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Response of Traditional Boat to Ocean Waves in Operational Conditions

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***Abstract*— Traditional boats haves played a significant role in maritime activities such as fishing, transportation, and trade, particularly in Kepulauan Riau. These boats are typically constructed from wood, with hull designs passed down through generations. However, this traditional approach raises potential safety concerns due to the absence of standardized construction practices and compliance with maritime safety regulations. Reports of frequent accidents suggest that human factors and inadequate hull responses to wave conditions are contributing causes. This study aims to analyze the response of traditional boats from Riau Islands using numerical simulation methods. The analysis is conducted using Maxsurf software, particularly Maxsurf Motions and Maxsurf Stability, applying the linear wave theory approach to evaluate pitch, roll, and heave responses under variations in loading, speed, and wave direction. The results indicate that the boat's intact stability and seakeeping performance meet IMO safety criteria (C1–C6) under both stationary and 6-knot speed conditions. The seakeeping evaluation conducted using Olson's criteria under wave height variations ranging from 0.5 to 1.0 meters demonstrates that the vessel's response consistently remains below the maximum permissible threshold. This research provides initial data and insights to better understand the intact stability and seakeeping characteristics of traditional boats in Riau Islands, particularly regarding their wave response behavior.**

Keywords— Ship Geometry, Seakeeping, Stability, Safety Operation, Maxsurf, Ship Motion.

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I. INTRODUCTION

The history of boatbuilding dates back to the earliest interactions between humans and the sea[1]. This relationship occurs because many human activities are related to the sea. In any part of the world, a country that manages to conquer other nations mostly has strong maririm power, especially in ability to build high-quality boats. Every region with water areas (rivers, seas, lakes) relies on boat transportation and the type of boat used is adjusted to the environment in which the boat operates[2][3][4][5][6][7]. Studies related to ship hulls, particularly regarding resistance, have already been conducted[8][9]. However, the performance of the ship in dealing with waves is still the least addressed. The evaluation of such performance is important, considering that safety is the most important priority in any maritime activity. Study shows that indicate that accidents involving traditional boats show fluctuating numbers, which suggests that the risks remain high and that mitigation measures are necessary[10]. Safety is an important element, but it is often underestimated in boat operations. It is not uncommon for boats accidents to occur due to negligent steering. Suboptimal design of the boat in responding to waves is also a factor in the many boat accidents due to the failure of the boat to withstand the waves[11]. Although research is currently emerging on ambulance ships as safety equipment at sea, it is also necessary to research the boats ability to respond to waves according to the place of operation[12][13].

Riau Islands, the nearest Indonesian province to Singapore, still operates traditional boats as transportation in certain place. Fishing, transporting and trading[14] are the most common activity related to the traditional boats. The boats commonly found in the Riau Islands are typically constructed from wood, fitted with outboard engines, 10 to 20 meters in length with a width between 0.8 and 2 meters. Previous studies on traditional boats in the Riau Island have primarily focused on hydrodynamic resistance[9], with limited exploration of other critical performance aspects. Although stability analyses have been conducted[15][16][17], they were generally confined to boats operating in different geographic contexts, limiting their applicability to the specific environmental and operational conditions of the Riau Islands. Furthermore, previous studies have not sufficiently considered the variation in operational and environmental characteristics across different local sailing areas, which may differ significantly from the specific conditions present in the Riau Islands. Considering the consistently high incidence of maritime accidents involving traditional boats in this region, there is a compelling need for more comprehensive research. Accordingly, this study formulates a research problem centered on analyzing the hull characteristics of traditional boats operating in the Riau Islands to determine their compliance with established maritime safety standards, thereby contributing to efforts in mitigating safety risks and enhancing vessel performance.

Based on the identified research problem, the purpose of this study is to analyze the wave-induced dynamic response of traditional boats to incoming waves

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from various angles of attack. The analysis will be conducted using Maxsurf software, which allows the results to be evaluated against established maritime safety criteria. The variables considered in this study include load conditions, wave direction, and operational speeds—both at minimum and typical operating conditions. These parameters are selected to represent standard operational scenarios, enabling an assessment of whether the boats performance characteristics remain within the acceptable safety margins under real-world conditions.

II. METHOD

A. Description

The research flowchart shown on Figure 1 was obtained by collecting data from operating boats including the length, width, and height of the boat. The model scale used in the boat design process is 1:1. In the design process, validation is also necessary by directly observing the boats condition while it is in the water. Through thorough and careful observation, aspects such as the loading condition, the submerged hull surface, and the load distribution are adjusted to reflect the actual operational conditions of the boat. Variable parameters are entered to obtain a simulation of boat operations that are in accordance with the conditions at the water location. There are at least three variables used to determine the response to varying conditions[18]. The software is a tool that will be used in the study, where the devices to be used are modelling devices, stability analysis, and analysis of boat response to waves. For the intact stability analysis, the hull geometry was defined using 20 stations, five waterlines, and for buttock lines to ensure adequate representation of the boats shape in hydrostatic computations. For the seakeeping analysis, a total of 41 longitudinal strips was employed, in alignment with standard practices for research-level accuracy. The selection of a higher number of strips improves the resolution of the hydrodynamic calculations, particularly in predicting heave and pitch responses, although it inevitably increases computational time. The research will use Maxsurf (Bentley) Software to conduct the simulation process, and it adopts a linear wave theory approach (Linear Strip Theory). From the process carried out, it will obtain intact stability data, which will indicate the ship's performance. The arrangement and calculation of load cases, the location of the center of gravity, and the buoyancy point will significanly affect the final results of the ship's performance in dealing with waves.The final report will be compiled as a form of data processing carried out to determine further the conclusions and research carried out.

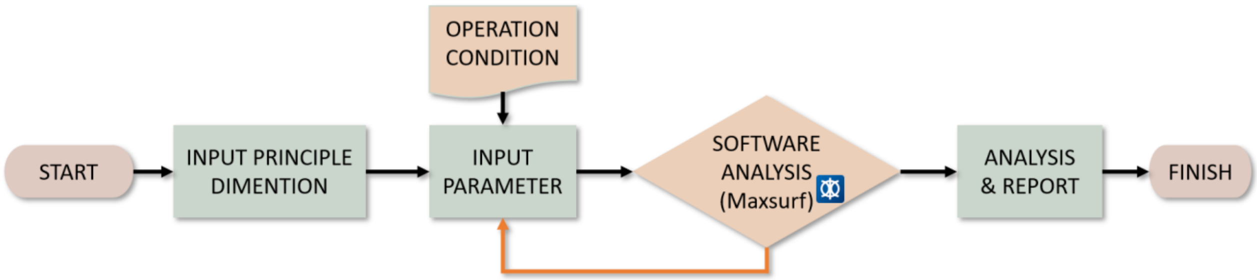


Figure. 1. Research Flowchart

B. Intact Stability Criteria

Capsizing experiments with models have primaly been conducted in irregular waves. While real ocean waves are naturally irregular, experiments using irregular waves must be repeated multiple times with different conditions to achieve statistically reliable results. The required number of repetitions increases significantly when the likelihood of capsizing is relatively low, as is the case for most real boats[19]. The stability curves (GZ) provide a quick and clear understanding of a vessel's stability characteristics[20]. In this study, significant differences have been observed in the stability curves of certain boats. These differences can be quantified by comparing individual stability criteria listed in Table 1. For a more effective comparison of regulatory stability between each fishing vessel and its predecessor, a single measure is preferred, leading to the development of an index related to the KG margin[19][21]. For each vessel, the maximum KG at which all stability criteria in Table 1 are met is determined, referred to as the Limiting KG. The Stability Index (SI) is then calculated as the ratio of the Limiting KG to the actual KG of the analysed loading condition. Expressed as a percentage, the SI indicates the vessel's stability reserve.

The traditional boat used in this study carries several types of loads. The loads on board include the engine, one crew member during the light load condition, and passengers during the full load condition. Additionally, accommodations such as mooring equipment, safety gear, and tools for minor repairs are also included. The total load case weight is 1860 kg under the light load condition and 2560 kg under the full load condition. The positions of the LCG (Longitudinal Center of Gravity), TCG (Transverse Center of Gravity), and VCG (Vertical Center of Gravity) are 3.881 m, 0.00 m, and 0.399 m, respectively, for the light load condition, and 3.758 m, 0.00 m, and 0.364 m for the full load condition. The use of an outboard engine on the boat minimizes the impact of the free surface moment effect; therefore, in the calculation performed, the effect of this moment is considered negligible. The graph displayed in Figure 2 represents a stability curve, also known as a righting lever curve or, in technical terms, a GZ curve. A simiIliar graph usually found for stability book of any typical boat. The small boat illustrations beneath the graph depict the corresponding roll angles and the shifting forces acting on the boat. This graph demonstrates the righting lever arm of a stationary boat in calm water as the roll angle increases. The shape of the righting lever curve varies based on the boats fuel, supplies, and cargo load

TABLE 1 .
IMO INTACT STABILITY CRITERIA RESOLUTION A.749(18) - CODE ON INTACT STABILITY FOR ALL TYPES

Criteria	Magnitude to check	Criterion type	Limiting value
C1	Area under GZ curve between 0º and 30º	Not less than	0.055 rad.m
C2	Area under GZ curve between 0º and 40º or the flooding angle	Not less than	0.090 rad.m
C3	Area under GZ curve between 30 and 40º or the flooding angle	Not less than	0.030 rad.m
C4	GZ at a heeling angle of 30º or more	Not less than	200 mm
C5	Heel angle corresponding to maximum GZ	Not less than	25º
C6	Initial metacentric height (GMo)	Not less than	350 mm

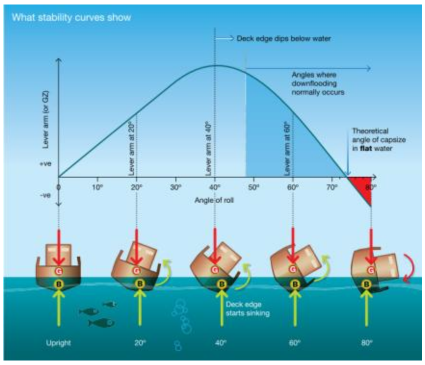


Figure. 2. Ship Stability Curve

C. Boat Response

Numerical calculations in irregular waves are performed after completing calculations in regular waves, where the results are obtained from the ratio between the response output (Sj) and the wave excitation input (Sζ) for the six degrees of freedom wave frequency (ωe), and wave heading (β),. This ratio is known as the Response Amplitude Operator (RAO), which serves as a key parameter in analyzing the ship's behavior in ocean waves. By utilizing RAO, the ship's response in irregular waves can be determined through the convolution of the ocean wave spectrum and the squared RAO, enabling the estimation of the boats motion characteristics under various operational conditions. This equation is shown as Equation 1.

$$RAO_j(\omega_e;\beta) = \frac{S_j\ (\omega;\beta)}{\zeta\ (\omega)} \tag{1}$$

The spectrum refines the Pierson–Moskowitz model, with the North Sea's extreme conditions characterized by limited fetch due to surrounding landmasses, yet generating large waves.[22][23]. Hasselmann et al. in their 1973 study, which analysed data from the Joint North Sea Wave Observation Project (JONSWAP), made an important discovery about ocean wave spectra. They found that the wave spectrum observed in the North Sea was not fully developed but continued to evolve through non-linear interactions between waves, even over extended periods and distances. To account for this phenomenon and to better match their measurements, they introduced an additional, somewhat artificial factor into the Pierson-Moskowitz spectrum. This additional factor modified the Pierson-Moskowitz spectrum by multiplying it with an extra peak enhancement factor(γr). This adjustment was necessary to improve the accuracy of their wave spectrum predictions based on the observed data, as the traditional Pierson-Moskowitz spectrum alone did not fully capture the evolving nature of the wave field in the North Sea as revealed by their analysis of the JONSWAP data. This modification led to what is known as the JONSWAP spectrum, which has become a valuable tool in ocean wave modelling and engineering. The JONSWAP Spectrum was applied in this study as it reflects the conditions of the Java Sea, Indonesia—an enclosed archipelagic area. [24][25][26] as described in Equation 2.

$$\begin{gathered} S_j(\omega) = \frac{\alpha g^2}{\omega^5} \exp\left[-\frac{5}{4}\left(\frac{\omega_p}{\omega}\right)^4\right]\gamma^r \\ r = \exp\left[-\frac{(\omega-\omega_p)^2}{2\sigma^2\omega_p^2}\right] \end{gathered} \tag{2}$$

To evaluate the ship's response in irregular waves, the wave spectrum must be transformed into a response spectrum, denoted as Sr(ω). This transformation is achieved by multiplying the wave spectrum Sζ(ω) by the squared Response Amplitude Operator (RAO), as described in Equation 3. The area beneath the response spectrum curve corresponds to m_n, also known as the n - th moment, as expressed in Equation 4. Specifically, for n = 0, it represents displacement; for n = 2, it denotes velocity, Root Mean Square (RMS), or standard deviation; and for n = 4, it signifies acceleration. The square root of m_n is referred to in Equation 5[15].

$$S_r(\omega) = RAO^2 \times S_\zeta(\omega) \quad 3)$$

$$m_n = \int_0^\infty \omega^n S_r(\omega) d\omega \quad 4)$$

$$RMS = \sqrt{m_n} \quad 5)$$

D. Sea Keeping Criteria

The basic calculation method used in boat seakeeping analysis is known as strip theory [18]. Strip theory is a widely employed technique for predicting a boats seakeeping performance, particularly in the frequency domain. In summary, strip theory is a valuable and efficient tool for boat seakeeping analysis, allowing engineers and naval architects to predict how a boat will respond to waves and other environmental conditions. Despite its widespread application, the use of strip theory requires careful consideration of several inherent limitations. As it is fundamentally grounded in linear potential flow theory, strip theory may yield less accurate predictions in conditions involving large-amplitude waves or significant boat motions due to the exclusion of nonlinear effects. Moreover, the inviscid flow assumption limits its applicability for low-speed operations or boats with complex hull geometries. While it primarily deals with linear responses, it remains a practical choice in many real-world applications[19]. Boat motion is a critical factor in boat design, as it determines a boat's ability to withstand varying sea conditions. Seakeeping calculations are rooted in the idea that a boat navigating through water will exhibit motion patterns dictated by the prevailing wave conditions. When shaping a boats hull, the performance characteristics of that hull shape are pivotal in understanding how the boat will respond to different wave conditions, including extreme ones where the boats performance could be compromised. Three primary boat movements govern boat seakeeping: heaving, rolling, and pitching. These movements demonstrate how effectively a boat can adapt to the specific wave spectrum it encounters. The term "water conditions," or "sea state conditions," pertains to categories established by the World Meteorological Organization (WMO), which classifies waves into three main categories: small (slight), moderate, and large. These categories help define the range of conditions a boat must contend with while navigating at sea[20].

In the field of oceanography, "sea state" refers to the overall state or condition of the water's surface in a specific area and at a particular time. It specifically pertains to the presence of wind-generated waves and swell. A sea state is typically described using statistical measures such as wave height, wave period, and wave spectrum. This condition in the sea is not constant but changes over time as a result of alterations in wind patterns and swell characteristics[27].

TABLE 2.
WMO SEA STATE CODE TABLE 3700

WMO Sea State Code	Wave height	Characteristics
0	0 metres (0 ft)	Calm (glassy)
1	0 to 0.1 metres (0.00 to 0.33 ft)	Calm (rippled)
2	0.1 to 0.5 metres (3.9 in to 1 ft 7.7 in)	Smooth (wavelets)
3	0.5 to 1.25 metres (1 ft 8 in to 4 ft 1 in)	Slight
4	1.25 to 2.5 metres (4 ft 1 in to 8 ft 2 in)	Moderate
5	2.5 to 4 metres (8 ft 2 in to 13 ft 1 in)	Rough
6	4 to 6 metres (13 to 20 ft)	Very rough
7	6 to 9 metres (20 to 30 ft)	High
8	9 to 14 metres (30 to 46 ft)	Very high
9	Over 14 metres (46 ft)	Phenomenal

The design of a boat is significantly influenced by its ability to handle the motion at sea. When determining the boats key measurements and planning its internal layout, the impact of boat movements is taken into account. For instance, in the majority of boats, the frontmost section of the boat encounters the most severe motion, making it generally unsuitable for accommodating passengers or crew. In rare instances where boat movements endanger the crew, the boats structure, or its machinery, or when they hinder the boats ability to fulfil its mission, adjustments to the design are necessary to minimize these boat motions[28]. The selection of wave criteria will also affect the determination of boat response criteria. Criteria are the basis for assessing the standard of acceptance calculation result, primarily as a form of mitigation in accepting the risk of events that may occur. In boat response calculations, there are some criteria that must be considered, as shown in table 3which is take from Olson's research [25]. These criteria can provide an initial hypothesis in the analysis

TABLE 3.
OLSON'S SEAKEEPING CRITERIA

Item	Maximum Value
Average Amplitude Roll	12 (deg)
Average Amplitude Pitch	3 (deg)
Significant Heave Acceleration	2 (m/s)

E. Boat Geometry and Condition

The construction of traditional boats in Indonesia has developed significantly long before foreign nations arrived, particularly in the Sulawesi region[5]. Many traditional shipyards have emerged and evolved in response to the needs of local communities. Internationally, several countries also develop traditional boats, where the construction process highly considers the function and usability of the boat[29][6][30][1][31]. In Indonesia, traditional boats have also evolved due to the country's archipelagic nature[32]. Despite varying regional characteristics, Indonesia shares a similar tropical climate and weather conditions, resulting in a rich diversity of local traditional boat designs. In the Riau Islands, boats are known as Lancang Kuning, while the type commonly used by local communities is called pompong, a boat similar to a longboat[4].

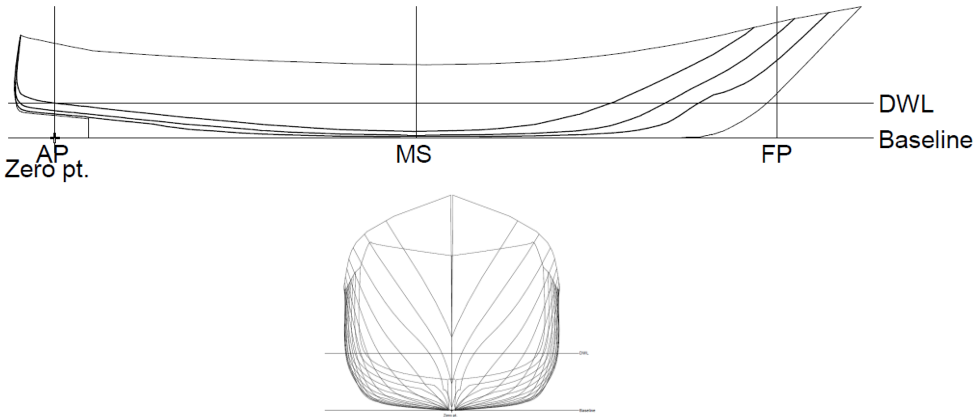


Figure. 3. Boat Lines Plan for research

A boat lines plan is needed to get a basic drawing pattern in boat design. The lines plan is a three-dimensional boat image represented in two-dimensional image. Figure 3 is a traditional boat lines plan image which includes data presented in Table 3. The main size data of the boat will then be used as a parameter entered into the software. The analysis results will be displayed directly by the software, further analysis. In it will be entered parameters, criteria that are in accordance with boat operations. In this case the results obtained can serve as a reference in boat operations.

TABLE 4 .
BOAT PRINCIPLE DIMENTION

Parameter	Value
Length Overall	9.693m
Breath	1.56m
High	0.764m
Draft	0.40m
Cb	0.534m
Displacement	3.229 ton

The principal dimensions of the long boat used in this study are presented in Table 4. The boat has an overall length of 9.693 meters, a breadth of 1.56 meters, and a height of 0.764 meters. The draft of the boat is 0.40 meters, indicating the depth of the hull submerged in water. The block coefficient (Cb) is 0.534, which signifies the fullness of the hull form, reflecting a balance between stability and hydrodynamic efficiency. Additionally, the total displacement of the boat is recorded at 3.229 tons, representing the total weight of the water displaced by the hull when fully loaded. These dimensions are crucial in determining the boats stability, maneuverability, and overall performance in various sea conditions

III. Results and Discussion

A. Intact Stability for Boat

Numerical computational calculations are performed using software to obtain maximum results with more optimal use of time. The use of maxsurf software can provide initial input that can be processed to find the initial hypothesis of the analysis. The calculations in this study use the variables of speed, wave angle of attack and load as the main variables. These variables are adjusted to the actual operational conditions of the boat so that the analysis results obtained are close to the real boat conditions. The traditional boat used for analysis is a monohull. The first condition of the analysis is when the boat is empty (lightship). Lightship is a condition where the weight that affects the condition of the boat includes the weight of the boat's construction, the weight of the cargo, the weight of the boat's driver, the weight of the machinery and the weight of accommodation or other equipment. The total weight of the empty boat is 1860 kg, which is the total weight of the main components of the boat. In the following condition, the boat load is added with the passenger load according to the maximum boat condition. The maximum passenger load is chosen to determine the most severe condition, which solutions can be found. The total load, including the boat passengers, is 2560 kg.

TABLE 5.
BOAT LOAD CASE AT MAXIMUM CONDITION

Item Name	Quantity	Unit Mass (kg)	Total Mass (kg)
Lightship	1	1650	1650
Engine	1	40	40
Crew	1	70	70
Passenger Line 1	1	140	140
Passenger Line 2	1	140	140
Passenger Line 3	1	140	140
Passenger Line 4	1	140	140
Passenger Liner 5	1	140	140
Accommodation	1	100	100
Total Loadcase			2560

TABLE 6.
INTACT STABILITY RESULT WITH IMO RESOLUTION A.749(18) CRITERIA FOR MAXIMUM CONDITION

Code	Value	Units	Actual	Status
IMO intact stability criteria C1	0.0550	m.rad	0.0620	Pass
IMO intact stability criteria C2	0.0900	m.rad	0.1028	Pass
IMO intact stability criteria C3	0.0300	m.rad	0.0408	Pass
IMO intact stability criteria C4	0.200	m	0.354	Pass
IMO intact stability criteria C5	25	deg	72.7	Pass
IMO intact stability criteria C6	0.350	m	0.506	Pass

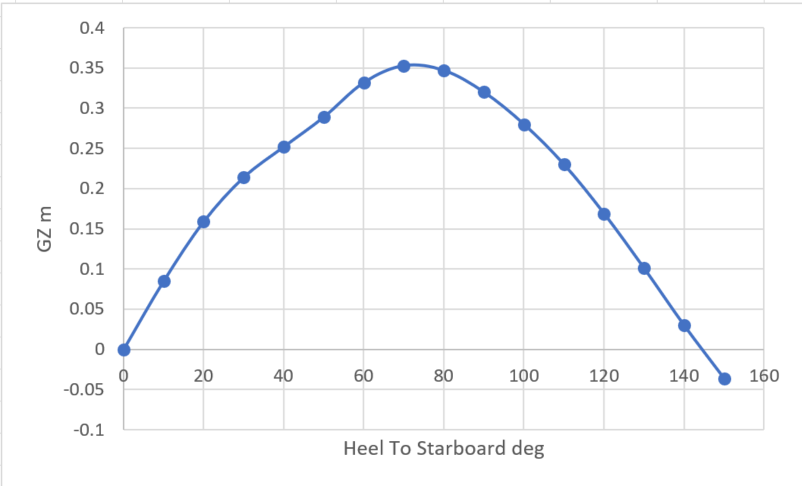


Figure. 4. Graphic GZ for Maximum Condition

Intact Stability Criteria evaluates the stability of the traditional boat in intact condition (see Table 6), based on the loading condition in Table 5, comparing the required standard values with the actual values achieved by the boat. The first criterion, GZ area between limits, has a standard value of 0.2 m with a minimum at 25 degrees and an actual value of 0.354m at 72.7 degree as shown on Figure 4, indicating that the boat exceeds the minimum requirements, with a status of PASS. The next criterion, initial GMt, shows that the traditional boat meets the set standards, The results indicate a PASS status, confirming that the boat not only meets but also exceeds the required stability standards, thereby ensuring a high level of safety and dependable performance across a range of operational conditions.

TABLE 7.
LOAD CASE AT LIGHTSHIP CONDITION

Item Name	Quantity	Unit Mass (kg)	Total Mass (kg)
Lightship	1	1650	1650
Engine	1	40	40
Crew	1	70	70
Accommodation	1	100	100
Total Loadcase			1860

TABLE 8.
INTACT STABILITY RESULT WITH IMO RESOLUTION A.749(18) LIGHTSHIP CONDITION

Code	Value	Units	Actual	Status
IMO intact stability criteria C1	0.0550	m.rad	0.0565	Pass
IMO intact stability criteria C2	0.0900	m.rad	0.0967	Pass
IMO intact stability criteria C3	0.0300	m.rad	0.0402	Pass
IMO intact stability criteria C4	0.200	m	0.359	Pass
IMO intact stability criteria C5	25.0	deg	69.1	Pass
IMO intact stability criteria C6	0.350	m	0.437	Pass

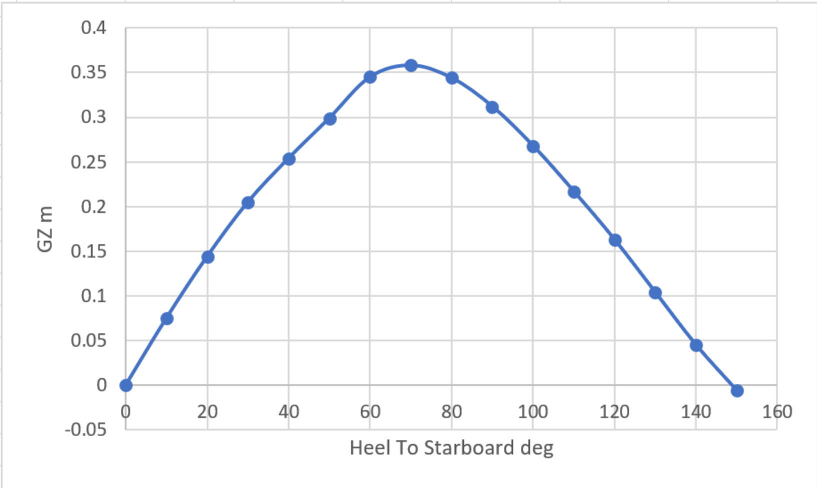


Figure. 5. GZ Graphic at Lightship Passenger and Load

The intact stability result (Table 8), based on the loading condition in Table 7, shows that the traditional boat exceeds the required standards. The GZ area shown on Figure 5 reaches 0.359 m at 69.1°, surpassing the minimum 0.2 m at 25°, and the GMt also meets the standard. Overall, the boat passes all criteria, indicating good stability and safe performance.

TABLE 9
DETAIL ESTIMATED MASS PROPERTIES MAXIMUM CONDITIONS

Item Name	Qtt	Unit Mass kg	Total Mass kg	Long. Arm m	Trans. Arm m	Vert. Arm m
Lightship	1	1650.00	1650.00	3.89	0.00	0.37
Engine	1	40.00	40.00	0.30	0.00	0.40
Crew	1	70.00	70.00	1.00	0.00	0.35
Passenger Line 1	1	140.00	140.00	1.70	0.00	0.35
Passenger Line 2	1	140.00	140.00	2.40	0.00	0.35
Passenger Line 3	1	140.00	140.00	3.10	0.00	0.35
Passenger Line 4	1	140.00	140.00	4.80	0.00	0.35
Passenger Liner 5	1	140.00	140.00	5.50	0.00	0.35
Accommodation	1	100.00	100.00	3.89	0.00	0.20
Total Loadcase			2560.00	3.65	0.00	0.36
FS correction						0.00
VCG fluid						0.36

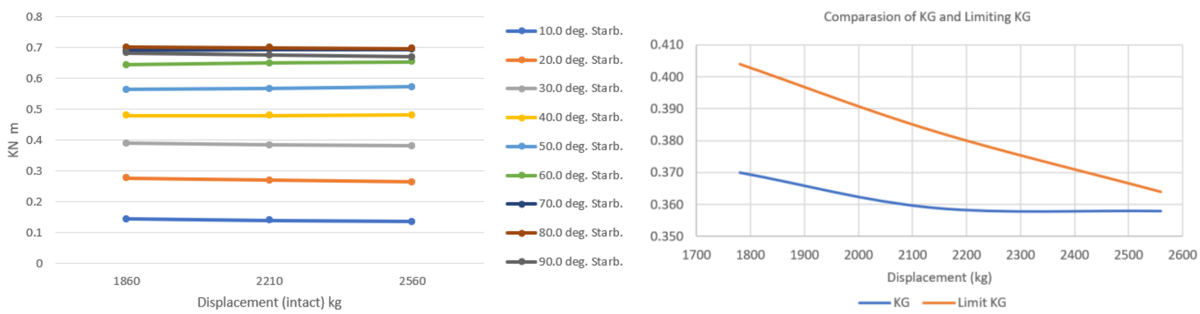


Figure. 6. KN, KG and Limit KG Value

From the stability analysis, we can also observe the values of KN and Limit KG, which help understand the condition of the boat. The availability of KN and Limit KG allows us to identify the boats characteristics, serving as a basis for adding, arranging, and determining load placement points. Figure 6 presents the software-calculated results showing the variation of KN and Limit KG values from the lightship condition to the maximum load condition based on the detail estimated mass properties presented in Table 9. The stability of the KN values across different displacement levels indicates that the hull form of the boat is well-designed to maintain stability under various heel angles, even as the ship's weight increases. The KG graph illustrates the relationship between actual KG and limiting KG across displacements from 1700 to 2600 kg. In all cases, actual KG remains below the limiting KG, indicating an adequate safety margin for vessel stability. Both values decrease with increasing displacement, reflecting changes in the vertical center of gravity and allowable stability limits.

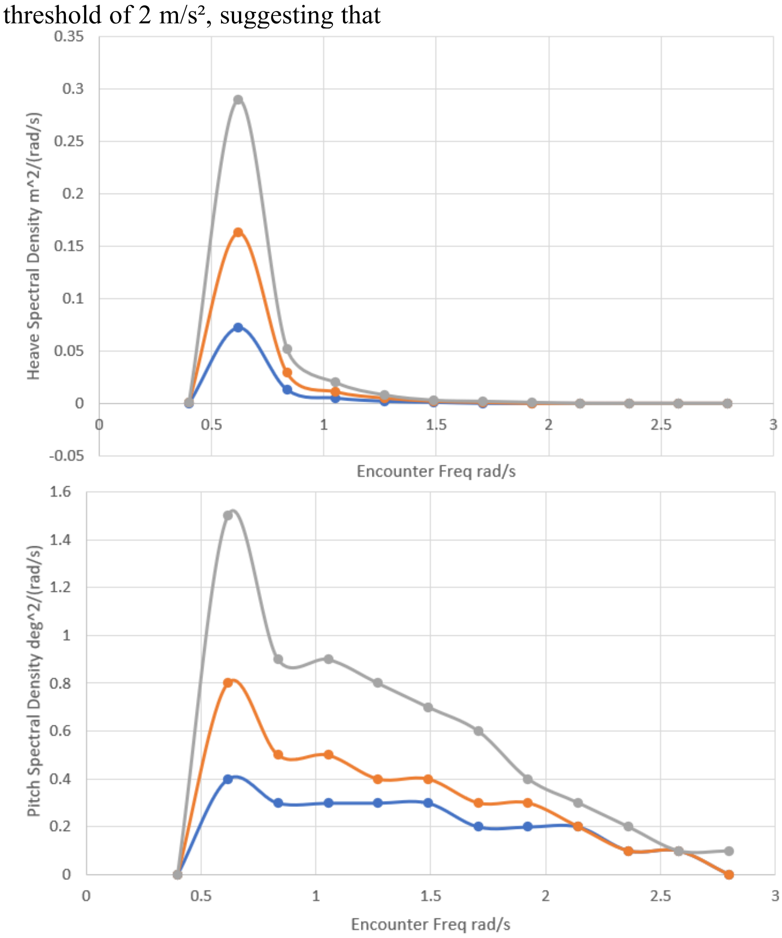
B. Boat Response to Wave

The results of the analysis of boat response to waves are important data to determine the characteristics of the boat in responding to waves. Several criteria are added as a measuring tool for analysis to comply with standards. The results obtained may exceed or fall short the minimum standards set by the regulations. Proper curation and adoption of the data obtained will be the next step taken by researchers to be realized in engineering solutions. Table 10 present the result of the analysis of boat motion response using general criteria from previous studies.

TABLE 10.
VALIDATION OF MAXSURF MOTION COMPUTATION RESULTS WITH OLSON'S CRITERIA AT 0 KNOTS SPEED

Wave Height	Average Amplitude Roll (max 12 deg)					Average Amplitude Pitch (max 3 deg)					Significant Heave Acceleration (max 2 m/s)				
	Speed 0 Knot														
	0	45	90	135	180	0	45	90	135	180	0	45	90	135	90
0.5	0.00	1.53	2.16	1.53	1.34	0.91	0.74	0.20	0.55	1.34	0.18	0.20	0.25	0.19	0.42
0.75	0.00	2.29	3.24	2.29	0.00	1.39	1.13	0.31	0.83	0.00	0.28	0.30	0.38	0.29	0.27
1	0.00	3.04	4.30	3.04	0.00	1.81	1.46	0.41	1.10	0.00	0.37	0.40	0.50	0.39	0.36

This research was conducted under three different sea state conditions (Smooth, Slight, and Moderate) to determine the extent of the boats capabilities. Based on the analysis results Figure 7, it can be concluded that 0 knots, the boat meets the seakeeping criteria in terms of average amplitude roll and significant heave acceleration under all tested wave conditions. The roll amplitude remains below the maximum allowable limit of 12 degrees, indicating that the boat exhibits good resistance to roll motion across various wave heights and directions. Additionally, the heave acceleration remains within the acceptable threshold of 2 m/s², suggesting that the boat does not experience excessive vertical acceleration under the tested sea conditions. The pitch motion remains stable with the highest response recorded at 1.81°, also considerably lower than the maximum threshold of 3°. These findings confirm that the boats can maintain safe and acceptable seakeeping performance under the tested wave conditions. It is also evident that the most responses occur at beam sea conditions (90° wave heading), which aligns with theoretical expectations, as this condition exerts the highest influence on roll and heave motions.



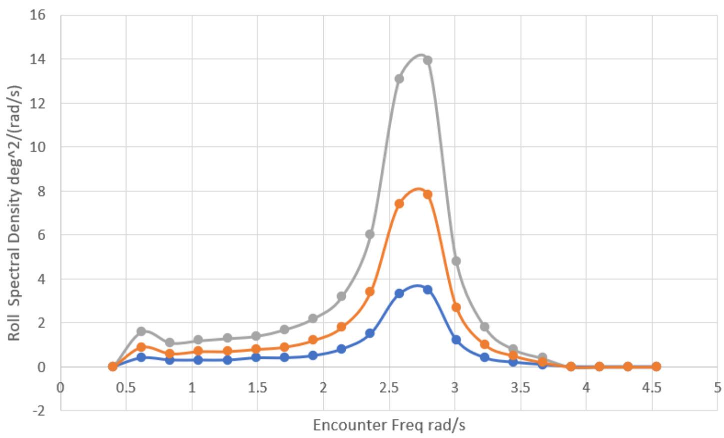


Figure. 7. Motion Spectrum Graph at 0 Knot Speed

It was observed in Figure 7 that the heave, pitch, and roll motions exhibit data trends that are generally linear, with wave peaks and troughs displaying consistent and periodic patterns. The response spectra indicate that the boat reacts in a relatively predictable manner to wave excitations, especially in heave and roll motions. However, an anomaly is evident in the pitch response, where under specific conditions, the spectral characteristics deviate from the expected trend and show a distinct pattern. The simulations were conducted by varying the wave heading angles — Head Sea (0°), Beam Sea (90°), and Following Sea (180°) — under three wave heights: 500 mm, 750 mm, and 1000 mm. From the response amplitude graphs, an increase in wave height leads to a proportional increase in motion amplitudes. Notably, the highest wave peaks result in the most significant motion responses, particularly in pitch, which becomes more sensitive under certain directional wave inputs.

TABLE 11.
VALIDATION OF MAXSURF MOTION COMPUTATION RESULTS WITH OLSON'S CRITERIA AT 6 KNOTS SPEED

Wave Height	Average Amplitude Roll (max 12 deg)					Average Amplitude Pitch (max 3 deg)					Significant Heave Acceleration (max 2 m/s)				
	Speed 0 Knot														
	0	45	90	135	180	0	45	90	135	180	0	45	90	135	90
0.5	0.00	0.69	2.16	1.34	0.00	0.88	0.69	0.30	0.61	0.79	0.08	0.10	0.24	0.42	0.49
0.75	0.00	1.03	3.24	2.01	0.00	1.30	1.03	0.45	0.91	1.19	0.12	0.15	0.33	0.64	0.74
1	0.00	1.36	4.30	2.68	0.00	1.75	1.38	0.60	1.21	1.56	0.16	0.21	0.44	0.85	0.97

Based on the resume of analysis in Table 11, the boat meets seakeeping criteria for roll and heave at 6 knots under all wave conditions. Roll amplitudes stay below the 12° limit, and heave acceleration remains under 2 m/s², indicating good stability in both aspects. Pitch response also remains moderate, with the highest recorded value of 1.75° at head sea (0°) for a 1.0 m wave, which is well below the 3° limit. These findings confirm that the traditional vessel demonstrates adequate seaworthiness for operations at a service speed of 6 knots in wave heights up to 1.0 m.

It is noteworthy to discuss the results of the seakeeping analysis comparison to the representative model. Calculations performed on a traditional "jukung" boat [33](LOA: 10.30 m, Beam: 1.20 m, Depth: 0.90 m, Draft: 0.4 m, Service Speed: 8 knots) revealsed a similar trend. Table 12 presents the analysis results of the "jukung" boat compared with research model

TABLE 12.
SEAKEPING ANALYSIS COMPARATION RESULT OF "JUKUNG" BOAT WITH RESEARCH MODEL

Item	Wave Heading	Amplitude		Velocity		Acceleration	
		Jukung	Research Model	Jukung	Research Model	Jukung	Research Model
Heaving	0	0.123	0.146	0.068	0.071	0.040	0.036
	45	0.123	0.147	0.076	0.083	0.052	0.050
	90	0.125	0.150	0.098	0.118	0.110	0.136
	135	0.125	0.151	0.123	0.156	0.212	0.282
	180	0.126	0.151	0.132	0.166	0.245	0.309

CONTINUED - TABLE 13.
SEAKEPING ANALYSIS COMPARATION RESULT OF "JUKUNG" BOAT WITH RESEARCH MODEL

Item	Wave Heading	Amplitude		Velocity		Acceleration	
		Jukung	Research Model	Jukung	Research Model	Jukung	Research Model
Rolling	0	0.000	0.000	0.000	0.000	0.000	0.000
	45	0.055	0.067	0.009	0.008	0.009	0.006
	90	0.173	0.194	0.078	0.058	0.216	0.108
	135	0.107	0.092	0.049	0.026	0.142	0.053
	180	0.000	0.000	0.000	0.000	0.000	0.000
Pitching	0	0.070	0.078	0.008	0.006	0.006	0.003
	45	0.055	0.063	0.009	0.008	0.009	0.006
	90	0.024	0.032	0.009	0.012	0.023	0.030
	135	0.049	0.059	0.021	0.027	0.068	0.091
	180	0.063	0.079	0.025	0.031	0.081	0.100

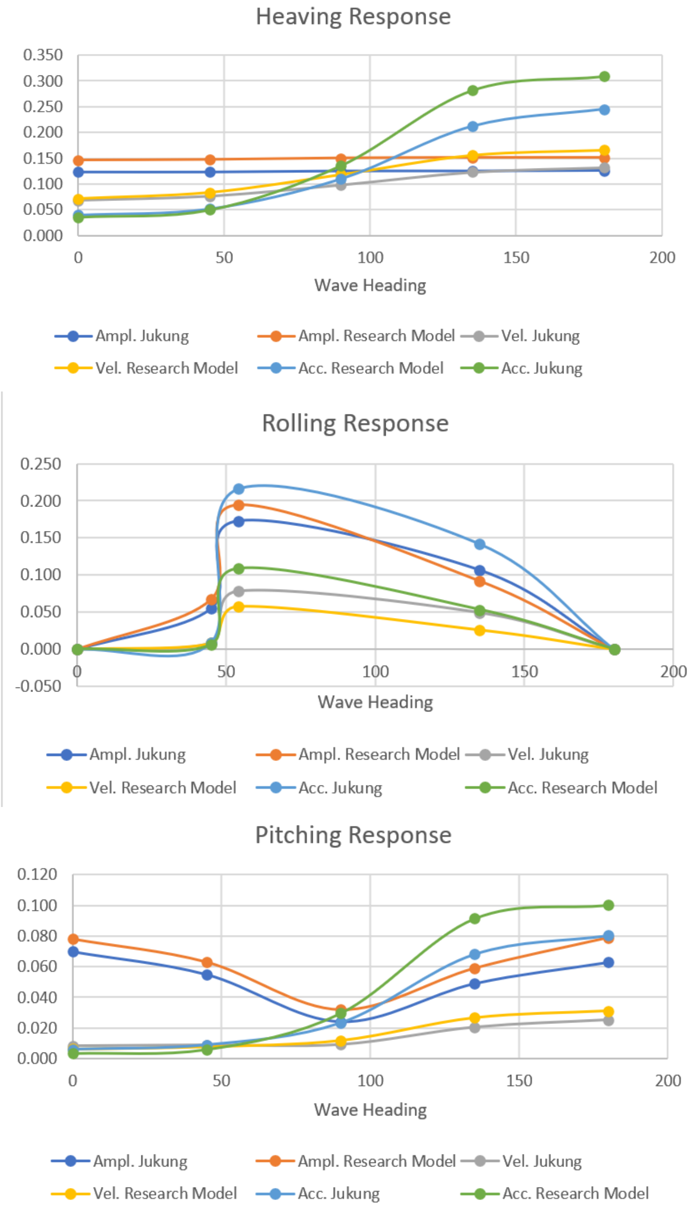


Figure. 8. Comparison Analysis Graph of "Jukung" Boat With Research Model

Table 12, further clarified by Figure 8, presents a comparison and validation to determine the conformity of the research findings with previous studies. The analysis shows that the vessel's response exhibits a similar pattern to that of comparable ship studies. The differences in higher or lower values indicate variations that may occur due to differences in ship size; however, the overall pattern remains consistent. In general, boats in the Riau Islands region display higher values, which means they are closer to the maximum threshold. This finding suggests that further studies are needed regarding the hull form of Riau Islands vessels, particularly concerning the addition of auxiliary components related to ship maneuverability. Consequently, this would provide data that moves further away from the maximum threshold and aligns more closely with the general motion response of ships as indicated by previous research.

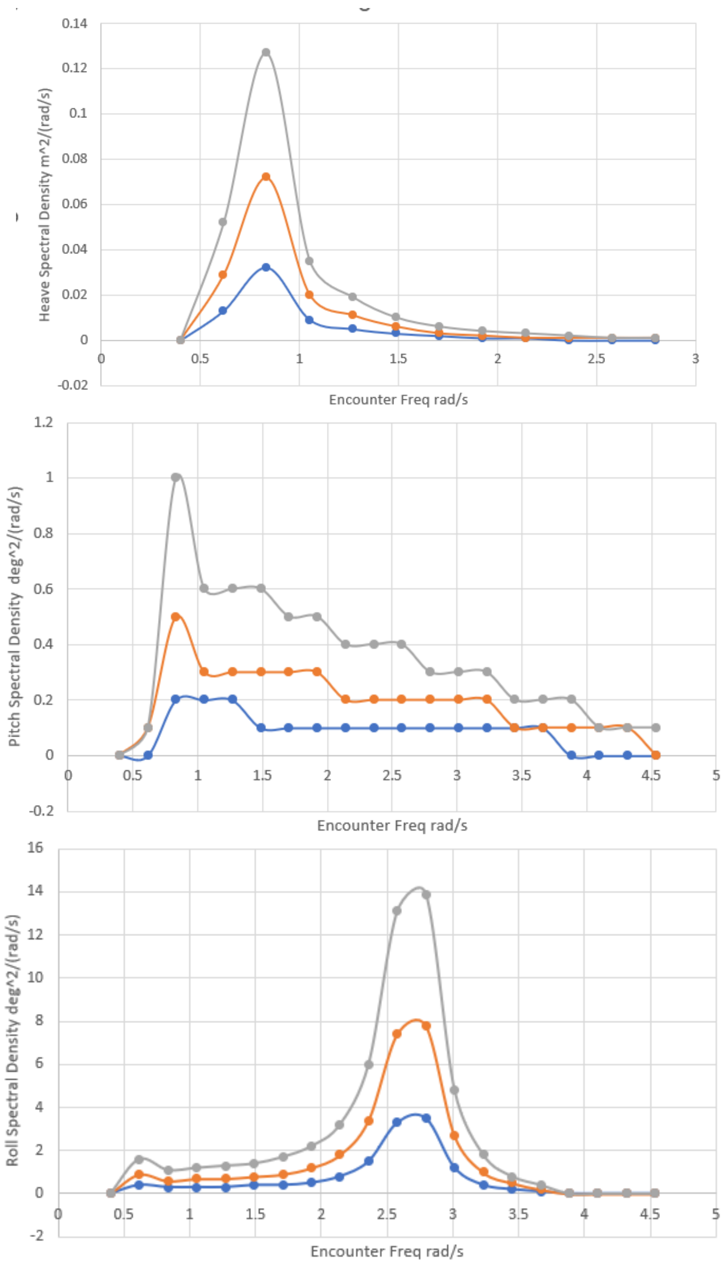


Figure. 9. Motion Spectrum Graph at 6 Knot Speed

The motion spectrum analysis at a speed of 6 knots (Figure 9) shows that the boat exhibits improved seakeeping behavior compared to the stationary condition. The heave response presents lower peak amplitudes across all wave heights, indicating that forward motion contributes to reducing vertical accelerations, likely due to increased hydrodynamic damping. Similarly, pitch motion demonstrates a flatter and more controlled spectral pattern, with fewer anomalies than those observed at 0 knots. Although the pitch remains sensitive, particularly at higher wave heights and specific wave headings, its response is noticeably mitigated by the boats forward speed. Meanwhile, roll motion shows a consistent spectral peak around 2.7 rad/s, similar to the stationary case, but remains within acceptable thresholds.

In comparison to the 0-knot condition, the 6-knot operation yields reduced motion responses in both heave and pitch, while roll motion remains relatively unaffected by the change in speed. These findings suggest that operating the boat at 6 knots enhances overall motion stability, particularly in reducing susceptibility to vertical and longitudinal excitations.

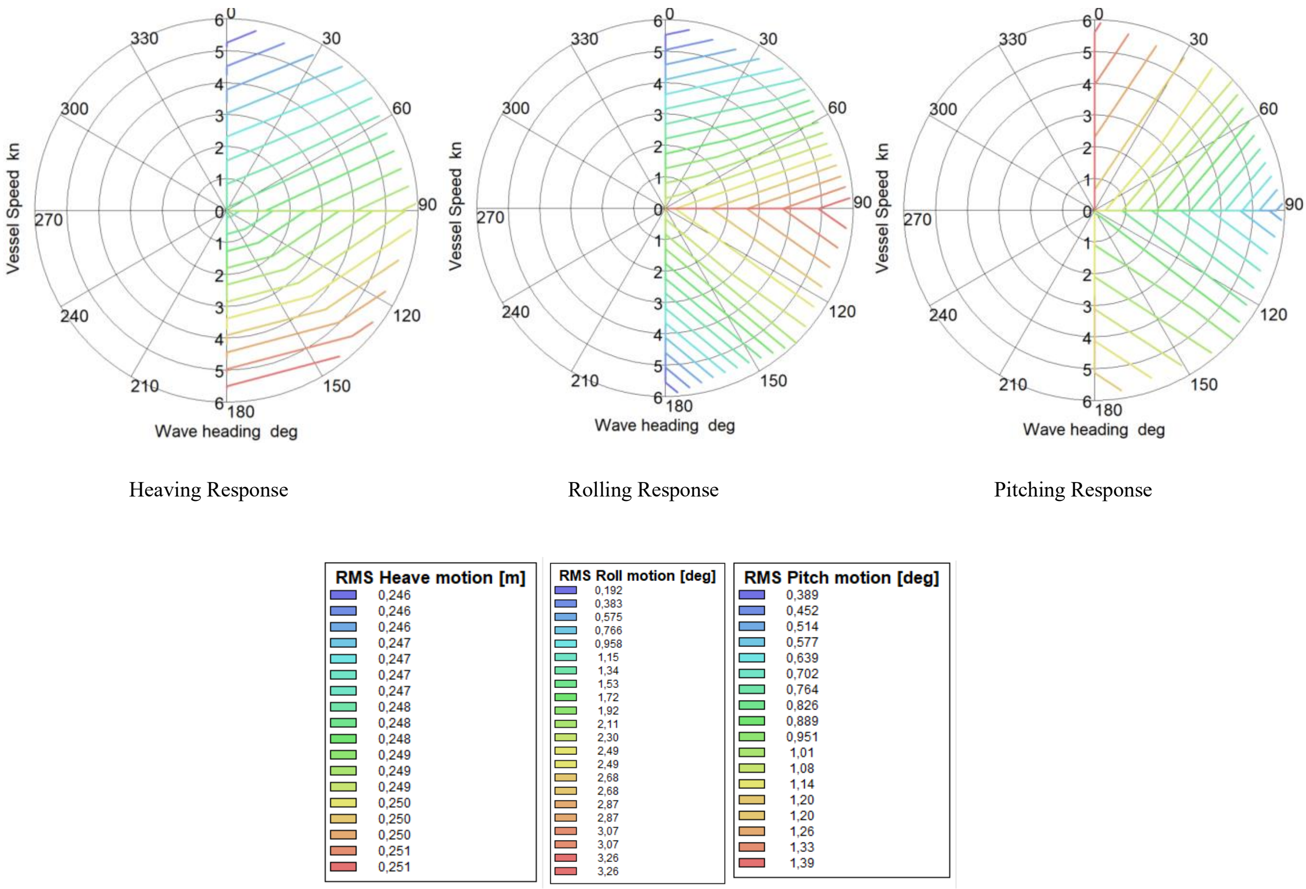


Figure. 10. Polar Diagram on Ship Motion Response

Figure 10 polar diagrams are generated under 6 knots boat speed, which is selected as it represents the boats typical operational speed, reflecting the range of sea conditions commonly encountered in Riau Islands. In the heaving condition, the boat exhibits the highest response when encountering waves from the head and stern sea direction (0 and 180 deg). This result is expected, as heave motion is highly sensitive to wave excitations approaching from the bow and stern. The gradual change in color on the polar plots indicates the emergence of damping effects, which can be attributed to the influence of the hull form. This behavior closely resembles the boats response under pitching conditions. The plots also demonstrate that the amplitude of the pitch response decreases with increasing wave frequency. This trend may result from the reduced interaction between the wave length and the boats length, effectively shortening the lever arm responsible for rotational motion. The damping characteristics observed in this pattern further suggest that the boat is well-tuned to mitigate pitch instability within the analyzed frequency range. As for rolling motion, a distinct peak occurs at beam seas (90° and 270°), where the boat is subjected to maximum transverse wave excitation. The ship experiences significantly higher lateral instability in these directions, which is typical for hulls with limited roll damping mechanisms. This trend may result from the reduced interaction between the wave length and the boat's length, effectively shortening the lever arm responsible for rotational motion. The damping characteristics observed in this pattern further suggest that the boat is well-tuned to mitigate pitch instability within the analysed frequency range. As for rolling motion, a distinct peak occurs at beam seas (90° and 270°), where the boat is subjected to maximum transverse wave excitation. The ship experiences significantly higher lateral instability in these directions, which is typical for hulls with limited roll damping mechanisms.

IV. CONCLUSION

The numerical computational analysis conducted in this study confirms that the boat meets the required stability criteria across various wave conditions and operational speeds. The assessment of intact stability criteria demonstrates that the boat not only complies with but also surpasses the IMO stability standards criteria C1-C6 in both empty and fully loaded conditions, ensuring a robust safety margin. At a stationary position

(0 knots) and operational condition (6 knots), the boat exhibits satisfactory pitch, roll stability and controlled heave acceleration across all tested wave heights and angles, indicating its resilience to external disturbances. It also meets Olson's standard for seakeeping criteria. Referring to previous studies, a comparative analysis with similar types of boats can be conducted to expand the reference base for boat modeling. Overall, the boat exhibits commendable performance in mitigating pitch, roll and heave acceleration. However additional improvements are essential to ensure optimal response, particularly for operations in rough sea conditions. It is noteworthy that the rolling response exhibits relatively high values, reaching up to 0.194, although still within the acceptable safety margin. This observation warrants further attention to ascertain whether such a response is consistently observed across different vessel models or if it is specific to the characteristics of this particular hull form. The implementation of fin stabilizers can help to actively reduce motion by generating counteracting hydrodynamic forces in response to wave-induced movements. Future research should focus on refining the hull geometry, implementing passive or active stabilization technologies, and conducting further experimental validation to enhance the boats overall seakeeping performance and ensure compliance with safety standards.

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