Assessment of the Stability and Response of a Catamaran-Hull Ferry to Operational and Environmental Conditions

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Article Info	Abstract
	Ship stability is a critical factor in operating a catamaran, especially when facing various sea conditions. The catamaran H-192, recently acquired by PT XY, is used as a case study in this research to assess its stability and response to operational and environmental conditions. Stability criteria based on Annex 7 of the High-Speed Craft (HSC) Code are used as the evaluation standard. This research aims to evaluate the stability and response of the catamaran H-192 under various operational and environmental conditions. The primary focus is to ensure that the vessel meets and exceeds the stability criteria set by Annex 7 and to understand how the ship behaves in real-world situations. The methods used in this research include stability calculations based on Annex 7 and model design using Maxsurf software. The calculations involve the analysis of the righting lever (GZ), metacentric height (GM), and other stability criteria. Operational data and load distribution are analyzed to determine the vessel's draft, trim, and stability under various loading conditions. The results show that the catamaran H-192 not only meets but also exceeds the stability criteria set by Annex 7. The high values of the righting lever (GZ) and metacentric height (GM) at various angles of the heel indicate excellent transverse and longitudinal stability. The evaluation of intact stability criteria shows that all parameters achieve "PASS" status, indicating the vessels capability to handle combinations of healing forces due to wind, high-speed maneuvering, and passenger crowding very well. The analysis of both full and empty operational conditions shows balanced load distribution and maintained stability.

1. Introduction

Catamaran ferries are known for their multi-hull design, which offers better stability compared to monohull ferries. The multihull structure provides a wider distribution, reducing healing when struck by waves and improving passenger comfort. This makes catamarans an increasingly popular choice in the maritime transport industry, particularly for ferry and passenger ferry services. PT XY, a shipping company in Indonesia, has recently acquired the catamaran ferry H-192 to expand its capacity and enhance its sea transportation services. The H-192 ferry is designed to operate on challenging routes in Indonesian waters, which include varying weather and sea conditions. Given the importance of ferry stability for passenger safety and efficient operations, it is crucial to conduct an in-depth evaluation of the H-192 ferry's stability based on international standards. Catamarans and trimarans have lower total resistance and power requirements compared to monohulls with the same displacement, making them more efficient [1]. The design of catamaran vessels with two symmetrical hulls provides advantages in stability and reduced wave resistance [2].

With the acquisition of the H-192 catamaran ferry, PT XY faces the challenge of ensuring that this ferry meets high safety standards under various operational conditions. The stability of a catamaran ferry is influenced by several factors, including load distribution, weather conditions, and wave patterns. The righting lever (GZ) curve, which shows the ferry's ability to return to its upright position after heeling, is a key parameter for evaluating ferry stability. However, the ferry's stability data must be verified and analyzed according to ANNEX 7, Stability of Multihull Craft standards to ensure that the H-192 ferry can operate safely in Indonesian waters. This involves calculating the GZ curve, evaluating the area under the GZ curve, and analyzing other stability parameters for various loading conditions [3]. With the acquisition of the H-192 catamaran ferry, PT XY faces the challenge of ensuring that this ferry meets high safety standards under various operational conditions. The stability of a catamaran ferry is influenced by several factors, including load distribution, weather conditions, and wave patterns. The righting lever (GZ) curve, which shows the ferry's ability to return to its upright position after heeling, is a key parameter for evaluating ferry stability. However, the ferry's stability data must be verified and analyzed according to ANNEX 7, Stability of Multihull Craft standards, to ensure that the H-192 ferry can operate safely in Indonesian waters. This involves calculating the GZ curve, evaluating the area under the GZ curve, and analyzing other stability

parameters for various loading conditions [4]. The main focus is on the calculation and evaluation of the following stability parameters, Righting Lever (GZ) Curve: A graph showing the ferry's ability to return to its upright position after heeling. Area Under the GZ Curve (A1): Evaluation of the area up to a certain heel angle to assess ferry stability. Heeling Lever: The impact of wind, passenger distribution, and ferry maneuvers on stability. Catamarans, having two hulls, distribute weight more evenly and reduce wave resistance, improving the vessel's stability, especially in rough sea conditions, and reducing the risk of capsizing or listing [5].

This analysis does not include actual operational evaluation of the ferry or sea trials. All calculations and evaluations are based on the stability data assumptions provided in the booklet. The purpose of this research is to evaluate the stability of the H-192 catamaran ferry according to ANNEX 7, STABILITY OF MULTIHULL CRAFT standards. This analysis will include Calculation of the Righting Lever (GZ) Curve: Calculating and analyzing the GZ curve for various loading conditions. Evaluation of the Area under the GZ Curve (A1): Measuring the area under the GZ curve up to a certain heel angle and comparing it with the established standards. A rounded symmetrical hull form shows the lowest total resistance. Stability analysis indicates that all variations of fishing gear meet the stability standards set by IMO MSC.36 (63) [6]. Catamarans demonstrate better stability compared to traditional fishing vessels due to having larger stabilizing arms [7]. The developed method for quantifying uncertainty is well-validated through these experiments. Statistical analysis of irregular waves produces accurate estimates of expected value (EV), standard deviation (SD), and quantile function. Results from regular wave tests indicate that the regular uncertainty quantification model can provide good estimates for optimized catamaran design [8]. There is a deficiency in maintaining a positive stability range, emphasizing the importance of design modifications or operational adjustments to ensure vessel safety in all operating conditions [9]. The configuration and separation of hulls are crucial in reducing resistance and increasing the efficiency of multihull vessels.

Analysis of the Heeling Lever: Assessing the impact of heeling due to wind, passenger loading, and maneuvers on ferry stability [10]. This research is expected to provide in-depth insights into the stability of the H-192 ferry, assisting PT XY in ensuring that this ferry is ready for safe and efficient operations in Indonesian waters. The stability of catamarans, particularly under varying sea conditions, has been the subject of extensive research due to its critical importance in maritime operations. Previous studies have focused on various aspects of ship stability, including the analysis of righting levers (GZ), metacentric height (GM), and other stability criteria. The High-Speed Craft (HSC) Code, specifically Annex 7, provides a comprehensive framework for evaluating the stability of high-speed vessels [11].

Recent advancements in computational tools, such as Maxsurf software, have enabled more precise and detailed stability calculations and simulations. These tools allow for the modeling of complex operational and environmental scenarios, providing deeper insights into the vessels behavior under different conditions.

Despite these advancements, there remains a need for case-specific studies that apply these methodologies to real-world vessels. The catamaran H-192, recently acquired by PT XY, serves as an ideal case study to assess the practical application of these stability criteria and computational tools. This research not only aims to ensure compliance with the HSC Code but also to exceed the stability standards, providing a benchmark for future studies and vessel designs.

2. Methods

This research evaluates the stability and response of the catamaran H-192 under various operational and environmental conditions, using the stability criteria outlined in Annex 7 of the High-Speed Craft (HSC) Code. The results from these analyses will provide a comprehensive understanding of the catamaran H-192 stability and response, ensuring it meets and exceeds the stability criteria set by Annex 7 of the HSC Code [12]. The methodology includes the following steps:

a. Stability Calculations:
Righting Lever (GZ) Analysis: Calculate the righting lever (GZ) at various angles of heel to assess transverse stability. Metacentric Height (GM) Analysis: Determine the metacentric height (GM) to evaluate the initial stability of the vessel. Other Stability Criteria: Analyze additional stability parameters as specified in Annex 7 of the HSC Code.

b. Model Design:
Software Utilization: Use Maxsurf software to design and simulate the catamaran model. Simulation Scenarios: Create various operational and environmental scenarios to test the vessel's stability.

c. Operational Data Analysis:
Load Distribution: Analyze the load distribution to determine the draft, trim, and stability under different loading conditions. Draft and Trim Calculations: Calculate the draft and trim for both full and empty operational conditions.

d. Evaluation of Stability Criteria:
Intact Stability Criteria: Evaluate the vessels intact stability criteria to ensure compliance with Annex 7. PASS Status Verification: Verify that all stability parameters achieve " PASS" status, indicating the vessels capability to handle various operational conditions.

e. Environmental Condition Assessment:
Wind and Maneuvering Forces: Assess the vessels response to healing forces due to wind and high-speed maneuvering. Passenger Crowding: Evaluate the stability under conditions of passenger crowding.

f. Data Collection and Analysis:
Operational Data: Collect operational data during different sea conditions. Analysis: Analyze the collected data to understand the vessels behavior in real-world situations.

2.1. Curve Righting Lever (GZ)

The righting lever, or GZ curve, is a critical indicator of a vessel's stability, representing its ability to right itself after heeling over due to external forces such as wind or waves. For multihull craft, the maximum value of this righting lever should occur at a heel angle of at least 10°, ensuring that the vessel has sufficient initial stability to counter small angles of

the heel effectively [13]. Additionally, the highest righting lever value must be observed at an angle of the heel not less than 15°, which means the vessel maintains adequate righting moment as it heels further, thus providing a buffer against capsizing [14]. This specification ensures that the vessel can recover from significant heeling angles without losing stability, which is crucial for the safety of multi-hull vessels operating in rough seas.

$$GZ = GM \times \sin\theta \tag{1}$$

Where GZ is righting lever (m), GM is Metacentric height (m) and θ is angle of heel (radians or degrees)

2.2. Area Under the GZ Curve (A1)

Multihull craft, such as catamarans and trimarans, have become increasingly prevalent in modern maritime operations due to their enhanced stability, increased deck area, and reduced hydrodynamic resistance. These vessels offer significant advantages in terms of stability and comfort for passengers compared to monohull designs. However, ensuring their stability under various operational conditions is crucial for safety at sea. The intact stability criteria outlined in Annex 7 provide a comprehensive framework to evaluate the stability characteristics of multihull vessels, ensuring that they can effectively withstand the forces encountered during typical sea operations [15]. This document defines the standards and calculations necessary for assessing the stability of multihull craft by section 2.1.3.4 of the Code.

A multihull craft, when intact, must possess sufficient stability to withstand the effects of passenger crowding or high-speed turning while navigating rough seas, as described in section 1.4. The craft's stability is deemed adequate if the following criteria are met:

$$A1 = 0.055 \times \frac{30°}{\theta} \text{ (m.rad)} \tag{2}$$

Where θ is the smallest of the following angles, the angle at which the maximum GZ occurs is an angle of 30°.

2.3. Calculation of Heeling Lever

The heeling lever caused by wind pressure on a vessel is a critical factor in assessing its stability, particularly for multihull craft. This lever represents the moment created by wind forces acting on the exposed surfaces of the vessel above the waterline, causing it to heel or tilt. To ensure accurate stability analysis, the heeling lever is treated as a constant value across all angles of inclination [16]. This calculation helps determine the vessel's ability to resist heeling forces, ensuring it can maintain stability under wind pressure by balancing the heeling moment against the righting moment provided by the vessel's hull form and ballast. The heeling lever due to the wind should be considered constant across all angles of inclination and is calculated as follows:

$$HL_1 = \frac{P_i . A . Z}{9800\,A} \; (m) \quad HL_2 = 1.5\; HL_1 \; (m) \tag{3}$$

Where Pi is 500 (VW / $\left(\frac{VW}{26}\right)^2$ (N/m2), VW is the wind speed under the worst expected conditions (m/s). A is the projected lateral area of the craft above the lightest service waterline (m²), Z is the vertical distance from the center of A to a point halfway down the lightest service draft (m) and Δ is the displacement (t).

$$HL_{wind} = \frac{P_i . A . h}{W} \; (m) \tag{4}$$

Where P is wind pressure, A is area exposed to wind, H is height of the wind pressure center from the waterline, and W is ship weight

$$HL_{passenger} = \frac{n . w . d}{W} \; (m) \tag{5}$$

Where n is number of passengers, w is average weight per passenger, d is distance from the ship center of gravity to the passenger crowding point, and W is Ship's weight

Combining HL4:
HL4 is the sum of these two heeling levers:

$$HL4 = HL_{wind} + HL_{Passenger} \; (m) \tag{6}$$

2.4. Heeling Lever Under Various Conditions

The Righting Lever (GZ) curve in wave conditions demonstrates how the stability of the ferry changes when exposed to dynamic sea conditions [17]. When the ferry is on a wave, the position of the wave crest relative to the ferry's hull can significantly affect the GZ value. As the wave crest moves from the front to the back of the ferry (or vice versa), the distribution of buoyant forces changes, shifting the center of buoyancy and affecting the righting lever [18]. This results in variations in the GZ curve that may enhance or diminish the ferry's ability to return to an upright position after heeling. This analysis is crucial for understanding the ferry's behavior in diverse wave conditions and helps in designing a ferry that has sufficient stability to operate safely in various sea states [19].

Heeling due to passenger crowding or high-speed turning: Should be applied together with the heeling lever due to wind (HL_2). Effect of Rolling in Seaway the stability effects due to rolling in a seaway must be demonstrated mathematically

[20]. The residual area under the GZ curve (A2), i.e. beyond the angle of heel (θ h), should be at least 0.028 m.rad up to the angle of roll.

    a. Area above the GZ curve and below ℓ w2, between θ R and the intersection of ℓ w2 with the GZ curve.

    b. Area above the heeling lever ℓ w2 and below the GZ curve, between the intersection of ℓ w2 with the GZ curve and θ2.

The angle of the heel under the action of steady wind (θ 0) is to be limited to 16° or 80% of the angle of deck edge immersion, whichever is less.
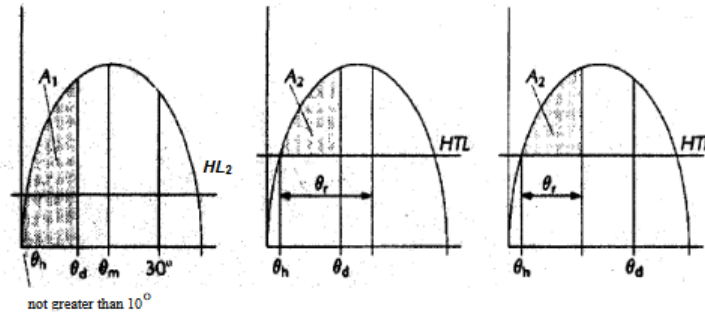
$$A2 > 0{,}028 \text{ m.rad} \tag{5}$$

Figure 1. Ship intact stability

Abbreviations used in figures:

- HL2 = Heeling lever due to wind + gusting
- HTL = Heeling lever due to wind + gusting + (passenger crowding or turning)
- HL3 = Heeling lever due to wind
- HL4 = Heeling lever due to wind + passenger crowding
- θm = Angle of maximum GZ
- θd = Angle of downflooding
- θr = Angle of roll
- θe = Angle of equilibrium, assuming no wind, passenger crowding, or turning effects
- θh = Angle of heel due to heeling lever HL2, HTL, HL3 or HL4
- A1 > Area required by 1.1
- A2 > 0.028 m.rad

3. Results and Discussion

3.1. Catamaran H-192 Hull Model

The H-192 catamaran ferry features a dual-hull (multi-hull) design that highlights two symmetrical hulls connected by a main deck. This design offers several key advantages. Stability: The dual-hull structure provides a greater width compared to monohull ferries, enhancing lateral stability and reducing rolling when exposed to waves. Capacity: The wide main deck increases cargo and passenger space, allowing for the transport of more cargo or passengers. Hydrodynamics: The slimmer hulls reduce water resistance, improving speed and fuel efficiency [21]. The main deck on this model is flat and spacious, ideal for passengers or vehicles if used as a ferry. The open deck structure also allows for flexibility in cargo arrangement or passenger layout. Each hull is equipped with watertight compartments, providing additional safety and increasing hull damage resistance. In operational conditions, if one hull experiences a leak, the other hull can provide sufficient buoyancy to keep the ferry stable.

Table 1. Catamaran H-192 Hull Specification

Dimension	Value	Unit
Length Overall	63	meters
Length B.P	56,09	Meters
Breadth mld.	16	meters
Depth mld.	5,6	meters
Design Draft (moulded)	1,6	meters
Summer Load Draft (extreme)	1,6	meters
Displacement at Load Draft	532,687	tonnes
Lightship Weight	0	tonnes
Deadweight at Load Draft	532,687	tonnes
Subdivision Length (Ls)	56,749	meters
Aft end of Ls aft of AP	0,659	meters
Subdivision Load Line (ds)	1,565	metres
Lightest Service Draft (d0)	0	metres
Length Overall	63	meters
Length B.P	56,09	meters
Breadth mld.	16	meters
Depth mld.	5,6	meters
Design Draft (moulded)	1,6	meters
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Subdivision Load Line (ds)	1,565	metres
Lightest Service Draft (d0)	0	metres

The H-192 catamaran ferry model depicts an optimal design for ferry operations with a dual-hull structure that offers stability, high cargo capacity, and operational efficiency (see Figure 2). With features such as a spacious main deck and good maneuverability, this ferry is designed to perform well in various sea conditions.
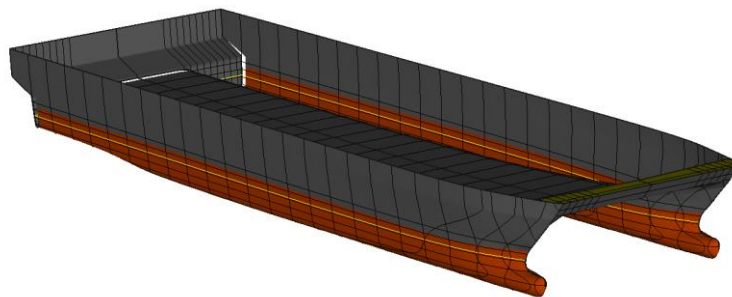

Figure 2. Catamaran H-192 Hull Model

3.2. Tank Plan

The fresh water tank, marked in blue, is centrally located in the middle of the ship as seen from the top view (see Figure 3). In the side view, this tank is visible at both ends of the ship, indicating that the freshwater tank may be distributed in several locations to maintain balance. The other tanks, marked in yellow, are symmetrically positioned along the centerline of the ship in the top view. In the side view, these yellow tanks are situated in the front and middle sections of the ship, suggesting a balanced load distribution. The tank plan above shows the distribution and placement of tanks in the H-192 catamaran ferry. This diagram illustrates the tank layout from both side and top views, which are used for storing various liquids such as freshwater (FW) and oil (OIL). Fresh water tanks are marked in blue, while oil tanks are marked in yellow.

The freshwater tanks are located at the front of the ferry on both hulls (port and starboard), while the oil tanks are situated in the middle of the ferry, also on both hulls. The placement of the tanks in the dual hulls helps distribute the load evenly, which is important for the ferry's stability. The tank locations also minimize the free surface effect that can impact the ferry's transverse stability. The tanks are designed to support the ferry's operational capacity by considering stability and load balance, ensuring that the ferry can operate with maximum efficiency and safety. With this tank plan, ferry operators can understand the distribution of liquid loads and how each tank affects the ferry's balance, which is crucial for cargo management and safe operation at sea.
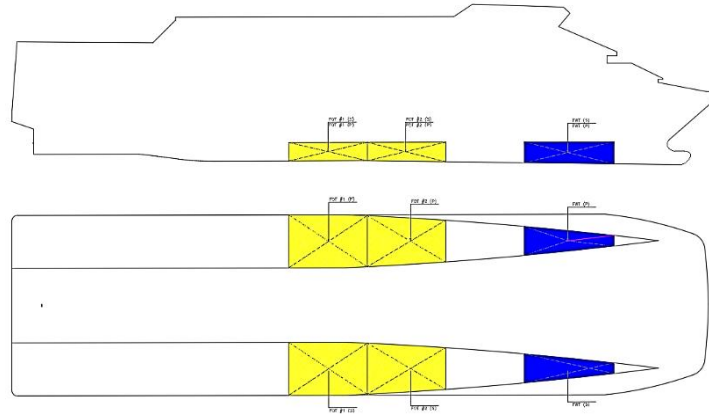
Figure 3. Tank Plan Catamaran H-192

Table 2 displays the details of the capacities and positions of the tanks in the H-192 catamaran ferry, which are used to store liquids such as freshwater (FW) and oil (OIL). The table includes information on the volume of each tank, as well as the coordinates of the center of mass of the tanks in three axes (LCG, TCG, and VCG) and Free Surface Moment (FSM). The table also shows the total volume of all tanks, which is 226.916 m³, with a combined longitudinal center of gravity (LCG) at 34.65 meters, no transverse deviation (TCG = 0.00), and a combined vertical center of gravity (VCG) at 0.770 meters. Colors are used to identify the type of liquid in the tanks: freshwater (FW) with a density of 1 t/m³ is marked in blue, and oil (OIL) with a density of 0.85 t/m³ is marked in yellow.

Table 2. Compartment Particular

Name	Frames	Volume (m³)	LCG (m)	TCG (m)	VCG (m)	FSM (t.m)
FOT 1 (P)	21 – 28	37,629	25,410	-6,049	0,784	0
FOT 1 (S)	22 – 28	37,867	32,197	-6,049	0,773	0
FOT 2 (P)	28 – 35	37,962	46,269	-6,050	0,752	0
FOT 2 (S)	29 – 35	37,629	25,410	6,049	0,784	0
FWT (P)	42 – 50	37,867	32,197	6,049	0,773	0
FWT (S)	42 – 50	37,962	46,269	6,050	0,752	0
Total		**226,916**	LCG = 34,65	TCG = 0,00	VCG = 0,770	0

3.3. Lightship Condition of the Ferry

The condition of the H-192 catamaran ferry in its lightship state refers to the ferry being empty, with no cargo or liquids in the tanks. Every tank on the ferry, including both oil tanks (FOT) and freshwater tanks (FWT), shows a quantity of 0%, meaning there are no liquids inside them. The oil tanks FOT 1 (P), FOT 1 (S), FOT 2 (P), and FOT 2 (S) located at frames 21-35 are all empty. Similarly, the fresh water tanks FWT (P) and FWT (S) at frames 42-50 are also empty. All passenger decks (Passenger Decks 1, 2, and 3), crew areas, and the entire lightship condition do not carry any cargo. This indicates that the ferry in this table is in its baseline condition without any additional load from liquids or passengers. This information is crucial for understanding the ferry's baseline stability and balance before loading, which can later be used as a reference for calculating stability and trim when the ferry is loaded with various types of liquids or cargo. The lightship condition provides a fundamental guide on the ferry's mass distribution without the influence of cargo, passengers, or liquids. This helps in planning the loading and assessing its impact on the ferry's stability during operation.

a. Drafts at Equilibrium Angle in Lightship Condition
At the equilibrium angle, the draft of the ferry, or the depth of the water at various key points, is measured to understand the load distribution and balance of the H-192 catamaran ferry. The draft at LCF (Longitudinal Center of Flotation) is recorded at 0.701 meters, indicating the depth of the water at the longitudinal center of buoyancy where the ferry tends to rotate

when the trim changes. The draft at AP (After Perpendicular), which is the water depth at the aft end of the ferry, is 1.210 meters, helping to determine the aft draft. At the front of the ferry, the draft at FP (Forward Perpendicular) is only 0.117 meters, indicating a low draft at the bow, which suggests a trim towards the stern. The Mean Draft at Midships, or the average draft at the midpoint of the ferry, is 0.664 meters, providing an overall picture of how the ferry sits in the water. These draft measurements are essential for assessing the ferry's stability in a lightship condition, ensuring that the load distribution allows for safe and efficient operation.

b. Hydrostatics at Equilibrium Angle in Lightship Condition

Hydrostatics at the Equilibrium Angle provides the hydrostatic information of the H-192 catamaran ferry at the equilibrium angle, which is crucial for assessing the ferry's stability and operational performance. The measured water density is 1.0218 tons/m³, affecting the ferry's buoyancy. The heel is 0°, indicating that the ferry is upright without any lateral tilt. The Trim by the Stern is recorded at 1.093 meters, indicating that the ferry has a sternward trim. The KG (Vertical Center of Gravity) is 1.900 meters, which is the vertical distance from the keel to the ferry's center of gravity, showing the vertical balance of the ferry. The GMt (Transverse Metacentric Height) is 66.275 meters and the BMt (Transverse Metacentric Radius) is 67.766 meters, indicating the distance between the center of gravity and the transverse metacenter, and the transverse metacentric radius, both crucial for the ferry's transverse stability. The BMl (Longitudinal Metacentric Radius) is 434.769 meters, indicating the longitudinal metacentric radius affecting the ferry's longitudinal stability. The Waterplane Area is 361.368 m², which is the area of the waterplane helping in stability calculations. The LCF (Longitudinal Center of Flotation) is at 26.159 meters, indicating the center point of the waterplane area where the ferry will rotate when the trim changes. Additionally, the TPI (Tonnes Per Inch Immersion) of 3.704 tons/cm and MCT (Moment to Change Trim) of 15.841 ton-m/cm are important metrics for measuring the change in draft and trim of the ferry when adding load, while the hull thickness of 6.000 mm indicates the structural strength of the ferry.

c. Righting Lever Hydrostatics at Equilibrium Angle in Lightship Condition

The Righting Lever (GZ) Curve provides data on the H-192 catamaran ferry's ability to return to an upright position when experiencing heeling or tilting. Heel to Starboard (Stbd) indicates the ferry's tilt angle to the right (in degrees), ranging from -30° (to port) to 60° (to starboard). GZ (Righting Lever) in meters is the horizontal distance between the vertical line through the center of gravity (G) and the center of buoyancy (B) at a specific heel angle. The GZ value indicates the restoring force generated to correct the ferry's tilt. At angles from -30° to -10°, the GZ values are negative (e.g., -5.155 meters at -30°), indicating a moment causing the ferry to tilt further from the upright position. At 0° angle, GZ is 0 meters, indicating no tilt and the ferry is in balance. As heeling reaches positive angles from 10° to 60°, the GZ values are positive (e.g., 5.909 meters at 10°), showing an increasingly strong restoring force to correct the tilt and stabilize the ferry. GM (Metacentric Height) in meters is the vertical distance between the center of gravity (G) and the metacenter (M), an indicator of the ferry's initial stability. High GM values indicate good stability; for example, GM reaches a maximum of 66.275 meters at the upright position (0° heel) and decreases with increasing heel angles, down to 3.607 meters at 60°. The decreasing GM values with increasing heel angles indicate a reduction in stability as the ferry tilts further from its upright position. The conditions that are considered stable include the results where the GZ values are positive, indicating a restoring force that helps the ferry return to an upright position.
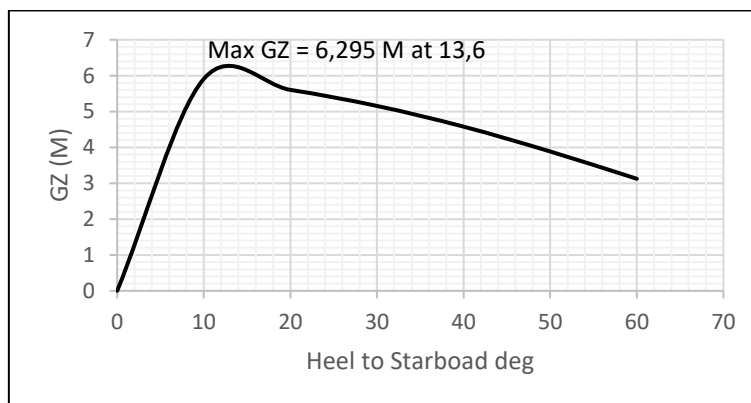

Figure 4. Max GZ in Lightship Condition 6.295 M at 13.6 deg

Intact Stability Criteria for the H-192 catamaran ferry, shows the ferry's compliance evaluation with stability standards in intact conditions according to the High-Speed Craft (HSC) code for multihull vessels (see Table 3). The first parameter, the area under the Righting Lever (GZ) curve between specified limits, indicates an actual value of 33.65 m.rad compared to the standard value of 9.454 m.rad, demonstrating that the ferry exceeds the minimum requirements, earning a PASS status. The next evaluation concerning the HLT area between GZ & HA, which assesses the area between the GZ curve and the heeling arm caused by high speed and wind conditions, also receives a PASS status, though specific values are not listed. The ferry shows excellent performance in withstanding the combined forces of Wind Heeling Arm + Turning Heeling Arm, with an actual value of 63.762 m exceeding the standard value of 1.604 m, demonstrating the ability to withstand forces generated from wind and high-speed maneuvers. Lastly, the combination of forces from Wind Heeling Arm + Passenger Crowding Heeling Arm is evaluated with a standard value of 1.6043 m and an actual value of 64.669 m, also showing that the ferry has ample capacity to withstand these conditions, earning a PASS status. Overall, this table confirms that the H-192 catamaran

ferry not only meets but far exceeds the required stability standards, ensuring safety and good performance in various operational conditions.

Table 3. Intact Stability Criteria for Lightship Condition

NO	Criterion	Value	Actual	Status
1	GZ area between limits type 3 - HSC multihull	9,454	33,65	PASS
2	HLT Area Between GZ & HA			PASS
	Wind heeling arm + Turning heeling arm	1,604	63,762	PASS
	Wind heeling arm + Passenger crowding heeling arm 1,6043	1,604	64,669	PASS

3.4. Intact Departure Full Passenger Condition

The condition of the H-192 catamaran ferry when operating at full capacity, with both passengers and tanks of fuel and fresh water fully loaded. Each fuel oil tank (FOT) and freshwater tank (FWT) is filled up to 98% of its capacity. Fuel tanks FOT 1 (P), FOT 1 (S), FOT 2 (P), and FOT 2 (S), located at frames 21-35, contain oil with a specific gravity (SG) of 0.850 t/m³, resulting in weights ranging from 35.533 tons to 37.962 tons each. Fresh water tanks FWT (P) and FWT (S) at frames 42-50 contain water with an SG of 1.000 t/m³, weighing 35.758 tons and 37.962 tons, respectively. Additionally, the table lists the load of passengers and crew on various decks. Passenger Deck 1 holds 568 passengers with an SG of 0.900 t/m³, resulting in a total weight of 51.120 tons. Passenger Deck 2 holds 440 passengers with a total weight of 39.600 tons, and Passenger Deck 3 holds 104 passengers with a total weight of 9.360 tons. The crew consists of 100 people with a total weight of 9.000 tons. The total weight of the empty ferry (lightship) is 205.101 tons. This comprehensive condition of the ferry provides an overview of the distribution and total load of the ferry when fully loaded, including fuel, fresh water, passengers, and crew, offering essential guidance for stability calculations and load management during full operation.

a. Drafts at Equilibrium Angle in Intact Departure Full Passenger Condition

Drafts at an Equilibrium Angle provide information about the depths of the H-192 catamaran ferry at various key points when the ferry is at an equilibrium angle. The Draft at LCF (Longitudinal Center of Flotation) is 1.565 meters, indicating the water depth at the longitudinal center of buoyancy of the ferry, where the ferry tends to rotate when there is a change in trim. The Draft at AP (After Perpendicular) is 1.468 meters, denoting the water depth at the aft end of the ferry, which is useful for determining the draft at the stern. The Draft at FP (Forward Perpendicular) is 1.678 meters, showing the water depth at the forward end of the ferry, which is important for understanding the forward trim of the ferry. The Mean Draft at Midships is 1.573 meters, which is the average draft at the midpoint of the ferry, providing a general overview of how the ferry sits in the water overall.

b. Hydrostatics at Equilibrium Angle in Intact Departure Full Passenger Condition

The hydrostatic characteristics of the H-192 catamaran ferry at the equilibrium angle are as follows: The density of water is 1.0218 tons/m³. The heel is 0°, indicating that the ferry is upright. The trim by the stern is -0.209 meters, showing that the stern is higher than the bow. The KG (Vertical Center of Gravity) is 2.396 meters, which is the distance from the keel to the ferry's center of gravity. The GMt (Transverse Metacentric Height) is 25.115 meters, indicating good transverse stability. The BMt (Transverse Metacentric Radius) is 26.691 meters, and the BMl (Longitudinal Metacentric Radius) is 162.111 meters, showing stability in both the transverse and longitudinal axes. The waterplane area is 368.828 m², while the LCF (Longitudinal Center of Flotation) is 25.895 meters. The TPI (Tonnes per Inch Immersion) is 3.780 tons/cm, and the MCT (Moment to Change Trim) is 15.245 ton-m/cm. The shell thickness is 6 mm.

c. Righting Lever (GZ) Curve in Intact Departure Full Passenger Condition

The Righting Lever (GZ) Curve shows the relationship between the heel angle of the ferry to the starboard side and the values of the righting lever (GZ) and metacentric height (GM) at various angles. Heel to Stbd (deg) indicates the heel angle of the ferry from -30° to 60°. GZ (m) is the horizontal distance between the vertical line through the center of gravity and the center of buoyancy at a specific heel angle, indicating the restoring force that returns the ferry to the upright position. Negative GZ values at angles -30°, -20°, and -10° indicate a moment that causes the ferry to heel further to the same side, while positive GZ values at angles 10° to 60° indicate a restoring force that brings the ferry back to the upright position. GM (Metacentric Height) is the vertical distance between the center of gravity and the metacenter, indicating the ferry's stability. The GM value peaks at 25.115 meters when the ferry is in the upright position (0° heel) and decreases as the heel angle increases, showing that the ferry's stability decreases with increasing heel.

The conditions that are considered stable for the ferry are those where the righting lever (GZ) values are positive, indicating a restoring force that brings the ferry back to the upright position. According to the Righting Lever (GZ) Curve, these stable conditions occur at heel angles from 10° to 60° to the starboard side. Within this range, the ferry experiences a positive GZ, meaning it has the ability to right itself and maintain stability. The graph shows that the maximum stability is achieved at a 20-degree heel angle to starboard, where the righting lever (GZ) reaches its peak value of 5.554 meters. This indicates the strongest restoring force at this angle, making it the most stable condition for the ferry. As the heel angle increases beyond 20 degrees, the GZ values gradually decrease, indicating a reduction in the ferry's stability. However, as long as the GZ values remain positive, the ferry is considered stable.
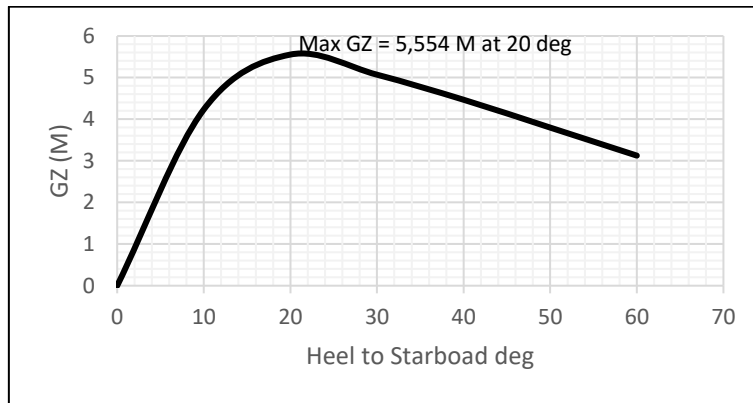
Figure 5. Max GZ Intact Departure Full Passenger Condition 5.554 M at 20 degrees

Intact Stability Criteria shows the evaluation of the stability of the H-192 catamaran ferry in an intact condition (see Table 4), comparing the required standard values with the actual values achieved by the ferry. The first criterion, GZ area between limits type 3 - HSC multihull, has a standard value of 9.454 m.rad and an actual value of 22.791 m.rad, indicating that the ferry exceeds the minimum requirements and receives a PASS status. The second criterion, HLT Area between GZ & HA, also shows that the ferry meets the established standards, receiving a PASS status, even though the specific value is not listed. The evaluation of Wind heeling arm + Turning heeling arm shows a standard value of 1.604 m and an actual value of 46.256 m, indicating that the ferry can handle the combined heeling forces from wind and high-speed maneuvers very well, thus receiving a PASS status. Finally, the combination of Wind heeling arm + Passenger crowding heeling arm has a standard value of 1.604 m and an actual value of 46.847 m, indicating that the ferry can also safely handle this combined force, receiving a PASS status.

Table 4. Intact Stability Criteria Intact Departure Full Passenger Condition

No	Criterion	Value	Actual	Status
1	GZ area between limits type 3 - HSC multihull	9,454	22,791	PASS
2	HLT Area Between GZ & HA			PASS
	Wind heeling arm + Turning heeling arm	1,604	46,256	PASS
	Wind heeling arm + Passenger crowding heeling arm 1,6043	1,604	46,847	PASS

3.5. Intact Arrival Full Passenger Condition

The Intact State (Arrival Full Passenger) indicates the condition of the H-192 catamaran ferry upon arrival with full passengers and partially filled tanks. Each fuel oil tank (FOT) and fresh water tank (FWT) are filled to 10% of their capacity. The FOT 1 (P) and FOT 1 (S) tanks located at frames 21-28, as well as the FOT 2 (P) and FOT 2 (S) tanks at frames 28-35, each contain oil with a specific gravity (SG) of 0.850 t/m³, weighing approximately 3.626 to 3.649 tons per tank. The fresh water tanks FWT (P) and FWT (S) at frames 42-50 contain water with an SG of 1.000 t/m³, each weighing 3.874 tons. Passengers are distributed across three decks: Passenger Deck 1 accommodates 568 passengers with a total weight of 51.120 tons, Passenger Deck 2 holds 440 passengers weighing 39.600 tons, and Passenger Deck 3 has 104 passengers weighing 9.360 tons. The ferry crew consists of 100 members with a total weight of 9.000 tons. The lightship weight of the ferry is 205.101 tons.

a. Drafts at Equilibrium Angle for Intact Arrival Full Passenger Condition

Drafts at Equilibrium Angle show the depth or draft of the H-192 catamaran ferry at various key points when it is at an equilibrium angle. The draft at LCF (Longitudinal Center of Flotation) is 1.041 meters, indicating the water depth at the longitudinal center of buoyancy of the ferry, which is the rotation point during trim changes. The draft at AP (After Perpendicular) is 1.399 meters, showing the water depth at the stern of the ferry, important for determining the aft draft. The draft at FP (Forward Perpendicular) is 0.643 meters, indicating the water depth at the bow of the ferry, used to measure the forward draft. The mean draft at midships is 1.021 meters, which is the average draft at the middle of the ferry, providing a general overview of how the ferry sits in the water overall.

b. Hydrostatics at Equilibrium Angle for Intact Arrival Full Passenger Condition

Hydrostatics at Equilibrium Angle provides data on the hydrostatic characteristics of the H-192 catamaran ferry at an equilibrium angle. The density of water is 1.0218 tons/m³. The heel is 0°, indicating the ferry is upright. The trim by the stern is 0.756 meters, showing the stern is slightly lower than the bow. KG (Vertical Center of Gravity) is 3.294 meters, and KGf is 3.704 meters, indicating the vertical position of the ferry's center of gravity. GMt (Transverse Metacentric Height) is 39.477 meters, indicating very good transverse stability. BMt (Transverse Metacentric Radius) is 42.619 meters, and BMl (Longitudinal Metacentric Radius) is 277.258 meters, showing stability in both axes. The waterplane area is 372.383 m², and LCF (Longitudinal Center of Flotation) is 26.557 meters. TPI (Tonnes Per Inch Immersion) is 16.442 tons/cm, indicating the weight required to increase the ferry's draft by 1 cm. MCT (Moment to Change Trim) is also 16.442 tons-m/cm, indicating the moment required to change the ferry's trim by 1 cm. The shell thickness is 6 mm.

c. Righting Lever (GZ) Curve for Intact Arrival Full Passenger Condition

The Righting Lever (GZ) Curve shows the relationship between the heel angle of the ferry to the starboard and the righting lever (GZ) value and the metacentric height (GM) at various angles. Heel to Stbd (deg) includes heel angles from -30° to 60°. GZ (m) is the horizontal distance between the vertical line through the center of gravity and the center of buoyancy at a specific heel angle, indicating the restoring force of the ferry to return to the upright position. Negative GZ values at angles -30°, -20°, and -10° indicate moments causing the ferry to heel further to the same side, while positive GZ values at angles 10° to 60° indicate forces restoring the ferry to the upright position. GM (Metacentric Height) is the vertical distance between the center of gravity and the metacenter, indicating the ferry's stability. The GM value peaks at 39.477 meters when the ferry is upright (0° heel) and decreases as the heel angle increases, indicating that the ferry's stability decreases with increasing heel angles. Overall, this table illustrates the ferry's ability to return to the upright position from various heel angles, which is crucial for assessing the stability and operational safety of the H-192 catamaran ferry.
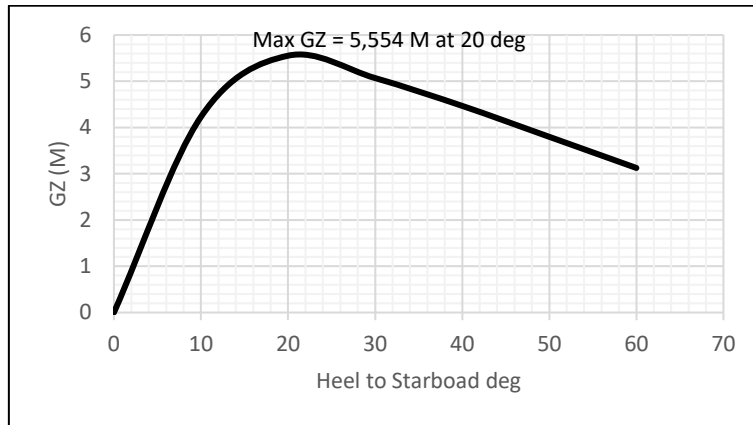

Figure 6. Max GZ for Intact Arrival Full Passenger Condition: 5.554 M at 20 degrees

Intact Stability Criteria evaluates the stability of the H-192 catamaran ferry in intact condition (see Table 5), comparing the required standard values with the actual values achieved by the ferry. The first criterion, GZ area between limits type 3 - HSC multihull, has a standard value of 9.454 m.rad and an actual value of 22.791 m.rad, indicating that the ferry exceeds the minimum requirements, with a status of PASS. The second criterion, HLT Area between GZ & HA, shows that the ferry meets the set standards, with a status of PASS. The evaluation of Wind heeling arm + Turning heeling arm shows a standard value of 1.604 m and an actual value of 46.256 m, indicating that the ferry is very capable of handling the combined heeling forces from wind and high-speed maneuvers, earning a status of PASS. Finally, the combination of Wind heeling arm + Passenger crowding heeling arm has a standard value of 1.604 m and an actual value of 46.847 m, showing that the ferry can also safely handle these combined forces, earning a status of PASS. Overall, this table demonstrates that the H-192 ferry not only meets but also exceeds the necessary stability standards, ensuring safety and optimal performance under various operational conditions.

Table 5. Intact Stability Criteria for Intact Arrival Full Passenger Condition

No	Criterion	Value	Actual	Status
1	GZ area between limits type 3 - HSC multihull	9,454	22,791	PASS
2	HLT Area Between GZ & HA			PASS
	Wind heeling arm + Turning heeling arm	1,604	46,256	PASS
	Wind heeling arm + Passenger crowding heeling arm 1,6043	1,604	46,847	PASS

3.6. Discussion

The stability analysis of the H-192 catamaran ferry shows that this vessel meets and even exceeds the standards set by Annex 7 for multihull craft. Here are the key points of the discussion related to the research results:

a. Righting Lever (GZ) Curve:

The GZ curve analysis shows that the H-192 ferry has a strong ability to return to an upright position from various angles of heel. At heel angles from -30° to -10°, the negative GZ values indicate a moment causing further heeling. However, from 10° to 60°, the positive GZ values peak at 20° (5.554 m), indicating strong righting moments. This shows that the ferry can effectively correct heel and return to an upright position, indicating good stability.

b. Metacentric Height (GM):

The GM value peaks at 39.477 meters at the upright position (0° heel) and decreases as the heel angle increases. Although GM decreases at larger heel angles, it remains at a level that indicates good stability, with the lowest value being 3.610 meters at 60°. This shows that the ferry has excellent transverse stability and can maintain balance even at significant heel angles.

c. Intact Stability Criteria:

The evaluation of intact stability criteria shows that the H-192 ferry not only meets but also exceeds the set standards. The criterion of GZ area between limits type 3 - HSC multihull shows an actual value of 22.791 m.rad compared to the

standard value of 9.454 m.rad, indicating excellent righting capacity. The evaluations of Wind heeling arm + Turning heeling arm and Wind heeling arm + Passenger crowding heeling arm show actual values far exceeding the standard values (46.256 m and 46.847 m compared to 1.604 m), indicating that the ferry can handle combined heeling forces from wind, maneuvering, and passenger crowding very well.

d. Operational Conditions:

The analysis of the ferry's full passenger (full load) and lightship (empty) conditions shows balanced load distribution and maintained stability. The tables illustrate how fuel and freshwater tanks are partially filled upon arrival, with passengers and crew distributed across various decks. This condition is important to ensure that the ferry remains stable and safe during operational voyages.

e. Hydrostatics at Equilibrium Angle:

The hydrostatic data shows important characteristics such as Density of water, Trim by the stern, KG, GMt, BMt, BMl, Waterplane area, LCF, TPI, MCT, and Shell thickness. These values confirm that the ferry is designed for optimal stability and safe operational performance. High GMt (39.477 m) and BMt (42.619 m) values indicate excellent transverse stability, while a high BMl value (277.258 m) shows strong longitudinal stability.

f. Calculation of HL4

Heeling Lever Due to Wind: This is the heeling lever generated by the wind force acting on the ship's superstructure. This wind force tends to cause the ship to heel to one side. Heeling Lever Due to Passenger Crowding: This is the heeling lever generated by the uneven distribution of passengers on the ship. When passengers crowd on one side of the ship, it can cause the ship to heel.

- Heeling Lever due to Wind

The area affected by the wind is 252 square meters. This means that the wind blowing will impact a surface area of 252 square meters. The height of the wind pressure center from the waterline is 2 meters, indicating that the point where the wind pressure acts is 2 meters above the water surface. The standard wind pressure applied is 25 Pascals, which measures the force of the wind acting on the area. As a result of this wind pressure, there is a force causing the ship or structure to heel, known as the heeling lever. In this case, the heeling lever due to the wind is approximately 0.0615 meters, indicating how far the ship or structure will tilt due to the wind pressure received.

- Heeling Lever due to Passenger Crowding

The ship with a lightship weight of 205,101 tons has several passenger decks and crew that contribute to the heeling lever due to passenger crowding. On Passenger Deck 1, there are 568 passengers, each weighing 0.090 tons, resulting in a total passenger mass of 51.120 tons on this deck. The vertical distance from the center of gravity of the passengers on this deck is 4.410 meters. On Passenger Deck 2, there are 440 passengers, each weighing 0.090 tons, resulting in a total passenger mass of 39.600 tons on this deck. The vertical distance from the center of gravity of the passengers on this deck is 7.280 meters. On Passenger Deck 3, there are 104 passengers, each weighing 0.090 tons, resulting in a total passenger mass of 9.360 tons on this deck. The vertical distance from the center of gravity of the passengers on this deck is 10.000 meters. Additionally, there are 100 crew members, each weighing 0.090 tons, resulting in a total crew mass of 9.000 tons. The vertical distance from the center of gravity of the crew is 12.360 meters. Due to this mass distribution, the heeling lever due to passenger crowding is approximately 3.502 meters.

- calculating HL4

To calculate the combined HL4, we need to sum the Heeling Lever due to wind and the Heeling Lever due to passenger crowding that we calculated earlier. The Heeling Lever due to wind is approximately 0.0615 meters, while the Heeling Lever due to passenger crowding is approximately 3.502 meters. By adding these two values, we obtain a combined HL4 of 3.5635 meters. This means that the total effect of the wind and passenger crowding causes the ship or structure to heel by 3.5635 meters.

Overall, the stability analysis of the H-192 ferry based on Annex 7 for multihull craft shows that this ferry has excellent stability and meets all required criteria. The ferry is well-designed to maintain balance and stability under various operational conditions, ensuring safety and optimal performance at sea.

4. Conclusion

This study evaluates the stability of the H-192 catamaran ferry using the criteria set in Annex 7 for multihull craft. Based on the analysis conducted, the main conclusions that can be drawn are as follows. The H-192 catamaran ferry not only meets but also exceeds the stability criteria set by Annex 7. This is shown by the high values of the righting lever (GZ) and metacentric height (GM) at various heel angles. The GZ value peaks at 20° (5.554 m), and the highest GM value at the upright position (0° heel) is 39.477 m. The evaluation of intact stability criteria shows that the ferry can handle combined heeling forces from wind, high-speed maneuvering, and passenger crowding very well, with all criteria showing a "PASS" status. This indicates that the H-192 ferry has excellent transverse and longitudinal stability, which is crucial for operational safety. The analysis of the ferry's full passenger (full load) and lightship (empty) conditions shows balanced load distribution and maintained stability. In the full load condition, the fuel and freshwater tanks are partially filled, while passengers and crew are distributed across various decks. The hydrostatic data at the equilibrium angle shows high KG (3.294 m) and GMt (39.477 m) values, as well as a large waterplane area (372.383 m²). This ensures that the ferry has a good balance and can maintain its stability under various load and operational conditions. The combined HL4, which includes the Heeling Lever due to wind and the Heeling Lever due to passenger crowding, is approximately 3.5635 meters. This indicates that the total effect of the wind and passenger crowding causes the ship or structure to heel by 3.5635 meters. Thus, the H-192 catamaran ferry meets and exceeds the required stability standards, ensuring safety and optimal performance under various operational conditions. These findings provide confidence that this ferry is ready for safe and efficient.

The analysis of the H-192 ferry's stability shows that it has a strong ability to return to an upright position from various angles of heel, with positive GZ values peaking at 20° (5.554 m), indicating good stability. The ferry not only meets but also exceeds the intact stability criteria, with actual values for GZ area and combined heeling arms (wind, turning, and passenger crowding) far surpassing the standards. Additionally, the operational conditions analysis demonstrates balanced load distribution and maintained stability in both full passenger and lightship conditions, ensuring the ferry remains stable and safe during voyages.

Acknowledgments

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