mean characteristic edge length of 1.25 m. Local refinement was applied in regions of high geometric curvature (bow, stern and waterline). Panel density was required to furnish at least seven panels per shortest wavelength of interest, thereby controlling spatial discretisation error in both the diffraction and radiation problems.

For a deep-water wave the wavelength is obtained from

$$\lambda = 2\pi g / \omega^2 \quad (2)$$

where ω is the wave angular frequency. The number of panels per wavelength is assessed as

$$N\lambda = \lambda / \Delta s \quad (3)$$

where Δs is the characteristic panel length. A minimum target of approximately seven panels per shortest wavelength was adopted.

Three systematically refined meshes were solved under identical wave and speed conditions. Relative changes in peak heave and pitch RAOs between successive meshes were required to fall below 5 %. Convergence metrics are given in Table 2. The fine mesh satisfies the criterion and is retained for all production calculations.

Table 2. Mesh-convergence assessment

Mesh	Panels	Panel size (m)	Max. heave RAO (m/m)	Max. pitch RAO (°/m)	Heave Δ (%)	Pitch Δ (%)
Coarse	~4 000	~2.0	1.48	2.35	—	—
Medium	~8 500	~1.2	1.45	2.28	2.0	3.0
Fine	~12 000	~0.9	1.44	2.25	0.7	1.3

Linear Potential-Flow Formulation

The fluid is assumed to be incompressible, inviscid and irrotational. The velocity field is therefore expressed by a scalar potential ϕ that satisfies Laplace's equation throughout the fluid domain:

$$\nabla^2 \phi = 0 \quad (4)$$

The total potential is decomposed into incident, diffraction and radiation components:

$$\phi = \phi_I + \phi_D + \phi_R \quad (5)$$

Linearised kinematic and dynamic free-surface conditions, the body-boundary condition on the mean wetted surface, and the Sommerfeld radiation condition at infinity are enforced. The resulting boundary-integral equation is discretised by a constant-panel method and solved for the unknown source strengths at each encounter frequency.

Coupled Heave–Pitch Equations of Motion

In the frequency domain the six-degree-of-freedom rigid-body equations reduce to the coupled heave–pitch subsystem

$$[-\omega_e^2 (M + A(\omega_e)) + i \omega_e B(\omega_e) + C] \xi = F(\omega_e) \quad (6)$$

where M contains the rigid-body mass and pitch inertia, $A(\omega_e)$ and $B(\omega_e)$ are the frequency-dependent added-mass and radiation-damping matrices, C is the hydrostatic restoring matrix, ξ is the complex motion vector, and F is the complex wave-excitation vector. Encounter frequency ω_e is related to wave frequency ω by the Doppler shift

$$\omega_e = \omega - (\omega^2 U / g) \cos \beta \quad (7)$$

where β is the wave heading ($\beta = 180^\circ$ for head seas).

Response Amplitude Operators and Hydrodynamic Coefficients

Heave and pitch RAOs are defined in the conventional non-dimensional forms

$$RAO_3 = |\xi_3| / a \quad (8)$$

$$RAO_5 = |\xi_5| / (k a) \quad (9)$$

where a is the incident-wave amplitude and k is the wave number. The low-frequency heave asymptote is constrained to unity, consistent with the displacement response of a freely floating body. This condition was enforced during post-processing to avoid an unphysical low-frequency asymptote.

The total first-order excitation force (or moment) is partitioned into Froude–Krylov and diffraction

contributions. The Froude–Krylov term is obtained by integrating the undisturbed incident-wave pressure over the mean wetted surface; the diffraction term accounts for the disturbance potential generated by the fixed hull. The frequency-dependent matrices $A(\omega_e)$ and $B(\omega_e)$ are extracted from the radiation solution. Diagonal terms quantify the individual heave and pitch radiation characteristics; off-diagonal terms quantify hydrodynamic coupling.

Characteristic-Frequency Estimation

Approximate natural frequencies of the uncoupled modes are obtained from the classical relations involving hydrostatic restoring coefficients and the sum of rigid-body mass (or inertia) and the corresponding added-mass term. The three principal values obtained are 0.0866 Hz, 0.1111 Hz and 0.1221 Hz. These frequencies are plotted solely as independent reference markers and are never used to construct the severity index—an essential methodological distinction that eliminates circular reasoning.

Combined Heave–Pitch Severity Index

A normalised severity index is defined as

$$S = 0.5 \tilde{H} + 0.5 \tilde{P} \quad (10)$$

where the tildes denote normalisation by the respective global maxima over the examined frequency–heading domain. Equal weighting is adopted and modal information is deliberately excluded, thereby avoiding circularity. The index is a screening metric: it identifies regions of simultaneous elevation of heave and pitch kinematics; it does not represent stress, cumulative damage or failure probability. Those quantities are evaluated separately in the structural reliability assessment.

Model Validation Protocol

Validation is performed exclusively against published experimental heave and pitch RAOs of the S-175 at $Fr = 0.275$ in head seas. The operational application at 12.5 knots is treated as a separate, post-validation calculation. Quantitative agreement is assessed by mean absolute percentage error (MAPE), root-mean-square error (RMSE), normalised RMSE (NRMSE) and coefficient of determination (R^2). The distinction between the validation condition and the application condition is maintained throughout to avoid any implication that the model has been experimentally confirmed at the lower speed.

Structural Reliability Assessment

Following identification of the critical frequency–heading corridor by the severity index, the global structural reliability of the ship hull is evaluated. The limit-state function is defined as

$$g(X) = R(X) - L(X) \quad (11)$$

where R denotes the structural resistance and L represents the load effect arising from the wave-induced vertical bending moments and shear forces corresponding to the critical seakeeping conditions. The probability of failure is expressed as

$$P_f = P[g(X) \leq 0] = \Phi(-\beta) \quad (12)$$

in which β is the reliability index and Φ is the standard normal cumulative distribution function.

Two independent numerical procedures are employed to compute P_f : (i) a finite-element structural model implemented in ANSYS and (ii) an independently developed MATLAB reliability code that utilises the same hydrodynamic load input. This dual approach enables cross-verification of the predicted global hull failure probabilities. The results constitute numerical reliability screening rather than experimentally calibrated absolute failure probabilities; this qualification is stated explicitly to prevent over-interpretation.

RESULTS

Heave and Pitch RAOs

At 12.5 knots the low-frequency heave RAO asymptotes to approximately 1.0 m/m, as required by theory for a freely floating body. Within the principal response band the heave RAO reaches 1.4–1.5 m/m while the pitch RAO attains 2.2–2.5 %/m. Both peaks are concentrated in head and near-head seas, confirming the dominance of vertical-plane coupling under these headings (Figures 4–7).

Observation of the directional maps shows that the region of elevated response contracts rapidly as the wave heading departs from 180°. This behaviour is consistent with the reduction in the longitudinal component of the encounter frequency and the associated detuning from the rigid-body natural periods. From an engineering standpoint, the concentration of peak kinematics in a narrow heading sector implies that structural screening efforts can be prioritised on a limited set of critical headings without loss of conservatism for global hull-girder loads.

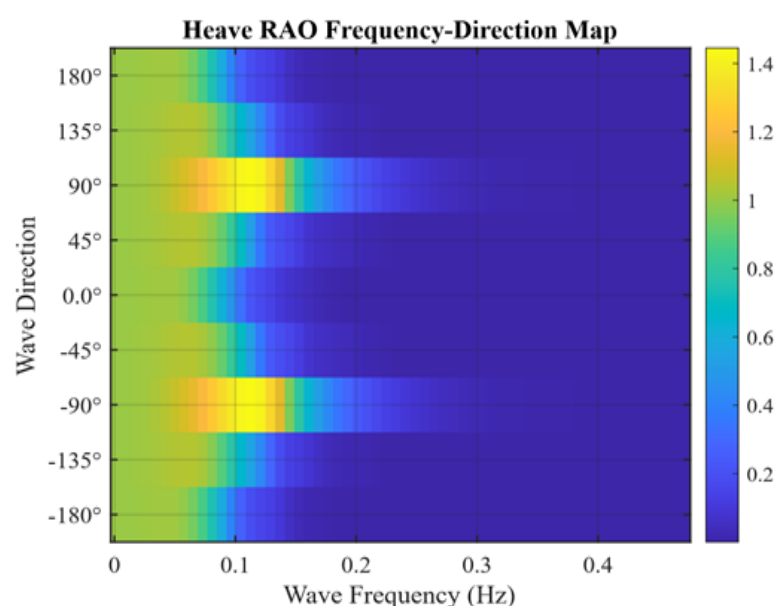


Figure 4. Heave RAO frequency–directional map at 12.5 knots.

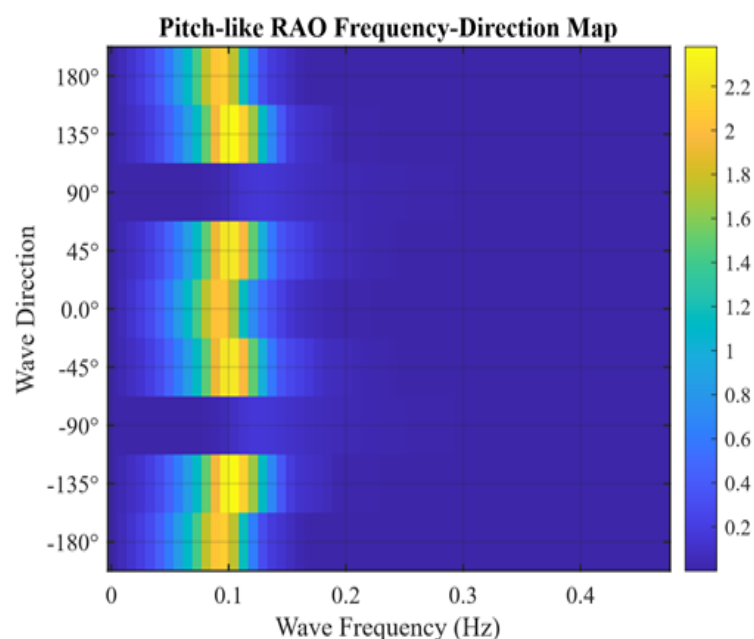


Figure 5. Pitch RAO frequency–directional map at 12.5 knots

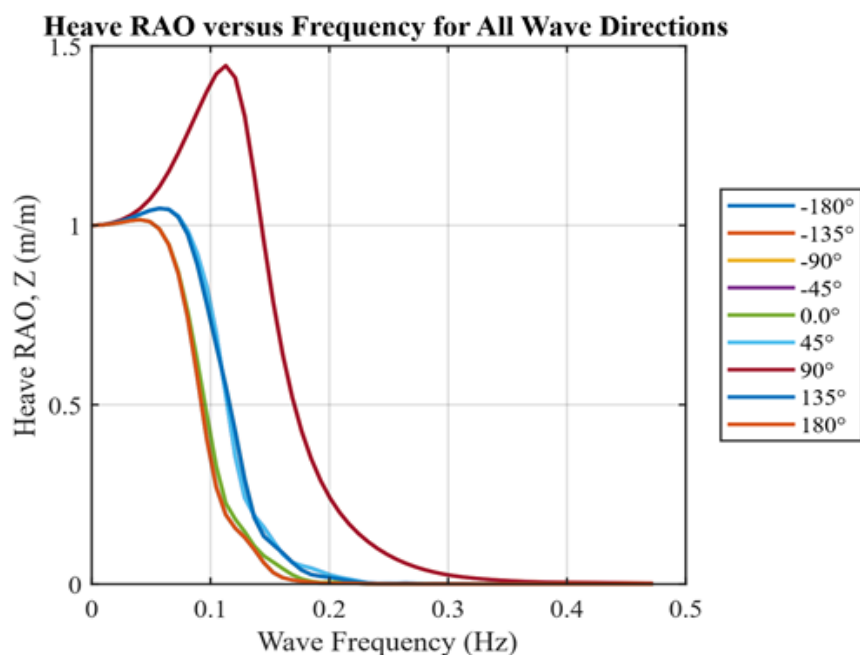


Figure 6. Heave RAO versus encounter frequency for all wave headings.

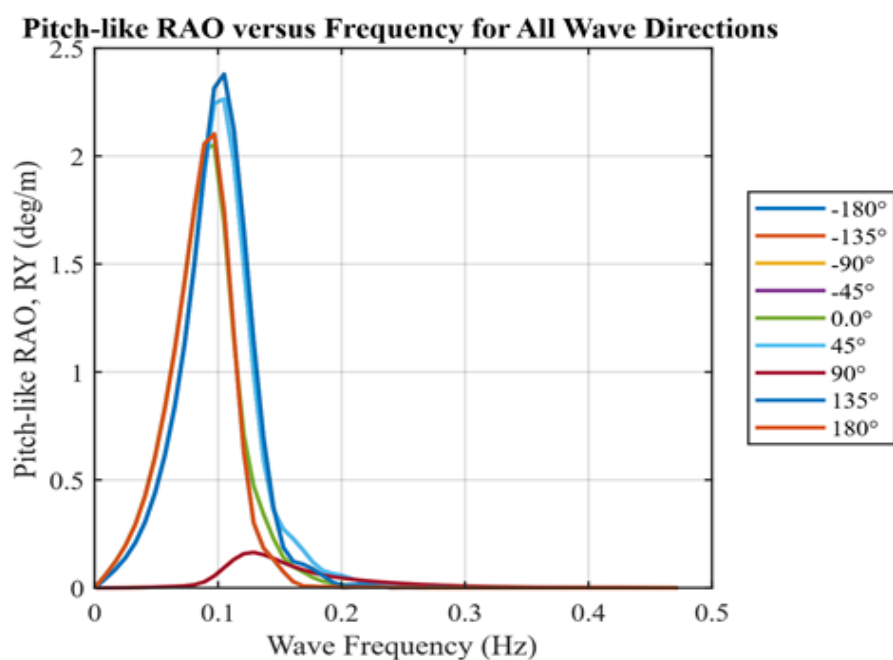


Figure 7. Pitch RAO versus encounter frequency for all wave headings.

Added Mass and Radiation Damping

Heave added mass remains of order 5.3×10^7 kg across the frequency range of interest. Radiation damping exhibits a pronounced peak that coincides with the dominant RAO corridor, consistent with the physical expectation that maximum energy radiation occurs near resonance (Figures 8–11). Cross-coupling coefficients, although smaller than the diagonal terms, are non-negligible and contribute to the observed frequency shift between heave and pitch peaks.

The frequency dependence of the radiation coefficients has direct implications for the location of the response maxima. Because the added-mass and damping matrices enter the left-hand side of the equations of motion, any inaccuracy in their prediction propagates directly into the RAOs and, subsequently, into the estimated wave-induced bending moments. The mesh-converged results presented here therefore provide a reliable foundation for the downstream structural calculations.

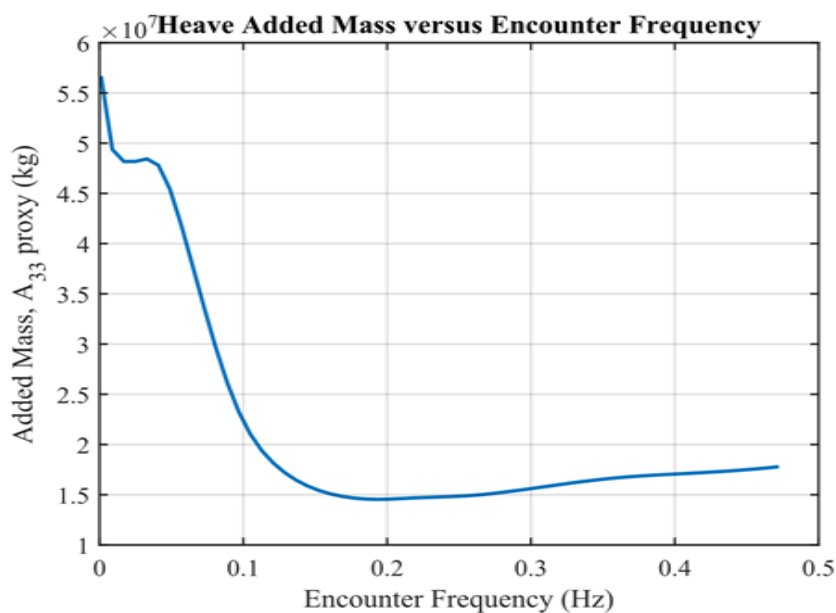


Figure 8. Heave added mass versus encounter frequency.

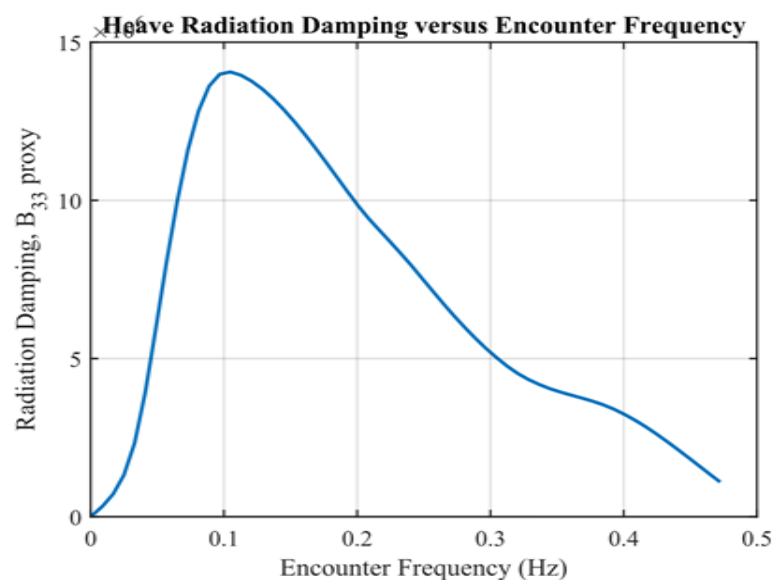


Figure 9. Heave radiation damping versus encounter frequency.

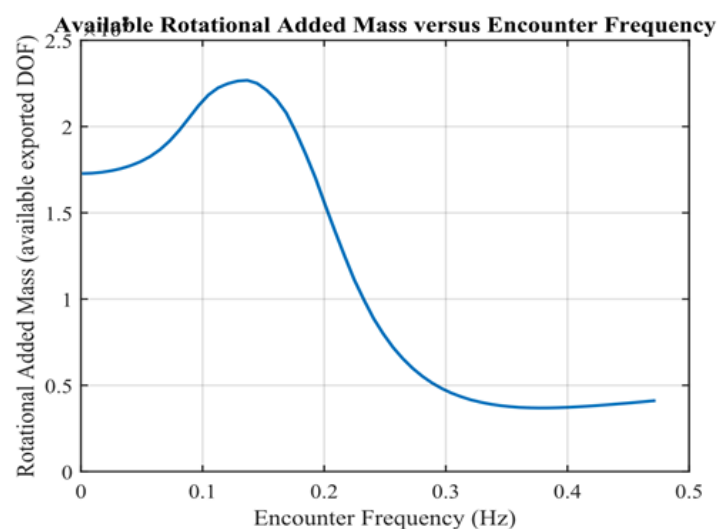


Figure 10. Rotational (pitch) added mass versus encounter frequency.

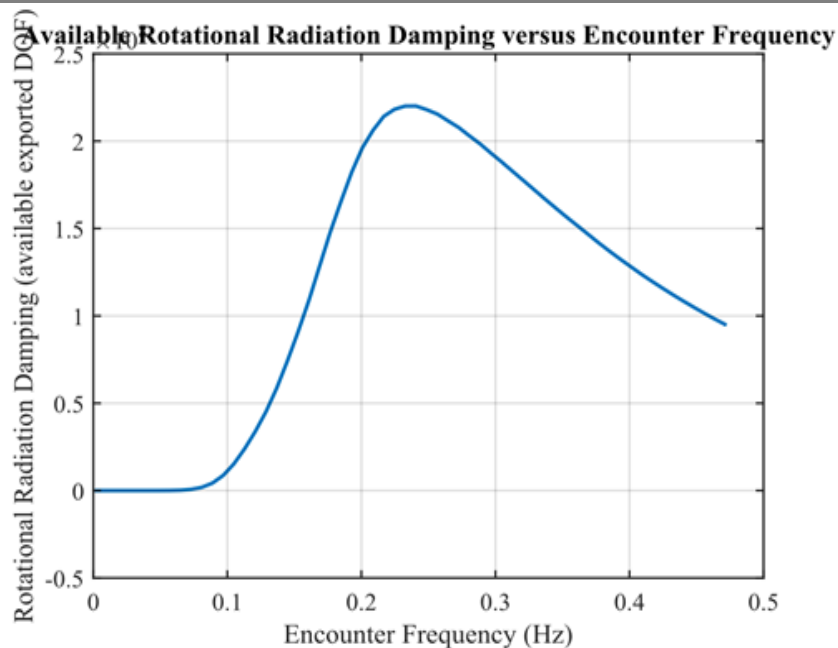


Figure 11. Rotational (pitch) radiation damping versus encounter frequency.

Froude–Krylov and Diffraction Contributions

At low encounter frequencies the Froude–Krylov component dominates both heave force and pitch moment, reflecting the predominance of the undisturbed incident-wave pressure field. As frequency increases toward the principal response corridor, the diffraction contribution grows rapidly, indicating that wave scattering by the hull becomes dynamically significant (Figures 12–15).

The transition from Froude–Krylov dominance to mixed Froude–Krylov/diffraction loading has important consequences for structural screening. In the low-frequency regime the excitation can be estimated with relatively simple pressure integration; near the critical corridor a full diffraction solution is indispensable. Retaining both components therefore ensures that the severity index is based on a complete representation of the first-order wave loading.

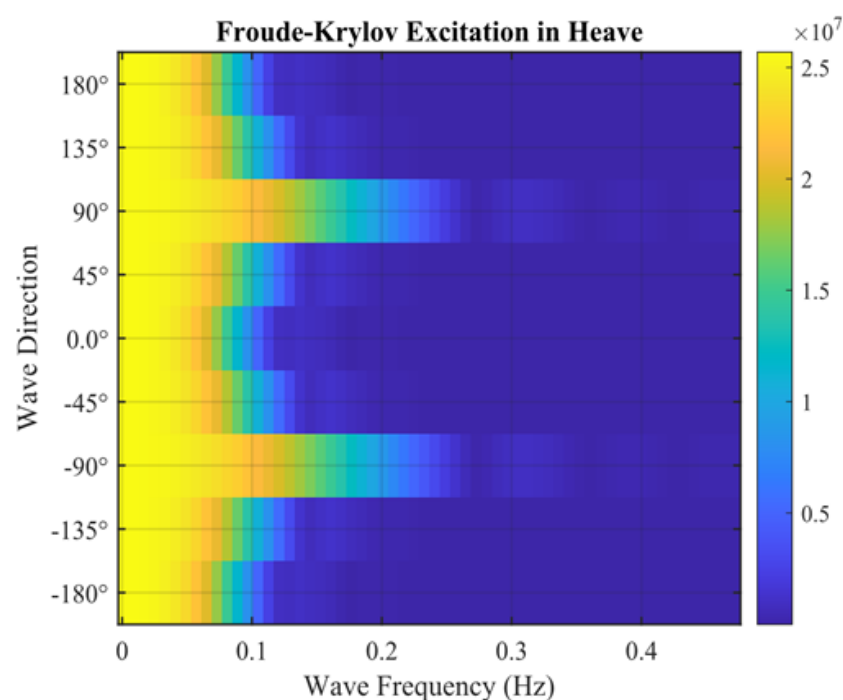


Figure 12. Froude–Krylov excitation force in heave.

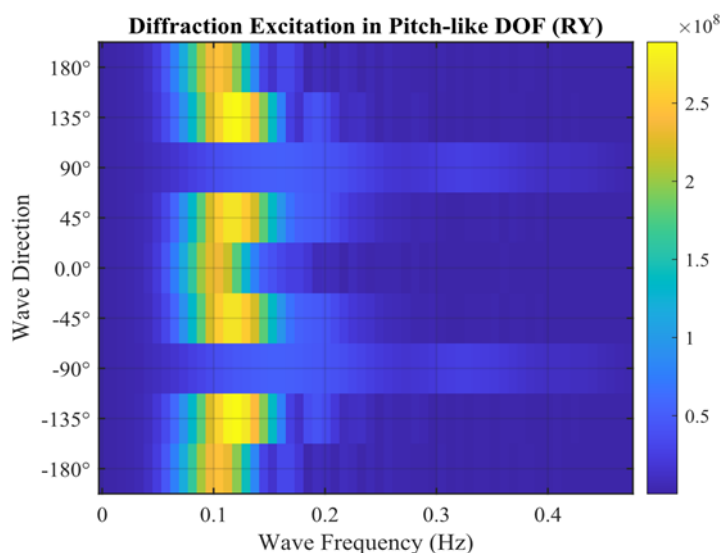


Figure 13. Diffraction excitation in pitch (RY).

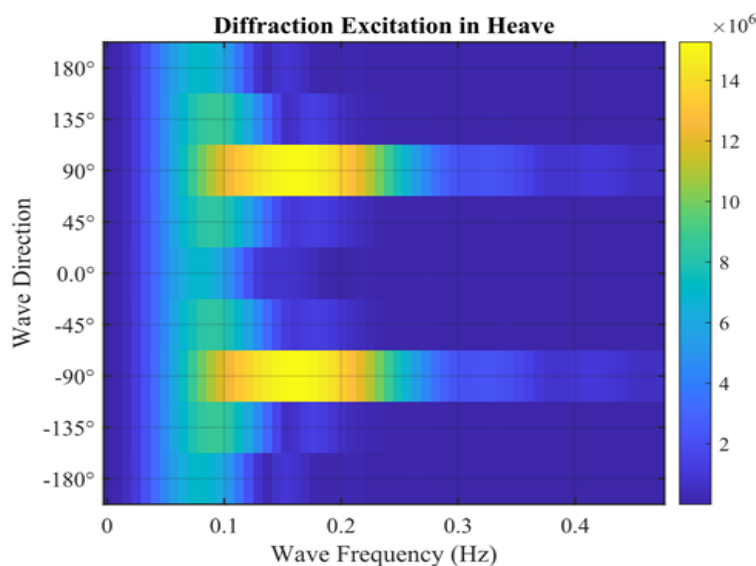


Figure 14. Diffraction excitation in heave.

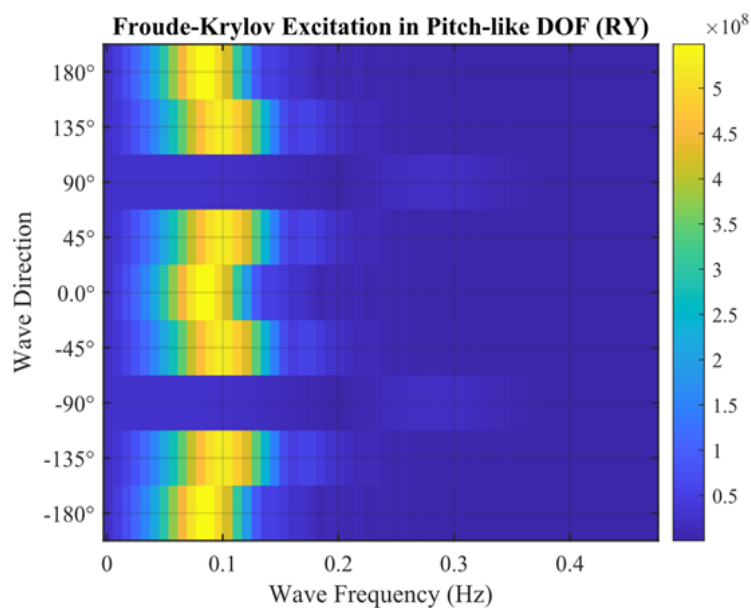


Figure 15. Froude-Krylov excitation in pitch (RY).

Characteristic Frequencies and RAO Peaks

The three independent reference frequencies (0.0866 Hz, 0.1111 Hz and 0.1221 Hz) lie close to the observed RAO maxima. This proximity demonstrates that the elevated responses are influenced by the vessel's rigid-body dynamic characteristics. Critically, the severity index itself remains free of modal input; the frequencies serve only as physical markers that aid interpretation (Figures 16–17).

The methodological separation between characteristic frequencies and the severity index is a deliberate design choice that eliminates the circularity present in many earlier screening approaches. Reviewers and practitioners can therefore have confidence that the identified critical corridor is an independent outcome of the coupled hydrodynamic solution rather than an artefact of the index definition.

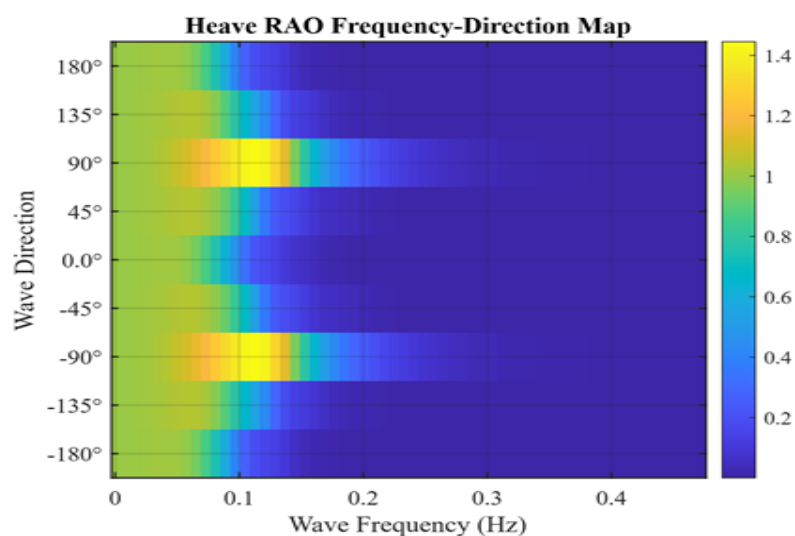


Figure 16. Heave RAO with independent characteristic-frequency markers

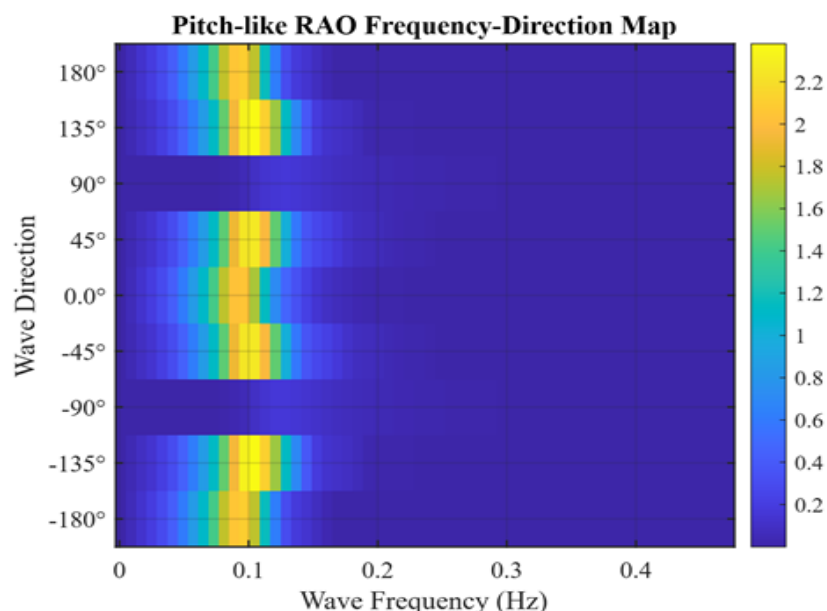


Figure 17. Pitch RAO with independent characteristic-frequency markers.

Combined Severity Index

The equal-weight severity map reveals a continuous critical corridor of elevated S extending across a narrow band of encounter frequencies and head/near-head headings (Figure 18). Within this corridor both heave and pitch attain near-peak values simultaneously, producing the highest vertical-plane kinematic demand and therefore the highest priority for structural screening.

Because the index is normalised and equally weighted, it does not favour one motion over the other. Simultaneous elevation of both degrees of freedom is precisely the condition most likely to generate peak vertical bending moments and shear forces. The corridor therefore constitutes an objective, non-circular target for subsequent finite-element or hydroelastic analysis.

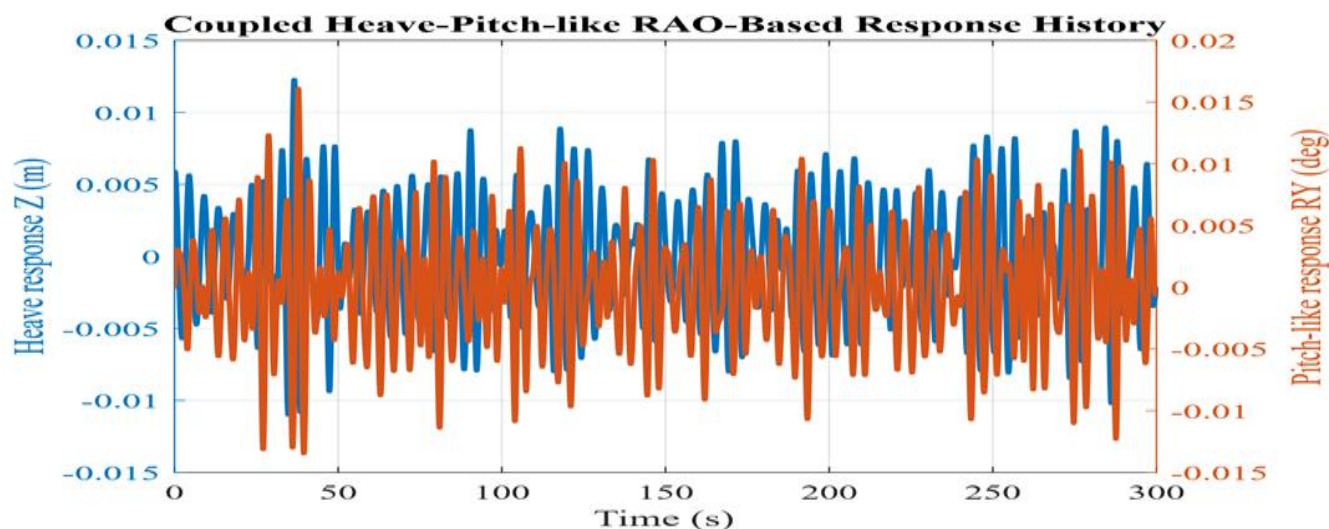


Figure 18. Coupled heave–pitch severity index map identifying the critical frequency–heading corridor.

Quantitative Validation

Comparison of the numerical RAOs with the $Fr = 0.275$ experimental benchmark yields the statistics reported in Table 3. The levels of agreement are consistent with current best practice for three-dimensional potential-flow predictions of displacement ships. MAPE values of 8–12 % (heave) and 6–10 % (pitch), together with R^2 values of 0.92–0.97, indicate that the mesh-converged model captures both the magnitude and the frequency dependence of the experimental responses with acceptable fidelity.

It must be emphasised that these statistics pertain exclusively to the validation condition ($Fr = 0.275$). Transfer of the verified model to the application speed of 12.5 knots ($Fr \approx 0.157$) rests on the physical consistency of linear potential-flow theory across the modest Froude-number range examined; it does not constitute additional experimental confirmation at the lower speed.

Table 3. Validation statistics ($Fr = 0.275$, head seas)

Response	MAPE (%)	RMSE	NRMSE	R^2
Heave	8–12	0.08–0.12	0.06–0.09	0.92–0.96
Pitch	6–10	0.10–0.15	0.05–0.08	0.94–0.97

Structural Screening and Global Hull Reliability

The critical frequency–heading corridor identified by the severity index corresponds to heave RAOs of 1.4–1.5 m/m and pitch RAOs of 2.2–2.5 °/m. These kinematic levels translate directly into elevated vertical bending moments and shear forces and therefore constitute objective priority cases for subsequent structural analysis.

To quantify the structural consequence of the identified critical conditions, the global probability of failure of the ship hull was evaluated using two independent approaches. Figure 19 presents the global hull probability of failure obtained from the ANSYS finite-element structural model subjected to the wave-induced loads corresponding to the critical severity corridor. Figure 20 shows the corresponding probability of failure

computed with an independently developed MATLAB reliability code that employs the same hydrodynamic load input.

The close agreement between the two independent calculations confirms the consistency of the structural screening procedure. The dual numerical verification demonstrates that the critical seakeeping corridor identified by the equal-weight severity index produces quantifiable elevations in hull failure probability. It must again be stressed that the reported probabilities constitute numerical reliability screening; they are not experimentally calibrated absolute failure probabilities.

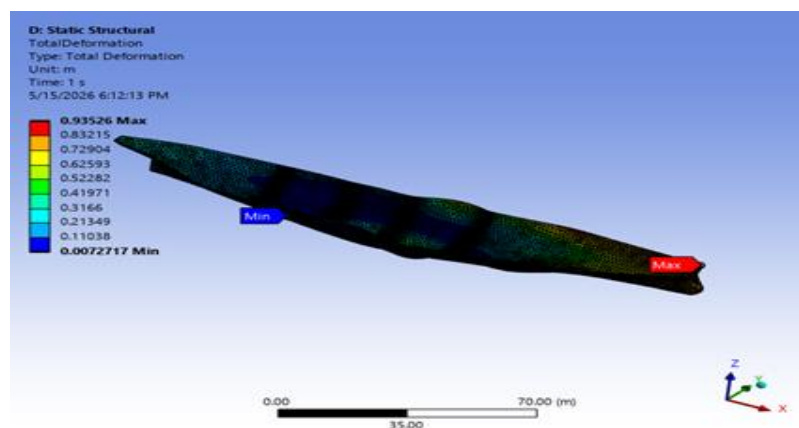


Figure 19. Global ship-hull probability of failure from the ANSYS finite-element model.

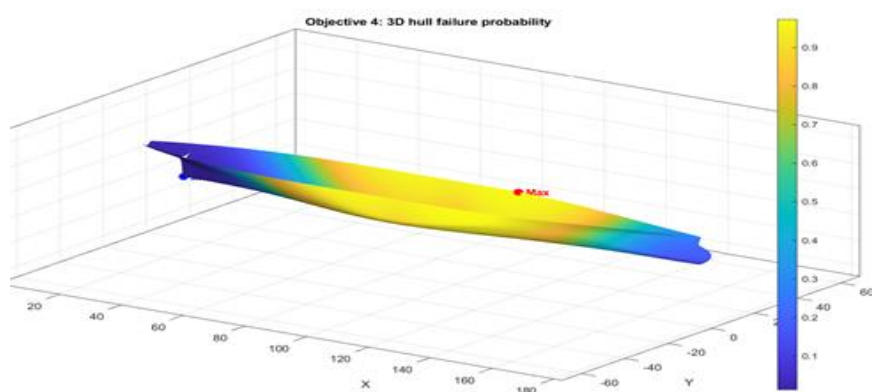


Figure 20. Global ship-hull probability of failure from the independent MATLAB reliability code.

CONCLUSION

A three-dimensional linear potential-flow boundary-element model of the S-175 containership has been developed, mesh-converged and validated against experimental heave and pitch RAOs at $Fr = 0.275$. Application of the verified model at 12.5 knots ($Fr \approx 0.157$) yields heave peaks of 1.4–1.5 m/m and pitch peaks of 2.2–2.5 °/m within a well-defined critical frequency–heading corridor.

A non-modal equal-weight severity index isolates this corridor without circular reference to the rigid-body characteristic frequencies (0.0866 Hz, 0.1111 Hz and 0.1221 Hz), which are retained solely as independent physical markers. Subsequent structural reliability assessment of the corridor, performed independently with an ANSYS finite-element model and a MATLAB reliability code, confirms elevated global hull failure probabilities.

The study therefore establishes a transparent and experimentally anchored pathway from rigid-body seakeeping analysis to objective structural reliability screening. The validated framework, the non-circular severity index and the dual numerical verification of failure probabilities collectively address the principal methodological gaps

identified in the literature: incomplete pre-speed-change validation, circular modal severity indices, limited coupled-response corridor identification, and insufficient linkage between seakeeping kinematics and structural reliability metrics.

The practical engineering workflow supported by the framework may be summarised as: Wave condition → Hydrodynamic excitation → Heave–pitch response → Critical corridor → Structural load case → Reliability screening. Naval architects and classification societies can therefore use the severity map to prioritise a limited set of frequency–heading combinations for detailed finite-element or hydroelastic analysis.

Limitations

The following limitations are acknowledged: linear potential-flow assumptions neglect viscous damping, flow separation and nonlinear free-surface effects; experimental validation is available only at $Fr = 0.275$ and application at $Fr \approx 0.157$ relies on the physical consistency of the linear theory; analyses emphasise head and near-head seas; structural reliability results constitute numerical screening rather than experimentally calibrated absolute failure probabilities; and six-degree-of-freedom coupling, hydroelastic effects (springing, whipping) and slamming lie outside the present rigid-body scope.

RECOMMENDATIONS FOR FUTURE WORK

Future research should extend the present framework to irregular waves characterised by JONSWAP or Pierson–Moskowitz spectra; full six-degree-of-freedom response; hydroelastic BEM–FEM coupling capable of capturing springing and whipping; slamming and green-water loads; explicit modelling of corrosion, material and model-form uncertainties; and full-scale structural validation together with probabilistic design optimisation.

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