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Study Of Fishing Vessel Motion Response At Muara Angke Port

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Abstract— **Muara Angke Port, one of Indonesia's busiest fishing hubs, faces significant challenges due to dynamic water conditions and heavy vessel traffic, including waves, currents, tides, and vessel interactions. These conditions impact the motion response of fishing vessels, affecting their stability, maneuverability, and operational safety. This study aims to analyze the motion response of fishing vessels operating, focusing on environmental factors influencing vessel operations. A comprehensive analytical approach is employed, including the panel method for seakeeping analysis. Specific seakeeping criteria for fishing vessels, as proposed by Tello, are applied to assess vessel performance in various sea states. The findings indicate that fishing vessels can operate effectively in sea states with wave heights up to 3 meters, or sea state 5 and below. These results provide valuable insights into how fishing vessels respond to environmental challenges at Muara Angke Port, offering recommendations for improvements in vessel design. The study emphasizes the importance of developing operational strategies to reduce accidents and enhance the sustainability of the fishing sector, while supporting the long-term resilience of Indonesia's fisheries industry.**

Keywords— Environmental Factors, Fishing Vessel Motion Response, Maritime Safety, Muara Angke Port, Sustainable Fisheries.

I. Introduction

Indonesia, as the largest archipelagic country in the world, has more than 17,000 islands scattered along the equator [1]. As a country with a vast marine territory, Indonesia possesses extraordinary marine resource potential. The fisheries sector is one of the main pillars of Indonesia's economy, not only supplying local food needs but also contributing significantly to the export of seafood products and creating job opportunities for millions of fishermen and workers in the fisheries supply chain [2]. Fisheries activities in Indonesia, especially those involving fishing vessels, play a vital role in supporting food security and the economy of coastal communities [3].

One of the vital centers of fisheries activity is the Muara Angke Port in Jakarta, which is one of the largest and busiest fishing ports in Indonesia [4]. This port plays a strategic role as the main distribution point for fisheries products, supporting fishing activities around Jakarta and its surrounding areas. Every day, hundreds of fishing vessels of various sizes dock to load and unload their seafood catch, utilizing facilities such as docks, cold storage areas, and processing and distribution rooms for seafood products [5]. This bustling activity makes Muara Angke Port an economic hub that supports the fisheries industry and other economic sectors in the region [6].

Fishing vessels in Indonesia, including those operating in Muara Angke, are predominantly made of wood with simple designs. These vessels are often designed without adequate technical calculations, resulting in performance, safety, and operational comfort that are far from ideal standards [7]. In the shipping industry, vessels are ideally designed based on engineering principles that include stability analysis, fuel efficiency, and motion response to waves. These calculations are crucial to ensure that the vessel can operate safely, stably, and comfortably, while also maximizing catch and minimizing the risk of accidents at sea [8].

Ideally, fishing vessels at Muara Angke Harbor should be designed with careful consideration of critical aspects of ship motion response, such as stability, maneuverability, and survivability in diverse water conditions [9]. An optimal vessel design will enhance its ability to withstand waves, currents, and extreme weather, while reducing the risk of accidents and damage. A well-designed vessel can operate more efficiently and safely, enabling fishermen to work more effectively and improving crew safety and comfort [6] [10].

However, in reality, most of the ships in Muara Angke still use traditional designs that are not based on accurate technical calculations [11]. These vessels are often built without considering important aspects such as stability and motion response to waves, making them vulnerable to the risk of accidents and discomfort for the crew [12]. This issue becomes even more complex considering that the

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majority of fishing vessels in the area are made of wood with a relatively long service life, adding challenges in maintaining the performance and safety of the ships [13]. Moreover, these suboptimal designs make the vessels inefficient in terms of fuel consumption, exacerbate environmental impacts, and limit the ships' ability to cope with changing sea conditions

Another issue that arises is the lack of attention given to the calculation of ship motion response, which is actually a critical aspect of ship design. If the ship's motion response is not properly calculated, the vessel may experience instability, especially when facing large waves, which jeopardizes the safety of the crew and can negatively impact the catch quality [14].

The presence of these traditional ships highlights the gap between current ship design practices and the technical standards required to improve the safety and operational performance of the vessels [15]. This issue becomes increasingly urgent considering the importance of the fisheries sector to Indonesia's economy and the large number of ships operating at major fishing ports such as Muara Angke. Therefore, efforts to improve the design and performance of fishing vessels in Muara Angke are critical, particularly to enhance the safety of fishermen and the operational efficiency of the ships, which in turn can boost the overall productivity of the fisheries sector [9].

Several previous studies have examined various aspects related to fishing vessels in Indonesia, particularly concerning the analysis of ship motion response. The investigation conducted by [16] shows that in the maritime sector, Indonesia's ability to build modern vessels such as tankers and cargo ships is quite adequate. However, in the fishing vessel sector, challenges remain significant, especially regarding vessel design, which still relies on traditional methods without adequate technical calculations[9].

Figure. 1 Muara Angke Port.

Another study conducted at the Nusantara Fisheries Port in Ternate also shows a similar phenomenon, where the planning and design of fishing vessels in Indonesia are still not fully based on comprehensive technical calculations[17]. In their study, the researchers found that the main characteristics of pole-and-line vessels in Ternate did not meet the recommended design standards, particularly regarding the main size ratio of the vessels.

Another study, in addition to the previous ones, highlights the importance of stability analysis and the motion response of fishing vessels, particularly in dealing with various loading conditions and water conditions. The results of this study show that changes in the loading of fishing vessels can significantly affect the stability characteristics and motion response of the vessel, which ultimately has implications for the safety and operational comfort of the vessel [18].

Previous studies have examined the maneuvering characteristics of full-scale ships during berthing and unberthing operations [19]. These studies have utilized comprehensive datasets and advanced statistical techniques to analyze key performance variables, such as approach speed, drift angles, turning motions, and actuator utilization. The findings from these studies have the potential to enhance the accuracy and reliability of conventional maneuvering models, providing valuable insights for the fishing vessel industry.

Additionally, research has been conducted on the maneuvering performance of smaller fishing vessels, including the use of asymmetrical propeller configurations to improve maneuverability [20]. Furthermore, studies have explored the integration of yacht wharfs within traditional fishing ports to better utilize available space and accommodate the changing needs of the fishing industry. [21]

While these studies have contributed to the understanding of vessel maneuvering, there is a need to specifically address the motion response of fishing vessels in the Muara Angke Harbor, considering the unique environmental and operational conditions present in this port. This study focuses on the motion response of fishing vessels operating at Muara Angke Port, aiming to understand how these traditional vessels respond to the dynamic environmental conditions at the port. The focus of this research is to analyze how waves, ocean currents, and weather conditions affect the maneuverability of fishing vessels, as well as to evaluate the potential for design improvements to enhance safety and operational efficiency.

Figure. 2. KM SPARTAN 2.

This research is expected to fill this knowledge gap and contribute to the development of maritime safety policies in the fisheries sector [12][17]. This research aims to provide insights that can lead to the development of more efficient and safer vessel designs, ultimately enhancing the overall productivity and sustainability of the fishing industry in the Muara Angke region. To achieve these objectives, this study uses the panel method to evaluate the motion response of vessels under various environmental conditions, including waves and ocean currents at Muara Angke Port [12]. The seakeeping criteria from M. Tello will be used to assess the ability of fishing vessels to cope with diverse sea conditions [22]. With this approach, the study is expected to provide deeper insights into the design and operation of fishing vessels in Indonesia, as well as contribute to improving safety and efficiency in the fisheries sector at Muara Angke Port and other fishing ports in Indonesia.

II. METHOD

To analyze ship motion behavior, it is essential to first define the coordinate system fixed at the ship's Center of Gravity (CoG), referred to as the body-bound coordinate system G (xb, yb, zb). Ship motions are described in six degrees of freedom relative to the CoG. Translational movements along the x, y, and z axes correspond to surge, sway, and heave, respectively. Rotational movements around the x, y, and z axes represent roll, pitch, and yaw, respectively [23].

The panel method was chosen for its ability to model the interaction between a ship and ocean waves in the frequency domain, allowing for effective analysis of the ship's motion response under different sea conditions. This method uses the principle of potential flow, which assumes that the water flow is irrotational, enabling the calculation of hydrodynamic forces acting on the ship, including the forces generated by waves and the interaction of the ship with the water surface [24]. Figure 3 illustrates the coordinate system along with the linear and angular displacements.

The total velocity potential can be expressed as:

$$\Phi = \varphi + \varphi_I \quad (1)$$

Where, ϕ is the perturbation potential, ϕ_I is the incident potential. The perturbed potential can be solved by Laplace equation.

$$\nabla^2 \varphi = 0 \quad (1)$$

Additionally, the velocity potential must satisfy both the hull boundary condition and the free surface boundary condition.

$$\frac{\partial^2 \varphi}{\partial t^2} + g\frac{\partial \varphi}{\partial z} = 0 \text{ On Z = 0} \quad (3)$$

Here, t represents time, and g denotes gravitational acceleration. The hull boundary condition is formulated as:

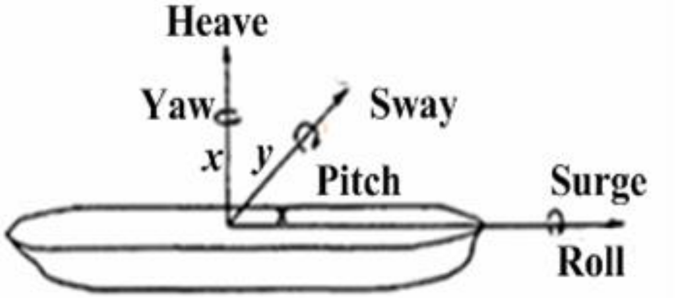

Figure. 3. 6 DOF Ship.

$$\frac{\partial \varphi}{\partial n} = V \cdot n - \frac{\partial \varphi_I}{\partial n} = 0 \text{ On the hull Surface} \quad (4)$$

Here, n is the unit normal vector pointing into the fluid, and V represents the instantaneous velocity of the body.

Additionally, the boundary condition at the bottom is:

$$\frac{\partial \varphi}{\partial n} = 0, z \to -\infty \quad (5)$$

Radiation Condition: r = $\sqrt{x^2 + y^2}$

$\varphi \to 0, r \to \pm\infty$

Considering that no waves exist at infinity, the boundary value problem must also satisfy the initial condition at t=0 (6)

$$\varphi = 0 \; dan \frac{\partial \varphi}{\partial t} = 0 \quad (7)$$

The velocity potential of the incident wave satisfies the Laplace equation and linearizes the boundary conditions on the free surface and the bottom. The velocity potential is determined using Equation (8):

$$\varphi 1 = Re\left\{ i * \left(\frac{ga}{w}\right) e^{[i(kx \cos\chi + ky \sin\chi)]} e^{[kz]} e^{[-i\omega t]} \right\}$$
(8)

Here, a represents the wave amplitude, ω is the wave frequency, and k denotes the wave number.

The hydrodynamic pressure on the hull is calculated using Bernoulli's Equation:

$$pT(P,t) = -\rho * \left[\frac{\partial \varphi}{\partial t} + \left(\frac{1}{2}\right) * |\nabla \varphi|^2 + g\right] \quad (9)$$

The hydrodynamic force of the hull can be expressed as

$$Fi(t) = \int pT(P0,t) * n0 \, dS, \; i = 1, 2, \ldots, 6 \quad (10)$$

Here, $n0i$ represents the component of the generalized normal vector pointing into the body.

The boundary value problem is solved using Green's theorem, where the unknown source strength is determined by integrating over the entire wetted surface using the surface source method. The fundamental equation is expressed as follows:

$$-\frac{1}{4\pi}\int_{S_B}\int_{(t)} \sigma(Q,t)\left(\frac{\partial G^0(P,Q)}{\partial n}\right) dS = -n \cdot (V - \nabla\varphi I()P,t))\frac{1}{n} \pm \frac{1}{4\pi}\int_0^t \left[\int_{S_B}\int_{(\tau)} \sigma(Q,t)\left(\frac{\partial G^{(t)}(P,Q,t,\tau)}{\partial n}\right) d\tau\right] - \frac{1}{4\pi} - \frac{1}{g}\int_0^t \left[\int_{\Gamma(F,t)} \sigma(Q,t)\left(\frac{\partial G^{(t)}(P,Q,t,\tau)}{\partial n}\right) u\_n \, U\_n \, d\Gamma\right] d\Gamma$$
(11)

Here, G denotes the Green's function, σ represents the source strength, (xP, yP ,zP) is the field point, and (xQ', yQ', zQ') is the source point.

$$\varphi(P,t) = \frac{1}{4\pi}\int\int_{Sb(Q,t)G^0(P,Q)dS} + \frac{1}{4\pi}\left[\int_0^t\int\int_{Sb(\tau)\sigma(Q,t)G^t(P,Q,t,\tau)dS}\right] d\tau - \frac{1}{4\pi} - \frac{1}{g}\int\_0\text{^}t \left[\int\_\Gamma(F,\tau)\, \sigma(Q,t)\, G^t(P,Q,t,\tau)\, u\_n \, U\_N \, d\tau\right] d\tau$$
(12)

The time derivative of the disturbed velocity potential ϕ is approximately expressed in the following form within Bernoulli's equation:

$$\frac{\partial \phi}{\partial t} = \frac{\phi k - \phi k - 1}{\Delta} - V \cdot \nabla \phi \quad (13)$$

Here, ϕk represents the velocity potential at time step k. The time derivative of the velocity potential is obtained by solving the boundary value problem.

$$\frac{\partial \varphi}{\partial t} = \frac{d}{dt}[(V - \nabla\varphi) \cdot n] \text{ On the hull Surface} \quad (14)$$

The right-hand side of the above equation can be further expanded to derive the velocity potential ϕ on the object's surface and the boundary condition SB.

$$\frac{\partial n}{\partial \phi} = n \cdot [(u + \omega + r) - (\omega \times u)] - \cdot n[\frac{\nabla \phi f}{\partial t} + (u + \omega + r)\nabla)\nabla \phi I - (\omega \times \nabla \phi I)] \quad (15)$$

The excitation forces are determined as follows [25]:

$$F\_j = -\rho \int\int\_S \, n\_j \, (i\omega\_e - U \frac{\partial}{\partial x})(\varphi\_I + \varphi\_D) \, ds$$
(16)

This expression can be decomposed into two components: the incident wave part and the diffraction part, as shown below:

$$F\_j\text{^}I = -\rho \int\int\_S \, n\_j \, (i\omega\_e - U \frac{\partial}{\partial x}) \, \varphi\_I \, ds \quad (17)$$

$$m\_0 = \int\_0\text{^}\infty \, S(\omega) \, d\omega = \int\_0\text{^}\infty \, S(\omega\_e) \, d\omega\_e \quad (18)$$

In the study of ship motions in waves, it is necessary to convert the wave frequency into the encountered frequency. The encountered frequency is determined by the wave velocity, ship speed, and the wave propagation direction, as illustrated in Figure 4. Assuming the ship is navigating in deep water, the encountered frequency can be calculated based on the relationship between wave velocity and deep water conditions, as follows [26]

$$\omega\_e = \omega - \frac{\omega^2 U}{g} \cos\mu \quad (19)$$

Here, U represents the ship speed, g is the gravitational acceleration, ω is the wave frequency, and μ is the encountering angle. For wave conditions, quartering seas occur at μ =135∘, and heading waves occur at (μ =180∘).

For any reference system, the total energy of the waves is constant. Therefore, the conversion of the spectrum and encountered spectrum can be achieved using the following formula:

$$m\_0 = \int\_0\text{^}\infty \, S(\omega) \, d\omega = \int\_0\text{^}\infty \, S(\omega\_e) \, d\omega\_e \quad (20)$$

$$S(\omega\_e) \, d\omega\_e = S(\omega) \, d\omega \quad (21)$$

Also

$$\omega\_e = \omega - \frac{\omega^2 U}{g} \cos\mu \quad (22)$$

$$d\omega\_e \,/\, d\omega = 1 - \frac{2\omega U}{g} \cos\mu \quad (23)$$

Therefore, the wave energy spectrum of the encountered frequency is:

$$S(\omega\_e) = \frac{S(\omega)}{\left|1 - \frac{2\omega U}{g}\cos\mu\right|} \quad (24)$$

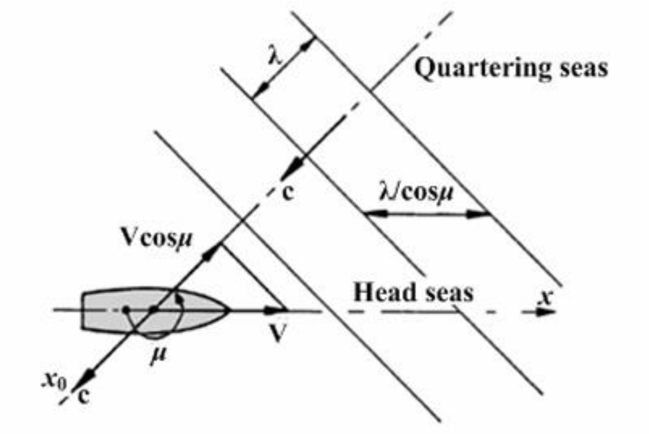

Figure. 4. Encountering angle μ.

III. Results and Discussion

The analysis is based on field data collected directly at Muara Angke Port for a 30 GT fishing vessel. The vessel was manually measured at the port, with key dimensions recorded, including the length overall (LOA), breadth (B), height (H), and draft (T). These measurements were taken using standard tools and methods, ensuring accuracy and reliability in the data collection process. Once the principal dimensions were obtained, a 3D model of the vessel was created for further analysis. This model was then used to evaluate the design performance and assess the suitability of the vessel's dimensions in meeting the operational requirements, particularly within the dynamic marine conditions of Muara Angke Port. The direct measurement of the vessel at the port provided a real-world basis for understanding how the vessel interacts with the surrounding environment, ensuring that the design and operational parameters align with the conditions found in the port.

Table 1.
Principal Dimension

No	Principal Dimension	Unit	30 GT
1	LOA	M	18,5
2	B	M	4,2
3	H	M	2
4	T	M	1,2

Figure. 5. Measurement KM SPARTAN 2.

The dimensions of a ship—such as overall length (LOA), beam (B), height (H), and draft (T)—have a significant impact on the stability and maneuvering behavior of the vessel, particularly when facing dynamic sea conditions such as high waves or strong currents. A larger ship length tends to improve the ship's directional stability (yaw stability), helping the vessel maintain a straight course when moving through waves or currents. However, longer ships may be more vulnerable to rolling (tipping movements) in larger waves, as the length affects the shift in the center of mass and the point of wave contact with the hull [27]. In contrast, shorter ships are often easier to maneuver (turn), but they are more susceptible to greater lateral movements or roll, especially in beam waves [28].

A wider beam increases the ship's transverse stability, reducing the risk of capsizing when facing large waves or strong currents. However, wider ships may have difficulty moving smoothly in confined spaces, such as busy ports. A larger beam can also increase hydrodynamic resistance, which reduces fuel efficiency and slows the ship's speed. A wide beam can also lead to greater pitching when encountering waves or navigating through high waves, as changes in the ship's trim angle are more pronounced on wider vessels [29].

The height of a ship can affect its vertical stability. Taller vessels tend to be more susceptible to pitching, the up-and-down movement of the ship’s bow and stern, which can disrupt crew comfort and operational efficiency. Taller ships may experience more wave impact, especially in sea state 5 or higher, where the ship must face larger and more frequent waves. This can affect the comfort and safety of the vessel’s operation [30].

The ship's draft, referring to the depth of the vessel below the water's surface, affects its static stability. Ships with a deeper draft have higher stability because the center of mass is lower, reducing the tendency of the ship to capsize or roll when waves occur. However, vessels with a deeper draft may struggle to operate in shallow waters or ports with limited depth, such as Muara Angke. Strong currents and large waves can further complicate navigation for vessels with a deep draft [12].

In High Waves: Longer and narrower ships tend to be more stable in large waves but may experience stronger rolling movements, especially when the waves come from the side (quartering seas). In contrast, wider and shorter ships are generally more resistant to rolling but may be more affected by waves coming from the front (head seas), with more pronounced pitching movements [31].

In Strong Currents: Ships with a deeper draft tend to have better stability in strong currents, as they are less affected by surface currents that can cause the vessel to sway or capsize. Ships with a shallow draft are more vulnerable to greater vertical and lateral movements due to the stronger effects of currents on the hull [25].

The seakeeping criteria were determined based on the standard guidelines provided in [32], which are presented in the table below. These criteria serve as a benchmark for evaluating the vessel's performance under various sea conditions, ensuring safety, stability, and operational efficiency during maritime activities.

TABLE 2.
SEAKEEPING CRITERIA

No	Parameter	Value
1	Roll	6 Deg
2	Pitch	3 Deg

A high roll value, for example, indicates that the ship is experiencing side-to-side rolling movements, which can affect the vessel's stability when operating in busy ports like Muara Angke. Excessive rolling can make it difficult for the ship to maintain its position accurately while docked or when maneuvering near the quay, increasing the risk of collisions with the dock or other vessels [12].

Additionally, a high pitch value, indicating up-and-down movement of the ship, can disrupt the comfort of the crew. The crew may have difficulty performing tasks efficiently or even face the risk of injury if the ship moves too excessively [33]. In terms of operational efficiency, both high roll and pitch values worsen the ship's ability to complete tasks quickly, such as loading or unloading cargo, slowing down the loading process and increasing the time needed to complete activities in the port. Both factors also affect fuel efficiency, as the ship must use more power to remain stable and move through rough waters, thereby reducing overall productivity [34].

The standard sea condition code, established by the World Meteorological Organization (WMO) in 1970, provides a universal framework for categorizing sea states based on wave heights. This classification system, as outlined below, assigns specific codes to different ranges of wave heights, facilitating a standardized understanding of sea conditions across the maritime industry. However, it is important to note that while wave heights are clearly defined within this coding system, the corresponding wave periods are not specified, which may limit its applicability in certain detailed seakeeping or operational analyses.

TABLE 3.
WMO SEA STATE CODE

WMO State Code	Relevant Wave Height (m)		Description
	Range	Mean	
0	0	0	Calm (Glassy)
1	0 to 0,1	0,05	Calm (Rippled)
2	0,1 to 0,5	0,3	Smooth (Wavelets)
3	0,5 to 1,25	0,875	Slight
4	1,25 to 2,5	1,875	Moderate
5	2,5 to 4	3,25	Rough
6	4 to 6	5	Very Rough
7	6 to 9	7,5	High
8	9 to 14	11,5	Very High
9	Over 14	Over 14	Phenomenal

Detailed data on the status of the sea can also be accessed for specific marine regions and seasons, providing valuable insights into local wave and weather patterns. This information is particularly useful when planning efficient and safe maritime routes, as it allows operators to anticipate and adapt to prevailing sea conditions. Among the most significant references for this type of data are the works of Hogben and Lumb, which remain key sources for understanding regional marine environments and their seasonal variations [35]

Different sea conditions, such as waves and currents, affect a vessel's ability to carry out operational activities safely and efficiently. In low wave conditions (sea state 1-3), ships can operate effectively for both fishing and loading/unloading cargo at ports like Muara Angke. The relatively calm waves allow the ship to remain stable, with controlled roll and pitch movements, enabling the crew to work efficiently and safely [36]. However, in moderate wave conditions (sea state 4), although the ship can still perform operational activities, the higher roll and pitch values begin to disrupt the ship’s stability, reducing crew safety and slowing down the loading or unloading process. Instability in these conditions can cause difficulties in positioning the ship at the dock, increasing the risk of cargo damage or accidents [37].

In high wave conditions (sea state 5 or higher), the ship experiences extreme movements, making fishing activities riskier and less efficient. Strong pitching can disrupt fishing gear and cause equipment damage or even cargo to be thrown overboard [38]. Additionally, the process of loading or unloading cargo becomes more difficult and risky because the ship cannot maintain a stable position at the dock, increasing the risk of collisions and cargo damage. In these more extreme sea conditions, the ship requires more time to carry out operational activities safely, which impacts overall operational efficiency [29].

In general, the effectiveness of a mission is significantly degraded when the amplitude of motions and accelerations in a seaway increases. From a seakeeping perspective, the operational success of a vessel can be evaluated by analyzing how ship motions impact its various subsystems. Subsystems refer to any component or element that contributes to the ship's ability to function and operate effectively, including the hull, machinery, personnel, sensors, and other critical components.

To determine whether a hull design is successful, specific criteria are established as benchmarks for analysis. These criteria allow for an objective assessment of the ship’s performance under varying sea conditions. For a thorough study, the criteria can be categorized into two groups: motion response criteria and derived response criteria.

Motion response criteria are directly based on the ship’s motions and include parameters such as root mean square (RMS) roll, pitch, and yaw angles, as well as RMS vertical and lateral displacements and RMS vertical velocities. These criteria, as outlined by the International Towing Tank Conference (ITTC) in 2005 [39], provide a foundational framework for evaluating seakeeping performance and determining the vessel’s ability to maintain its operational effectiveness in challenging maritime environments.

To evaluate the performance of fishing vessels, specific criteria are assessed against their prescribed benchmark values. These benchmark values are critical to the study, as they define the vessel's operational status, categorizing it as either operable or inoperable under given conditions. However, in the case of fishing vessels, it appears that there are limited prescribed values readily available in existing literature or industry standards. This lack of established benchmarks presents a challenge for conducting comprehensive performance evaluations and highlights the need for further research to develop and standardize criteria tailored specifically for fishing vessels.

TABLE 4.
QUARTERIMG SEA

Wave Height (m)	RMS of Pitch	RMS of Roll	Status
0,5	0,91	0,28	Pass
1	1,82	0,56	Pass
1,5	2,73	0,84	Pass
2	3,65	1,12	Pass
2,5	4,56	1,4	Pass
3	5,47	1,68	Pass
3,5	6,38	1,96	Fail
4	7,3	2,24	Fail

TABLE 5.
HEAD SEAS

Wave Height (m)	RMS of Pitch	RMS of Roll	Status
0,5	0,9	0,34	Pass
1	1,81	0,68	Pass
1,5	2,71	1,02	Pass
2	3,61	1,36	Pass
2,5	4,52	1,7	Pass
3	5,42	2,04	Pass
3,5	6,32	2,37	Fail
4	7,23	2,71	Fail

A high RMS value indicates that the ship is experiencing more extreme movements from its equilibrium position, which can affect its stability. For example, a high RMS roll value suggests that the ship is experiencing significant side-to-side motion, which can make it difficult for the vessel to maintain its position accurately when operating in busy ports like Muara Angke [40]. This instability can interfere with the ship's ability to maneuver with precision, such as docking safely or positioning itself near the quay without colliding with other ships or port facilities. Similarly, a high RMS pitch value indicates that the ship is moving up and down significantly, disrupting the crew's comfort and increasing the risk of injury or accidents while they work onboard [41]. Furthermore, these larger movements affect the operational efficiency of the ship, as it will require more time to complete tasks such as loading or unloading cargo, which can slow down the process, increase the risk of cargo damage, and reduce productivity.

In this study, "pass" refers to the vessel meeting the criteria set by Tello in Table 2, while "fail" indicates that the vessel does not meet the established criteria. The sea state conditions for the analysis are taken from sea states 3 to 5, based on data provided by BMKG (the Meteorological, Climatological, and Geophysical Agency). As discussed earlier, fishing vessels typically operate in open waters, far from the shore. However, the overall results showing failure do not imply that the fishing vessel is incapable of sailing in such conditions. Instead, the term "fail" refers to the vessel's reduced effectiveness in these conditions.

The analysis indicates that the vessel may still be able to sail under sea states 3 to 5, but it is less effective in terms of stability, maneuverability, and operational performance. In contrast, the vessel performs optimally in sea states below 5, with wave heights ranging from 2.5 to 3.0 meters, where it can maintain better stability and maneuverability. Therefore, while the fishing vessel is capable of operating in rougher sea conditions, its overall efficiency and performance are compromised when the sea state exceeds 5.

IV. CONCLUSION

This study shows that the tested ship can operate in sea conditions with waves up to 3 meters (sea state 5), but the ship's performance is not optimal in such conditions. In this context, "not optimal" refers to the decreased stability of the ship, which affects the comfort of the crew and the vessel's maneuverability in busy ports. In sea state 5, higher roll and pitch values can cause crew fatigue, slow down operational speed, and increase the risk of accidents during docking and loading/unloading cargo. Fuel efficiency also tends to decrease because the ship requires more energy to maintain a stable course and maneuver in extreme sea conditions.

Based on these findings, several practical recommendations can be considered:

1. Improvement of ship design, such as adjusting the hull shape and enhancing transversal stability, to reduce the impact of excessive roll and pitch movements, especially in high waves.
2. Enhancement of the ship's maneuvering system in ports, including the use of autopilot technology or automated controls to help the ship maintain the correct position during loading and unloading in busy port areas.
3. Crew training to manage extreme sea conditions, including maneuver simulations involving higher sea states, to reduce the risk of accidents and improve operational efficiency.

However, this study has limitations that should be considered when interpreting its results:

1. The data scope is limited to one port, Muara Angke, which may affect the generalization of results to other ports with different or calmer sea conditions.
2. Limited variation in ship design, with only one ship type (30 GT) tested. To obtain a more comprehensive understanding of ship motion response in different ports, further research is needed that includes various ship types with different dimensions and designs.
3. The absence of external weather factors that could influence the results, such as strong winds or more extreme tidal conditions, which were not analyzed in depth in this study.

With further research that addresses these limitations, it is hoped that more effective design solutions and safer operational strategies can be found to support the sustainability of Indonesia's fisheries sector.

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