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Experimental and Theoretical Investigation of Trim Tab Effects on Hydrodynamic Resistance and Planing Performance of High-Speed Planing Vessels

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ABSTRACT

This study presents a comprehensive experimental investigation into the hydrodynamic performance of high-speed Planing vessels equipped with adjustable trim tabs. Two scaled 40-foot beam-type models were tested under controlled towing tank conditions to assess the effects of trim angle variations on resistance, dynamic stability, and transition into the Planing regime. The tests evaluated both untrimmed and trimmed configurations using multiple trim tab heights, measuring resistance forces, trim behavior, and Planing onset velocities. Results demonstrate that optimal trim tab deployment significantly reduces hydrodynamic resistance, lowers the Hump Resistance Region, and enhances vessel stability at critical speeds. Trim tab configuration "B" showed superior performance, enabling earlier Planing transition with lower power demand and reduced bow impact. Additionally, this study addresses model scaling effects, construction tolerances, and control system calibration to ensure fidelity with full-scale vessel behavior. The findings underscore the importance of trim tab integration in the design of modern high-speed vessels, offering practical insights for resistance minimization, propulsion efficiency, and structural safety in dynamic marine environments.

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1. Introduction

The performance of structural components plays a decisive role in the hydrodynamic efficiency, stability, and safety of high-speed marine vessels. Among these components, longitudinal beams and their associated appendages such as trim tabs are critical for modulating resistance and controlling dynamic behavior during motion. This study examines the influence of trim-angle variation and different trim-tab configurations on hydrodynamic resistance and Planing dynamics, using two scaled 40-foot beam models as experimental benchmarks [1]. Understanding the effects of beam geometry, density, and structural mass distribution on vessel response is essential for optimizing design parameters and enhancing overall maritime performance. Prior investigations have confirmed that well-proportioned beams, particularly under reduced density conditions, provide superior pressure resistance and improved energy efficiency when subjected to wave-induced loads [1,2].

Building on this foundation, the present work moves beyond static analysis by experimentally comparing untrimmed and trimmed configurations across a range of speeds, employing both speedboats and beam-equipped high-speed vessels. The findings indicate that appropriate adjustment of trim tabs can substantially reduce total resistance, promote earlier transition into the Planing regime, and stabilize vessel attitude. In small craft such as speedboats, trimming directly generates lift force, diminishes stern squat, and improves forward visibility, especially when weight distribution is uneven. High-speed beam-type vessels, in turn, benefit from enhanced hydrodynamic resilience and smoother motion through careful management of trim angle [5,6].

Extensive theoretical and experimental research underpins these concepts. Foundational studies established the hydrodynamic framework for planing hulls and trim-flap interactions [36], while subsequent investigations quantified the performance gains of trim devices and interceptors using computational fluid dynamics and systematic towing-tank tests [3–6]. These efforts collectively demonstrate that dynamic control systems can markedly reduce fuel consumption and structural loading, even under rough-sea conditions [7,8,9].

The continuous drive for higher speeds in naval, commercial, and recreational vessels has intensified the focus on drag-mitigation strategies. High-speed craft operate under complex force balances in which hydrodynamic lift compensates for much of the weight at planing speeds. Despite lower displacement-induced drag, power requirements remain high because of second-order velocity effects; for example, the propulsion demands of a 20-ton planing craft at 50 knots can match those of a 5,000-ton displacement vessel at 20 knots [40]. Consequently, precise trim control has become a central design priority. Initially introduced on catamarans to enhance maneuverability, trim tabs are now widely adopted in both mono- and multi-hull Planing vessels. In waterjet and other propulsion systems, they provide directional control independent of thrust vectoring. Experimental and numerical studies have confirmed the efficiency of such devices across a range of operating conditions [1,3,4].

Planing behavior—where the hull lifts from the water surface at high speed—is highly sensitive to speed, weight, and balance. Variations in these parameters, caused for instance by payload changes or asymmetrical distribution, can degrade control, increase drag, and induce yawing or loss of visibility. Trim tabs act as corrective appendages that redistribute hydrodynamic loads and restore operational balance. Structurally, they consist of a stainless-steel plate and a controllable actuator, functioning in a manner analogous to aerodynamic stabilizers on aircraft. Their proper integration enables efficient energy use, smoother Planing transitions, and improved overall safety and performance of modern high-speed vessels [36,35,37].

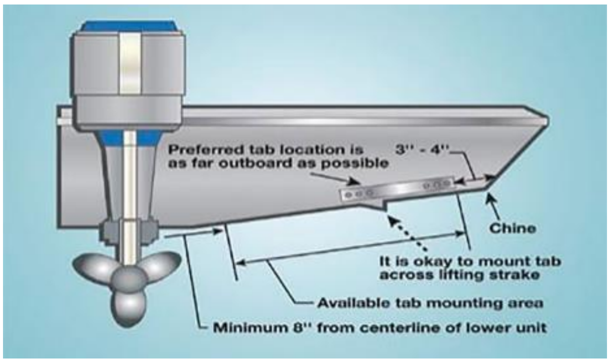

Fig. 1. Main components of a trim tab

1.1 Trim Tab Functionality and Application in High-Speed Craft

As illustrated in Figure 1, the trim tab assembly consists of two primary components—a stainless-steel plate and a controllable actuator. Functionally, the trim tab operates analogously to an aircraft's aileron or elevator, generating lift to counterbalance speed fluctuations, asymmetrical weight distributions, and varying sea states. By adjusting the stern's hydrodynamic profile, trim tabs actively improve vessel balance and performance during acceleration, maneuvering, and cruising.

1.2 Fundamentals of Trim Tab Integration in Planing Craft

To achieve higher speeds and ensure dynamic stability in calm water conditions, high-speed vessels must efficiently transition through the Planing regime—a zone often characterized by elevated hydrodynamic resistance. In this region, excessive drag becomes the dominant concern for naval architects and marine engineers, particularly due to induced flow separations and unsteady wave interactions. Therefore, improving flow quality over the hull and minimizing unsteady motions such as dynamic pitch and roll are critical. Extensive hydrodynamic analyses have confirmed that active trim control mechanisms play a pivotal role in mitigating resistance. By stabilizing the vessel's dynamic trim angle and redistributing hydrodynamic loads, these mechanisms help maintain an optimal Planing posture. Empirical data suggest that vessels operating within a Froude number range of 0.4 to 0.5—where resistance due to skin friction becomes most prominent—require precise control over trim to overcome this hydrodynamic barrier and achieve design speeds efficiently.

1.3 Trim Control and Hydrodynamic Optimization in High-Speed Planing Craft

High-speed marine craft frequently encounter significant resistance when transitioning through the Planing regime, particularly under heavy load and high-power conditions. In these scenarios, the propulsion system—especially semi-submerged propellers—often operates away from its optimal efficiency point, resulting in elevated energy consumption and reduced performance. One of the most effective strategies to improve dynamic efficiency is to reduce hydrodynamic resistance, especially the skin friction component that becomes dominant at intermediate Froude numbers. Within the resistance peak zone, any increase in trim angle can exacerbate total resistance, leading to decreased vessel efficiency. To address this, advanced trim control mechanisms have been developed to actively manage and reduce the trim angle, thereby lowering resistance and stabilizing the vessel during acceleration and cruising. These systems—particularly trim tabs and Planing-surface-mounted appendages—enhance hydrodynamic lift and redistribute pressure forces, allowing the craft to maintain an optimal Planing attitude. Prior studies have confirmed the effectiveness of such devices in reducing total drag and fuel consumption, with trim tab systems often achieving efficiency gains of up to 2% at design speeds when properly configured. The relationship between trim behavior and vessel performance is strongly governed by the Froude number. At lower Froude numbers, displacement-type hulls rely entirely on buoyancy for lift, exhibiting minimal change in waterline profile. As the Froude number increases, semi-displacement or semi-Planing craft begin to derive part of their lift from hydrodynamic forces, resulting in noticeable changes in trim and waterline length. Beyond a Froude number of approximately 1.1, fully Planing craft experience significant lift from dynamic pressures beneath the hull, with buoyancy playing a secondary role. While the precise onset of the Planing regime varies depending on hull geometry and weight distribution, the general trend is a marked reduction in wetted surface area and a dramatic shift in hydrodynamic behavior. When the Planing velocity decreases or vessel mass increases—due to additional payload or asymmetrical weight distribution—hydrodynamic performance degrades. The hull tends to sink deeper into the water, forward visibility is reduced, and the stern may experience increased impact forces. This also leads to greater propeller immersion angles, higher fuel usage, and in some cases, undesirable yawing or lateral instability. To counteract these effects, dynamic balance must be actively maintained. Design solutions aimed at improving dynamic performance typically focus on reducing wetted area, optimizing pressure distribution along the hull bottom, and maintaining stable trim during acceleration and turns. Trim tabs, installed on the aft section of the hull, play a central role in these objectives. These devices consist of a stainless-steel plate actuated by a hydraulic or electric mechanism, allowing real-time adjustment of the vessel's trim in response to load, speed, and environmental conditions. Functionally analogous to aircraft control surfaces such as elevators and ailerons, trim tabs generate corrective lift at the stern, enabling smoother transitions to Planing, enhanced maneuverability, and improved propulsion efficiency. The basic structure of a trim tab includes a robust flat plate mounted to the transom and a controllable actuator that adjusts the deflection angle. By manipulating the pressure distribution at the aft hull surface, trim tabs effectively decrease the bow rise and reduce resistance peaks. Their integration into modern vessel design not only enhances fuel efficiency and operational safety but also contributes to superior control under variable sea states and dynamic loading conditions.

1.4 Trim Tab Functionality and Influence on Trim Correction

The functional principle of trim tabs closely resembles that of movable horizontal stabilizers found on aircraft. These hydrodynamic devices generate corrective lift forces to accommodate changes in vessel speed, compensate for asymmetrical weight distribution, and adapt to varying environmental conditions. By dynamically adjusting the stern angle, trim tabs play a pivotal role in maintaining the vessel's optimal trim and stability across a range of operating scenarios. This force effectively pushes down the stern of the vessel while simultaneously lifting the bow. The resulting change in trim reduces wetted surface area and drag, thereby enhancing Planing performance and fuel efficiency. When hydraulic actuators adjust the trim tab to a predefined angle, the flow of water is redirected, generating a vertical lift component that corrects the vessel's trim angle in real-time. The effectiveness of this mechanism is highly dependent on the surface area of the trim tab. larger vessels or those operating at relatively lower speeds typically require trim tabs with greater surface area to generate sufficient corrective force. Proper sizing and angular adjustment are critical to ensure synchronized and stable trim correction, especially during acceleration or under varying load conditions. Trim tabs equipped with hydraulic systems can deliver precise and responsive control, making them an indispensable tool in the design and operation of high-speed Planing craft.

1.5 Performance and Operational Advantages of Trim Tabs and Interceptor Systems

Trim tabs modify the stern geometry of the vessel to redirect water flow in a manner that minimizes bow impacts during motion. By altering the pressure distribution along the hull, trim tabs effectively reduce the bow's tendency to slam into the water, particularly at high speeds or under uneven loading conditions. This not only improves forward visibility—enhancing navigational safety—but also reduces structural stress, contributing to smoother operation, increased cruising speed, and improved fuel economy. Larger trim tabs, when properly integrated on the transom, tend to yield superior performance. Their effectiveness is strongly influenced by vessel characteristics, including overall dimensions, speed regime, and the engine’s power-to-weight ratio. Appropriately sized trim tabs provide more reliable control authority and enable better hydrodynamic efficiency. The advantages of incorporating trim tabs into high-speed vessel design can be broadly categorized into three domains. From a functional perspective, they facilitate increased speed, reduce bow impacts, correct transverse inclination (heel), prevent porpoising, and maintain optimal propeller thrust angles. In terms of efficiency, trim tabs contribute to reduced fuel consumption, decreased engine workload, and the elimination of stern squat during acceleration. From a safety standpoint, they enhance visibility, reduce wake turbulence, improve maneuverability, and mitigate hull stress under dynamic sea states. In parallel with trim tabs, interceptor control systems have gained significant traction in recent years for use in Planing hull vessels. These systems utilize vertically deployable blades mounted along the transom to adjust hull pressure and trim in real time. Interceptors offer multiple advantages, including substantial resistance reduction at high speeds, minimized spray and wave generation, increased top-end speed, and improved attitude control during turning maneuvers. Their compact design allows for easy retrofitting or integration into new hulls, and as shown in Figure 2, they are particularly well-suited for applications where limited transom space restricts the use of traditional trim tabs. Interceptors also contribute to refined trim angle management, which is critical for optimizing ride comfort, stability, and propulsion efficiency.

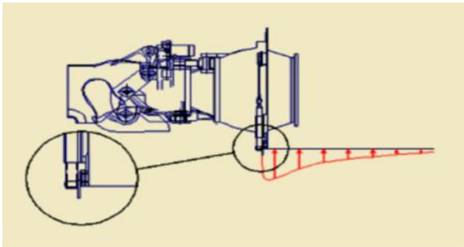

Fig. 2. Interceptor control system installed on the hull bottom [3]

1.6 Parameters Influencing Lift Generation in Interceptor Control Systems

The magnitude of lift force produced by interceptor-based control systems is governed by several interrelated hydrodynamic factors. Chief among these is the vessel's operating speed, the vertical deployment height of the interceptor blade relative to the hull bottom, and the specific configuration—including the type and number—of blades installed along the transom. Each of these parameters directly affects the pressure distribution beneath the hull and thus determines the overall effectiveness of the lift force generated. As the vessel’s speed increases, the dynamic pressure acting on the interceptors rises accordingly, enhancing their lift-producing capability. Similarly, greater blade extension results in a larger control surface, which amplifies the induced hydrodynamic force. The type of interceptor—whether fixed, adjustable, or active—and the number of blades installed contribute to both the granularity and responsiveness of trim adjustments. Figure 3 illustrates a representative hull bottom equipped with four interceptors and the associated control system layout. This configuration allows for multi-point control of the vessel's longitudinal and lateral trim, providing enhanced maneuverability, improved stability, and optimized resistance performance under varying operational conditions.

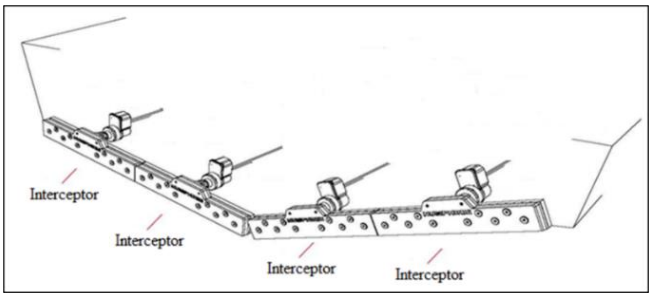

Fig. 3. Hull bottom equipped with four interceptors [15]

1.7 Comparative Assessment of Trim Tabs and Interceptor Control Systems

Trim tabs and interceptor systems represent two distinct approaches to dynamic trim control in high-speed marine vessels. Each system offers unique advantages and trade-offs that influence their suitability for various hull configurations and operational scenarios. One of the primary advantages of trim tabs lies in their ability to generate greater lift forces and respond more rapidly to control inputs compared to interceptors. This superior lift capacity enables more aggressive trim corrections, which can be particularly beneficial during Planing transitions or sudden changes in load conditions. However, the mechanical complexity of trim tab systems often results in increased structural bulk, weight, and installation space requirements. Moreover, they demand greater actuator force for operation, which may limit their applicability in compact or weight-sensitive designs. In contrast, interceptor systems offer a lighter, more compact alternative with simpler mechanical configurations. While they generally produce lower lift forces and operate at slower response rates, interceptors can effectively maintain dynamic stability in many practical applications. The selection between these two systems is not solely based on lift magnitude. In many cases, the design objective is not to maximize lift, but to ensure consistent and controllable vessel behavior under varying trim conditions. Interceptors can achieve this goal with minimal mechanical intrusion, particularly in cases where available transom area is limited or the center of gravity location restricts trim tab installation. In such scenarios, interceptors can be positioned more flexibly and closer to the stern's soleplate without compromising vessel geometry. Determining the appropriate height of an interceptor blade is critical to maximizing its hydrodynamic effectiveness. Empirical and theoretical studies suggest that the optimal interceptor height should remain fully embedded within the boundary layer at its mounting location to avoid flow separation and minimize drag. The boundary layer thickness in turbulent flow conditions can be estimated using established empirical formulas [30]. Based on global towing tank studies, it has been observed that interceptor height is typically much smaller than the local boundary layer thickness, ensuring effective performance without disrupting flow stability [29, 32]. Several benchmarks exist in the literature regarding practical interceptor height selection. For example, Hamfri proposed a height of up to 50 mm for powerboats ranging from 18 to 45 meters in length [31], while other researchers recommended up to 75 mm for heavier vessels within the 18-to-60-meter range. Brizzolara implemented a 200 mm interceptor on the STENA HSS-1500, a 127-meter high-speed ferry operating at 40 knots [4]. These values illustrate the variability in interceptor sizing based on vessel scale and operating speed. Furthermore, dimensionless analysis of test data from multiple towing tanks suggests that the optimal interceptor height, for a Reynolds number on the order of 10^7, falls within approximately 0.5% of the total wetted length of the hull. This ratio provides a practical guideline for interceptor design that ensures functional effectiveness while maintaining flow conformity.

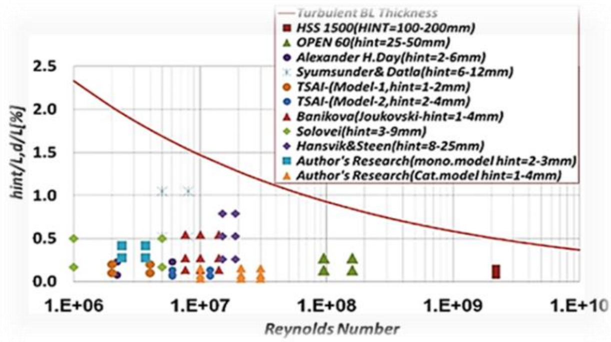

Fig. 4. Experimental data for the dimensionless height of the interceptor [29]

2. Equations of Motion

In most engineering problems, the model under investigation is often an idealized version of the real model. A series of simplifications are made to reduce the complexity of the problem. However, it's crucial to ensure that the characteristics or properties removed from the problem are negligible and won't significantly impact the results. The study and modeling of Vessel bodies involve investigating their statics and dynamics. Statics deals with the behavior of a Vessel in a stationary state or at constant velocity, while dynamics examines the behavior of a Vessel under acceleration. In the analysis of static stability of a Vessel, the Archimedes principle is utilized, which relates to the hydrostatic buoyancy force, expressed as:

$$w = \gamma . \nabla \quad (1)$$

Where W is the weight of the body, γ is the specific weight of seawater, and ∇ represents the submerged volume of the body. In dynamic stability analysis, Newton's laws are employed. According to these laws, the study of dynamics involves two components: kinematics, which deals with velocity and acceleration, and kinetics, which focuses on the forces causing motion.

2.1 Principles of Vessel Stability Modeling and Experimental Model Construction

The development of shipbuilding, from early handcrafted vessels to modern industrially engineered watercraft, has resulted in a wide variety of hull forms, propulsion systems, construction materials, and operational functions. One persistent challenge in this field is the accurate estimation of propulsion power required for a newly designed vessel to achieve a target speed based on its size and displacement. To address this, the use of fluid dynamics similarity laws has become a reliable and validated approach. Among these, towing tank experiments remain essential for evaluating resistance and motion characteristics under controlled conditions. Although numerical simulations have advanced considerably, they still require experimental validation due to the complex nature of fluid–structure interactions. For this reason, physical model testing continues to play a central role in confirming hydrodynamic performance, particularly in high-speed craft design. To ensure methodological consistency and scientific rigor, this study follows the experimental framework recommended by the International Towing Tank Conference (ITTC). These standardized procedures define all aspects of testing, including parameter selection, model fabrication tolerances, installation methods, instrumentation, resistance and trim measurements, calibration protocols, and data filtering. Adopting ITTC guidelines guarantees that the present work conforms to internationally recognized standards of reproducibility and scientific credibility.

2.2 Scale Effects in Planing Hull Model Experiments

Selecting an appropriate model scale is crucial in physical model testing, as it directly affects the accuracy and relevance of hydrodynamic performance results. In Planing hull regimes—where both buoyant and dynamic lift forces influence vessel motion—the Froude number is prioritized over the Reynolds number to preserve similarity in wave-making resistance and trim response. Despite this, scale effects remain non-negligible and must be carefully addressed. Empirical research has shown that using models smaller than approximately one-fifth of the full-scale vessel length can lead to inverse trends in resistance behavior, resulting in misleading data. Conversely, excessively large models require extensive facilities and high towing speeds, which may be impractical. Striking a balance between physical feasibility and experimental fidelity is therefore essential.

The effects of reduced scale are evident in several ways: the location of the spray root line shifts aft, the wetted surface area changes, and transom pressure drag becomes significant at higher speeds. Frictional resistance also requires careful estimation through boundary-layer modeling, especially for small models. Furthermore, variations in trim angle can distort pressure distribution across the hull bottom, amplifying scaling inaccuracies. To address these challenges, recent studies have applied refined experimental and numerical methodologies in the hydrodynamic analysis of Vessels and offshore structures [35-43]. Their findings confirm that integrating experimental calibration with numerical approaches significantly improves the accuracy of small-scale model predictions and enhances similarity with full-scale performance.

In addition, complementary work demonstrated that models around 60–90 cm in length yield reliable results consistent with full-scale vessels, while smaller models often produce distorted data.

3. Construction and Experimental Evaluation of Hull Models in Towing Tanks

Accurate construction of hull models is essential for evaluating resistance characteristics in towing tanks. A representative hull model was constructed in accordance with the full-scale hull geometry.

3.1 Tolerances and Stability Considerations

For hull width and draft, construction tolerances must be within ±1 mm, while the length must be within ±0.05% of the total length or ±1 mm, whichever is greater. In multi-body models, tolerances for transverse and longitudinal spacing must be within ±0.05% of LPP or 1.0 mm. Hatch openings should also conform to ±1 mm tolerance. Auxiliary equipment—such as shaft brackets, housings, struts, and propulsion pods—must meet a positioning tolerance of ±5 mm and maintain surface finishes equivalent to the hull model. Dimensional stability must be preserved despite environmental conditions; for instance, a 5°C temperature variation may alter the length of a 7-meter model by ±0.15% (i.e., 10 mm). Materials such as wax, wood, high-density foams, and fiber-reinforced polymers (FRP) are commonly used. CAD files (e.g., IGES format) define geometries for CNC machining. The surface finish should meet a dry sandpaper grade of 300–400, with special care taken to model spray rails and trim transoms accurately.

3.2 Station and Waterline Definitions

Stations are numbered from the AP (0) in 10 or 20 equal segments, with decimals used for finer resolution (e.g., 5/9). Negative numbers indicate positions aft of the AP. Waterlines are referenced from the keel top and must be spaced and labeled according to height above this reference line.

3.3 Construction and Experimental Evaluation of Hull Models in Towing Tanks

Accurate construction of hull models is essential for evaluating resistance characteristics in towing tanks.

3.4 Definition of Variables

Key parameters essential for hull model construction are summarized in Table 1.

Table 1. Principal Parameters in Hull Model Construction

Parameter	Symbol	Unit
Coordinate Axes	X, Y, Z	—
Length between Perpendiculars	LPP	m
Length on Waterline	LWL	m
Breadth	B	m
Draft	T	m
Displacement Volume	∇	m³
Displacement Mass	Δ	kg
After Perpendicular	AP	—
Forward Perpendicular	FP	—

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3.6 Turbulence Generation

Turbulence generators are used to replicate realistic flow conditions. Acceptable methods include wires (0.5–1 mm diameter) placed at ~50% LPP aft of FP, sand belts (5–10 mm width, ~0.5 mm grit), and bilge keels located ~1/3 hull length from the bow.

3.7 Hull Model Fabrication Techniques

Material choice depends on test objectives. Wax models offer reusability but have high thermal expansion and water absorption. Wooden models are affordable but heavy; beech wood is preferred due to stability. Fiberglass models, while costlier, are lighter, water-resistant, and ideal for speed and inertial control.

Table 2. Recommended Hull Materials for Towing Tank Testing

Vessel Type	Test Objective	Recommended Material
Towing, Semi-towing	Resistance, Self-propulsion, Wave-making	Wood
Towing, Semi-towing	Maneuvering and Seakeeping	Fiberglass
Surface-piercing	Multi-purpose	Fiberglass
Submerged	Multi-purpose	Metal
Foils	Resistance	Metal
Propellers	Self-propulsion	Metal

3.8 Wooden Model Construction Process

Steps include section layout, structural analysis, drying and shaping wood, gluing, CNC carving, finishing, painting, dimensional control, and line drawing.

3.9 Fiberglass Model Construction Process

Processes involve sectional layout, structural analysis, mold preparation, three-dimensional CNC shaping, molding, surface finishing, dimensional control, and line drawing.

Wax Model Protocols:

Wax models must soak for 36 hours before testing, but re-immersion should not exceed 12 hours. Surfaces must be cleaned thoroughly to remove debris. Long-term submerged models require scraping before re-testing.

Model Documentation Requirements:

Specifications such as dimensions (LPP, LWL, B, T), displacement (Δ), wetted surface area, turbulence devices, and material composition must be reported.

Real Vessel Specifications:

The full-scale Golf Vessel used for comparison is a golf cart-type hull with the specifications in Table 3.

Table 3. Specifications of Full-Scale Golf Vessel

Length (mm)	Width (mm)	Draft (mm)	V-Angle (°)	Displacement (kg)	Immersed Area (mm²)
13187	2719	735	23.43	11000	25752601

3.10 Sea Trial Results

Table 4 presents data collected during real-world testing. Note that measurements were only recorded at high-confidence intervals.

Table 4. Real Vessel Performance Data

Speed (knots)	Propeller Pitch	RPM	Power (hp)

8.5–55.5	0.38–2.50	1200–3000	287–1568

Validation was performed by comparing towing tank measurements with full-scale sea trial data of the reference vessel. The close agreement in resistance curves and Planing onset speeds confirmed the reliability of the experimental results.

Speed increases with nearly constant RPM indicate transition into Planing mode around a pitch of 1.0.

Towing Tank Specifications:

Tests were conducted in a 402 m tank operated by NEDSA and IMALLA. Specifications are shown in Table 5.

Table 5. Towing Tank Characteristics

Feature	Value
Length	402 m
Width	6 m
Depth	4.5 m
Water Depth	4 m
Max Speed	19 m/s

Scaling Laws and Model Description:

The Froude number was used for geometric scaling. A 26.7:1 scale was selected for the model with the specifications in Table 6 and Figure 3.

Table 6. Model Specifications

Parameter	Value
Length	2638 mm
Width	543.8 mm
Draft	144 mm
V-Angle	23.43°
Displacement	85 kg
Water Plane Area	1.025 m²

Fig. 5. Initial mold used for hull model construction

Fig. 6. Photograph of the completed hull model

Weight, CG, and Thrust Alignment:

Accurate center of gravity (CG) and thrust line alignment are critical. The model's CG is placed 870.34 mm from the transom. A thrust angle of 3° is replicated from the original vessel using geometric projection techniques. Figure 5 and Figure 6 display the mold and final model, respectively.

Table 7. Comparison of Model and Full-Scale Dimensions

Feature	Model	Full-scale
Length	2.64 m	13.2 m
Width	0.544 m	2.72 m
Draft	0.144 m	0.735 m
V-Angle	23.45°	23.45°
Displacement	85 kg	11000 kg
Water Area	1.025 m²	25.75 m²
CG from Transom	0.87 m	4.352 m
Weight Ratio	33–27%	33–27%

Trim Tab Height Selection:

The wetted length of the Vessel, a 0.5% criterion yields 11.45 mm as a guideline. Heights of 0.8, 3, 6, and 12 mm were selected for experimental testing.

4. Experimental Testing and Results Analysis

A total of 26 tests were conducted to evaluate the hydrodynamic behavior of the Planing hull models, encompassing center of gravity optimization, performance without trim tabs, and behavior under varying trim tab configurations (Table 8). Each experiment was repeated at least three times to minimize uncertainty and ensure consistency of results.

Table. 8. Summary of Conducted Experiments

Row	Test Subject	Number of Tests Conducted
1	Determining the Proper Center of Gravity	2
2	Tests conducted for the model without trim tabs	6
3	Tests conducted for the model with trim tabs	18
5	Total number of tests conducted	26

Experimental uncertainties, primarily arising from sensor calibration, towing carriage speed fluctuations, and wave reflections, were quantified within ±3%. Repeated trials (three per configuration) confirmed that the variability in resistance values did not exceed this margin. These uncertainties slightly shifted the onset velocity of Planing but did not alter the overall trends or conclusions.

It should be noted that during all experiments the trim and sinkage remained within the prescribed tolerance range, and since the primary objective of the present study was focused on resistance and planing behavior, a detailed analysis of these parameters has been deferred to a separate study.

4.1 Evaluation of the Hull Without Trim Tabs

To establish a baseline for comparison, the hull model was first tested without any trim tab intervention. The results, presented in Table 9, indicate that the Vessel demonstrated stable spray patterns across various trim angles up to 5.04 degrees. However, instability was observed at a trim of 5.5 degrees, suggesting a limit for unassisted dynamic equilibrium.

Table. 9. Values Related to Without trim tab Vessel Tests

Test Number	Center of Gravity (%)	Static Trim (°)	Speed (m/s)	Resistance (N)	Description
1	0.1	1	4.3	19.7	Stable and suitable spray of water
2	0.1	2	24.7	19.7	Stable and suitable spray of water
3	0.1	3	28.8	19.7	Stable and suitable spray of water
4	0.1	4	27.6	19.7	Stable and suitable spray of water
5	0.1	5.04	27.7	19.7	Stable and suitable spray of water
6	0.1	5.5	30.5	–	Unstable

The resistance-speed curve (Figure 8) for the untrimmed model revealed that drag force increased exponentially up to a velocity of 3 m/s, beyond which the slope of the curve decreased, indicating reduced resistance and increased efficiency in speed gain. This behavior persisted until 5 m/s, after which resistance again began to rise. These observations align with classical Planing hull dynamics, where the transition into the Planing regime is marked by the ability to surpass a peak in the speed-resistance curve with reduced hydrodynamic drag.

Stability during the experiments was assessed based on maintaining a consistent spray pattern, absence of proposing, and trim angle oscillations below ±0.2°. Configurations exceeding these thresholds were classified as unstable.

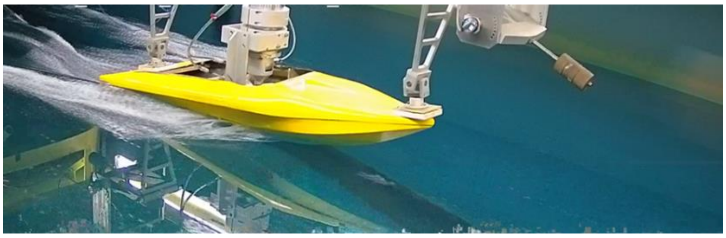

Fig. 7. Model Testing Without Trim Tabs at 2 m/s

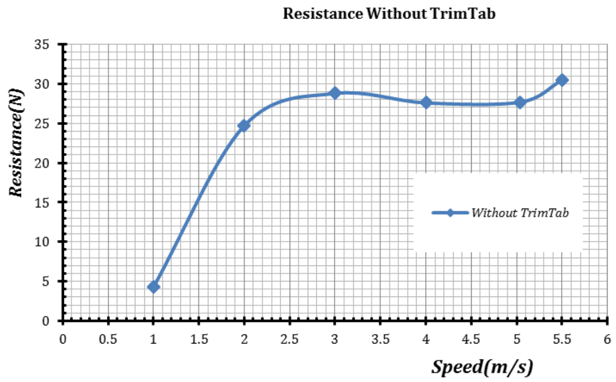

Fig. 8. Resistance vs. Speed for Without trim tab Model

These baseline results emphasize the sensitivity of resistance variation to changes in trim angle and center of gravity; a trend consistently observed during the transition into Planing conditions.

Two trim tab configurations, referred to as Size A and Size B, were fabricated for comparative testing. Trim Tab A had a height of 6 mm and a chord length of 50 mm, optimized for moderate corrective lift at transitional speeds. Trim Tab B was designed with a greater height of 12 mm and a chord length of 70 mm, providing stronger stern lift for earlier planing onset. Both configurations were constructed from stainless steel plates with a thickness of 2 mm and mounted at the transom with identical hinge mechanisms to ensure comparable installation conditions.

4.2 Performance Evaluation with Trim Tab Size A

To improve performance, trim tabs were introduced. Table 10 outlines the results using trim tab size A. The experimental data and the corresponding resistance-speed curve (Figure 9) suggest a smoother transition past the resistance peak, which occurred at 4 m/s—an improvement over the 3 m/s peak in the untrimmed condition. However, despite this enhancement, the selected tab size delayed the Planing onset and was deemed suboptimal for initiating takeoff.

Table. 10. presents the values corresponding to model Vessel tests with trim tab size A.

Test Number	Center of Gravity (%)	Static Trim (degrees)	Velocity (m/s)	Resistance (Newton)
1	0.1	1	5	Stable, suitable spray pattern of water
2	0.1	2	21.5	Stable, suitable spray pattern of water
3	0.1	3	30.7	Stable, suitable spray pattern of water
4	0.1	4	33.2	Stable, suitable spray pattern of water
5	0.1	5.04	27.48	Stable, suitable spray pattern of water
6	0.1	5.5	37.5	Unstable

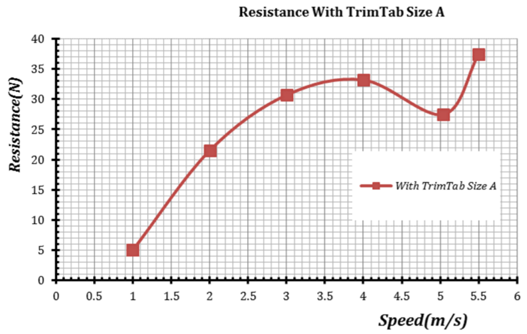

Fig. 9. Resistance versus velocity with trim tab size A

Fig. 10. Model under test with trim tab A at a speed of 3 meters per second

Fig. 11. Model under test with trim tab size A at a speed of 4 meters per second

4.3 Performance Evaluation with Trim Tab Size B

Subsequent testing with trim tab size B demonstrated further improvement. As shown in Table 11 and Figure 12, the resistance peak occurred at 2 m/s, indicating an earlier entry into the Planing regime compared to both the untrimmed and trim tab A cases. This configuration facilitated an efficient rise out of the water, optimizing thrust-to-drag ratio at moderate speeds. However, at higher velocities, instability emerged, limiting the effectiveness of this trim tab size in sustained high-speed operation.

Table. 11. Values related to Vessel model tests with trim tab size B

Test Number	Center of Gravity (%)	Static Trim (degrees)	Velocity (m/s)	Resistance (Newton)
1	0.1	1	5.9	Stable, suitable spray pattern of water
2	0.1	2	26.4	Stable, suitable spray pattern of water
3	0.1	3	23.5	Stable, suitable spray pattern of water
4	0.1	4	31.5	Stable, suitable spray pattern of water
5	0.1	5.04	32.5	Stable, suitable spray pattern of water
6	0.1	5.5	43.5	Unstable

Fig. 12. Resistance to Velocity with Trim Tab Size B

4.4 Comparative Analysis of Trimmed vs. Untrimmed Conditions

A comparative evaluation of resistance-to-weight performance between untrimmed and trimmed (Trim Tab B) configurations is illustrated in Figure 13. The trimmed model exhibited earlier Planing onset and a more favorable resistance gradient, validating the efficacy of trim tab size B in reducing hydrodynamic load during transitional and moderate-speed operations. However, the presence of performance degradation at higher speeds underscores the need for adaptive or variable-geometry trim tab systems in real-world applications.

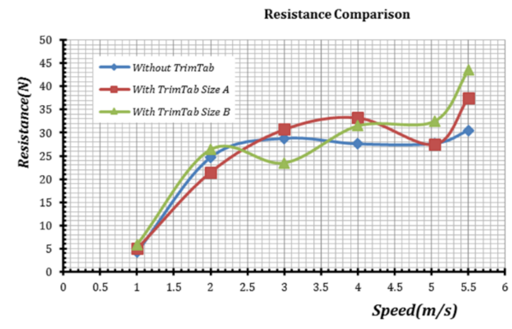

Fig. 13. Comparison of resistance-to-weight ratio between the untrimmed hull and the trimmed condition with Trim Tab B, highlighting earlier Planing onset and reduced resistance gradient

In summary, the inclusion of trim tabs, particularly size B, significantly enhanced the model's performance by enabling earlier Planing and smoother resistance transitions. Despite the instability observed at high speeds, the trimmed configuration achieved improved propulsion efficiency and reduced stress during transitional acceleration phases.

4.5 Additional Analysis of Trim and Sinkage Behavior

In addition to resistance measurements, supplementary data on dynamic trim angle and sinkage were extracted from the towing-tank sensors to provide a more comprehensive assessment of hydrodynamic behavior. The recorded trends demonstrated that optimal trim-tab deployment consistently reduced the dynamic trim angle and minimized sinkage during acceleration and Planing transitions. These reductions facilitated earlier Planing onset and improved hydrodynamic stability. Where continuous sensor readings were unavailable, visual observations and discrete measurements confirmed that the variation of trim and sinkage followed the same pattern as resistance, validating the robustness of the main conclusions.

5. Conclusion

This study presented a comprehensive experimental and analytical investigation of the hydrodynamic performance of high-speed planing vessels, with particular focus on the decisive role of trim systems—and especially trim tabs—in governing resistance, lift generation, and dynamic stability. The full-scale vessel examined in this work measures 13.2 m in length (approximately 43 ft), and its geometrically scaled models were evaluated under controlled towing-tank conditions using a range of trim-tab configurations.

The results consistently demonstrated that resistance variation is strongly influenced by the coupled effects of trim angle and the longitudinal position of the center of gravity, a relationship observed throughout the transition from displacement to planing regimes. In addition to resistance, continuous and spot measurements of trim angle and sinkage confirmed that optimized trim-tab deployment lowers dynamic trim and limits sinkage, which accelerates entry into the planing regime and enhances stability and propulsion efficiency. Where continuous sensor data were not available, visual inspection and high-frequency snapshots verified that trim and sinkage trends closely followed the resistance behavior, ensuring that the overall conclusions remain robust.

Among the tested configurations, Trim-Tab Size B yielded the most favorable performance at moderate speeds by reducing resistance, decreasing effective trim, and enabling earlier planing. At higher velocities, however, this configuration introduced minor instability, highlighting the need to tailor trim-tab geometry to the specific operational envelope of a vessel. These findings emphasize that careful consideration of hydrodynamic loads on appendages and control surfaces is essential in the design of fast craft.

Strategic integration of advanced trim systems not only minimizes drag and engine loading but also enhances fuel economy, ensures smoother planing transitions, and improves navigational safety. Taken together, the extended resistance, trim, and sinkage analyses presented in this work provide a robust scientific basis for the next generation of high-speed vessel design, offering practical guidance for both commercial and recreational applications.

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