Widening Study of a 45-Meter Tuna Fishing Vessel Based on Multi-Objective Optimization

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Abstract

Stability issues in fishing vessels represent a significant risk to maritime safety, despite advances in stability regulations by the International Maritime Organization (IMO). This paper presents a multi-objective optimization study focused on the widening of a 45.1-meter tuna fishing vessel to improve stability by increasing its beam. The optimization was developed based on the IMO's Second Generation Stability Criteria (SGSC), evaluating the vessel's critical failure modes. The Non-Linear Generalized Reduced Gradient (GRG) method method was applied to obtain a balanced solution that improves stability and increases cargo capacity while maintaining operational safety.. The vessel's improved performance was validated under operational conditions, demonstrating the feasibility of the proposed modifications.

Key words: Multi-Objective Optimization, Ship Widening, Fishing Vessel Stability, Second Generation Stability Criteria (SGSC), GRG Method, International Maritime Organization (IMO).

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Introduction

Stability issues in Ecuador's fishing vessels have been a critical maritime safety concern. These problems have led to several accidents, endangering both the crew and the vessel itself [1]. Despite having an approved stability booklet under the criteria of the International Maritime Organization [2] which is required for vessel operations, these are not sufficient to determine the complete safety of a vessel for navigation.

Due to this limitation, the IMO subsequently developed the Second-Generation Stability Criteria (SGISC), which introduces improvements to more accurately assess the stability and accelerations of fishing vessels under real operating conditions. Five failure modes have been clearly identified: Parametric Roll, Loss of Stability, Sudden Surf and Yaw, Unmachined Ship Condition, and Excessive Steering and Accelerations. [3]. However, in spite of these regulations, accidents still occur in Ecuadorian waters, such as the 2014 sinking of a fishing vessel 180 miles off the Galápagos Islands, involving human and equipment losses [4].

The present analysis is carried out comprising all aspects related to the failure modes, structure and hierarchy for the application of the criteria. In addition, the description of the characteristics of the vessel under study is presented, and it is intended to give a perspective to know the background of the IMO Second Generation Intact Stability Criteria used for tuna vessels [5]. The application of these criteria is reflected in the evaluation of the vulnerability to five failure modes in the vessel.

The case study involves the following analysis process:

- Generate confidence intervals for the design parameter.
- Establish the critical load condition.
- Study various models with beam increments.
- Evaluation of Second-Generation Stability Criteria.

The IMO has identified the following failure modes to which ships are vulnerable, [3]:

- Parametric roll
- Excessive accelerations
- Pure loss of stability
- Surf-riding/broaching
- Dead ship

IMO presents a report to help contribute to the need to mathematically describe the phenomena of parametric resonance and dynamic instability; this allows to take into consideration its recommendations to analyze roll resonance during the development of ship operations.

Literature Review

Parametric Roll. When a ship faces bow or stern waves, it experiences a variation in the restoring moment for roll over time.

$$\frac{\delta GM_1}{GM} \leq R_{PR} \text{ and } \frac{\nabla_D - \nabla}{A_W(D-d)} \geq 1.0 \quad (1)$$

Excessive Accelerations. If the GMt is considerably large, the natural roll period can be very small, so that a large acceleration under synchronous resonance could affect the crew or cargo at a specific point on the ship.

$$\varphi \bullet k_L \bullet \left(g + \frac{4\pi^2 h_r}{T_r^2}\right) \leq R_{EA} \quad (2)$$

$$R_{EA} = 4.64\,(\text{m/s}^2)$$

Pure Loss. Dynamic response when a wave, with length like the ship, has its crest positioned at the center of this, reducing the restoring moment of roll.

$$GM_{min} \geq R_{PR} \text{ and } \frac{\nabla_D - \nabla}{A_W(D-d)} \geq 1.0 \quad (3)$$

$$R_{PLS} = 0.05[\text{m}]$$

Surf-riding and Broaching-to. Broaching-to is a violent and uncontrollable turn that occurs despite applying maximum effort to steer the ship to avoid it. This phenomenon is preceded by another, surf riding, where the following wave 'catches' the vessel and accelerates it to the wave's phase speed.

$$L \geq 200[m] o\ Fn \leq 0.3 \quad (4)$$

Dead Ship Condition. Ship loses its propulsion, and is subjected to side waves, wind action and its combined effects (wind, aerodynamics and hydrodynamic relationship) caused by the transverse motion of the ship.

$$l_{lw1} = \frac{P_{pres} * A_v * Z}{\Delta * tan\,\theta}\ [m] \quad (5)$$

$$l_{lw2} = 1.5\, l_{lw1}\, [m] \quad (6)$$

Table 1. General characteristics and coefficients of the prototype fishing vessel.

Characteristic	Value	Units
Length	45.10	[m]
Length water line	40.16	[m]
Length between perp	38.48	[m]
Beam	7.94	[m]
Depth main deck	4.72	[m]
Velocity max	10	[knots]
HorsePower	1076	[hp]
Carrying capacity	265	[ton]
Displacement max	815.76	[ton]
Froude number	0.26	[-]
Block Coeff	0.597	[-]
Midship Coeff	0.856	[-]
Water line Coeff	0.840	[-]
Long. Prismatic Coeff	0.697	[-]
Vert. Prismatic Coeff	0.711	[-]

Methodology

The methodology applied in this investigation follows a quantitive optimization approach combined with statistical analysis to evaluate design modifications that enhance ship stability. Specifically, a parametric optimization method was employed, utilizing the Generalized Reduced Gradient (GRG) algorithm for nonlinear constraints. These constraints were defined by including limits related to roll acceleration, beam confidence intervals, budget, anchoring period, cargo capacity, ship speed, and dead engine criteria. The parameters involved in these constraints were formulated as functions dependent on the beam, facilitating their implementation and analysis within the Nonlinear GRG optimization method.

The widening analysis began with a survey of similar ships, allowing the establishment of confidence intervals for key design parameters, such as length, beam, draft, and depth, as well as for the propulsion system characteristics, speed, and power. These intervals were developed using linear regressions based on the length, which enabled the determination of upper and lower beam limits for the vessel´s current length.

Five models with different beam values within the confidence interval were generated to obtain the corresponding hydrostatic characteristics. The widening of each model was performed while maintaining the deadwood constant and extending the first chine. The additional weight due to the increased beam was determined using the vessel’s weight curve, which facilitated the stability analysis of the ship. The obtained hydrostatic parameters allowed for the evaluation of roll acceleration and anchoring period for each model, thus establishing a function to rank these behaviors.

Since the widening of a vessel generally reduces its operational speed due to hull shape, each model was numerically and

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analytically evaluated regarding speed reduction, considering the relationship between the transport coefficients and the Almirantazgo equation. A restriction for beam increase was set, which consisted of limiting speed reduction to no more than 0.5 knots. This restriction was integrated into the GRG optimization model to define the optimal design for ship widening.

Finally, the stability criteria evaluation was conducted with the selected beam increment, following the gidelines established by the International Maritime Organization (IMO) for First and Second Geneation. Intermediate stability criteria, such as those form Pascual O' Dogherty, J. Ramón, Kempf and Tagaki, were also include, providing a complementary approach between first and second-generation criteria. Additionally, a comporison of the vessel's stability before and after the beam widening was performed, thereby assessing the effectiveness of the widening in enhancing stability and ensuring compliance with with regulatory requirements.

Results and Discussions

According to the methodology selected to optimize the design of the fishing vessel, the main priority was to increase stability, but

Fig. 1. Original and model with removed sides in front and side view.

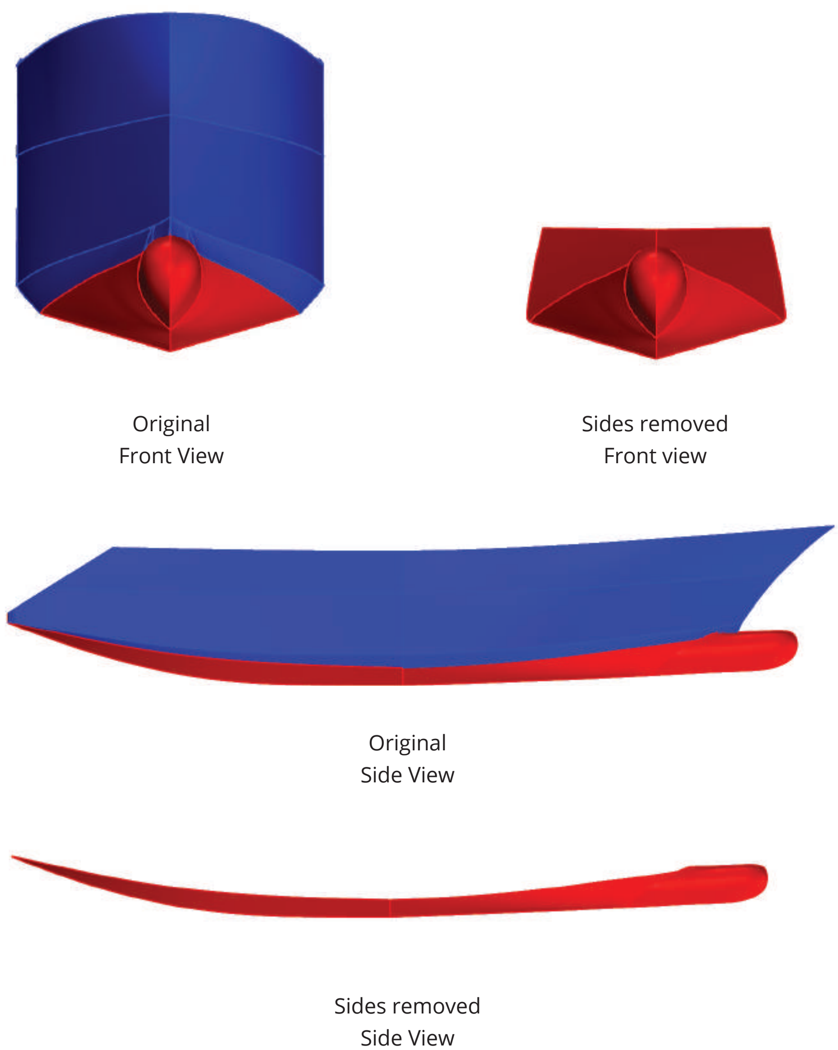


Fig. 2. Model widened by keeping the dead rise until the first chine.

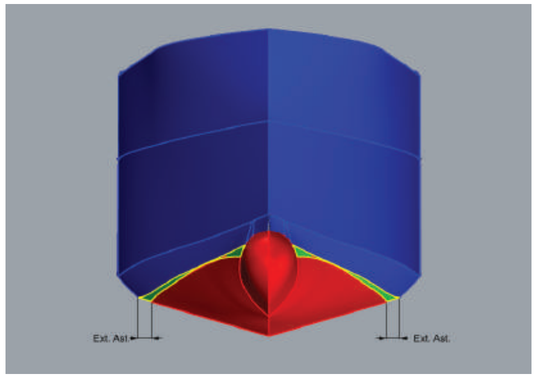
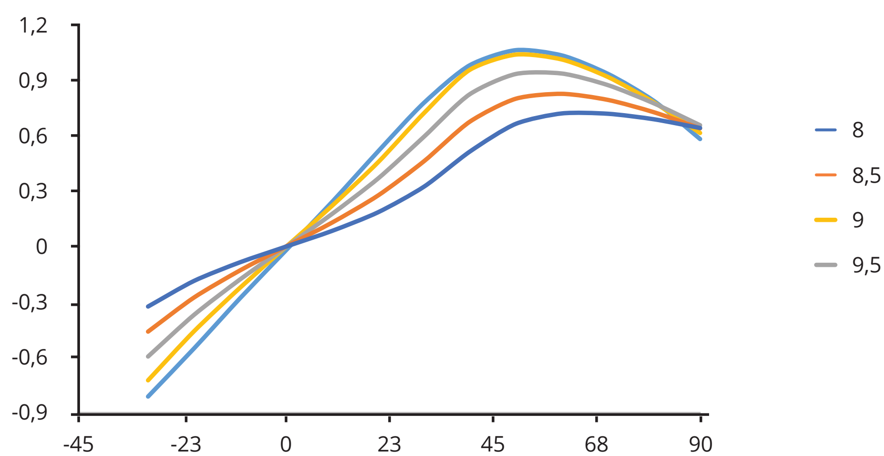


Table 2. Registration parameters to obtain the new model beam.

Project restrictions				
B [m]	9.84	>	8	Min Beam
B [m]	9.84	<	11	Max Beam
Tbs 1.05	7.12	<	7.3	Period of depth
ab	1.95	<	2	Max Acceleration
V [knot]	9.60	>	9	Velocity
Capacity	350.00	>	265	Capacity
Investment	$2,713,179.41	<	$2,800,000.00	Initial investment
2nd criteria	1.16	>	1	Pure loss

Fig. 3. GZ results of the optimized models in the critical load condition.



also to improve loading efficiency. From the initial prototype, four designs with different breadths were developed and evaluated using MaxSurf software in the most critical loading condition.(Fishingrown).

Note that all these models meet the mandatory first-generation stability criteria (IMO), evaluated in critical load condition. However, widening the ship to improve stability and efficiency inevitably increases hull resistance. Therefore, using the Holtrop method, we proceed to estimate the velocity values that would be obtained by keeping the proposed system with the widenings.

Fig. 4. GMt results of the optimized models in critical load condition.

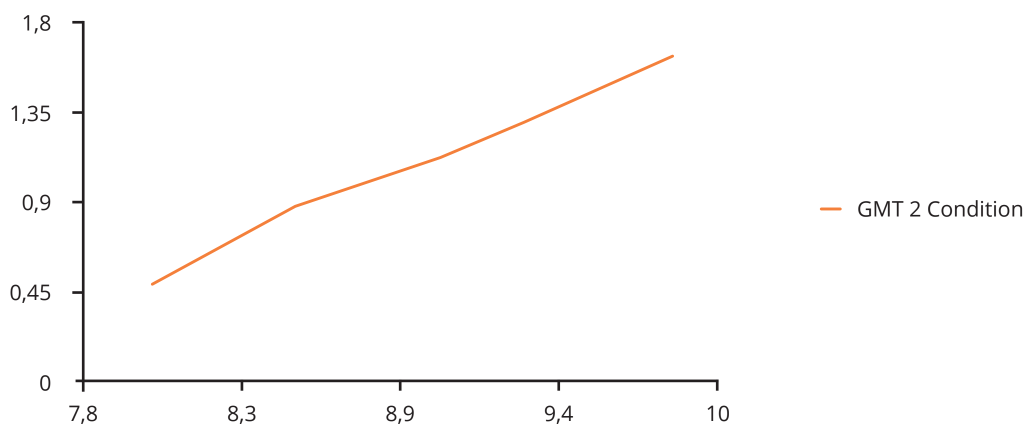
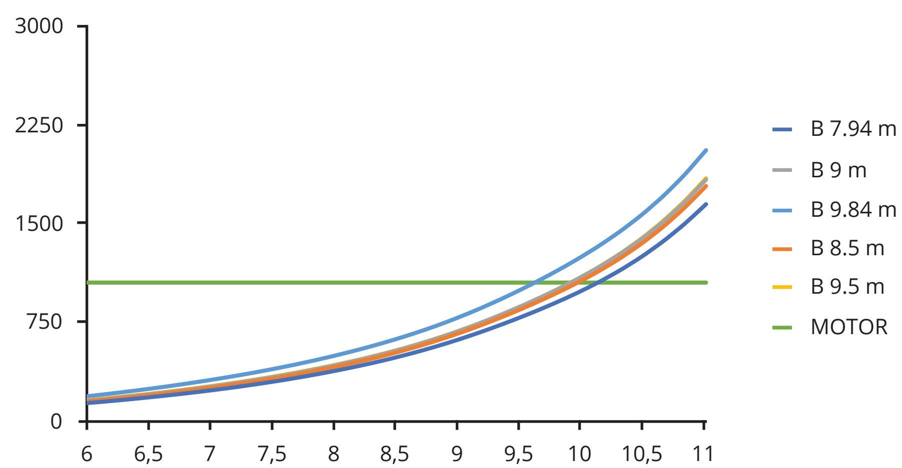


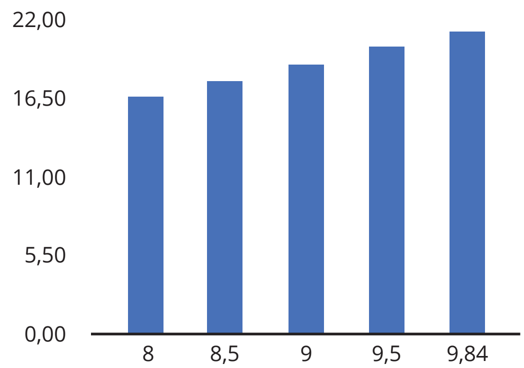
Fig. 5. Speed vs power curve of the original model and optimized with the Holtrop method.



From the results obtained, the 9.84 m beam model was chosen as the optimized model, because it has the highest transport coefficient and has an adequate velocity value.

The vessel's results were validated using the "Tecnavin Ship Roll Program" to evaluate resonance, comfort, and stability. The analysis determined the absence of significant resonances in heave and pitch motions relative to roll, and confirmed stability without parametric resonances at different speeds. Acceleration estimates at key points on the vessel did not exceed 2 m/s2, indicating adequate comfort for the crew. Additionally, the stability criteria of J. Ramón

Fig. 6. Results of the transport coefficients as a function of the beam value of the optimized models.



and P. Dogherty were validated, showing an improvement after optimizing the vessel's beam width by 9.94. No resonance issued were detected while anchored, with all values remaining well away from the vessel's natural period.

Analysis of possible resonances in anchorages is essential to prevent problems during navigation. The study, which included four points with different depths and periods, verified that none of them coincided with the vessel's rolling period in the most critical loading condition.

Conclusions

This study evaluated four beam widths (8.5 m, 9 m, 9.5 m, and 9.84 m) for a 45-meter fishing vessel to optimize stability and operational performance. Initial assessment of the GZ curve and GMT values confirmed that all designs the First-Generation Stability Criteria, although the original vessel exhibited limitations under Second Generation Criteria, highlighting the need for an optimized design. The analysis identified the 9.84-meter beam width as the most efficient configuration, offering a balance between stability and minimal speed reduction (a decrease of approximately 5% reaching 9.5 knots). Resonance and comfort analyses confirmed that this beam width maintains acceleration within acceptable levels, even near the bow,

Fig. 7. Roll acceleration at 3 different heights. H1 (main deck), H2 (wheelhouse) and H3 (cofferdam). Obtained through the software "Tecnavin Ship Roll Program".

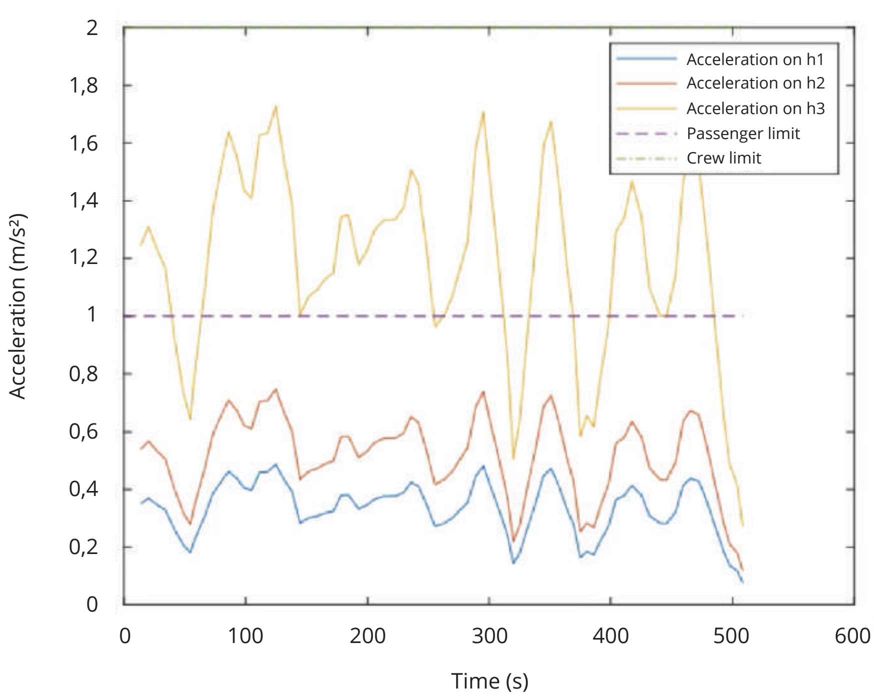
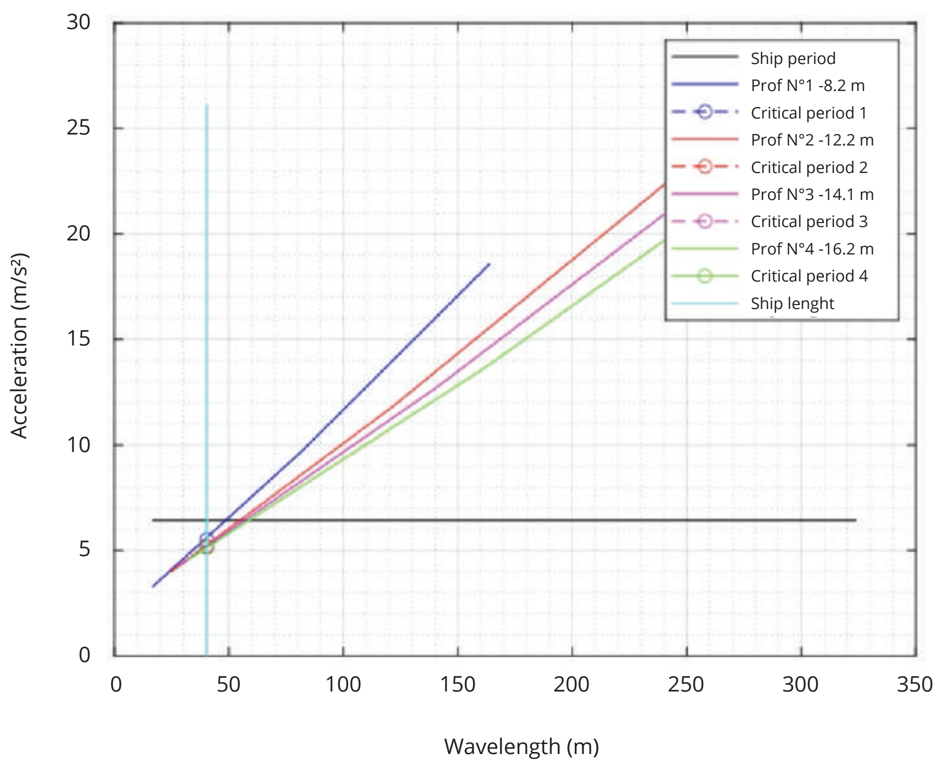


Fig. 8. Analysis of possible roll resonance in anchorage. Obtained by means of the software "Tecnavin Ship Roll Program".



providing adequate safety for the crew during operational activities.

The optimized design successfully addressed Second Generation Stability Criteria, achieving non-vulnerability to parametric roll, excessive acceleration, and pure loss of stability through the addition of bilge keels and increased volumes. The optimized vessel also passed criteria for Surf riding- Broaching and Dead ship condition, ensuring stable and safe operations across varying conditions. Thus, the 9.84-meter beam width configuration is validated as a reliable design choice that enhances stability, safety, and regulatory compliance for fishing vessels.

Recommendations

It is recommended that in the case of the prototype vessel, the analysis of the second level of vulnerability of Second-Generation Intact Stability Criteria be carried out to analyze whether it is still present, as well as analyzing this level for the optimized vessel to observe if there is any discrepancy between these two levels.

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