Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 131 **2026**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2026.131.16

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Wulandari, A.I., Alamsyah, Syahab, H., Agusty, C.L., Pratama, F.W. Human comfort and safety investigation on ro-ro ferries through ship motions under varying operational conditions. *Scientific Journal of Silesian University of Technology. Series Transport*. 2026, **131**, 275-301. ISSN: 0209-3324. DOI: https://doi.org/10.20858/sjsutst.2026.131.16

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HUMAN COMFORT AND SAFETY INVESTIGATION ON RO-RO FERRIES THROUGH SHIP MOTIONS UNDER VARYING OPERATIONAL CONDITIONS

Summary. The coexistence of vehicles and passengers on roll-on/roll-off (Ro-Ro) ferries demands rigorous management of operational comfort and safety, particularly in Indonesia's archipelagic waters, which are characterized by high vessel traffic density and seasonally rough seas. This study investigates the seakeeping performance of a Ro-Ro ferry through the computation of Response Amplitude Operators (RAOs) and the evaluation of passenger comfort using Motion Sickness Incidence (MSI) and Motion-Induced Interruption (MII) indices. Numerical simulations were conducted at wave incidence angles of 0°, 90°, and 180° for significant wave heights of 3.0 m and 3.5 m. MSI and MII were quantified for the passenger, vehicle, and navigation decks at vessel speeds of 0 and 12 knots.

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The results indicate that RAOs satisfy the 1987 NORDFORSK criteria at 0° and 180°, whereas the roll response at 90° exceeds the 3.97° threshold, reaching 5.6°. MSI values largely fall within the moderate category under ISO 2631 guidelines, with an alert condition observed at 12 knots and 180°. MII results classify interruption probability as “possible” for most scenarios, but “probable” on passenger and vehicle decks at 90°. These findings highlight that while the ferry demonstrates acceptable seakeeping performance in head and following seas, beam seas (90° incidence) substantially degrade stability and passenger comfort, underscoring the importance of operational speed management and voyage planning for inter-island ferry operations in Indonesian waters.

Keywords: motion sickness incidence, motion-induced interruptions, passenger comfort, seakeeping, ro-ro ship

1. INTRODUCTION

1.1 Background

In ship design, particular attention must be given to the comfort of passengers and crew, as this factor plays a decisive role in the quality and safety of operations (Misra 2016). During voyages, individuals on board are directly exposed to ship motions, which may arise from the vessel’s own dynamics or from external environmental conditions such as waves and weather (Bhattacharya 1978). Unfavorable sea states, including storms and large waves, are known to reduce comfort significantly while simultaneously increasing risks to both vessel safety and human wellbeing (Manik, 2013). For this reason, the assessment of ship motion responses is an essential component of the design process. Motions such as roll, heave, and pitch are of particular concern, as they are closely related to the ship’s natural frequencies and determine whether the vessel can return to equilibrium or remain unstable when disturbed (Djatmiko 2012).

Roll-on/Roll-off (Ro-Ro) ferries represent a ship type with unique operational characteristics. These vessels are designed to transport wheeled cargo such as cars, trucks, and buses, which are driven directly on and off the ship via ramps (IMO 1997). Unlike conventional cargo vessels, where goods are stowed below deck, Ro-Ro ferries carry vehicles on the main deck together with passenger spaces. This arrangement produces a distinctive load distribution, with the cargo weight positioned higher above the waterline compared to traditional ship designs (Zhai and Jin, 2024). As a result, the combined presence of passengers and vehicles requires careful management of both stability and comfort during operation.

The concept of seakeeping, defined as a vessel’s ability to maintain effective and comfortable operation in a seaway, is therefore of particular relevance to Ro-Ro ferries (Lin, 2019). Their relatively high center of gravity and uneven load distribution often amplify roll and pitch motions, which may compromise both comfort and operability (Ariesta, 2021). Poor seakeeping performance not only causes discomfort for passengers but also increases the likelihood of cargo shifting, operational delays, and safety hazards (Luhulima, 2018). Since wave characteristics such as height, period, and direction strongly influence ship responses, variations in wave angle must be carefully examined when evaluating the seakeeping performance of Ro-Ro ferries.

One crucial aspect of this management is understanding and minimizing Motion Sickness Incidence (MSI), as passenger comfort is a significant determinant of service quality, operational reputation, and crew performance. MSI refers to the percentage of passengers or crew expected to experience motion sickness under a given set of sea conditions (Scamardella,2013). MSI is affected by ship motion characteristics such as pitch, roll, and heave, which stimulate the human vestibular system beyond comfortable thresholds (Fang, 2007). Prolonged exposure to unfavorable motion can result in discomfort symptoms like dizziness, nausea, and vomiting, negatively impacting passenger satisfaction and crew efficiency (ISO 1997). Motion-Induced Interruptions (MII) represent instances where ship motion disrupts the physical activities of passengers or crew, such as walking, carrying loads, or operating equipment (Graham 1990). While MSI focuses on physical discomfort, MII relates to operational safety and performance, as excessive motion can increase the likelihood of accidents or inefficiencies. For Ro-Ro ferries, which often operate in open sea routes exposed to significant wave action, both MSI and MII must be analyzed to ensure optimal vessel design and operation.

The study uses Linear Strip Theory, a widely applied method in seakeeping analysis for conventional ships. This method simplifies the three-dimensional ship hull into a series of two-dimensional cross-sectional “strips” along the length of the vessel (Samuel, 2021). Hydrodynamic forces are then calculated for each strip and integrated to obtain the overall motion responses. Key advantages of Linear Strip Theory include computational efficiency, suitability for slender ship forms, and the ability to model different wave angles and sea states (Tran, 2025). The approach assumes linear wave theory and small-amplitude motions, making it well-suited for preliminary design and comfort analysis studies. The aim of this research is to analyze the motion characteristics of a Ro-Ro ferry under varying wave incidence angles and to evaluate the associated MSI and MII for both crew and passenger decks.

Therefore, this study aims to comprehensively evaluate the motion responses of a Ro-Ro ferry under varying wave heights and incidence angles, with a particular focus on roll, pitch, and heave motions that critically affect vessel performance. By applying Linear Strip Theory, the research quantifies the resulting MSI and MII on both passenger and vehicle decks, considering the unique load distribution of Ro-Ro ferries where vehicles and passengers share space above the waterline. The goal is to provide insights into passenger comfort, crew safety, and overall operational reliability, thereby contributing to the development of safer and more efficient Ro-Ro ferry designs.

1.2 Research Framework

In this study, the analysis of Ro-Ro ferry seakeeping performance was carried out under varying operational conditions by considering different wave headings (0°, 90°, and 180°), wave heights (3.0 m and 3.5 m), and ship speeds (0 and 12 knots). The dependent responses evaluated included heave, pitch, and roll motions, along with Motion Sickness Incidence (MSI) and Motion-Induced Interruptions (MII). These responses were analyzed with respect to the vessel’s principal dimensions, load distribution on passenger, vehicle, and crew decks, as well as tank arrangements, which were kept constant as control parameters. The method applied combined linear strip theory for hydrodynamic predictions, Response Amplitude Operator (RAO) analysis, and irregular wave input, with human comfort assessed based on ISO 2631 for MSI and established criteria for MII. The overall research framework adopted in this study is presented schematically in Figure 1.

Previous studies have examined seakeeping performance and its relation to safety and comfort across various vessel types. (Park, 2024) investigated small fishing vessels, deriving MSI and MII values to assess crew workability and safety. However, their focus was limited to small-scale vessels, leaving larger passenger ferries unaddressed. Piscopo and Scamardella (Piscopo, 2015) applied the Overall Motion Sickness Incidence (OMSI) framework to high-speed catamarans, using hull form optimization to improve passenger comfort. While this work highlighted comfort as a design driver, its applicability was restricted to multihull vessels rather than monohull ferries. (Dewi, 2019) analyzed Ro-Ro ferries of 500 GT, 1100 GT, and 1300 GT using Linear Strip Theory to evaluate stability, seakeeping, MSI, and MII. Although the study is directly relevant to Ro-Ro vessels, the emphasis was placed on comparing vessel performance and suitability for operation, with less focus on the detailed human comfort implications of ship motion. Taken together, these studies show that while motion analysis and comfort indices have been widely applied, there remains a gap in research focusing specifically on the passenger and crew comfort aspect of larger Ro-Ro ferries, where both vehicles and passengers share deck space above the waterline. Moreover, prior works often emphasize operational performance or comparative vessel assessments, rather than systematically quantifying MSI and MII as comfort and safety criteria under varied sea states and headings. This study addresses that gap by applying strip theory-based simulation to evaluate the seakeeping behavior of a Ro-Ro ferry, with an explicit focus on motion-induced discomfort and interruptions affecting passengers and crew.

In this study, the linear strip theory was applied to analyze the influence of ocean waves on the motion of a Ro-Ro passenger ferry and to evaluate the resulting MSI and MII for crew and passengers. This work addresses the operational challenge highlighted in the background, where the unique load distribution of Ro-Ro ferries, with vehicles and passengers on the same deck, makes them particularly sensitive to wave-induced motions that can impact both comfort and safety. The hydrodynamic analysis was carried out by calculating the vessel's Response Amplitude Operators (RAOs) for selected wave headings of 0°, 90°, and 180° under representative sea states and vessel speeds. From these results, key motion responses (heave, roll, pitch) were determined at both passenger and crew deck locations. These values were then used to estimate MSI and MII according to internationally recognized comfort and safety criteria, allowing an assessment of vessel operability under different conditions.

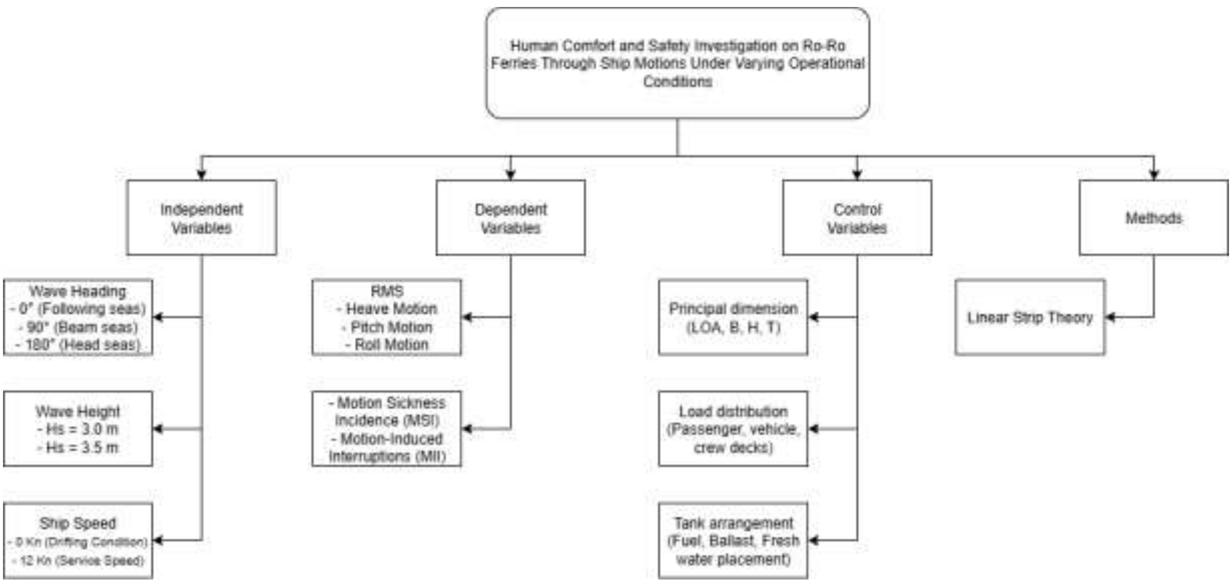


Fig. 1. Research framework

This methodological approach has several strengths. By using the actual vessel geometry and load distribution, it captures the distinct motion behavior of Ro-Ro ferries more accurately than simplified models. The simulation-based approach also enables flexible and efficient evaluation of multiple operating scenarios without the high costs and logistical complexity of sea trials or towing tank experiments, making it particularly useful for early-stage design and operational planning. Nevertheless, some limitations must be acknowledged. The lack of experimental validation introduces uncertainty regarding the accuracy of the motion predictions, as noted by Li et al. (2019). Furthermore, the reliance on linear strip theory restricts the analysis to linear hydrodynamic assumptions, meaning nonlinear and viscous effects are not fully accounted for, potentially reducing accuracy in severe sea states or large-amplitude motions, as shown in a study by Fitriadhy et al. (2017). The use of regular waves also simplifies real-world sea conditions, where irregular and multidirectional spectra are more common, the gap that can be observed in study by Jifaturrohman et al. (2024). Despite these constraints, the framework provides a practical and efficient means of assessing the motion-related comfort and operability of Ro-Ro ferries. The findings can inform design improvements, operational adjustments, and safety protocols aimed at reducing motion sickness and minimizing activity disruptions for crew and passengers. Therefore, the strengths and limitations of this study can be concluded as presented in Table 1.

Tab. 1

Strengths and Limitations of the study

Aspect	Strengths	Limitations
Model accuracy	Uses actual ship geometry and load distribution, resulting in more representative motion predictions.	No experimental validation; accuracy relies entirely on theoretical assumptions.
Methodology	Linear Strip Theory enables fast and cost-effective analysis of various operational conditions without physical tests.	Assumes linear behavior; nonlinear and viscous effects are not fully captured, especially in large waves or high-amplitude motions.
Operational focus	Explicitly evaluates Motion Sickness Incidence (MSI) and Motion-Induced Interruptions (MII) for passenger comfort and crew safety.	Analysis is limited to RAO, MSI, and MII; other design factors such as fuel efficiency or dynamic stability are not examined in depth.
Practical contribution	Provides design and operational recommendations to enhance Ro-Ro ferry safety and comfort.	Focused on a single case-study vessel, limiting the generalizability of the findings to other Ro-Ro ferry types.
Sea condition modeling	Considers multiple wave headings (0°, 90°, 180°) and varying wave heights for comprehensive evaluation.	Uses regular wave conditions; real-world irregular and multidirectional seas are not fully represented.

This study stands out from previous research by explicitly integrating ship motion analysis with passenger and crew comfort metrics, specifically MSI and MII, for a large Ro-Ro ferry with realistic load distribution where vehicles and passengers share deck space above the waterline. Unlike many prior works that focus primarily on operational performance, vessel comparisons, or simplified hull models, this research applies Linear Strip Theory to actual ship geometry, enabling a more accurate assessment of vessel motion behavior under varied sea states and headings. The findings provide actionable insights for ferry design improvements, operational planning, and safety management, addressing a critical gap in maritime engineering literature on passenger comfort and workability in challenging seaways.

2. OBJECT STUDY AND ANALYSIS APPROACH

2.1 Ship data and operational condition

In this study, the object of analysis is a Roll-on/Roll-off (Ro-Ro) ferry, selected due to its distinctive operational characteristics and the combined presence of passengers and vehicle cargo on the main deck. To enable an accurate evaluation of the vessel's motion behavior, as well as the resulting Motion Sickness Incidence (MSI) and Motion-Induced Interruptions (MII), the ship's design parameters were first defined in detail. The principal dimensions of the vessel, which serve as the foundation for the hydrodynamic analysis, are presented in Table 2. These parameters ensure that the numerical simulations reflect the actual geometry and proportions of the ship, rather than relying on simplified or generic models. To provide further clarity, Figure 2 presents the general arrangement of the Ro-Ro ferry, highlighting the layout of passenger, vehicle, and crew spaces. In addition, Figure 3 depicts the hull model that was developed for the purpose of motion analysis, serving as the basis for evaluating the vessel's response under various wave conditions.

Tab. 2

Ro-Ro ship dimensions

Data	Dimension	Unit
LOA	39.36	m
Breadth (B)	11.00	m
Depth (H)	3.30	m
Draught (T)	2.30	m
Operational Speed (Vs)	12	Knot
Crew	16	People
Passenger	180	People

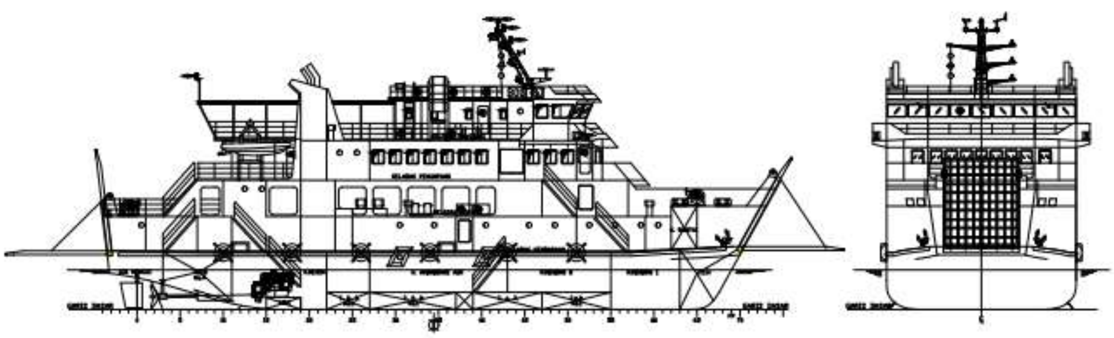


Fig. 2. CAD design of the Ferry Ro-ro ship

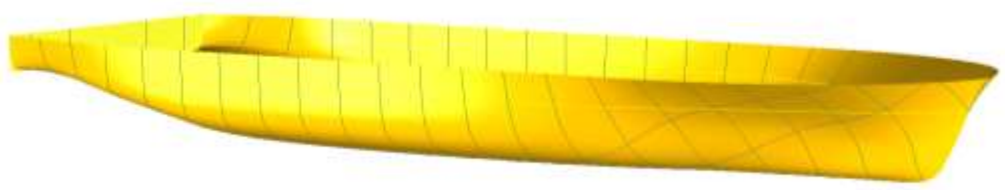


Fig. 3. 3D Hull model of the Ro-ro ship

The operational conditions considered in this study represent typical service scenarios for a Ro-Ro passenger ferry in moderate to rough seas. Sea states are modeled as irregular wave spectra to capture realistic wave energy distributions, with significant wave heights (Hs) of 3.0 m and 3.5 m. Vessel forward speed is set at 0 kn (drifting/loitering, e.g., awaiting berth or adverse-weather maneuvering) and 12 kn (representative service speed). Wave headings of 0°, 90°, and 180° are examined, visualized in Figure 4, corresponding respectively to head seas, beam seas, and following seas, to bracket the principal directional exposures that govern roll, pitch, and heave responses. This combination of Hs, speed, and heading provides a targeted yet comprehensive envelope for evaluating motion responses and their implications for MSI and MII under realistic operating conditions.

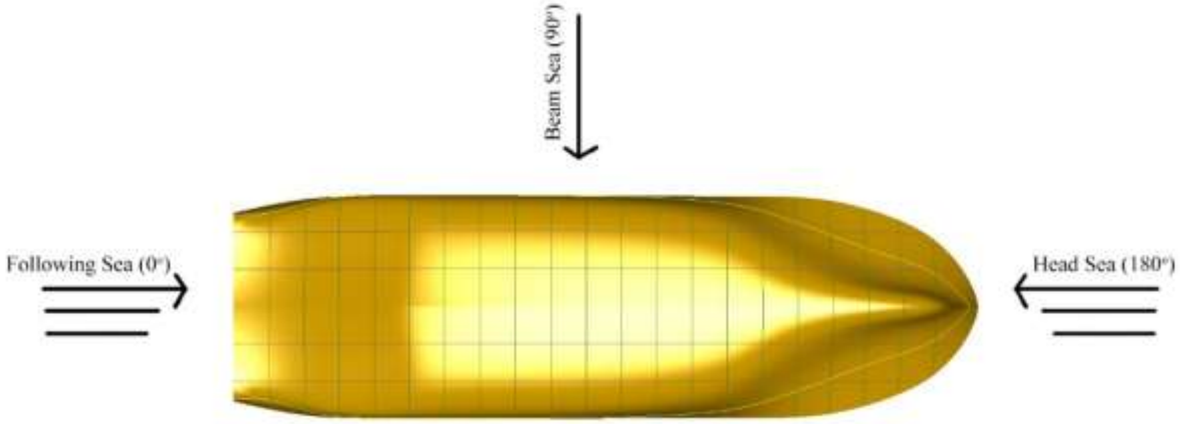


Fig. 4. Wave heading

In this study, specific mass points were defined to represent the locations of passengers, crew, and vehicles onboard the Ro-Ro ferry as shown in Figure 5. These points are crucial in calculating the ship's motion responses as they determine where accelerations are experienced and where MSI and MII are evaluated. Three primary mass points were considered: the passenger deck, the navigation (crew) deck, and the vehicle deck. The passenger deck is located at a longitudinal position of approximately 17.23 m from the aft perpendicular with a height of 7.50 m above the baseline, reflecting the central passenger accommodation area. The navigation deck, representing the crew working location, is positioned further forward at 23.00 m from the aft perpendicular and 12.20 m above the baseline, which corresponds to the bridge and control station where crew operability and workability are most critical. The vehicle deck, by contrast, lies lower and slightly aft at a 13.50 m longitudinal position and 3.30 m above the baseline, reflecting the car and cargo stowage area. These three points capture the distinct exposure of passengers, crew, and cargo to ship motions, providing a realistic distribution for the motion analysis. In addition to the mass points, the positioning of tanks within the hull plays a vital role in the vessel's weight distribution and stability. Ballast tanks are symmetrically arranged on the port (PS) and starboard (SB) sides at both aft and forward sections, ensuring transverse stability can be managed effectively. Fuel oil tanks are located centrally on both port and starboard sides, close to the midship, to minimize trim variation as fuel is consumed. Freshwater tanks are similarly placed in the forward midship section, again balanced on both sides. This arrangement follows conventional practice, where consumable tanks (fuel and freshwater) are positioned near the ship's centerline to reduce the influence on trim and heel during operation, while ballast tanks provide flexibility for adjusting the vessel's draft and stability according to loading conditions.

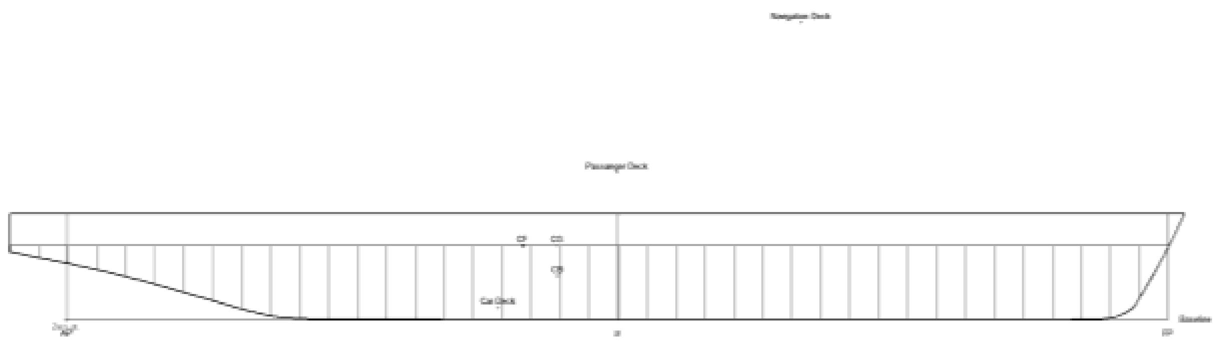


Fig. 5. Mass remote point for passenger and navigation deck

2.2 Linear Strip Theory

Strip theory is a numerical approach used to predict a ship's hydrodynamic response in waves by reducing its three-dimensional hull form into a series of two-dimensional longitudinal cross-sections, or "strips." Under the assumption of linear wave theory, each strip is evaluated independently, and the overall motion response is obtained by integrating the hydrodynamic forces along the vessel's length (Corigliano, 2024) (Wulandari, 2025). In this method, the vessel is modeled as a rigid body moving forward at a constant speed U and subjected to harmonic wave excitation with angular frequency ω and heading angle β. The motion of the ship is described in terms of six degrees of freedom, but in this study, the focus is placed on heave, pitch, and roll motions, which are considerable for predicting deck wetness and bottom slamming (Nam, 2022).

The governing equations of motion for coupled heave and pitch responses in the frequency domain are expressed in Eq. (1).

$$\sum_{j=3.5} [-\omega^2(M_{kj} + A_{kj}) + i\omega B_{kj} + C_{kj}]\, \xi_j = F_k \tag{1}$$

Where M_{kj} is the rigid-body mass or inertia coefficient, A_{kj} is the hydrodynamic added mass, B_{kj} is the damping coefficient, C_{kj} is the restoring coefficient, and F_k is the external wave excitation force. The theory solves for the velocity potential function Φ, which is decomposed into components from heave and pitch as described in Eq. (2) & Eq. (3).

$$\Phi = \mathrm{Re}\{\Phi e^{i\omega t}\} \tag{2}$$

$$\Phi = \Pi_3 X_3 + \Pi_5 X_5 \tag{3}$$

Hydrodynamic coefficients such as added mass and damping are computed for each section through 2D potential flow analysis, then integrated along the ship length to obtain 3D coefficients:

$$A_{33} = \int_0^L a_{33}(x)dx,\ B_{33} = \int_0^L b_{33}(x)dx \tag{4}$$

The encounter frequency ω is corrected for forward speed and wave heading as:

$$\omega = \omega_0 - \frac{U\omega_0}{g} cos\beta \tag{5}$$

By solving the coupled equations, one can determine the ship's response to a given sea state. These results feed directly into the estimation of vertical relative motion and accelerations, which are the key inputs for predicting deck wetness and slamming probabilities. This formulation, while based on linear assumptions, provides sufficiently accurate predictions for early-stage design or operational assessment where computational efficiency is crucial (Begović, 2023).

In strip theory-based seakeeping analysis, the accuracy of the results is influenced by the precision of the hull discretization along its length. This precision is improved by increasing the number of longitudinal strips, thereby enhancing the resolution used to integrate hydrodynamic responses. The strip or grid independence study was conducted to ensure that the results remained stable despite changes in refinement, mirroring procedures commonly applied in resistance calculations under calm water conditions (ITTC, 2021) (Wulandari, 2025) (Rizal, 2022). A systematic variation in the number of strips was carried out to examine the sensitivity of motion responses, namely heave, roll, and pitch, to discretization levels. A comparison between each precision is concluded in Table 3, with the uncertainty behavior can be seen by the chart concluded for each motion in 5. Each strip precision is visualized in Figure 7.

Tab. 3

Uncertainty analysis for seakeeping simulation

Precisions	Wave Heading (°)	Comparison (%)		
		`Heave	Roll	Pitch
Coarse	0	2,53%	0,00%	3,85%
	90	1,58%	0,00%	5,92%
	180	2,67%	0,00%	3,55%
Medium	0	0,11%	0,00%	0,11%
	90	0,83%	0,00%	4,91%
	180	0,60%	0,00%	2,12%
Fine	0	1,43%	0,00%	2,65%
	90	0,55%	0,00%	2,94%
	180	0,66%	0,00%	1,01%

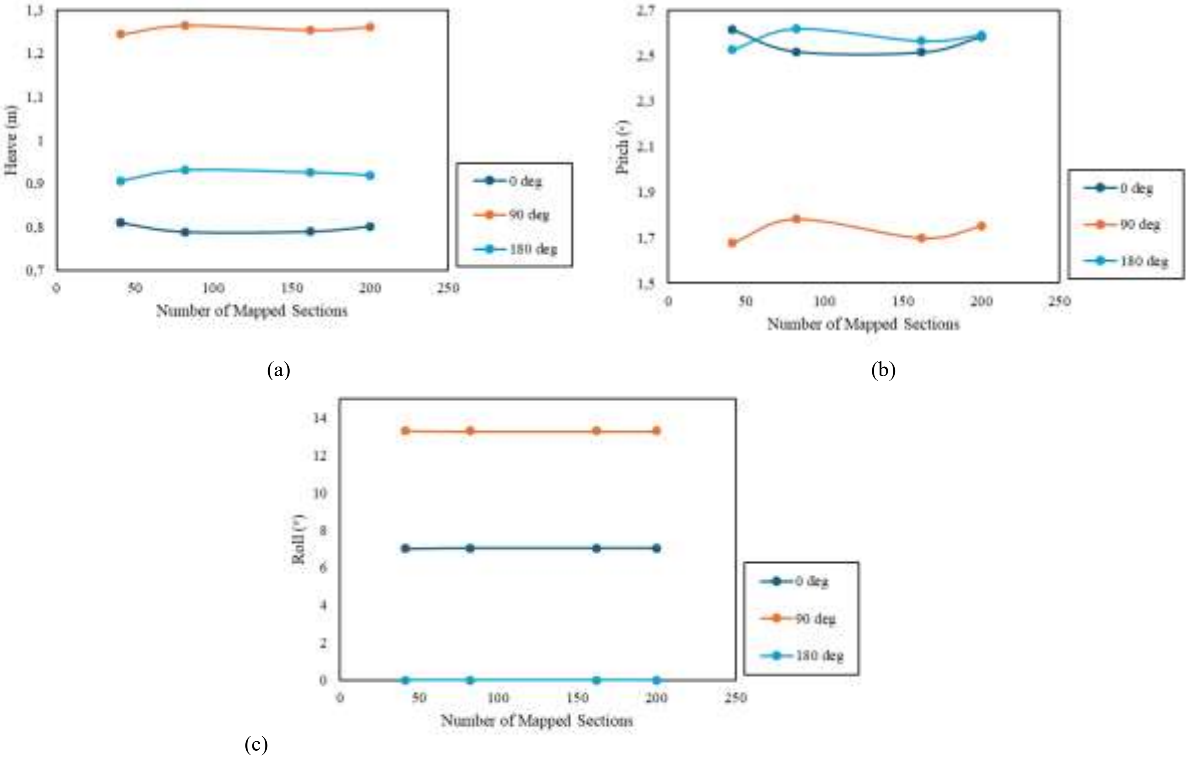


Fig. 6. Comparison of each strip precision for each motion; (a) Heave, (b) Roll, (c) Pitch

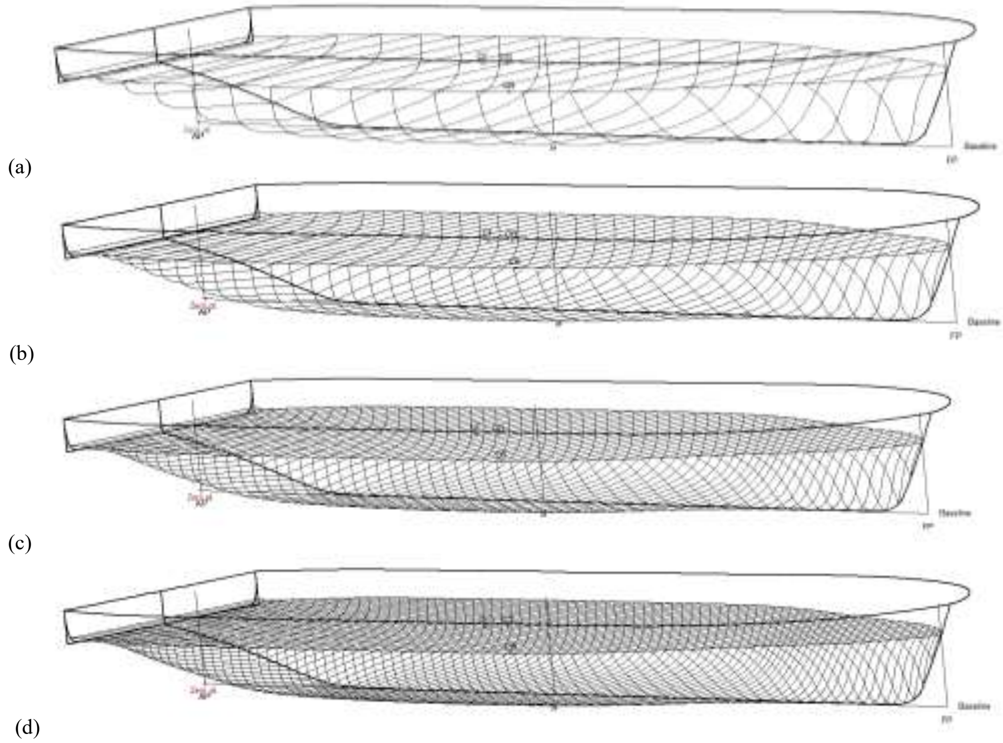


Fig. 7. Strip precision for uncertainty analysis;
(a) Coarsest, (b) Coarse, (c) Fine, (d) Finest

The simulations were conducted using several strip configurations: 41 sections (coarsest), 82 sections (coarse), 164 sections (medium), and 200 sections (fine). This refinement process was intended to verify the consistency and reliability of the predicted ship motions at different levels of resolution. It was noted that although structured meshes generally improve accuracy, the gains in precision become marginal once a certain refinement threshold is exceeded. The results indicated that the relative deviations between configurations remained within acceptable limits. In engineering analysis, a deviation of less than 5% is typically considered satisfactory, and this criterion was achieved in most cases. This suggests that roll motion is largely unaffected by strip resolution, likely due to the influence of wave heading and the vessel's symmetrical hull form. Based on these findings, it can be concluded that while finer discretization enhances detail, the coarse configuration is sufficiently accurate for practical applications. Moreover, it provides a favorable balance between reliability and numerical efficiency, making it suitable for subsequent motion response and probability analyses, as also seen in Wulandari et al.'s hydrodynamic study (2024).

2.3 Seakeeping Motion

Seakeeping analysis aims to evaluate how a ship behaves in a wave environment, particularly how it responds in terms of motion (e.g., heave, pitch, roll), acceleration, and relative displacement (Bunnik, 2010). The key step in seakeeping calculations is to compute the Response Amplitude Operators (RAOs), which define the ratio of a specific ship motion amplitude to the wave amplitude at a given frequency:

$$RAO_j(\omega) = \frac{|\xi_j(\omega)|}{|A(\omega)|} \tag{6}$$

Where $\xi_j(\omega)$ is the complex amplitude of motion in degree of freedom j (e.g., heave, pitch), and $A(\omega)$ is the wave amplitude at angular frequency ω. To evaluate how the ship performs in a realistic wave environment, irregular sea conditions are modeled using wave energy spectra such as Pierson-Moskowitz or JONSWAP (Lee, 2022). In practical conditions, sea waves are irregular and can be represented as the superposition of multiple regular wave components with varying frequencies, amplitudes, and phases. When a ship moves forward at a constant speed, it encounters waves at a frequency different from their actual frequency in a stationary reference frame (Tran, 2025). This results in a Doppler-like shift, where the encounter frequency ωe differs from the natural wave frequency ωw. The relationship is defined as:

$$\omega_e = \omega_w - \frac{g.cos\mu}{V_s} \tag{7}$$

Where ω_e is the encounter frequency (rad/s), ωw is the wave frequency (rad/s), g is the gravitational acceleration (m/s^2), Vs is the ship speed, and μ is the wave heading (o). In the case where the vessel is at zero speed (i.e., stationary), the encounter frequency equals the wave frequency. The wave energy spectrum applied in this analysis is the Pierson-Moskowitz spectrum, commonly used to model fully developed seas. It is defined as:

$$S(\omega) = \frac{AH_s^2}{\omega^5}\exp(-\frac{B}{\omega^4 T^4}) \tag{8}$$

Where S(ω) is the wave spectral density, Hs is the significant wave height, ω is the angular wave frequency, and A and B are empirical constants. The ship's motion response in that sea condition is then statistically evaluated using spectral moments of the motion response function:

$$m_n = \int_0^{\infty} \omega^n |A(\omega)|^2 \, S(\omega) \, d\omega \tag{9}$$

Where m_n is the nth spectral moment, S(ω) is the wave spectral density function, and |RAO(ω)| is the modulus of the motion RAO (Bielicki 2021).

2.4 Human Comfort Index

Human comfort on board ships is strongly influenced by vessel motions, which can lead to both physical discomfort and operational disruptions. Two widely recognized measures used to evaluate these effects are Motion Sickness Incidence (MSI) and Motion-Induced Interruptions (MII). MSI reflects the degree of discomfort experienced by passengers and crew due to motion-induced seasickness, while MII represents the frequency of activity disruptions caused by the need to maintain balance during excessive ship motions. Together, these indices provide a comprehensive assessment of how vessel dynamics affect comfort, safety, and efficiency at sea. In general, MSI is defined as the percentage of the total number of passengers and crew expected to experience vomiting as a result of seasickness after sailing for two hours in adverse weather conditions. Passenger comfort can also be quantified through this index by referring to the ISO-2631/1997 standard (ISO 1997), which specifies the percentage of individuals likely to be affected within a given exposure period. In this study, MSI was estimated based on simulations performed at several locations on the ship to evaluate the vertical accelerations experienced at those points. The calculation of MSI follows Equation (10) (Santoso 2015):

$$\text{MSI}= 100 \, [0{,}5 \pm \text{erf}(\frac{\pm \log 10\frac{a_v}{g} \pm \mu MSI}{0{,}4})] \tag{10}$$

In this study, the Motion Sickness Incidence (MSI) is represented as indexMSI, which is calculated using the error function (erf). The primary input for this calculation is the average vertical acceleration (a_v) at a specified point or location on the ship. Additionally, the parameter μMSI is determined based on Equation (11), which provides the necessary reference value for evaluating MSI under varying motion conditions.

$$\mu_{MSI} = -0.819 + 2.32 \, (\log 10) 2\omega_E \tag{11}$$

IndexSM (Subjective Magnitude) is a scale to assess the severity of Motion Sickness Incidence symptoms. SM index can be calculated by equation 12 (Lloyd 1998):

$$SM = A \; 1.43\left(\frac{\ddot{s}_{30}}{g}\right) \tag{12}$$

Where A is a parameter that is a function of frequency, which can be calculated by the equations (13) & (14) (Lloyd 1998):

$$A = x[1 - exp(-\,1{,}65\;\omega_e^2)][7{,}56 - 49{,}6\;log_e\;\omega_e + 13{,}5\;(log_e\omega_e)^2] \tag{13}$$

$$\ddot{s}_{30} = 2\sqrt{m_4}\ m/sec^2 \tag{14}$$

The MSI assessment categories are based on a range of values, concluded in Table 4.

Tab. 4

MSI value range

MSI Range (SM)	Status
0 - 5	Moderate
5 - 10	Caution
10 - 15	Extreme
15 - 20	Dangerous
>20	Very Risky

Meanwhile, Motion-Induced Interruptions (MII) refer to situations in which crew members are forced to pause their activities or tasks in order to stabilize themselves by holding onto the ship's structure. Such interruptions typically arise from excessive ship motions that compromise balance, with common consequences including slipping or loss of stability while moving on board. To better illustrate the severity of these events, Table 5 presents the categorization of MII risk levels, expressed in terms of both interruptions per hour and per minute.

Tab. 5

MII risk level

MSI Range	MII per hour	MII per minute
Possible	6	0.1
Probable	30	0.5
Serious	90	1.5
Severe	180	3.5
Extreme	300	5.0

3. RESULTS AND DISCUSSION

3.1 RAO Analysis

The RAO curves illustrate the dynamic response of the Ro-Ro ferry to wave excitation across different encounter frequencies and headings (0°, 90°, and 180°). The results highlight that the vessel exhibits frequency-dependent sensitivity, with distinct peaks corresponding to its natural motion periods. RAO curves for stationary condition (0 speed) are shown in Figure 8. For heave and pitch, the RAO values show amplification at lower to mid-frequency ranges, particularly in head seas (180°). This behavior reflects resonance with the ship's natural vertical motions, where longer waves induce significant displacement. The peak RAO in heave and pitch underlines the influence of vessel length and hull form, indicating that the ferry is more susceptible to wave energy when the encounter period approaches its natural oscillation period. In contrast, roll RAOs demonstrate the most critical behavior in beam seas (90°). The response is markedly higher compared to head and following seas, with RAO values exceeding unity over a broader frequency range. This result emphasizes the vessel's vulnerability to lateral wave action, where rolling motions dominate and present risks for passenger comfort and cargo safety. The amplification in roll responses is consistent with the high center of gravity and unique load distribution of Ro-Ro ferries, which reduce roll stability margins. At following seas (0°), the RAO values remain comparatively moderate across motions, with no significant amplification peaks. This suggests that, under these conditions, wave excitation tends to align with the vessel's forward motion, producing less severe vertical and rolling responses. The RAO transfer functions presented in the charts are expressed in a non-dimensional form. This means that each motion response has been normalized against the corresponding wave amplitude, allowing the results to be represented as ratios. For heave, the RAO is given in units of displacement per wave amplitude (m/m), while for pitch and roll, the responses are expressed in angular displacement per wave slope (deg/deg). By presenting the RAOs in this non-dimensional manner, the results become independent of the actual wave height, enabling direct comparison across different motions and operational conditions.

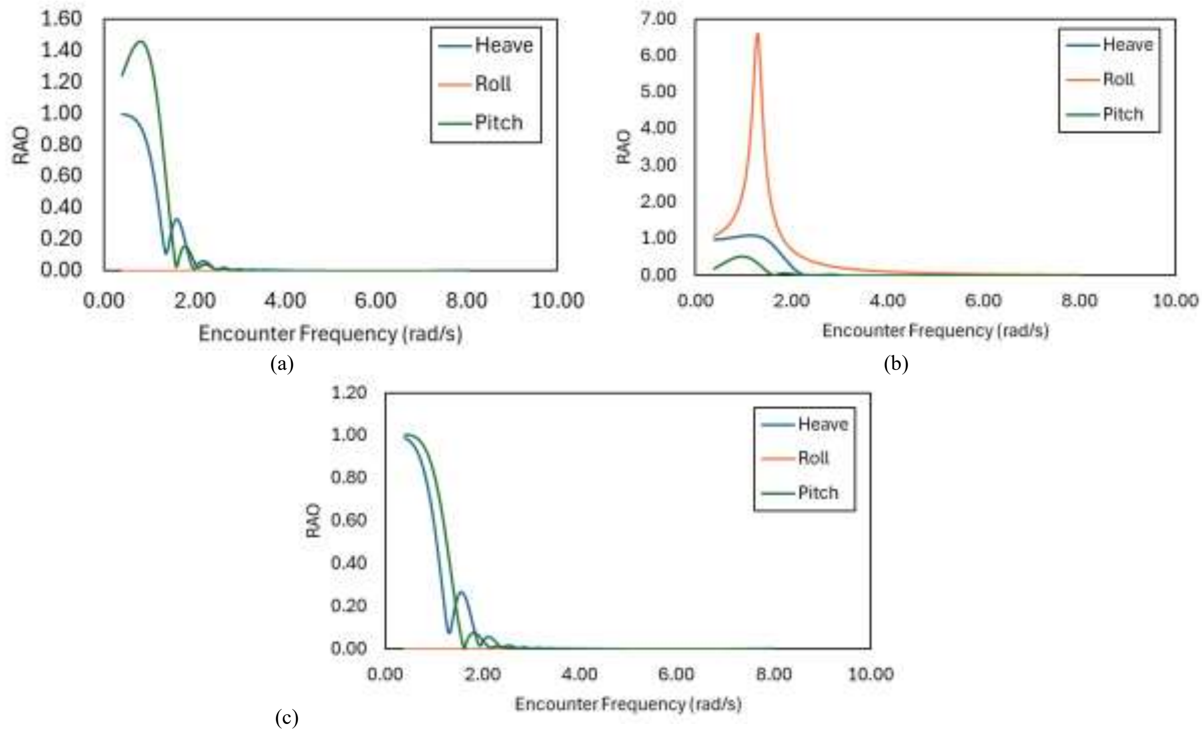


Fig. 8. Ro-ro ship RAO at 0 speed and each heading;
(a) Following Sea, (b) Beam Sea, (c) Head Sea

RAO for a ship in operational speed condition (12 kn) is shown in Figure 9. For heave and pitch, the RAO values show amplification at lower to mid-frequency ranges, particularly in head seas (180°). This behavior reflects resonance with the ship's natural vertical motions, where longer waves induce significant displacement. The peak RAO in heave and pitch underlines the influence of vessel length and hull form, indicating that the ferry is more susceptible to wave energy when the encounter period approaches its natural oscillation period. In contrast, roll RAOs demonstrate the most critical behavior in beam seas (90°). The response is markedly higher compared to head and following seas, with RAO values exceeding unity over a broader frequency range. This result emphasizes the vessel's vulnerability to lateral wave action, where rolling motions dominate and present risks for passenger comfort and cargo safety. The amplification in roll responses is consistent with the high center of gravity and unique load distribution of Ro-Ro ferries, which reduce roll stability margins. At following seas (0°), the RAO values remain comparatively moderate across motions, with no significant amplification peaks. This suggests that, under these conditions, wave excitation tends to align with the vessel's forward motion, producing less severe vertical and rolling responses. Overall, the RAO analysis demonstrates that while the Ro-Ro ferry performs adequately in head and following seas, beam sea encounters result in amplified roll responses, which could significantly impact MSI and MII. These findings reinforce the importance of operational planning to minimize beam sea exposure and highlight potential areas for design improvements, such as the incorporation of roll stabilization devices.

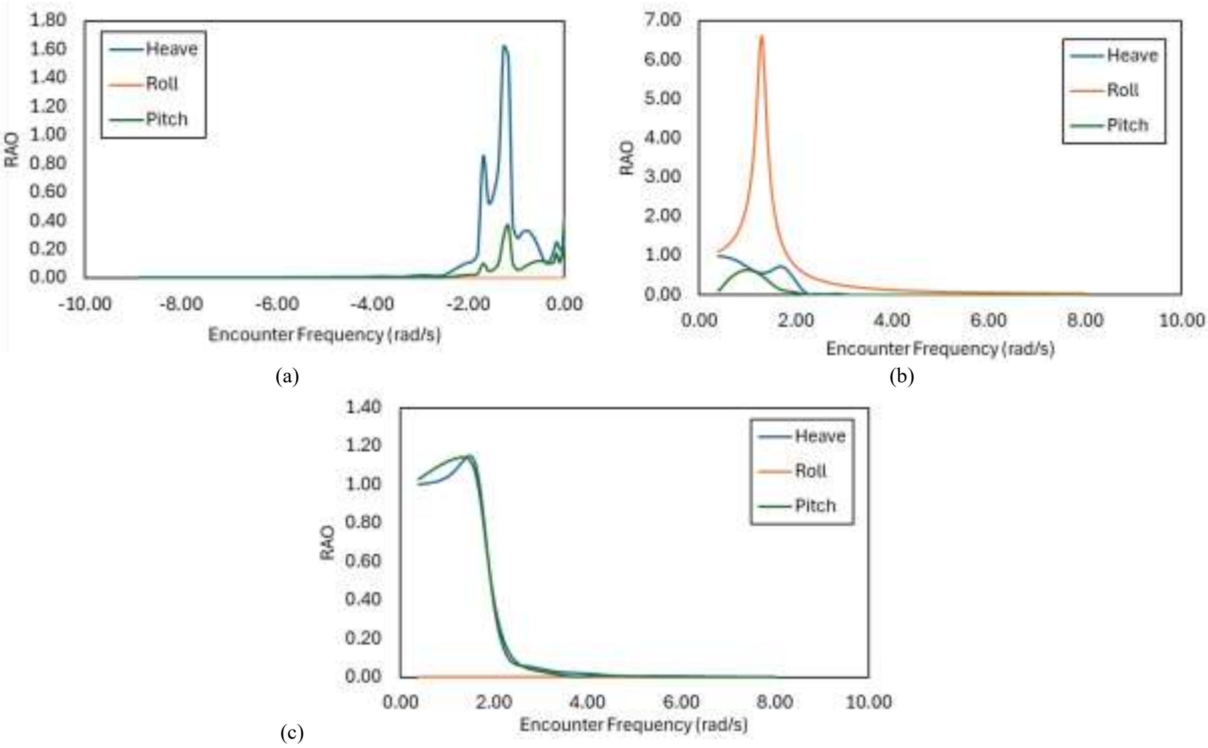


Fig. 9. Ro-ro ship RAO at12 Kn speed and each heading;
(a) Following Sea, (b) Beam Sea, (c) Head sea

The RAO results at 0 knots provide a useful baseline for understanding the vessel's natural motion characteristics, while the comparison with 12 knots reveals how forward speed influences the encounter frequency and overall responses. In head seas (180°), the heave and pitch RAOs at 0 knots show distinct peaks near the natural vertical motion periods, reflecting resonance with longer waves. When the vessel advances at 12 knots, the encounter frequency shifts toward shorter periods, causing the RAO peaks to move to the right and, in some cases, narrow. This shift generally reduces the amplitude of vertical motions at longer periods but can increase the severity if the operating speed brings the vessel closer to resonance. Roll remains minimal in head seas at both speeds, indicating limited vulnerability in this heading. In beam seas (90°), the roll RAO is the dominant response. At 0 knots, a strong peak is observed near the roll natural frequency, while at 12 knots the peak shifts slightly due to the encounter-frequency effect. Although forward speed can introduce additional damping that may reduce the amplitude of the peak, the response often broadens across a wider frequency range, maintaining roll as the most critical motion for comfort and operability. Heave and pitch motions in beam seas remain secondary compared to roll, with only minor differences between 0 and 12 knots. In following seas (0°), the RAO behavior is markedly different: at 0 knots, the vessel experiences vertical motion peaks similar to the head-sea case, but at 12 knots the encounter frequency decreases as waves approach from astern, shifting the peaks to longer periods and generally reducing their amplitude. As a result, forward speed tends to alleviate vertical motions in following seas, improving both comfort and operability.

3.2 Seakeeping Motion

The comparison of RMS motions between wave heights of 3.0 m and 3.5 m clearly demonstrates the sensitivity of the Ro-Ro ferry's responses to sea state severity. A comparison between wave heights can be seen in Figure 10. For heave motions, the RMS values increase consistently with wave height across all headings, indicating the direct influence of wave energy on vertical displacements. The most significant increments are observed in beam seas, where the RMS heave rises from 0.77 m to 0.90 m at 0 kn and from 0.68 m to 0.79 m at 12 kn. This shows that larger waves acting laterally on the hull produce stronger vertical oscillations. In head seas, the heave motion also increases with wave height, particularly at service speed, suggesting that advancing against longer, steeper waves induce stronger vertical excitations. Pitch motions are even more sensitive to wave height. In following seas, RMS pitch increases from 3.44° to 4.01° at 0 kn, while in head seas it grows from 2.23° to 2.60° at the same condition. These increments underline that longer-period waves at higher sea states strongly excite the vessel's longitudinal oscillations, especially when wave crests align with the vessel's length.

For roll motions, the effect of wave height is dominant only in beam seas, where RMS values rise from 9.58° to 11.18°, a level significantly exceeding the comfort threshold. Both following and head seas result in negligible roll regardless of wave height, as expected for longitudinal wave incidence. The results highlight that increases in sea state exacerbate all motions but affect each differently: heave and pitch grow across all headings, while roll is almost exclusively dictated by beam seas. This finding is similar to the study by Ariani et al. (2023) that obtained higher motion on larger wave heights.

The effect of ship speed reveals distinct behaviors between vertical and transverse motions, visible in Figure 11. For heave, increasing speed from 0 kn to 12 kn generally reduces responses in following and beam seas but increases them in head seas. At a 3.5 m wave height, heave grows from 0.76 m at 0 kn to 0.88 m at 12 kn in head seas, showing that forward motion enhances vertical excitation when encountering waves directly. This behavior is linked to the Doppler shift in encounter frequency, where advancing speed moves the vessel closer to resonance in head seas, as also presented in Ariani et al.'s study (2023). In following seas, the opposite occurs: RMS heave decreases at 12 kn because the relative encounter frequency lowers as the ship overtakes the waves. Pitch motions follow a similar trend. At 3.0 m wave height in following seas, RMS pitch decreases from 3.44° at 0 kn to 2.88° at 12 kn, confirming that forward motion reduces longitudinal oscillations when moving with the waves. Conversely, in head seas, RMS pitch increases from 2.23° to 2.46° under the same conditions, indicating stronger bow immersion and stern lift when advancing into steep waves. Roll motions remain unaffected by speed, with constant RMS values of 9.58° in 3.0 m and 11.18° in 3.5 m beam seas across both 0 and 12 kn. This stability reflects that roll is governed primarily by wave heading and hull geometry rather than forward motion. Overall, ship speed redistributes vertical motions between following and head seas but has no mitigating effect on beam-sea roll.

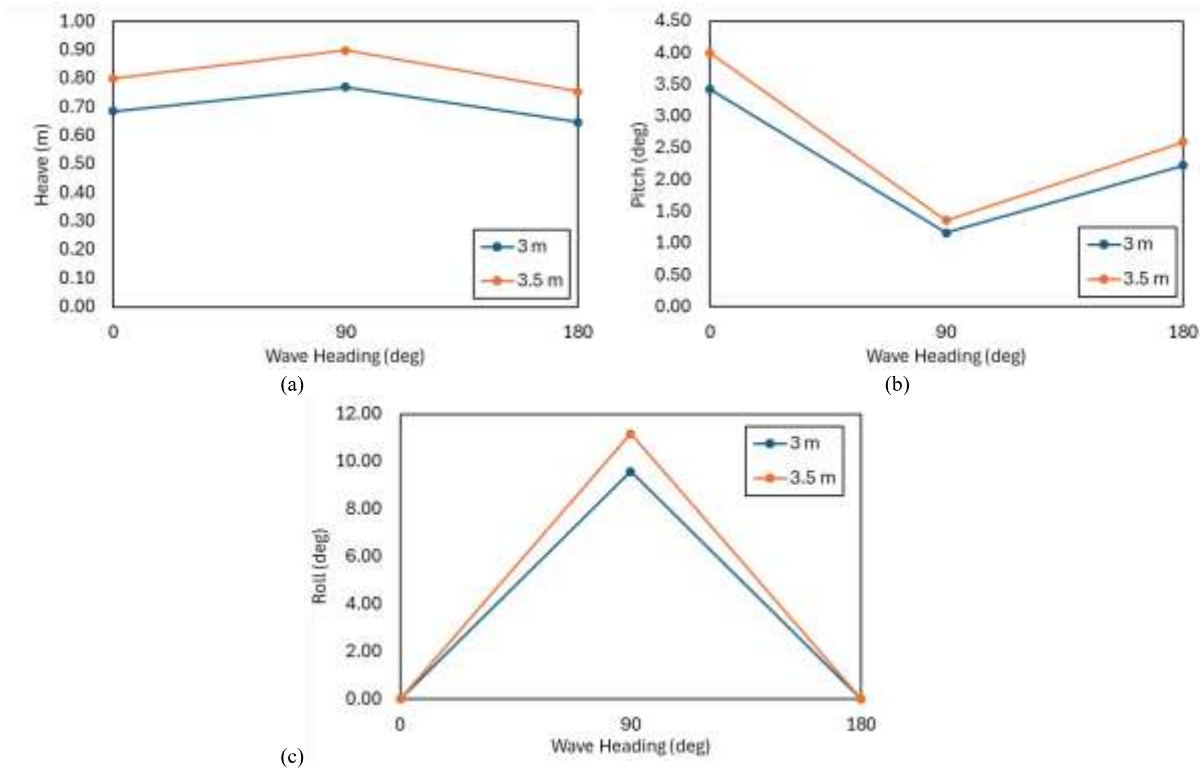


Fig. 10. RMS comparison between wave height at each wave heading;
(a) Heave, (b) Pitch, (c) Roll

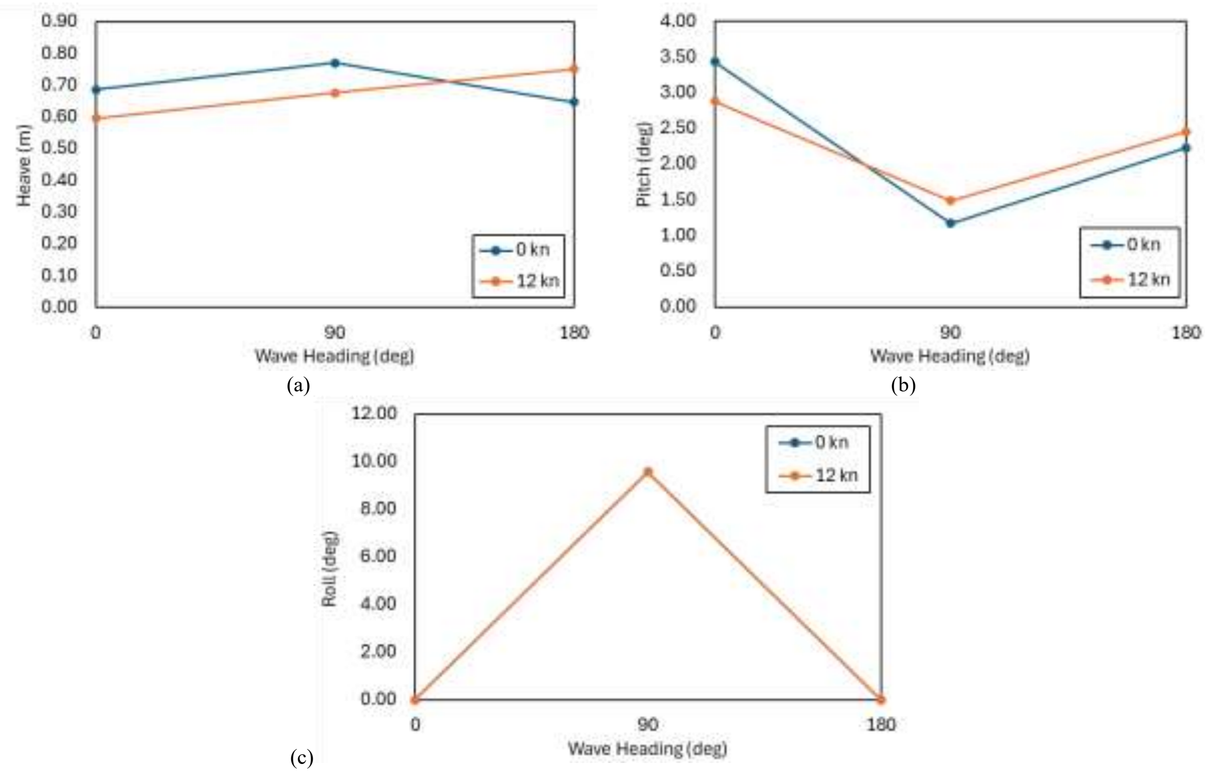


Fig. 11. RMS comparison between ship speed at each wave heading;
(a) Heave, (b) Pitch, (c) Roll

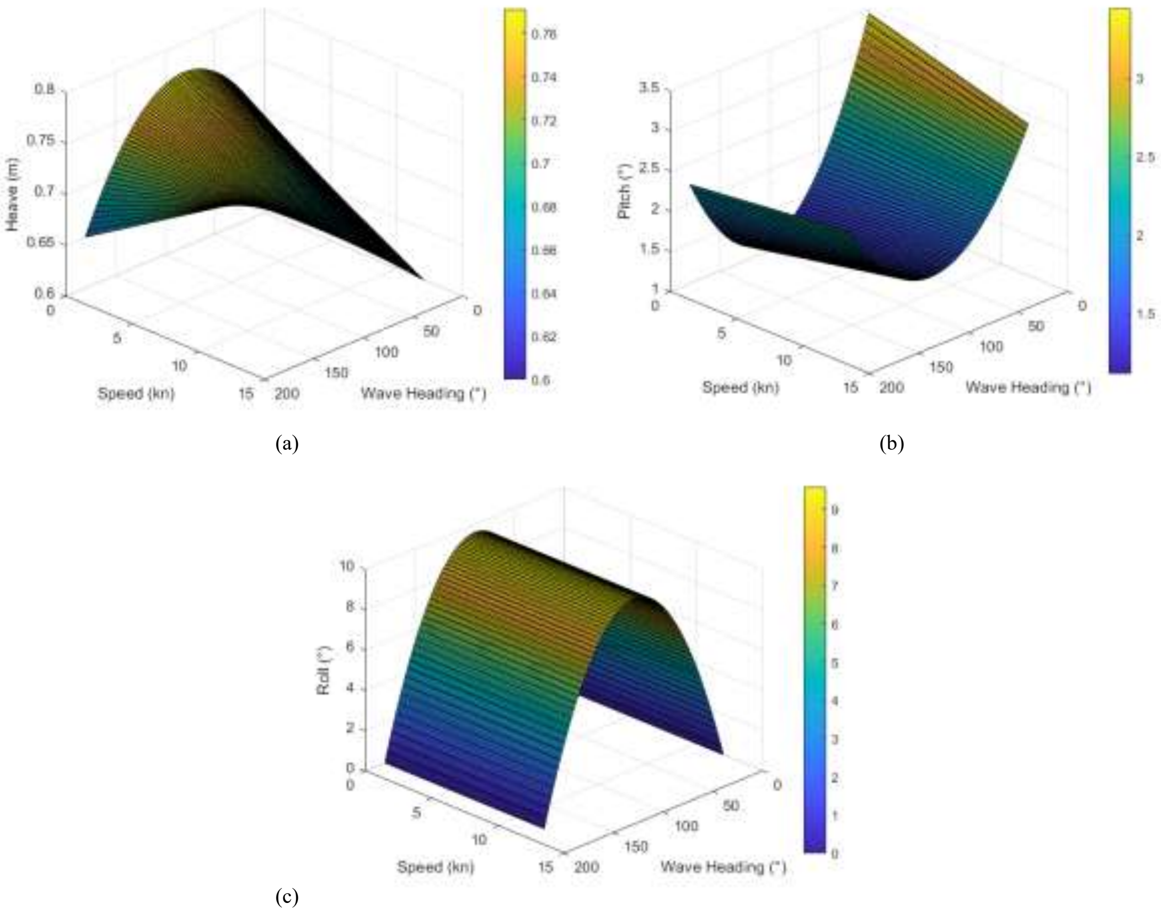
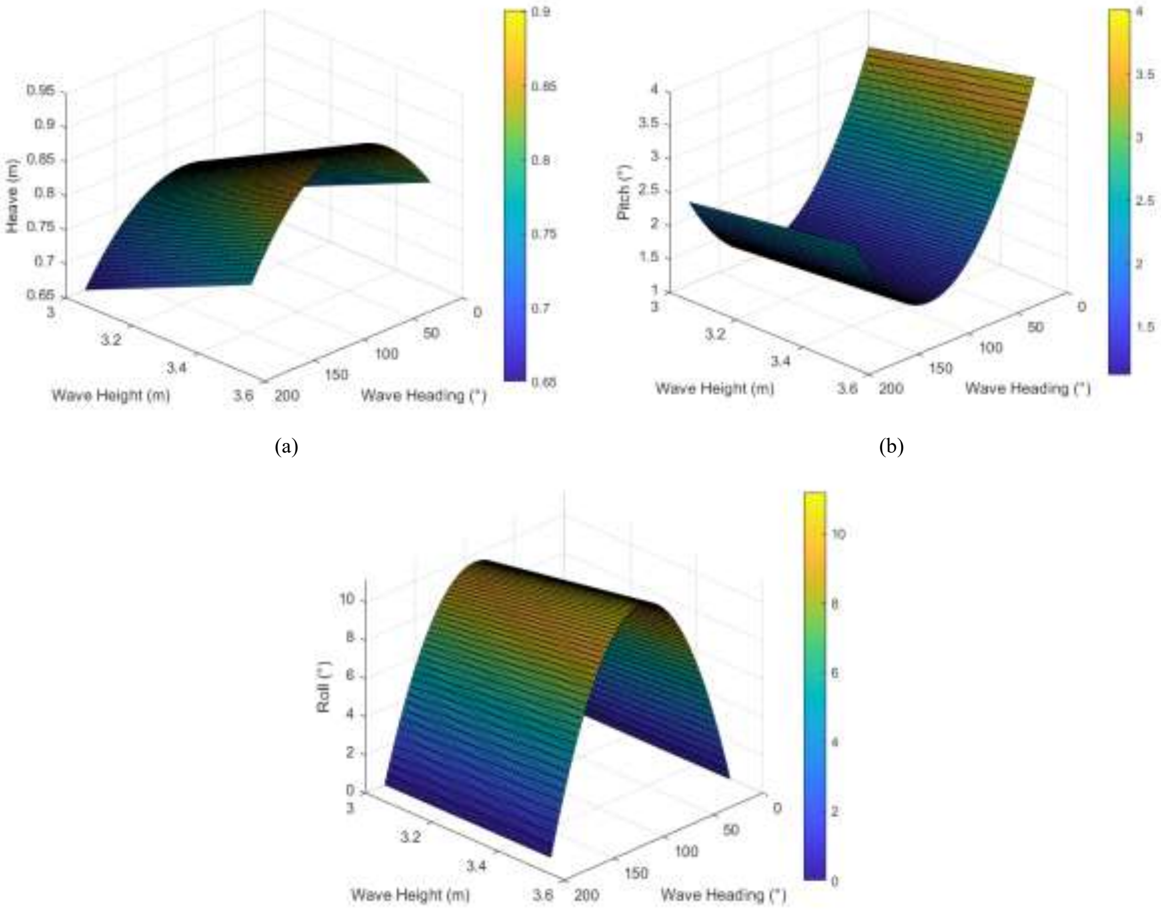


Fig. 12. Effect comparison between ship speed and wave heading on each motion; (a) Heave, (b) Pitch, (c) Roll

When analyzing the combined effect of ship speed and wave heading in Figure 12, clear patterns emerge that distinguish vertical plane responses from transverse motions. For heave, the highest RMS values consistently occur in beam seas across both speeds, reflecting the strong excitation from lateral wave action on the ferry's broad beam. In head seas, heave increases significantly at 12 kn compared to 0 kn, confirming that advancing speed enhances vertical accelerations when meeting waves head-on. Following seas show the opposite effect, with lower heave at higher speeds due to reduced relative encounter frequency. Pitch motions present a more complex interaction. At 0 kn, following seas produce the largest RMS pitch values, with 4.01° observed at 3.5 m wave height. However, at 12 kn the head-sea response becomes more severe, with pitch rising to 2.87°, while following-sea pitch decreases to 3.36°. This indicates that forward speed shifts the dominant excitation of pitch from following to head seas. In contrast, roll motions remain almost exclusively dependent on heading. Beam seas consistently produce extreme values of 9.58° at 3.0 m and 11.18° at 3.5 m, regardless of speed. Both following and head seas contribute negligibly to roll, confirming the predominance of lateral wave incidence. This combined analysis highlights that while speed modulates heave and pitch depending on heading, roll remains entirely governed by wave direction, reinforcing its role as the most critical motion response for Ro-Ro ferries. The interaction between wave height and heading, visualized in Figure 13, emphasizes how sea state severity amplifies motion responses, though the extent varies by motion type. For heave, increases in wave height result in higher RMS values across all headings, with the most pronounced responses occurring in beam seas and head seas at service speed. This underscores that larger seas amplify vertical displacements most significantly when the vessel faces or is struck laterally by waves. Pitch motions show strong sensitivity to wave height, particularly in following seas, where RMS pitch increases from 3.44° to 4.01° at 0 kn, reflecting the resonance between wave length and ship length. In head seas, higher wave heights also amplify pitch, particularly at 12 kn, further indicating that speed magnifies vertical plane responses under severe conditions. For roll, the effect of wave height is concentrated entirely in beam seas, where RMS values grow from 9.58° to 11.18°. Such high roll amplitudes exceed both comfort and safety thresholds, highlighting beam seas as the most limiting condition for Ro-Ro ferry operations. Neither following nor head seas produce meaningful roll responses, regardless of wave height, confirming the directional dependence of transverse stability. Overall, the results show that wave height exacerbates all motions but with distinct patterns: heave and pitch are amplified across headings, particularly under head seas at speed, while roll is almost entirely driven by beam seas, where higher sea states lead to dangerous levels of motion severity.



(c)

Fig. 13. Effect comparison between ship speed and wave heading on each motion; (a) Heave, (b) Pitch, (c) Roll

3.3 Human comfort index

The comfort level of passengers and ship crew can be seen from various parameters, namely the SM index and MSI percentage, as well as MII/hour. Each of these parameters is based on the location point that has been inputted into motion with various conditions, namely variations in ship speed, angle of direction of arrival of waves, and different wave heights, the results of the analysis are as follows.

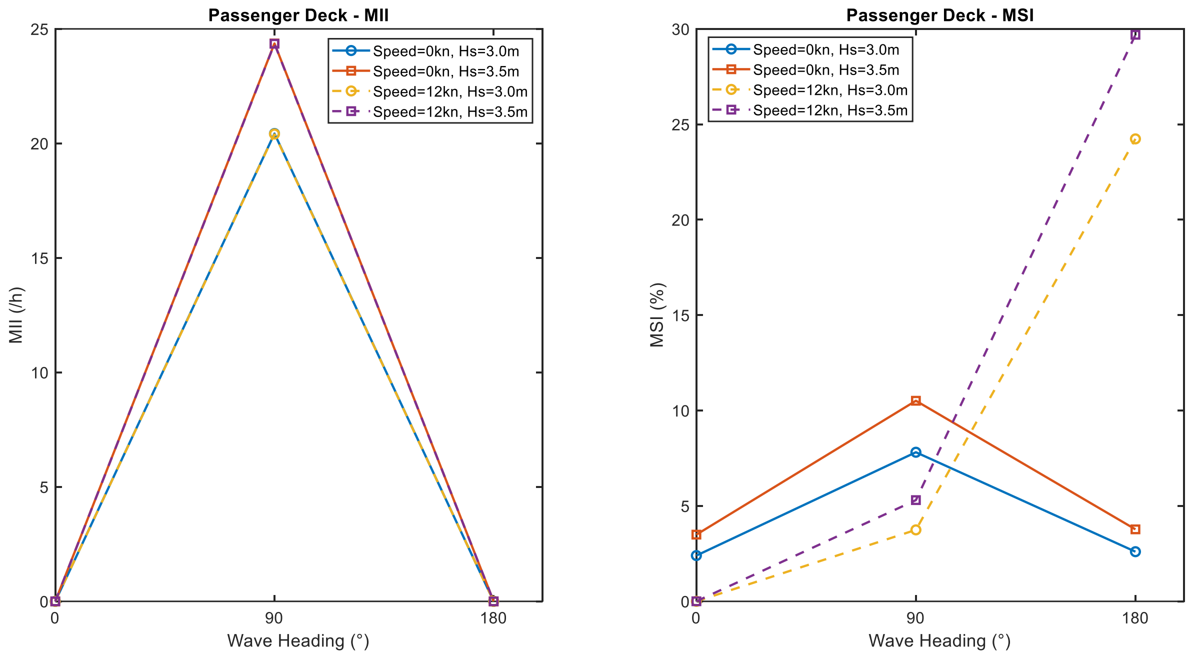


Fig. 14. MII and MSI conditions of each operational conditions on the passenger deck

On the passenger deck, the analysis reveals distinct patterns between activity disruption (MII) and seasickness incidence (MSI), shown in Figure 14. MII shows a sharp peak in beam seas at 90°, where the values exceed 20 interruptions per hour under both 3.0 m and 3.5 m wave conditions. This indicates that passengers are most likely to experience difficulty moving around the vessel in side waves, which can interfere with walking, carrying belongings, or performing routine activities. By contrast, following seas (0°) and head seas (180°) result in negligible MII, suggesting that longitudinal wave directions impose little impact on passenger mobility. In terms of MSI, the results highlight a strong influence of ship speed. At 0 knots, MSI values remain moderate, ranging between 7-11% across headings, with beam seas producing the most discomfort. However, when the vessel operates at 12 knots, head seas become the most critical condition. Under 3.5 m waves, MSI rises dramatically to nearly 30%, meaning that almost one-third of passengers could be affected by seasickness. Thus, while beam seas disrupt activities through MII, head seas at service speed present the greatest risk to passenger comfort due to high MSI. The navigation deck, located at the highest level above the vessel's center of gravity, experiences the most severe motion effects of all decks, which can be seen in Figure 15. Motion-Induced Interruptions again peak under beam seas at 90°, with values surpassing 30-35 interruptions per hour in 3.5 m waves. At this level, such extreme MII means that crew members could face significant difficulty performing operational duties on the bridge, including navigation, equipment handling, and maintaining situational awareness. For MSI, the navigation deck proves even more critical. At 0 knots, MSI remains relatively low at 5-7%, showing that stationary operations do not strongly impact crew comfort. Yet at 12 knots, head seas amplify motion sickness risks dramatically. In 3.5 m waves, MSI values rise to more than 35%, the highest across all decks. Such conditions would seriously compromise crew health and effectiveness, potentially impairing decision-making and safety. This suggests that, while beam seas are the most problematic for MII, head seas at higher speeds pose the greatest threat to sustained crew performance on the navigation deck.

The vehicle deck, positioned closest to the vessel's center of gravity, experiences significantly lower motion responses compared to the upper decks, as visualized in Figure 16. MII responses on this deck remain relatively small even in beam seas, peaking at only 3-5 interruptions per hour under 3.5 m wave conditions. This reduced sensitivity reflects the deck's proximity to the roll axis, minimizing the lateral displacements that drive activity disruption. From an operational perspective, this means vehicles and cargo are less likely to shift significantly, although some risk persists under strong beam seas. For MSI, the vehicle deck shows moderate but noteworthy values. At 0 knots, MSI remains low, between 4-6% across headings. However, at 12 knots in head seas, MSI climbs to between 20-27% in 3.5 m waves. Although these values are lower than those on the navigation deck, they remain operationally significant, particularly for crew working on or near the vehicle deck during rough sea conditions. Overall, while the vehicle deck is least affected by motion compared to the passenger and navigation decks, head seas at higher speeds still present a considerable risk of discomfort and seasickness for the condition.

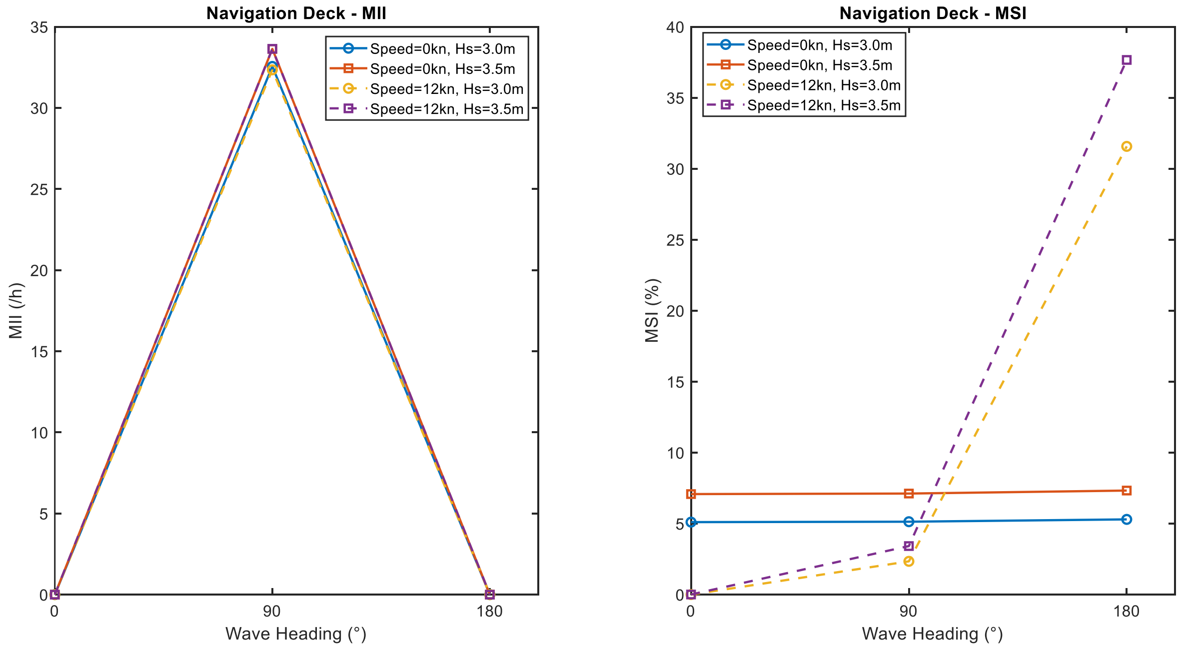


Fig. 15. MII and MSI conditions of each operational conditions on the navigation deck

When comparing motion effects across the three decks, a clear relationship emerges between vertical location on the ship and the severity of responses. The navigation deck, being the highest above the center of gravity, experiences the strongest amplification of both MII and MSI, making it the most critical area in terms of crew comfort and safety. The passenger deck shows intermediate responses, where MII peaks in beam seas and MSI peaks in head seas, indicating that passengers are vulnerable to both activity disruption and seasickness depending on the wave direction and ship speed. By contrast, the vehicle deck located closest to the roll axis experiences the least severe responses, with MII remaining relatively small and MSI only becoming problematic under head seas at service speed. These findings demonstrate that both vertical location and operational conditions strongly govern the comfort and safety outcomes on Ro-Ro ferries. Beam seas primarily drive high MII, disrupting activities on the passenger and navigation decks, while head seas at service speed pose the greatest risk for MSI, particularly on the navigation deck where seasickness incidence reaches critical levels. The vehicle deck benefits from its low vertical position but still faces challenges under unfavorable conditions. Collectively, the results emphasize the need to carefully consider deck layout, speed selection, and route planning in order to mitigate passenger discomfort and ensure safe, efficient operations for crew and cargo.

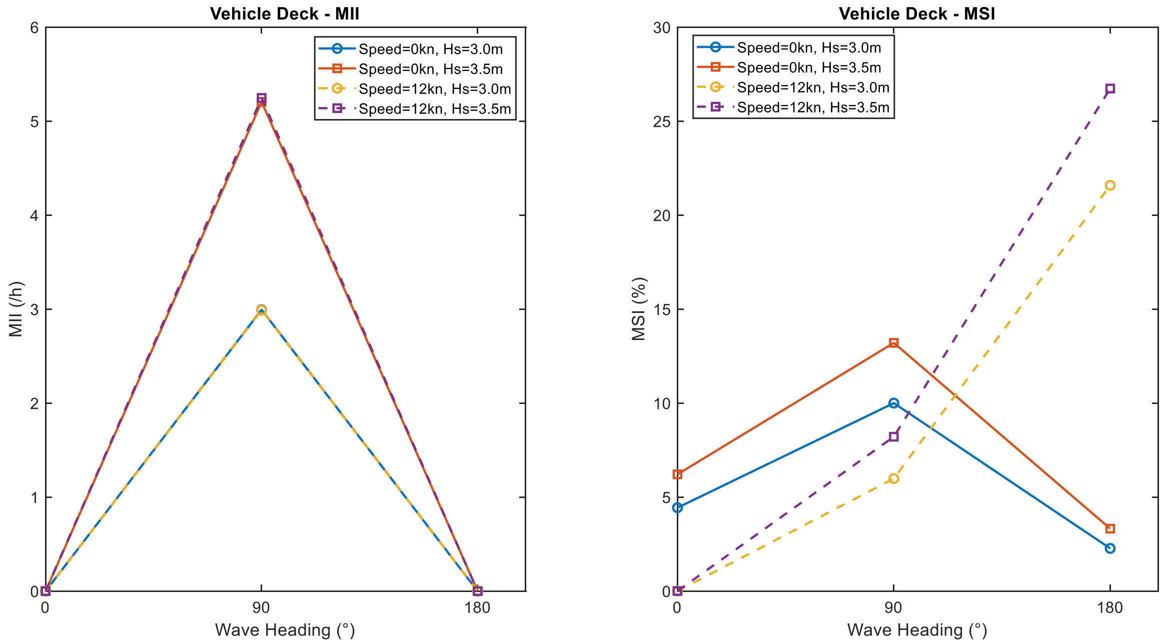


Fig. 16. MII and MSI conditions of each operational conditions on the vehicle deck

The results of this study can be validated by earlier research conducted on ship motion and passenger comfort. Scamardella and Piscopo (2010) highlighted the use of MSI as a critical criterion for assessing passenger comfort in catamarans, demonstrating that MSI levels vary significantly with wave height, heading, and vessel type. Their findings support the present observation that head seas at service speed generate the most severe MSI conditions on Ro-Ro ferries, while beam seas dominate in terms of activity disruption through MII. Similarly, Tezdogan et al. (2014) emphasized the importance of incorporating seakeeping analysis in realistic irregular wave conditions, showing that passenger comfort is highly sensitive to both wave parameters and ship operating conditions. This aligns with the trends identified in the current work, where variations in wave height, heading angle, and vessel speed were shown to directly affect MSI and MII outcomes across different decks. Together, these studies reinforce the reliability of using MSI and MII indices to assess passenger comfort and operational safety in Ro-Ro ferries.

The findings of this study highlight two main operational challenges for Ro-Ro ferries: excessive roll in beam seas, which results in high MII, and elevated MSI in head seas at service speeds. To mitigate these issues, both design modifications and operational measures can be employed. From a design perspective, the application of motion-reducing appendages has proven effective in improving seakeeping performance. For instance, a computational study on a 1200 GT passenger vessel demonstrated that fitting a NACA 4412 stern foil reduced resistance by 3.6% while also significantly decreasing heave and pitch amplitudes, thereby improving passenger comfort in head seas (Asmara, 2021). Similarly, numerical investigations into the use of interceptors and stern flaps reported reductions in vertical motion responses, with heave and pitch transfer functions decreasing by approximately 7.2% and 3.9% under certain wavelength conditions (Sun, 2023), (Song, 2024). These results suggest that appendages such as stern foils and flaps can play a crucial role in lowering vertical accelerations, thereby mitigating motion sickness and improving operational safety. On the operational side, the implementation of weather-routing systems offers considerable benefits. These systems allow voyage planning that avoids severe sea states, improving safety and minimizing motion-related disruptions. Weather routing has demonstrated tangible results in optimizing routes to reduce both fuel consumption and exposure to adverse conditions, leading to safer and more comfortable voyages (Pennino, 2020), (Nguyen, 2016), (Cui, 2016), (Lloyd, 1998).

4. CONCLUSIONS

This study analyzed the motion responses, Motion Sickness Incidence (MSI), and Motion-Induced Interruptions (MII) of a Ro-Ro ferry using strip theory under varying operating conditions. The simulations considered wave heights of 3.0 m and 3.5 m, vessel speeds of 0 knots and 12 knots, and wave headings of following seas (0°), beam seas (90°), and head seas (180°). The analysis was carried out at three representative locations on board: the passenger deck, the navigation (crew) deck, and the vehicle deck, ensuring that both comfort and safety aspects could be evaluated in relation to international criteria. The results show that the ship's motion responses generally met the NORDFORSK (1987) operability limits under following and head sea conditions. However, under beam sea conditions, the roll motion exceeded the allowable limit, reaching values between 3.97° and 5.6°, which highlights a significant vulnerability to lateral wave excitation. From the MSI analysis based on ISO 2631 criteria, passenger and crew exposure was found to remain within the moderate (tolerable) category for most conditions, both in still and service speed. An exception was observed at 12 knots in head seas, where MSI levels reached the alert category, suggesting a potential risk for passenger discomfort. The evaluation of MII further indicated that both passenger and crew activities could generally continue without major disruption in following and head seas, as the conditions were classified as possible (feasible). In contrast, beam sea conditions again presented the most critical scenario, particularly on the passenger and vehicle decks, where the MII values reached the probable category, signifying a higher likelihood of interruptions to standing and walking activities. Overall, the study highlights that while the Ro-Ro ferry maintains acceptable motion and comfort performance in most operating conditions, beam sea encounters remain a critical challenge due to excessive rolling, leading to increased motion sickness risk and activity disruption.

These findings emphasize the importance of considering human comfort and safety, alongside vessel stability, in the design and operational planning of Ro-Ro ferries. From a design perspective, improvements such as the implementation of bilge keels, active stabilizer fins, or optimized hull form modifications could be considered to reduce roll amplitudes. In addition, careful distribution of passenger and vehicle loads on the main deck could help lower the ship's vertical center of gravity and enhance overall stability. From an operational standpoint, voyage planning plays a crucial role in minimizing discomfort and risk. Avoiding prolonged exposure to beam seas, adjusting vessel speed when encountering rough head seas, and selecting routes that reduce direct lateral wave impact can significantly improve onboard comfort. Furthermore, real-time monitoring of motion responses may be applied as part of safety management to determine operational limits for both crew and passengers. Together, these design improvements and operational strategies can provide a more comprehensive framework for ensuring that Ro-Ro ferries operate not only within technical stability standards but also in ways that safeguard passenger comfort and safety.

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Received 08.04.2026; accepted in revised form 27.05.2026