Mechanical Design of Fishing Vessels: A Hydrodynamic Assessment to Optimize the Engineered Hull Geometry

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ABSTRACT

The waters of Bengkulu hold significant potential in marine resources, particularly in the fisheries sector. However, the effective utilization of these resources largely depends on the performance of fishing vessels, which must operate efficiently and maintain stability in a wide range of maritime conditions. This study evaluates the hydrodynamic performance of fishing vessels using computational modeling. The simulation focuses on five hull designs, assessing key parameters, such as resistance, stability, and seakeeping at a speed of 20 knots. The resistance simulations utilized the Savitsky method to calculate the total resistance. The stability was analyzed using the righting arm (GZ) method, with tilt angles ranging from 0° to 180°. The seakeeping performance was evaluated using the strip theory. The simulation results indicated that the optimal performance for the fishing vessels was achieved with a resistance of less than 14.80 kN and power requirements ranging from 158.6 kW to 190.9 kW. The stability values ranged from 3.78 to 14.63 m.deg, the seakeeping parameters, including heave motions, ranged from 5.01 to 9.68 m/m, the roll motions from 6.37 to 6.69 rad/rad, and the pitch motions from 6.69 to 10 rad/rad. These findings provide valuable insights for developing optimized fishing vessel designs to exploit Indonesia's marine resources sustainably.

Keywords-fishing vessel design; hydrodynamic characteristics; Bengkulu waters fishing; boat optimization

I. INTRODUCTION

Air Rami is one of the villages in Air Rami District, Mukomuko Regency, in northern Bengkulu Province. Air Rami District has an area of 99.20 km², as established by the Regional Regulation No. 8 of 2005. Air Rami District is a rural area consisting of 12 villages. Geographically, the Air Rami village borders the Indian Ocean [1]. As shown in Figure 1, the Air Rami village is located approximately 81 km away from Mukomuko Regency, a 2 h drive, with a travel time of around 2 h and 13 min by road. The road access to Air Rami village from the nearest major city, Bengkulu, is also quite large, requiring around 3 h and 30 min of travel by land, or approximately 147 km. With its geographical location bordering the Indian Ocean, some residents of the Air Rami village work as fishermen [2]. In 2022, according to the Mukomuko Regency Statistics Bureau, 861 individuals in Air Rami village were registered as fishermen. The fishing production system practiced by the fishermen in the Air Rami District is primarily a capture fishery system. The fishermen use simple technology, with the most commonly utilized fishing gear being gill nets, trammel nets, lobster shrimp nets, fish nets, fishing rods, and traditional trawl nets [3].

The fishing vessels should consider several key factors, including the water conditions, target fish species, suitable fishing gear, storage requirements, and the optimal range for effective catches. A stable vessel is essential for handling such situations in the Bengkulu waters, where the wave heights can reach up to 1.5 m. To address this issue, the vessel's dimensions could be extended to 9-10 m, compared to the average length of 8 m for traditional fishing boats. Improving the vessel's range and stability will enhance the fishing yield and ensure better catches [4].

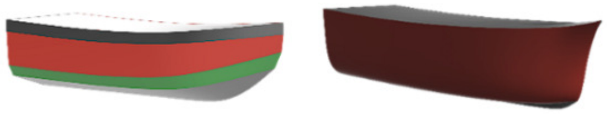
This research simulates resistance, stability, and seakeeping on five reference fish hulls. The results establish regulations for the resistance, stability, and seakeeping values. These regulations are expected to serve as guidelines for designing fishing vessels with optimal performance.

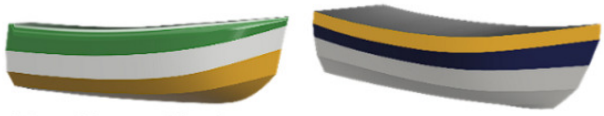
II. METHODOLOGY

This study evaluates the hydrodynamic performance of five fishing vessel hulls using numerical simulations. The research was conducted in four stages. First, the principal dimensions of the reference vessels, including Length Overall (LOA), beam, depth, draft, and displacement, were collected for monohull fishing boats with LOA between 9 and 10 m [5–7]. These parameters were then used to generate 3D hull models based on standard naval architecture principles [8–12]. The 3D geometries of the five hulls, as presented in Figure 1 and Table I, demonstrate the vessel's principal dimensions.

TABLE I. MAIN DIMENSIONS OF HULL REFERENCE

Parameter	**Type of Hull**				
	Ardent	**Emilie**	**Happy Hooker**	**Kingfisher B15**	**Tuna Trolling**
LOA (m)	9.150	9.100	9.150	9.30	9.50
Beam (m)	3.300	3.300	3.300	3.20	2.70
Depth (m)	2.400	2.500	2.500	2.52	2.59
Draft (m)	1.000	1.000	1.000	0.90	1.20
Disp. (t)	17.62	17.04	17.27	16.97	17.79


(a) Ardent (b) Emilie


(c) Happy Hooker (d) Kingfisher B15


(e) Tuna Trolling

Fig. 1. 3D models of the five fishing vessel hulls used in this study: (a) Ardent, (b) Emilie, (c) Happy Hooker, (d) Kingfisher B15, (e) Tuna Trolling.

Subsequently, the hydrodynamic responses of the hulls were simulated, excluding the effects of propulsion and structural construction to focus solely on the hull behavior [6]. The resistance was analyzed using the Savitsky method over speeds ranging from 15 to 50 knots to estimate the wetted surface, drag, and required power [13–15]. Stability was evaluated using righting arm (GZ) curves across heel angles from 0° to 180°. The seakeeping performance was assessed employing the strip theory at a constant speed of 20 knots under beam (90°), bow-quartering (135°), and head (180°) seas, with JONSWAP spectra to determine the heave, roll, pitch, and Motion Sickness Incidence (MSI) [16]. Finally, statistical analyses were conducted to assess the impact of hull dimensions on the overall hydrodynamic performance.

III. RESISTANCE ANALYSIS

The ship resistance is a force that is opposite to the direction of the ship's motion. The former must be predicted because drag is significant in ship hydrodynamics. The resistance analysis determines the resistance values and power requirements of the reference vessel models. The hydrodynamic characteristics of the ship can be determined through numerical calculations, including the wetted surface, drag, and resistance [17-19]. The total resistance is given by [20]:

$$R_T = R_F + R_{VP} + R_W \tag{1}$$

where R_T is the total resistance, R_F is the frictional resistance, R_{VP} is the viscous pressure resistance, and R_W is the wave resistance. The method used for the resistance simulation is the Savitsky method, with an efficiency of 80%. Daniel Savitsky conducted research on ship hydrodynamics by estimating the ship resistance and trim angle [21]. Daniel Savitsky's equation is [22]:

$$R_T = \Delta \tan\tau + \frac{0.5\rho V^2 \lambda b^2 C_F}{\cos\tau} \tag{2}$$

where τ is the trim angle, and C_F is the frictional resistance coefficient. The analysis compares the five hull designs based on the resistance value. The resistance simulations were conducted using the Savitsky method at speeds ranging from 15 to 50 knots. This analysis was performed on five variations of reference fishing vessels. The relationship between the resistance values and the vessel speed is depicted in Figure 2. The relationship between the power values and vessel speed is portrayed in Figure 3.

The results of the resistance simulation for the five reference vessels at a speed of 20 knots, which is the average speed for the fishing vessels in the Bengkulu waters, showed that the Emilie hull had the lowest resistance value of 12.30 kN. In contrast, the Tuna Trolling hull had the highest resistance value of 14.80 kN at the same speed of 20 knots. The power versus the speed simulation results show a similar trend to that observed in the resistance simulation results. Based on the obtained results, at a speed of 20 knots, the tuna trolling vessel requires the highest power of 190.9 kW compared to the other vessels. Meanwhile, the Emilie vessel requires the lowest power of 158.6 kW at the same speed. It can be seen that the simulation results for resistance and power have a direct proportional relationship. These values are lower than those reported in [23], where a total resistance in the range of 18–22 kN was found for larger fishing vessels. Meanwhile, authors in [24] demonstrated that the variations in the deadrise angle can alter the resistance by 1.9–6.9% at 20 knots [24]. The observed percentage aligns with the 14% discrepancy reported between the Emilie and Tuna Trolling hull configurations, underscoring the significant influence of the hull-form variation on the hydrodynamic efficiency.

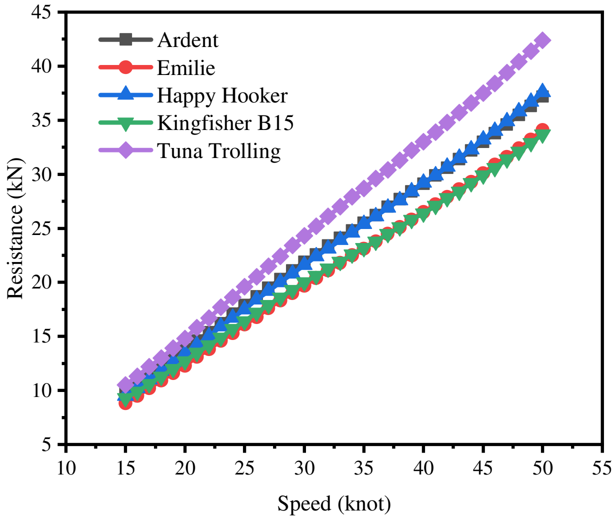


Fig. 2. Simulation results of the boat resistance.

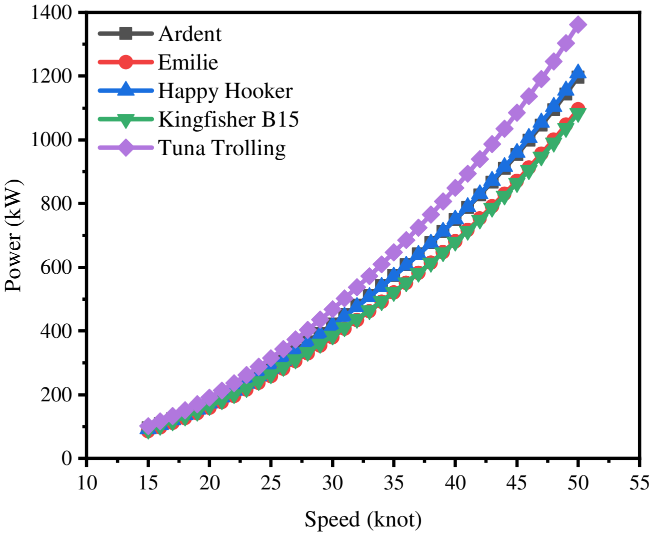


Fig. 3. Simulation results of the boat power.

IV. STABILITY ANALYSIS

Ship stability refers to a vessel's ability to return to a balanced position after being disturbed by forces, such as waves or wind. The Stability Regulation of the International Maritime Organization (IMO) aims to enhance the ship safety by promoting safe ship stability [25]. Hull stability ensures the boat's and its passengers' safety during sailing. The stability analysis determines the vessel's balance when subjected to forces from the ocean waves. The results of the stability simulation are presented in the *GZ* graph, which shows the relationship between the *GZ* value and the vessel's tilt angle. The maximum *GZ* value on the heel's angle should not be less than 25°, as shown in [26]:

$$\frac{dGZ}{d\varphi}(\varphi \geq 25°) = 0 \qquad (3)$$

where φ is the angle of heel. The *GZ* can be defined using:

$$GZ = GM_0 \sin\emptyset + M_0 S \qquad (4)$$

where M_0S is the residual stability lever.

Figure 4 illustrates the stability simulation results, according to which the model with the highest *GZ* value of 0.281 m is Ardent, with a maximum tilt angle of 86.04°, allowing the ship to return to its upright position. On the other hand, the model with the lowest *GZ* value of 0.094 m is the Tuna Trolling vessel, having a tilt angle of 72.07°. The stability results demonstrate that the *GZ* value affects the hull's stability. The larger the *GZ* value is, the smaller is the possibility of the ship capsizing when subjected to external forces. The *GZ* value of the Ardent hull is higher than that of the traditional fishing vessels analyzed in [27], where several conventional types exhibited *GZ* values of approximately 0.27 m. Furthermore, authors in [28] reported that the variations in the beam-to-draft ratio significantly influence the shape of the *GZ* curve and the overall stability of the traditional fishing vessels, supporting the finding that the hull dimensions, such as those applied in the Ardent design, are critical for achieving improved stability.

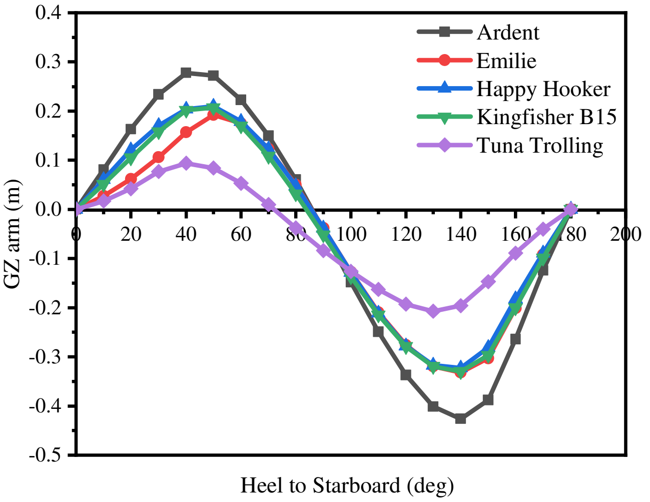


Fig. 4. *GZ* from variations of five boats.

V. SEAKEEPING ANALYSIS

Seakeeping analysis is used to understand a vessel's response to specific water conditions, ensuring the comfort of the crew and passengers during navigation. The wave directions considered are 90° (beam seas), 135 degrees (bow quarter seas), and 180° (head seas), with a constant speed of 20 knots. The results of the seakeeping analysis on five ship variations produce Response Amplitude Operator (RAO) graphs, which include values for heaving, rolling, and pitching motions [29]. The heaving value is determined by:

$$a\ddot{z} + b\dot{z} + cz = F_0 \cos\omega_\theta t \qquad (5)$$

where $a\ddot{z}$ is the inertial force, $b\dot{z}$ is the damping force, cz is the restoring force, and $F_0 \cos\omega_\theta t$ is the value of the exciting force. The Ardent hull exhibits the lowest motion response, with an RAO of 5.01 m/m at 3.017 rad/s, while the Tuna Trolling hull shows the highest heave response, reaching 9.68 m/m at 3.304 rad/s. After analyzing the heaving motion, the next step is to examine the rolling motion. Rolling refers to the rotational movement of the vessel to the right or left while underway [30]. The rolling simulation uses a wave direction of 90° at 20 knots. The roll motion analysis can be performed using [31]:

$$a\frac{d^2\emptyset}{dt} + a\frac{d\emptyset}{dt} + c\emptyset = M_o \cos\omega_\theta t \qquad (6)$$

where $a\frac{d^2\emptyset}{dt}$ is the inertial force value, $a\frac{d\emptyset}{dt}$ is the damping force value, $c\emptyset$ is the restoring force value, and $M_o \cos\omega_\theta t$ is the exciting force value. The results of this simulation show the highest RAO of 6.69 rad/rad at 1.797 rad/s, corresponding to the Ardent hull, indicating greater vulnerability to beam wave-induced rolling. After analyzing the heaving and rolling motions, the next step is to explore the pitching motion. Pitching refers to the movement of the vessel around the y-axis, i.e. the rotational motion that occurs along the transverse axis, or the angular movement about the y-axis. This motion occurs due to waves causing a difference in the height between the front and rear sections of the ship's hull. The pitching motion analysis can be conducted using [32]:

$$d\ddot{\emptyset} + e\emptyset + h\emptyset = M_o \cos\omega_e t \qquad (7)$$

where $d\ddot{\emptyset}$ is the inertial force value, $e\emptyset$ is the damping value, $h\emptyset$ is the restoring force value, and $M_o \cos\omega_e t$ is the exciting force value. The simulation uses a wave direction of 180° at 20 knots. Based on the pitching motion simulation results, the model with the minimum motion response is the Ardent, with an RAO value of 6.69 rad/rad at an encounter frequency of 3.017 rad/s. Meanwhile, the maximum pitching motion response model is the Tuna Trolling vessel, with an RAO value of 10.00 rad/rad at an encounter frequency of 3.304 rad/s.

VI. MSI CALCULATION

MSI is a crucial parameter for assessing the passenger comfort on a boat. The latter is a key factor in designing a boat's hull to achieve an optimal seakeeping performance. A seakeeping analysis of ships was conducted in [33], taking into account the vessel speed, wind speed, wave angle of incidence, and wave height to enhance the passenger safety during sailing. The MSI results are depicted in Figure 5. The MSI analysis was performed at a vessel speed of 20 knots with a wave direction of 135°. The MSI index can be calculated using [34]:

$$MSI = 100\left[0.5 + erf\left(\frac{\log 10(0.798\sqrt{m_4}/g) - \mu_{MSI}}{0.4}\right)\right] \qquad (8)$$

where m_4 is the spectral moment of the ship, and g is the gravitational force. Based on the simulation results, the Ardent hull exhibits the lowest habitability acceleration Root Mean Square (RMS) of 1.993 m/s^2, indicating a superior comfort and a lower likelihood of inducing motion sickness among passengers. In contrast, the Tuna Trolling hull records the highest habitability acceleration RMS of 3.003 m/s^2. The Ardent hull demonstrates a favorable comfort level, as the motion sickness symptoms are expected to occur only after more than 30 min of operation. In comparison, the RMS values exceeding 2.5 m/s^2, as identified in [35], surpass the proposed threshold, indicating that the Tuna Trolling hull exceeds this limit. In contrast, the Ardent hull remains acceptable [35]. Furthermore, authors in [36] reported that higher RMS roll responses are correlated with a decreased comfort and operability in traditional small fishing vessels, supporting the conclusion that hull-form optimization, as exemplified by the Ardent design, can significantly enhance the passenger habitability.

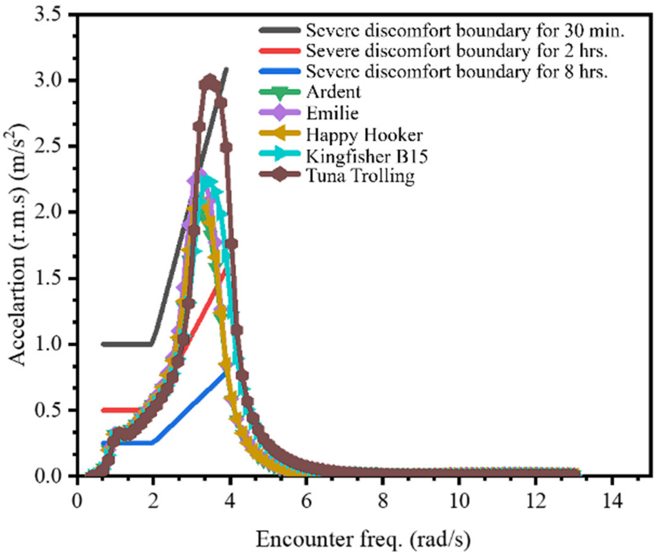


Fig. 5. MSI of five boat variations.

VII. DISCUSSION

The hydrodynamic performance analysis of the fishing vessel models highlights several key findings related to their design efficiency in various operational conditions. The primary focus of this study was to assess the resistance, stability, and seakeeping characteristics of five reference fishing boats: Ardent, Emilie, Happy Hooker, Kingfisher B15, and Tuna Trolling, to identify the optimal hull form for use in the waters of Bengkulu. The result summary is presented in Table II. The results indicate significant variations across the hull forms. The resistance analysis at 20 knots revealed a performance range from 12.30 kN to 14.8 kN, which corresponds to a required power from 158.6 kW to 190.9 kW.

The Emilie hull was identified as the most efficient, exhibiting the lowest resistance of 12.30 kN. Regarding stability, the area under the *GZ* curve varied substantially, with values ranging from 3.78 to 14.63 m.deg. The Ardent hull demonstrated superior stability by achieving the maximum *GZ* of 0.281 m. In the seakeeping analysis, the vessel motions for heave were in the range of 5.01–9.68 m/m, for roll 6.37–6.69 rad/rad, and for pitch 6.69–10.00 rad/rad. These motions resulted in a MSI between 1.993 m/s^2 and 3.003 m/s^2. Notably, the Ardent hull also showed the most favorable seakeeping, achieving the lowest MSI value of 1.993 m/s^2, and thus ensuring the highest level of passenger comfort.

TABLE II. RECAPITULATION OF HULL CHARACTERISTICS

Parameters	Minimum value	Maximum value
Resistance (kN)	12.30	14.8
Power (kW)	158.6	190.9
Stability (m.deg)	3.78	14.63
Heave motion (m/m)	5.01	9.68
Roll motion (rad/rad)	6.37	6.69
Pitch motion (rad/rad)	6.69	10.0
MSI (m/s^2)	1.993	3.003

VIII. CONCLUSIONS

This study concludes that an optimal balance of resistance, stability, and seakeeping can be achieved for traditional fishing vessels operating in the 2 m wave conditions of Bengkulu waters through a specific set of optimized dimensions. Derived from the superior performance of the Emilie and Ardent hull forms, the proposed optimal dimensions are a Length Overall (LOA) of 9.10–9.15 m, a beam of 3.30 m, a depth of 2.40–2.50 m, and a draft of 1.00 m. The implementation of this hull design, with an expected displacement of 17.04–17.62 tons, can significantly improve the seaworthiness and economic viability of small-scale fishing operations. These findings provide a robust framework for future vessel development in the region.

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