

(RESEARCH ARTICLE)



TIME-FREQUENCY CHARACTERIZATION AND SEVERITY SCREENING OF COUPLED HEAVE-PITCH MOTIONS OF AN S-175 CONTAINER SHIP

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ABSTRACT

This study characterizes coupled rigid-body heave and pitch motions of the S-175 U-Waters containership under irregular head-sea conditions and develops a non-modal severity measure for structural screening. A three-dimensional linear potential-flow model in ANSYS AQWA was used to simulate a long-crested JONSWAP sea state with $H_s=1.2$ m, peak frequency $f_p=0.23$ Hz, head waves, and a vessel speed of 12.5 knots over a 300 s record. Response statistics, moving RMS, continuous wavelet analysis, cross-correlation, and a normalized coupled-response severity index were applied. Heave varied from -0.01102 to 0.01230 m with an RMS of 0.00826 m, while pitch varied from -0.01349° to 0.01612° with an RMS of 0.01055° . Dominant response bands were approximately $0.08\text{--}0.11$ Hz for heave and $0.10\text{--}0.13$ Hz for pitch. The maximum heave-pitch cross-correlation was approximately 0.82 at a lag close to zero, indicating strong temporal coupling. The normalized severity index reached 1.00 , with a mean of approximately 0.63 ; severity exceeded 0.50 for approximately 60% of the record and 0.75 for approximately 25% . The identified response bands encompass the rigid-body characteristic frequencies of 0.0866 , 0.1111 , and 0.1221 Hz, which are used only as independent reference markers. The results provide a practical basis for identifying elevated rigid-body response conditions for subsequent structural screening.

Keywords: S-175 Containership; Heave-Pitch Coupling; Rigid-Body Seakeeping; Irregular Waves; Time-Frequency Analysis; Response Severity; Cross-Correlation; Structural Screening.

1 INTRODUCTION

Ships operating in waves experience continuous wave excitation that produces rigid-body motions and fluctuating hydrodynamic loads. Heave and pitch are particularly important in head and near-head seas because they dominate the vertical-plane response of conventional displacement vessels and influence vertical acceleration, relative motion, slamming potential, and hull-girder loading (Haddara, 1998; Ghadimi et al., 2016; Song et al., 2022; Vijith et al., 2023).

The S-175 U-Waters containership is a well-established benchmark hull with documented experimental and numerical seakeeping data, making it suitable for numerical investigation of ship motions (ITTC, 1996; Grande et al., 1991; Ye et al., 2012; Taghva et al., 2018). Conventional seakeeping assessments commonly rely on response amplitude operators (RAOs), response spectra, and global statistical measures. Although these methods effectively describe overall response behaviour, they may not adequately identify short periods during which heave and pitch are simultaneously elevated. Time–frequency analysis provides information on the distribution of response energy with time and frequency, while cross-correlation quantifies the temporal relationship between motion components (Hanaki & Minoura, 2022; Schirrmann et al., 2022; Schirrmann et al., 2023). In the present study, these techniques are combined with moving RMS and a simple non-modal response-severity index to identify elevated coupled-response conditions. The severity index is calculated directly from normalized heave and pitch, amplitudes and does not incorporate natural frequencies, eigenvectors, or modal weighting. The rigid-body characteristic frequencies are instead used only as independent reference markers. The analysis is limited to rigid-body seakeeping and does not directly evaluate flexible-hull deformation, springing, whipping, or fluid–structure interaction. The objective is therefore to characterise coupled heave–pitch motions of the S-175 containership in irregular head seas and identify elevated response conditions suitable for subsequent structural screening.

Aim of the Study

The aim of this study is to characterize the coupled rigid-body heave–pitch response of the S-175 U-Waters containership in irregular head seas and identify elevated response conditions for structural screening.

Objectives

The objectives are to:

- Determine the heave and pitch responses under the specified irregular head-sea condition;
- Identify the dominant response-frequency range;
- Quantify the temporal coupling between heave and pitch; and
- Develop a simple severity measure for identifying elevated coupled responses.

1.1 Significance of the Study

The study provides a practical screening approach for identifying critical periods in ship-motion records before detailed structural analysis. By combining response magnitude, temporal variation, frequency characteristics, and heave–pitch coupling, the approach can help select representative loading conditions for subsequent hull-girder or structural assessment. The severity index is intended only as a relative rigid-body response indicator and does not represent structural stress, damage probability, or failure probability.

2 MATERIALS AND METHODS

2.1 S-175 U-Waters Container Ship

The S-175 U-Waters containership was selected because of its established use in experimental and numerical seakeeping studies. The principal particulars used in the ANSYS AQWA model are given in Table 1.

Table 1: Principal Particulars of the S-175 U-Waters Containership

Particular	Value
Deadweight	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
Operating speed	12.5 knots
Operating speed, (V)	6.43 m/s

The three-dimensional hull model used for the hydrodynamic analysis is shown in Figure 1, while the body plan and plan view are presented in Figures 2 and 3, respectively.

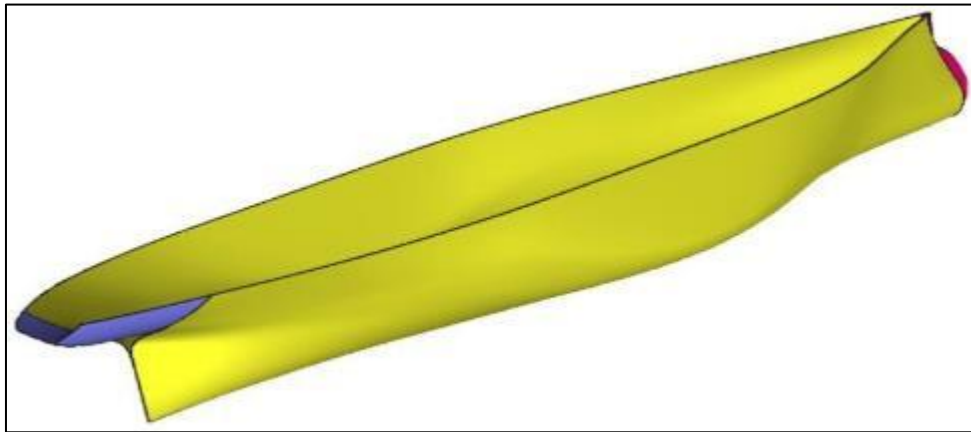


Figure 1: S-175 U- Waters Container Ship

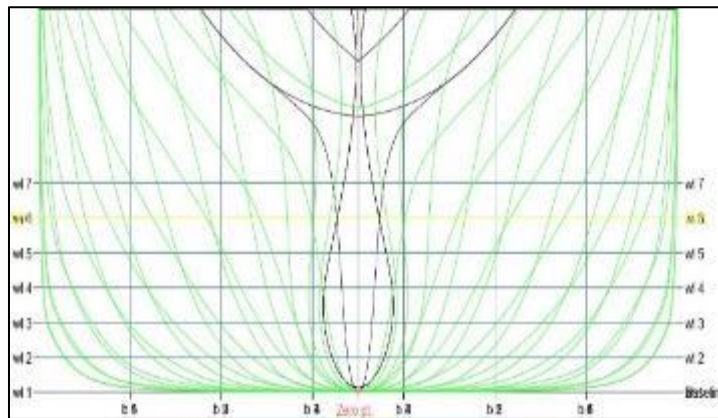


Figure 2: Body Plan of S-175 U- Waters Container Ship

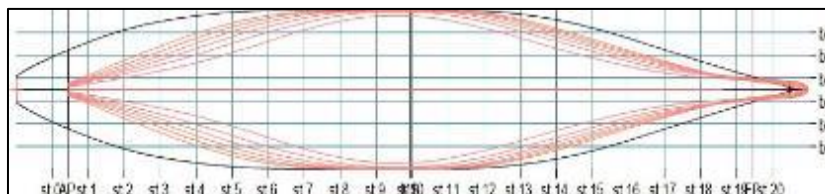


Figure 3: Plan View of S-175 U- Waters Container

The Froude number is calculated from

$$Fr = \frac{V}{\sqrt{gL_{WL}}} \quad (1)$$

where ($g = 9.81\text{m/s}^2$). Using ($V = 6.43\text{m/s}$) and ($L_{WL} = 170.566$) m gives

$$Fr \approx 0.157 \quad (2)$$

The vessel was considered in head seas with a wave heading of

$$\beta = 180^\circ \quad (3)$$

Under this condition, heave and pitch constitute the principal vertical-plane rigid-body motions considered.

2.2 Operating and Wave Conditions

The vessel operated at 12.5 knots in a long-crested irregular sea represented by a JONSWAP spectrum. The significant wave height was 1.2 m and the peak frequency was 0.23 Hz. The corresponding peak period was

$$T_p = \frac{1}{f_p} \approx 4.35\text{s}. \quad (4)$$

The main simulation parameters are summarized in Table 2.

Table 2: Numerical Simulation Parameters

Parameter	Symbol	Value
Wave spectrum	—	JONSWAP
Wave type	—	Long-crested irregular
Significant wave height	(H_s)	1.2m
Peak frequency	(f_p)	0.23 Hz
Peak period	(T_p)	4.35 s
Wave heading	(β)	(180°)
Vessel speed	(V)	12.5 knots
Froude number	(Fr)	0.157
Simulation duration	(T_d)	300 s
Sampling interval	(Δt)	0.1 s
Sampling frequency	(f_s)	10 Hz
Number of samples	(N)	3001
Number of realizations	(N_r)	1
JONSWAP (α)	—	0.5
JONSWAP (γ)	—	2.0
Frequency range	—	0.001–0.47 Hz

The wave elevation is represented as

$$\eta(t) = \sum_{n=1}^{N_f} a_n \cos(\omega_n t + \varepsilon_n), \quad (5)$$

where a_n is the component amplitude, ω_n is the angular frequency, and ε_n is the random phase. The component amplitude was obtained from

$$a_n = \sqrt{2S_\eta(\omega_n)\Delta\omega} \quad (6)$$

2.3 Record-Duration Assessment

The 300 s simulation corresponds to approximately 69 peak-wave periods. Because only one irregular-wave realization was used, the record provides limited statistical representation of the underlying sea state. A longer simulation, preferably at least 1800 s, would improve statistical convergence.

For the available record, segment statistics can be used to assess stability. The segment mean is

$$\mu_j = \frac{1}{N_j} \sum_{i=1}^{N_j} x_i \quad (7)$$

and the standard deviation is

$$\sigma_j = \sqrt{\frac{1}{N_j-1} \sum_{i=1}^{N_j} (x_i - \mu_j)^2} \quad (8)$$

A change of approximately 5% or less between successive estimates may be considered an indication of practical stability.

2.4 Rigid-Body Response Analysis

2.4.1 Heave and Pitch

The vertical-plane rigid-body responses were represented by heave $z(t)$ and pitch $\theta(t)$. The mean and standard deviation were calculated from

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i \quad (9)$$

and

$$\sigma_x = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2} \quad (10)$$

The RMS response was calculated as

$$x_{\text{RMS}} = \sqrt{\frac{1}{N} \sum_{i=1}^N x_i^2}. \quad (11)$$

2.4.2 Moving RMS

Moving RMS was used to identify periods of relatively elevated response:

$$RMS_z(t_j) = \sqrt{\frac{1}{M} \sum_{i=j}^{j+M-1} z_i^2}, \quad (12)$$

with an equivalent expression for pitch. Window durations of 30, 60, and 120 s were considered with 50% overlap as shown in table 3

$$RMS_\theta(t_j) = \sqrt{\frac{1}{M} \sum_{i=j}^{j+M-1} \theta_i^2}. \quad (13)$$

Table 3: Moving-RMS Parameters

Parameter	Value
Window 1	30 s
Window 2	60 s
Window 3	120 s
Sampling interval	0.1 s
Overlap	50%

The final window is selected based on the balance between temporal resolutions and smoothing.

2.5 Response-Severity Formulation

Heave and pitch were normalized using their maximum absolute responses:

$$\tilde{z}(t) = \frac{|z(t)|}{z_{max}}, \quad (14)$$

and

$$\tilde{\theta}(t) = \frac{|\theta(t)|}{\theta_{max}}. \quad (15)$$

A combined response-severity index was then defined as

$$S(t) = \sqrt{\frac{\tilde{z}^2(t) + \tilde{\theta}^2(t)}{2}}. \quad (16)$$

Thus,

$$0 \leq S(t) \leq 1 \quad (17)$$

The index is independent of natural frequencies, eigenvectors, modal participation factors, and modal weighting coefficients. It therefore represents the instantaneous relative magnitude of the combined rigid-body response.

2.6 Time-Frequency and Coupling Analysis

2.6.1 Continuous Wavelet Transform

The continuous wavelet transform was defined as

$$W_x(a, b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t) \psi^* \left(\frac{t-b}{a} \right) dt \quad (18)$$

where a is the scale parameter, b is the time-location parameter, and ψ is the mother wavelet. The wavelet power is

$$P_x(a, b) = |W_x(a, b)|^2 \quad (19)$$

A Morlet wavelet was selected for oscillatory ship-motion signals.

Table 4: Time-Frequency Analysis Parameters

Parameter	Symbol	Value
Mother wavelet	(ψ)	Morlet
Sampling interval	(Δt)	0.1 s
Frequency range	(f)	0.001–0.47 Hz
Number of scales	(N_s)	128
Frequency resolution	(Δf)	0.0037 Hz
Cone of influence	COI	Applied
Significance level	—	95%
Band width	(Δf_b)	0.05 Hz

The nominal frequency increment was

$$\Delta f = \frac{f_{max} - f_{min}}{N_s - 1} = \frac{0.47 - 0.001}{127} \approx 0.0037 \text{ Hz} \quad (20)$$

2.6.2 Frequency-Band Energy

The response-energy fraction within a frequency band was defined as

$$E_b = \frac{\int_{f_1}^{f_2} P(f) df}{\int_{f_{min}}^{f_{max}} P(f) df}. \quad (21)$$

The frequency corresponding to maximum response energy was obtained from

$$f_c = \arg \max_f P(f). \quad (22)$$

2.6.3 Rigid-Body Characteristic Frequencies

The AQWA eigenvalue analysis identified the following characteristic frequencies:

$$f_{n1} = 0.0866\text{Hz}, \quad (23)$$

$$f_{n2} = 0.1111\text{Hz}, \quad (24)$$

$$f_{n3} = 0.1221\text{Hz}. \quad (25)$$

These values were used only as independent reference markers and were not included in the severity-index formulation.

2.6.4 Heave-Pitch Cross-Correlation

The normalized cross-correlation was calculated as

$$\rho_{z\theta}(\tau) = \frac{\sum_t [z(t) - \bar{z}][\theta(t+\tau) - \bar{\theta}]}{\sqrt{\sum_t [z(t) - \bar{z}]^2 \sum_t [\theta(t+\tau) - \bar{\theta}]^2}}. \quad (26)$$

The maximum correlation was determined from

$$\rho_{max} = \max_{\tau} |\rho_{z\theta}(\tau)| \quad (27)$$

and the corresponding lag is

$$\tau^* = \arg \max_{\tau} |\rho_{z\theta}(\tau)| \quad (28)$$

2.7 Severity Classification

The severity distribution was divided into four relative categories using the 25th, 50th, and 75th percentile:

Low severity: $S < P_{25}$

Moderate severity: $P_{25} \leq S < P_{50}$

High severity: $P_{50} \leq S < P_{75}$

Severe severity: $S \geq P_{75}$

The percentage exceeding a selected threshold S_{th} was calculated as

$$P_s = \frac{N(S \geq S_{th})}{N} \times 100 \quad (29)$$

These thresholds are relative screening criteria and are not universal structural failure limits.

3 RESULTS AND DISCUSSION

3.1 Heave and Pitch Response

The simulated vessel exhibited continuous heave and pitch variation throughout the 300 s irregular-wave record. The principal response statistics are presented in Table 5.

Table 5. Heave and pitch response statistics

Parameter	Heave	Pitch
Minimum	−0.01102 m	−0.01349°
Maximum	0.01230 m	0.01612°
Mean	0.00064 m	0.00132°
Standard deviation	0.00824 m	0.01047°
RMS	0.00826 m	0.01055°
Peak-to-peak	0.02332 m	0.02961°

As shown in Table 5, heave varied from −0.01102 to 0.01230 m, giving a peak-to-peak displacement of 0.02332 m. Pitch varied from −0.01349° to 0.01612°, giving a peak-to-peak excursion of 0.02961°. The small mean values indicate that both responses remained generally centred around the equilibrium position.

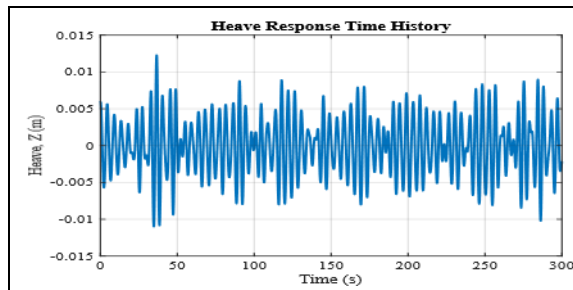


Figure 4: Heave Response Time History

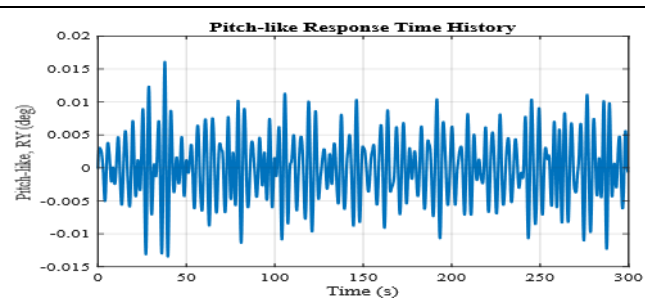


Figure 5: Pitch-like Response Time History

The time histories in Figures 4 and 5 illustrate the continuous variation of the two rigid-body responses throughout the irregular-wave record. The moving-RMS results provide additional information on the portions of the record where the response magnitude was relatively high.

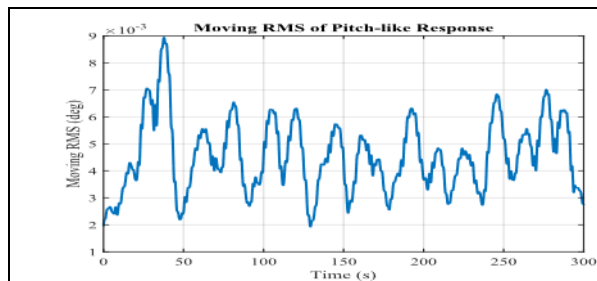


Figure 6: Moving RMS of Heave Response

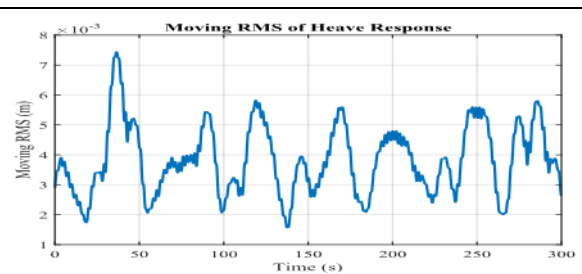


Figure 7: Moving RMS of Pitch-like Response

The maximum moving-RMS values are presented in Table 6.

Table 6: Maximum Moving-RMS Responses

Response	Maximum moving RMS	Approximate time
Heave	0.01167 m	142 s
Pitch	0.01486°	147 s

As indicated in Table 6, the maximum heave moving RMS of 0.01167 m occurred at approximately 142 s, while the maximum pitch moving RMS of 0.01486° occurred at approximately 147 s. The close timing of these maxima suggests that the strongest individual responses occurred during a similar portion of the record. This supports further examination of their coupled behaviour.

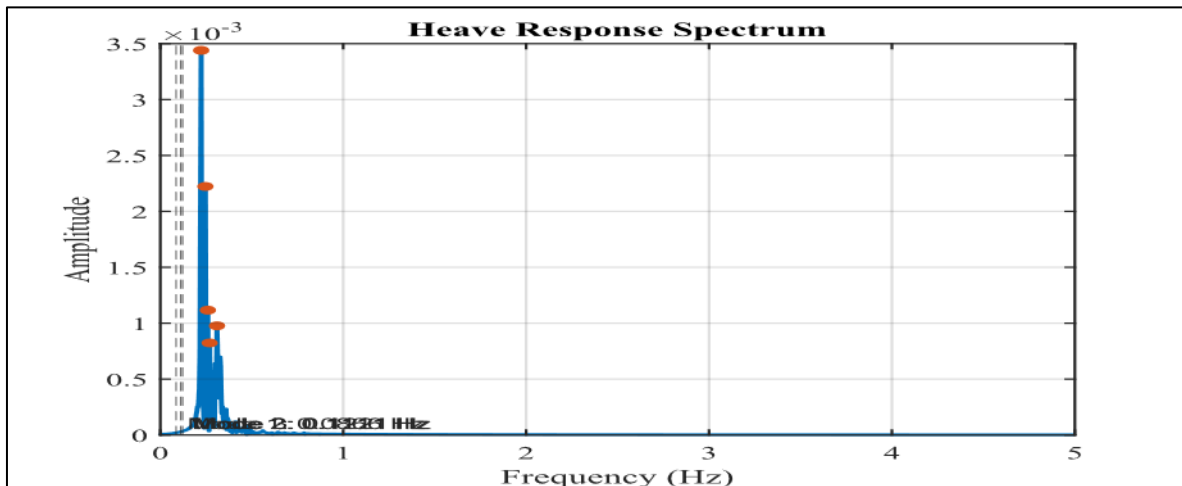
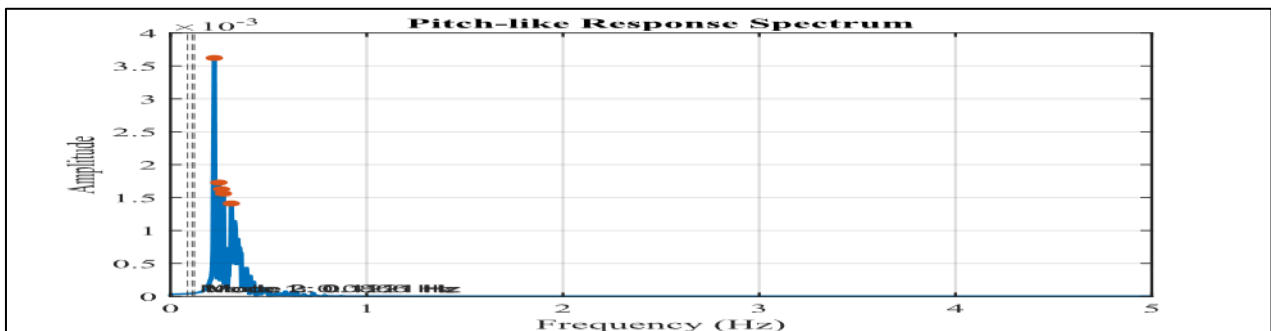
3.2 Frequency Characteristics

The dominant response-frequency ranges are summarized in Table 7.

Table 7: Dominant Frequency Characteristics

Response	Dominant Frequency Range	Estimated Energy Fraction	Period of Maximum Energy
Heave	0.08–0.11 Hz	≈ 70%	≈ 10.0 s
Pitch	0.10–0.13 Hz	≈ 75%	≈ 8.3 s

As shown in Table 7, heave was primarily concentrated between 0.08 and 0.11 Hz, whereas pitch was concentrated between approximately 0.10 and 0.13 Hz. Together, these ranges form a principal response corridor of approximately 0.08–0.13 Hz.

**Figure 8: Heave Response Spectrum****Figure 9: Pitch-like Response Spectrum**

The spectra in Figures 8 and 9 provide visual confirmation of the concentration of response within the low-frequency region. The corridor encompasses the independently identified rigid-body characteristic frequencies of 0.0866, 0.1111 and 0.1221 Hz. This correspondence indicates that the principal vertical-plane response occurs close to the characteristic rigid-body frequency range. The reported energy fractions of approximately 70% for heave and 75% for pitch should be regarded as estimated values based on the available response analysis. They should not be presented as exact wavelet-energy percentages unless recalculated directly from the exported AQWA time histories.

3.2.1 Heave-Pitch Temporal Coupling

The cross-correlation analysis produced a maximum normalized correlation of approximately 0.82 at a lag close to zero. The result is presented in Table 8.

Table 8: Heave-Pitch Temporal Coupling

Parameter	Value
Maximum cross-correlation coefficient	≈ 0.82
Corresponding lag	≈ 0 s
Interpretation	Strong positive temporal coupling

As shown in Table 8, the correlation coefficient of approximately 0.82 indicates a strong positive temporal relationship between heave and pitch. The near-zero lag indicates that elevated heave and pitch responses occurred approximately simultaneously.

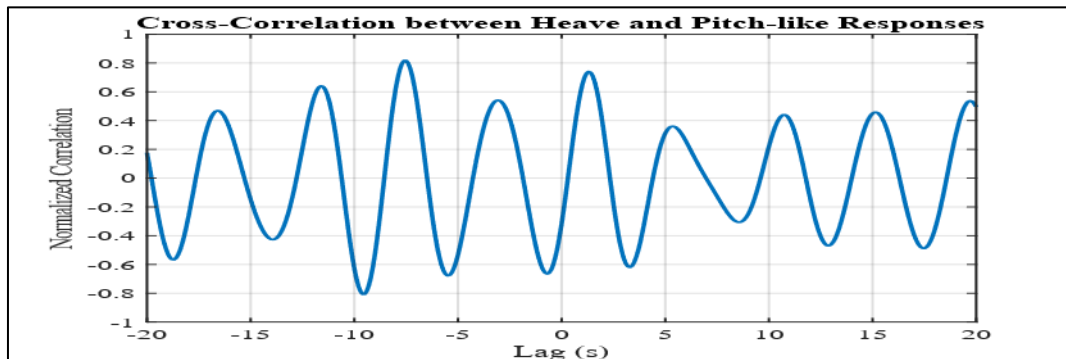


Figure 10: Cross- Correlation between Heave and Pitch-like Response

The cross-correlation presented in Figure 10 supports the use of a combined response measure because the two motion components exhibit a strong temporal relationship. The coupled behaviour can also be illustrated using a phase portrait.

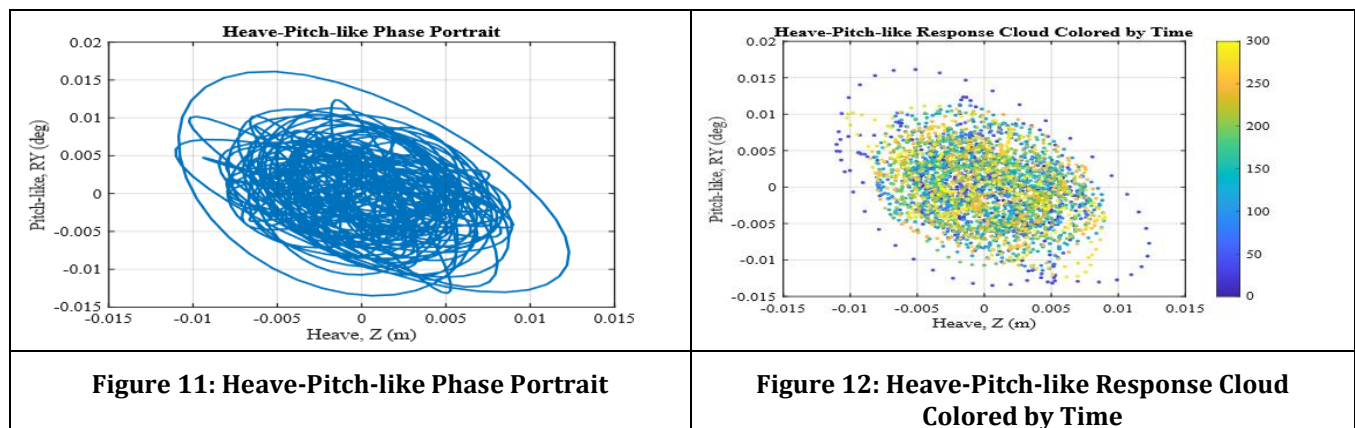


Figure 11: Heave-Pitch-like Phase Portrait

Figure 12: Heave-Pitch-like Response Cloud Colored by Time

The phase portrait in Figure 11 and time-coloured response cloud in Figure 12 provide complementary representations of the relationship between heave and pitch.

3.3 Combined Response Severity

The normalized severity index was applied to identify periods during which heave and pitch were simultaneously elevated. The principal results are summarized in Table 9.

Table 9. Severity-Index Statistics

Severity Measure	Value
Maximum severity	1.00
Mean severity	0.63
Duration for $S > 0.50$	≈ 180 s
Percentage for $S > 0.50$	$\approx 60\%$
Duration for $S > 0.75$	≈ 75 s
Percentage for $S > 0.75$	$\approx 25\%$

As presented in Table 9, the severity index reached a maximum value of 1.00 and had a provisional mean of approximately 0.63. Approximately 180 s, equivalent to 60% of the record, exceeded $S = 0.50$, while approximately 75 s, equivalent to 25%, exceeded $S = 0.75$.

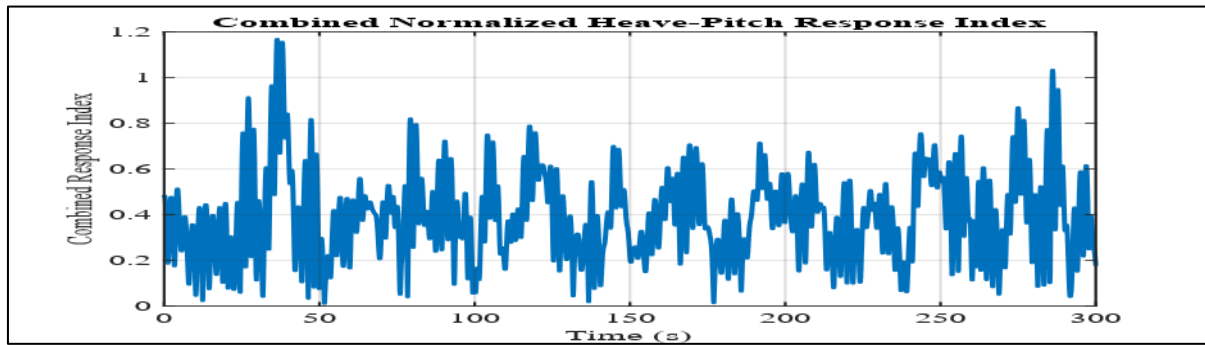


Figure 13: Combined Normalized Heave-Pitch response Index

The severity history in Figure 13 identifies periods in which the combined magnitude of heave and pitch was relatively high. Importantly, the severity index is not structural stress, damage probability, or failure probability. It is a dimensionless response-screening parameter that describes the relative magnitude of the two rigid-body motions

3.4 Critical Response Conditions

The combined results identify approximately 0.08–0.13 Hz as the principal frequency corridor associated with the elevated coupled response. This range encompasses the dominant heave and pitch bands and the independently determined characteristic frequencies.

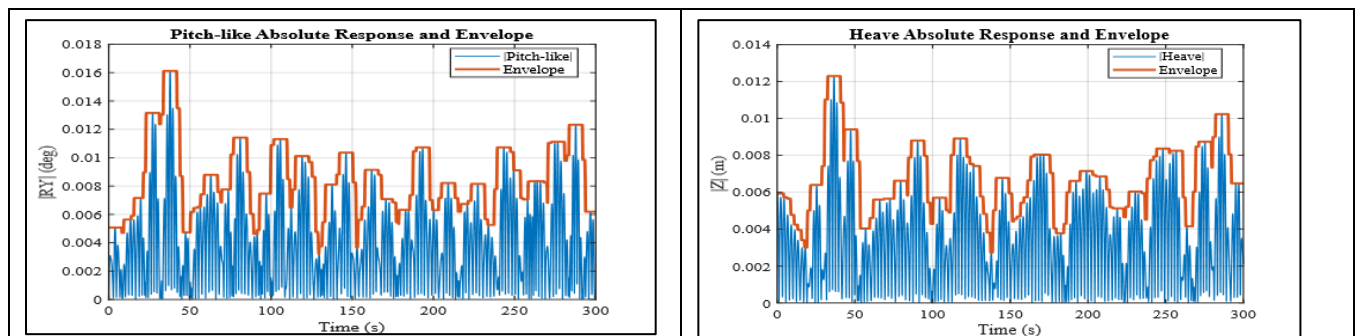


Figure 14: Absolute Heave and Pitch Response Envelopes

The response envelopes in Figure 14 show the magnitude and variation of the two motion components. A detailed portion of the coupled response is shown in Figure 15.

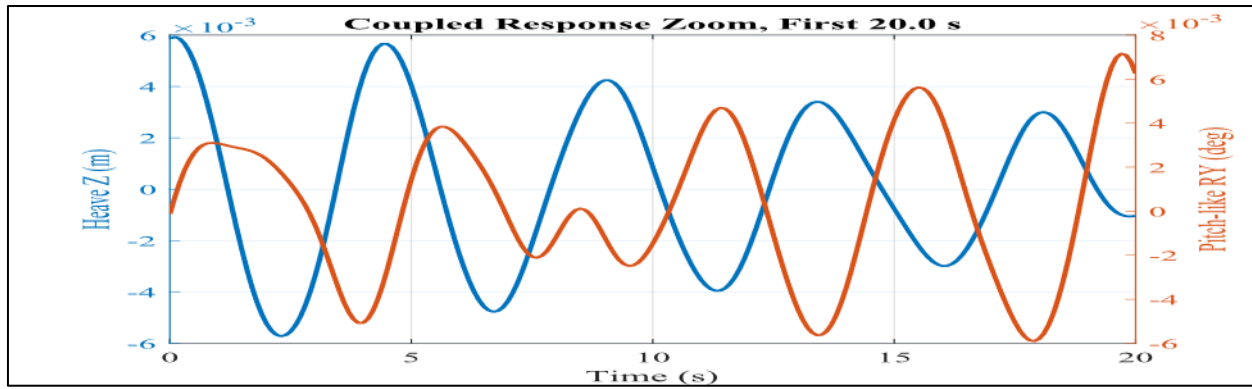


Figure 15: Coupled Heave-Pitch Response during the First 20 s

The response behaviour can also be interpreted against the RAOs and characteristic-frequency markers.

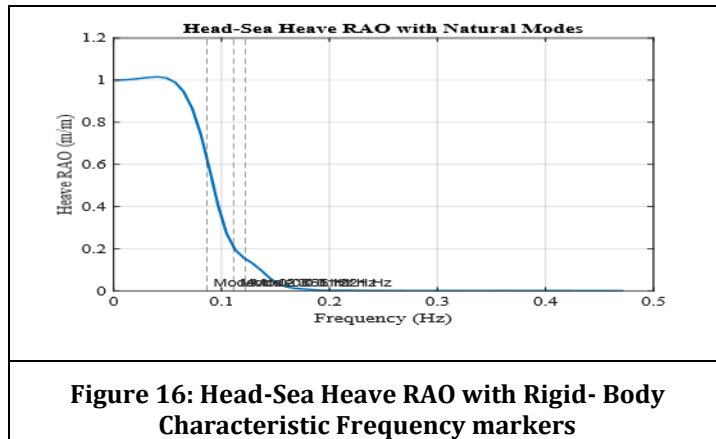


Figure 16: Head-Sea Heave RAO with Rigid- Body Characteristic Frequency markers

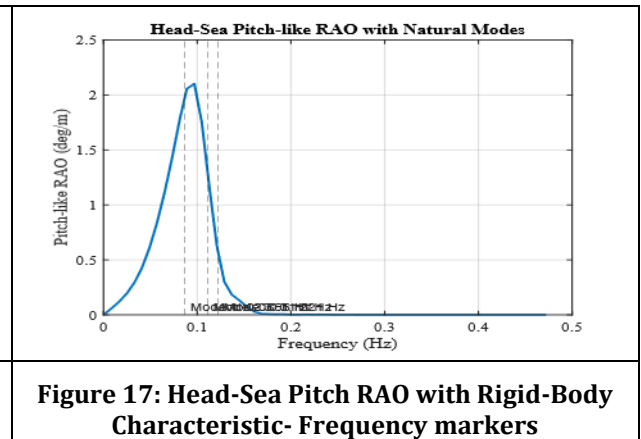


Figure 17: Head-Sea Pitch RAO with Rigid-Body Characteristic- Frequency markers

As shown in Figures 16 and 17, the principal response corridor occurs close to the identified rigid-body characteristic frequencies. These frequencies are used only for interpretation and are not included in the severity-index formulation.

3.5 Severity-Threshold Sensitivity

The influence of the selected threshold on the duration of identified elevated-response conditions is summarized in Table 10.

Table 10: Severity-threshold sensitivity

Threshold	Duration identified	Percentage
25th percentile	225 s	75%
50th percentile	150 s	50%
75th percentile	75 s	25%

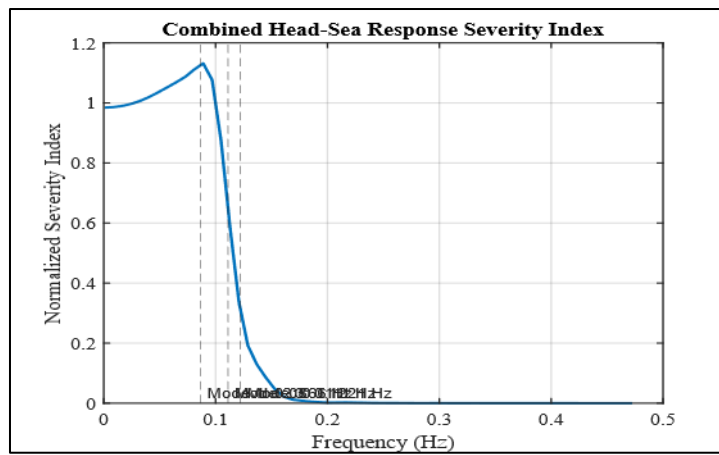


Figure 18: Severity Distribution and Screening Thresholds

As shown in Table 10 and Figure 18, lower thresholds identify longer portions of the response record, whereas higher thresholds isolate shorter periods of greater normalized response. The threshold analysis therefore provides a simple means of controlling the sensitivity of the screening procedure. The percentile thresholds should be interpreted as relative screening criteria rather than universal physical limits. Because the current analysis is based on a 300 s single realization, the reported threshold durations should be considered provisional until verified using the complete exported response series and longer simulations.

4 CONCLUSIONS AND STRUCTURAL SCREENING IMPLICATIONS

The coupled heave–pitch response of the S-175 U-Waters containership was analysed under irregular head seas. Heave ranged from -0.01102 to 0.01230 m, while pitch ranged from -0.01349° to 0.01612° . Their maximum moving-RMS responses occurred at approximately 142 s and 147 s, indicating closely occurring peak responses. The main response energy was concentrated within 0.08–0.13 Hz, covering the identified characteristic frequencies, while the cross-correlation of approximately 0.82 at near-zero lag confirmed strong temporal coupling. The severity index reached 1.00, with about 60% and 25% of the record exceeding 0.50 and 0.75, respectively. The novelty of this study is the integration of response statistics, moving-RMS, frequency analysis, temporal coupling, and a non-modal severity index to identify critical coupled-motion conditions for structural screening. The index is a response-screening measure, not a direct measure of stress, damage, or failure. Longer simulations and subsequent structural or hydroelastic analyses are recommended.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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