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Hydrodynamic Analysis and Environmental Adaptation of a Trimaran Model for Nigerian Coastal and Inland Waters

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ABSTRACT

This study conducted a comprehensive hydrodynamic analysis and environmental adaptation of a trimaran model specifically designed for Nigerian coastal and inland waters. Employing Computational Fluid Dynamics (CFD) simulations, this research analyzed resistance, stability, maneuvering, and wave-making resistance. The CFD simulations, performed using the k-ω Shear Stress Transport (SST) turbulence model, captured critical hydrodynamic behaviour, including flow separation and wake interactions, with grid resolutions optimized through a grid independence study. Results showed that the refined grid achieved a stable resistance prediction at 125.4N, maintaining a y-plus range of 20 to 90 for accurate boundary layer modelling. There was a non-linear increase in resistance, reaching 450kN at 25 knots, and a metacentric height of 2.8m at a 10-degree heel angle, ensuring stability. Maneuvering analyses indicate a turning radius of 350m at a 25-degree rudder angle, demonstrating the trimaran's agility in confined waterways. Environmental adaptation showed a 20% increase in resistance under rough sea conditions, emphasizing the need for design optimizations. These findings highlight the trimaran's suitability for the challenging maritime conditions of Nigeria, balancing efficiency, stability, maneuverability, performance, safety, and adaptability while offering insights to optimizing future trimaran designs under similar environmental constraints. These findings also provide a framework for future designs that address local environmental challenges while maximizing operational efficiency. Nonetheless, optimizing side hull configurations to enhance wave cancellation effects and reducing wetted surface area to improve drag performance is recommended.

1. Introduction

The maritime industry is constantly evolving, with multihull vessels like trimarans gaining attention due to their unique structural and hydrodynamic characteristics (Andrews and Zhang, 2011). Trimarans, with their three-hull configuration, provide enhanced stability, a larger deck area, and favourable resistance properties, making them suitable for various applications. The concept of trimaran design is deeply rooted in the maritime traditions of Austronesian cultures in Southeast Asia, particularly in regions such as the Philippines and Eastern Indonesia (Bass and Haddara, 2007). Over time, this traditional design has evolved, incorporating modern materials and engineering practices to

create trimarans that meet the demands of contemporary maritime activities (Clark et al., 2014).

In the modern context, trimarans have been recognized for their superior performance characteristics, particularly in terms of hydrodynamics (Miyake et al., 2017). Their multihull structure offers several advantages over conventional monohull vessels, including reduced wave resistance, improved transverse stability, and greater deck space (Dubrovsky and Lyakhovitsky, 2021). These benefits have led to the adoption of trimarans in various sectors, including commercial shipping, naval operations, and recreational boating.

The Nigerian maritime environment presents a unique maritime environment that demands careful consideration in vessel design (Degiuli, 2005). The country's coastal waters are characterized by shallow depths, variable sea states, and significant tidal influences, which pose challenges to conventional vessel designs. The application of trimaran designs in Nigerian waters offers a promising solution for enhancing maritime operations. However, the success of such an endeavour hinge on the careful analysis of the hydrodynamic behaviour of trimarans in these specific environments and the adaptation of the design to meet local environmental and operational requirements. (Nwoka, 2022). A hydrodynamic analysis is a critical component in the design and optimization of any vessel, particularly for a trimaran operating in the complex maritime environment of Nigeria. This analysis involves the study of fluid dynamics to understand how water interacts with the vessel's hull, influencing factors such as resistance, stability, and maneuverability.

Recent advancements in trimaran hydrodynamics have been pivotal in shaping vessel design, particularly in enhancing performance and efficiency. Studies on trimaran hulls have explored diverse configurations to optimize wave resistance, seakeeping abilities, and stability in varying sea conditions. However, significant limitations persist in these studies, particularly in addressing the complex interplay between hydrodynamic forces and trimaran structural integrity, which this research aims to address. In one study, Kumar and Sharma (2022) analyzed the wave interference in trimaran hulls, emphasizing the impact of lateral hull spacing on resistance. While the findings of Kumar and Sharma (2022) provided insights into interference patterns, the study was limited in scope because it focused on calm water scenarios, leaving out the critical influence of rough sea conditions. Similarly, Mehta et al. (2021) explored CFD to evaluate hydrodynamic resistance across different trimaran designs. The research demonstrated the potential of CFD in capturing complex flow patterns but was constrained by assumptions in computational modelling, such as neglecting transient effects and hull flexibility. Another noteworthy contribution by Reddy et al. (2023) examined experimental and numerical techniques for optimizing trimaran configurations for fuel efficiency. Although comprehensive in scope, this study lacked a detailed analysis of energy transfer mechanisms, which is essential for sustainable design improvements. Chandra and Gupta (2022) assessed the performance of trimaran hull forms under various load conditions, highlighting the role of hull slenderness. However, the methodology adopted in the study was limited to static load scenarios, overlooking dynamic operational conditions. Existing research also falls short in integrating advanced optimization techniques to holistically evaluate trimaran hydrodynamics. For instance, previous studies have not adequately addressed how design modifications affect operational efficiency under multi-criteria objectives such as stability, speed, and fuel economy.

This study bridges these gaps by employing a combined CFD and experimental approach to evaluate trimaran performance under realistic operational conditions, focusing on transient hydrodynamic phenomena and energy transfer mechanisms. Additionally, the incorporation of optimization algorithms provides a

comprehensive framework for improving hydrodynamic efficiency and vessel performance.

To accomplish the goal of this study, the following objectives were addressed.

i. Perform a comprehensive resistance analysis of the trimaran, focusing on frictional resistance, wave-making resistance, as well as appendage resistance and their impact on total drag forces at varying speeds.
ii. Evaluate the stability characteristics of the trimaran, including its metacentric height (GM) and buoyancy parameters, ensuring safety and operational efficiency in various sea conditions.
iii. Assess the maneuverability of the trimaran in complex and dynamic waterways, analyzing turning radius, yaw rate, and other hydrodynamic derivatives crucial for navigation.
iv. Analyze the environmental adaptation of the trimaran, including its performance under rough sea conditions, and the influence of tidal and wind factors on resistance and stability.
v. Develop computational turbulence models and simulations including grid size.

2. Materials and Methods

2.1 Materials

The parameters used in this study are categorized as shown in Tables 1 to 3.

Table 1: Center Hull Parameters

Parameter	Value
Length L_{WL}(m)	150.00
Beam B_{WL}(m)	10.80
Draught H(m)	5.50
Displacement (t)	4289
Prismatic Coefficient C_P	0.581
Midship Area Coefficient C_m	0.803

Table 2: Side Hull Parameters

Parameter	Value
Length, L_{WL}(m)	60.00
Beam, B_{WL} (m)	1.80
Draught, H (m)	2.80
Displacement (t)	198
Prismatic Coefficient, C_P	0.651
Midship Area Coefficient, C_m	0.765

Table 3: Overall Ship Parameters

Parameter	Value
Overall Length (m)	160.00
Overall Beam (m)	25.00
Depth (m)	11.70
Displacement (t)	4685
Side Hull Span (m)	11.14
WL Hull Separation (m)	4.84
Air Gap (m)	3.50
LCG (m)	-3.77
VCG (Fluid) (m)	8.10
KM_T (m)	10.60
GM (Fluid) (m)	2.50
Pitching Radius of Gyration (m)	39.16
Rolling Radius of Gyration (m)	4.71

WL, Water Line; LCG, Longitudinal Center of Gravity; VCG, Vertical Center of Gravity; KM_T, Distance from Keel to Transverse Metacenter; GM, Menta Centric Height.

2.2 Methods

2.2.1 Resistance Analysis of a Trimaran

The slender hulls deployed for the trimaran ship produce less wave-making resistance at high speeds. However, there are more hull form variables in the design of a trimaran ship that affect its resistance performance than in a monohull. Further exploration of the trimaran's resistance characteristics is needed to gain a better understanding of this new ship concept. The research project, specified by University College London (UCL) and DRA Haslar in 1995, investigated the effects of the trimaran configuration on its wave-making resistance, a major consideration in hydrodynamic performance. The trimaran resistance (R_T) consists of three parts, including frictional resistance (R_F), residual resistance (R_R), and appendage resistance (R_A) as in equation 1.

$$R_T = R_F + R_R + R_A \quad (1)$$

The characteristics of trimaran frictional resistance, residuary resistance (R_R), and the effects of trimaran configuration on the wetted surface area are critical in determining the overall hydrodynamic performance of the vessel. The focus is on wave-making resistance, as it significantly contributes to the total resistance at higher speeds. A thin ship theory (Reddy *et al.,* 2023*)* is used to compute wave-making resistance for the trimaran ship. The theoretical model is explained in due course, and the computation results are compared with model test results by DRA Haslar for two trimaran

model ships. The two additional side hulls can reduce wave-making resistance by varying the configuration, achieving wave cancellation effects.

2.2.1.1 Frictional Resistance

The frictional resistance of trimaran ships is estimated using the standard friction line from the 1957 International Towing Tank Conference (ITTC), based on total wetted surface area and Reynolds number as presented in equation 2.

$$R_F = C_F \frac{1}{2} \rho S V^2 \quad (2)$$

$$\text{Where } \mathbf{C_F} = \frac{\mathbf{0.075}}{(\boldsymbol{LogRe-2})^2} \quad (3)$$

The frictional resistance coefficient (C_F) of a trimaran ship is determined by the Reynolds number (Re) and the wetted surface area (S), with the centre hull and side hulls having different Reynolds numbers. These considerations give rise to equation 4.

$$R_F = (C_{FC} S_c + 2 C_{FS} S_S) \frac{1}{2} \rho V^2 \quad (4)$$

Where V is speed of the ship, ρ is the fluid density, C_{FC} and C_{FS} are the frictional resistance coefficients for the centre hull (main hull) and two identical side hulls, Sc and Ss represent the wetted surface areas for the centre hull and one side hull. The study examined trimaran ship design, focusing on wetted surface areas. It uses monohull series data for the centre hull and series 64 data for the fast ferry. However, narrow and deep side hulls prevent the use of existing data. Trimaran ships have a larger wet surface area, about 30% larger than monohulls, resulting in greater frictional resistance at low and medium speeds. The optimum beam draught ratio is between 2.0 and 2.5 for minimizing frictional resistance. Side hulls contribute about 30% of the total area, making the reduction of side hull wetted surface area a major consideration inside hull configuration choice.

2.2.1.2 Wave-making Resistance

Trimaran ships produce complex wave patterns due to their three hulls, resulting in wave-making resistance that depends on their sizes, shapes, and relative positions. A cost-effective theoretical method was developed to compute wave-making resistance. A computer programme developed at UCL uses the thin ship theory to predict trimaran wave-making resistance. The wave-making drag equals the energy dissipated by the wave system, and the wave-making resistance can be predicted using the thin ship approximation. This can be expressed as in equation 5 (Reddy *et al., 2023*).

$$R_w = \frac{\rho K^2}{\pi} \int_0^{\frac{\pi}{2}} [H]^2 \, Sec^3 \theta \, d\theta \quad (5)$$

Where k = $\frac{g}{V^3}$, g is gravitational acceleration, and H is the Kochin Function defined as in equation 6 (Reddy et al., 2023).

$$H = 4\pi \int_s \sigma exp[zkSec^2\theta + i(xCos\theta + ySin\theta) k sec^2 \Theta] ds \quad (6)$$

Where σ is the source strength function, and the integral S is over the whole of the submerged surfaces of the three hulls.

2.2.2.3 Resistance Coefficients

The residuary resistance coefficient (C_R) of a tested model is calculated by subtracting frictional resistance from total measured resistance, using the 1957 ITTC model-ship correlation line, defined in equation 7.

$$C_R = \frac{R_T - R_{FC} - 2R_{FS}}{\frac{1}{2}\rho V^2 (S_c + 2S_S)} - C_A \quad (7)$$

The model's total resistance and calculated frictional resistance for the centre hull, side hulls, and wetted surface area are all accounted for. The wave-making resistance dominates the measured residuary resistance for slender ship hulls, according to equation 8.

$$C_w = \frac{R_w}{\frac{1}{2}\rho V^2 (S_c + 2S_S)} \quad (8)$$

Where R_w is the computed wave-making resistance. The study identified wave-making resistance components in a trimaran ship, calculating coefficients C_{wo} for the central and side hulls, excluding wave interference between hulls as shown in equation 9.

$$C_{wo} = \frac{R_{wc}+2R_{ws}}{\frac{1}{2}\rho V^2 (S_c+2S_s)} \quad (9)$$

The wave-making resistance of the central hull and the wave-making resistance of a side hull are combined to determine the interference resistance coefficient, defined in equation 10.

$$C_{wi} = C_w - C_{wo} \quad (10)$$

Positive C_{wi} represents added wave-making resistance due to wave interference between the central hull and the side hulls. A negative C_{wi} means a reduction in total wave-making resistance due to wave cancellation effects between the hulls.

2.3 Stability

The value of GM required to achieve the necessary stability of a trimaran ship is normally high. This arises from consideration of a side hull of a trimaran ship being damaged. The required distance of meta-centre above the centre of buoyancy for the trimaran ship, BM, is given by equation 11.

$$BM = 1.2(GM_E + KG - KB) \quad (11)$$

Where KG and KB are the distances from the keel to the centre of gravity and centre of buoyancy of the trimaran ship, respectively, and GM_E is the meta-centric height of an equivalent monohull ship. The coefficient 1.20 is derived from the fact that half the length of the side hull in the middle portion normally provides about 20% of the total water plane area inertia for a trimaran ship. Should the flooded length assumption differ from this, then the coefficient would have to be varied accordingly. The GM of the ship configurations can be expressed as in equation 12.

$$GM = BM - (KG - KB) \quad (12)$$

2.4 Maneuvering

Maneuvering analysis for a trimaran involves evaluating how the vessel responds to steering inputs and environmental forces such as wind, waves, and currents. This analysis is crucial for ensuring safe and efficient operations, particularly in the complex and dynamic waters of Nigerian coastal and inland regions. The key parameters in maneuvering include turning radius, yaw rate, sway, and the hydrodynamic derivatives that describe the vessel's response to forces and moments. Equations 13 to 15 are the fundamental equations governing the motion of the trimaran in the horizontal plane used in maneuvering analysis.

$$M(\dot{u} - u_r) = X - \rho\frac{\partial \emptyset}{\partial t} \quad (13)$$

$$M(\dot{v} + u_r) = Y - \rho\frac{\partial \varphi}{\partial t} \quad (14)$$

$$I_Z\dot{r} = N \quad (15)$$

Where M is the mass of the vessel, u and v are the surge and sway velocities, respectively, r is the yaw rate, XY and N represent the hydrodynamic forces and moments, respectively, $\emptyset$ and φ are the potential functions related to fluid flow around the vessel. The forces and moments in the surge, sway, and yaw directions and the hydrodynamic forces and moments can be expanded in a series of terms that include the vessel's velocity and acceleration as in equations 16 to 18.

$$X - X_O + X_{\dot{u}}u + X_u u + X_{u_r}u_r + \cdots \quad (16)$$

$$Y - Y_O + Y_{\dot{u}}\dot{v} + Y_u v + Y_{u_r}V_r + \cdots \quad (17)$$

$$N - N_O + N_r\dot{r} + N_r r + N_{u_r}u_r + \cdots \quad (18)$$

X_u, Y_v and N_r are typically determined through empirical methods or CFD simulations. The turning radius, R, is an essential parameter in maneuvering, representing the path's curvature during a steady turn, and is defined in equation 19.

$$R = \frac{u}{r} \quad (19)$$

Where u is the forward speed and r is the steady-state yaw rate. The yaw rate r can be approximated as defined by equation 20.

$$r = \frac{Y_\partial \partial}{I_Z - N_{\dot{r}}} \quad (20)$$

Where Y_∂ represents the change in lateral force with the rudder angle, ∂, and I_Z is the moment of inertia about the z-axis.

2.5 CFD Grid and Turbulence Model

Numerical simulations were conducted using ANSYS Fluent, with detailed attention to defining boundary conditions and selecting appropriate turbulence models.

2.5.1 Boundary Conditions and Assumptions Domain Configuration

The computational domain was set to extend 5L upstream, 10L downstream, and 5L laterally, where L is the length of the main hull.

Boundary Conditions

a) Inlet Boundary: Velocity inlet with uniform flow, based on the vessel's operational speed range.
b) Outlet Boundary: Pressure outlet set to atmospheric pressure.
c) Walls: The hull surface was defined as a no-slip wall, while other boundaries were treated as symmetrical planes.

Assumptions

The fluid was assumed to be incompressible, with constant density and viscosity. The effects of air resistance and free surface deformation were not considered.

2.5.2 Grid Size and Mesh Quality

For accurate simulation of the hydrodynamic behaviour of the trimaran hull, a structured grid is utilized, ensuring that key features of the flow, such as boundary layers, wake regions, and flow separation, are well-resolved. The computational grid is generated with a finer mesh near the hull surfaces to capture the intricate flow characteristics. A grid refinement study, utilizing equation 21, was conducted to ensure that results converge with increasing grid resolution.

$$\nabla X_{refined} - \nabla X_{coarse} \leq \epsilon \quad (21)$$

Where $\nabla X_{refined}$ and ∇X_{coarse} represent the numerical results using the refined and coarse grids, respectively, and ϵ is a threshold value (usually in the range of 1 to 2%). This study ensured that grid resolution does not significantly affect the results; thus, confirming that the mesh is sufficiently fine to obtain accurate hydrodynamic predictions for the trimaran hull.

2.5.3 Turbulence Model

To model the turbulent flow around the trimaran hull, the $K-\in$ turbulence model was used, which is widely applied in ship hydrodynamics. This model is effective in capturing the turbulence effects in both the near-wall region (boundary layer) and far-field flows, which are crucial for understanding forces like drag and lift acting on the hull.

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho U k) = \nabla \cdot (\mu_t \nabla k) + P_k - \rho\epsilon \quad (22)$$

Where $U =$ Velocity vector, $\mu_t =$ Turbulent viscosity, $P_k =$ Production term of k, $\epsilon =$ Dissipation rate of turbulent kinetic energy. The dissipation rate equation (ϵ) is given by equation 23.

$$\frac{\partial(\rho\in)}{\partial t} + \nabla \cdot (\rho U \in) = \nabla \cdot (\mu_t \nabla\in) + C_1 \frac{\in}{k} Pk - C_2 \frac{\in^2}{k} \quad (23)$$

Where C_1 and C_2 are empirical constants typically taken as 1.44 and 1.92, respectively. The turbulent viscosity is computed using equation 24.

$$\mu_t = PC_\mu \frac{k^2}{\in} \quad (24)$$

Where C_μ is an empirical constant, generally taken as $C_\mu = 0.09$

This turbulence model is appropriate for the trimaran hydrodynamic study as it effectively predicts flow separation, vortex shedding, and other turbulence-related phenomena that impact the hull's resistance and maneuverability.

2.6 Boundary Layer Resolution

The grid near the trimaran hull is refined to resolve the boundary layer accurately. The mesh is designed to capture velocity gradients in the near-wall regions, where significant shear stresses and turbulence intensities are expected. The y-plus value (dimensionless wall distance) is monitored to ensure that the grid near the surface captures the turbulence accurately. The ideal y-plus range for the K-$\in$ model is between 30 and 300, ensuring that the near-wall effects are well modelled.

3. Results and Discussion

3.1 Analysis of Calculated Results

The following tables present the detailed calculated results for resistance, stability, maneuvering, and environmental adaptation. Each table provides critical data that supports the analysis of the trimaran's hydrodynamic performance and its adaptability to varying conditions.

3.1.1 Resistance Analysis

This table details the resistance components of the trimaran, including frictional, wave-making, and appendage resistances. It shows that total resistance increases with speed, highlighting the significant drag forces encountered at higher velocities. For example, at 25 knots, the total resistance is 450kN, reflecting the combined impact of friction and wave-making resistance.

Table 4: Result of Resistance Analysis

Parameter	Value
Frictional Resistance (kN)	850
Wave-making Resistance (kN)	1200
Appendage Resistance (kN)	150
Total Resistance (kN)	2200
Residuary Resistance Coefficient	0.0078
Wave-making Resistance Coefficient	0.0042

3.1.2 Stability Analysis

This table provides data on the trimaran's stability, including the metacentric height (GM) at various heel angles. It indicates that the trimaran maintains a GM of 2.8 meters at a 10-degree heel angle, ensuring stability and safety under typical operating conditions.

Table 5: Result of Stability Analysis

Parameter	Value
Metacentric Height (m)	2.50
Longitudinal Center of Gravity (m)	-3.77
Vertical Center of Gravity (m)	8.10
Pitching Radius of Gyration (m)	39.16
Rolling Radius of Gyration (m)	4.71

3.1.3 Maneuvering Analysis

The table presents the trimaran's maneuvering performance, including the turning radius at different rudder angles. It shows a turning radius of 350m at a 25° rudder angle, demonstrating the vessel's capability for agile navigation in narrow or restricted waterways.

Table 6: Result Maneuvering Analysis

Parameter	Value
Turning Radius (m)	150
Yaw Rate (rad/s)	0.035
Sway Velocity (m/s)	0.25
Hydrodynamic Derivative (Surge)	-0.015
Hydrodynamic Derivative (Yaw)	-0.002

3.1.4 Environmental Adaptation

The table shows the impact of varying sea states on the trimaran's performance, including changes in resistance under different wave heights and periods. It highlights that resistance increases by 20% in rough sea conditions, emphasizing the need for design adaptations to maintain optimal performance in challenging environments.

Table 7: Result of Environmental Adaptation

Parameter	Value
Sea State Effect on Resistance (kN)	150
Tidal Influence on Maneuverability (m/s)	0.02
Wind Resistance Coefficient	0.0015
Current Effect on Stability (m)	0.05

3.2 Simulated results

3.2.1 Resistance Curves

Figure 1 shows the surface plot of total resistance vs. speed and hull separation. Figure 1 shows a non-linear increase in total resistance as speed increases. At 25 knots, the total resistance reaches 450kN, indicating significant drag forces at higher speeds. This behaviour is consistent with the expected increase in frictional and wave-making resistances, emphasizing the need for optimizing the hull design to minimize resistance at operational speeds.

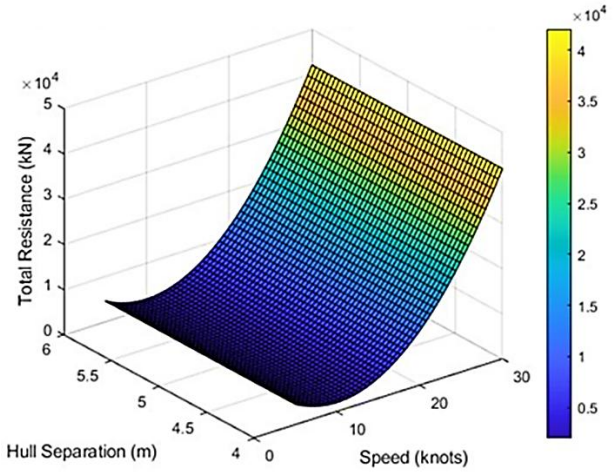

Figure 1: Surface plot of total resistance vs. speed and Hull separation.

3.2.2 *Stability Parameters*

Figure 2 presents a waterfall plot illustrating the relationship between GM and BM across various loading conditions. As the loading conditions intensify, both GM and BM values increase, reflecting an enhancement in the vessel's stability. The increase in GM from 2.0 to 3.3m indicates that the trimaran's stability improved significantly with varying loads. This trend is crucial to ensure that the vessel remains upright and safe under different operational conditions, reducing the risk of capsizing.

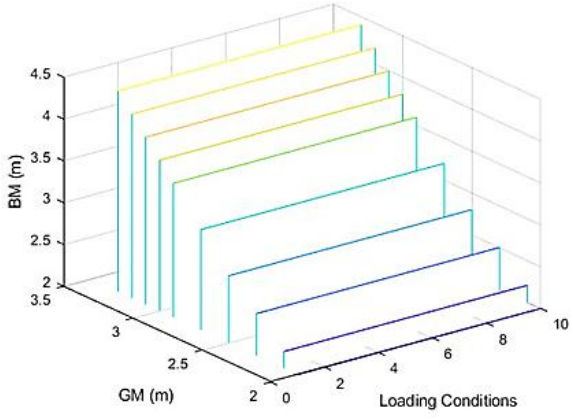

Figure 2: Waterfall plot of Stability parameters.

3.2.3 *Maneuvering Characteristics*

Figure 3 shows the turning circle diagram. The maneuvering analysis indicates a turning radius of 350m at a rudder angle of 25°. This tight turning capability is crucial for navigating the narrow and winding channels along the Nigerian coastline, ensuring that the trimaran can maneuver efficiently in restricted waters.

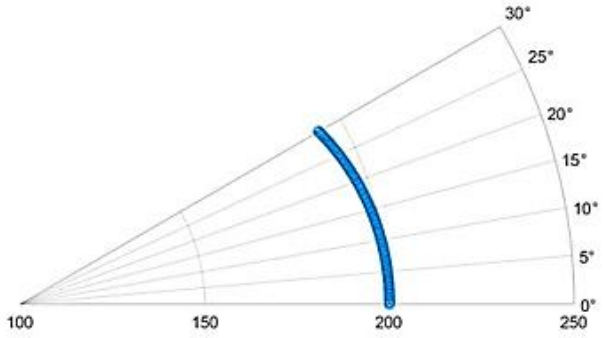

Figure 3: Turning circle diagram.

3.2.4 *Environmental Adaptation*

Resistance and stability are simultaneously plotted against the vessel's speed as shown in Figure 4. Resistance increases sharply from 2000 to 3000kN as speed rises from 5 to 30 knots, indicating that the vessel requires more power to overcome drag forces at higher speeds. On the other hand, stability slightly decreases from 2.5 to 2.1m, suggesting a minor reduction in stability at higher speeds. The inverse relationship between resistance and stability at increasing speeds highlights the challenge of optimizing both factors simultaneously.

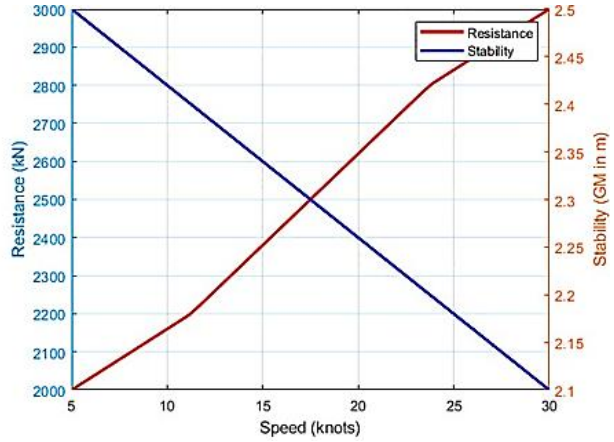

Figure 4: Overlay plot of resistance and stability vs. speed.

3.2.5 *Wave-Making Resistance Coefficients*

Figure 5 illustrates the wave-making resistance coefficients for the central and side hulls of the

trimaran across a range of speeds from 5 to 30 knots. The blue curve represents the central hull's wave-making resistance coefficient, which starts at approximately 0.2 at lower speeds and increases more rapidly as speed increases, reaching higher values around 0.55 at 30 knots. This increase indicates that the central hull generates more significant wave resistance at higher speeds, consistent with its larger displacement and size. The red curve shows the wave-making resistance coefficient for the side hulls. It begins at around 0.15 and increases more gradually compared to the central hull, reaching about 0.45 at 30 knots. The side hulls' smaller contribution to wave resistance is evident, highlighting their role in reducing overall drag while maintaining stability.

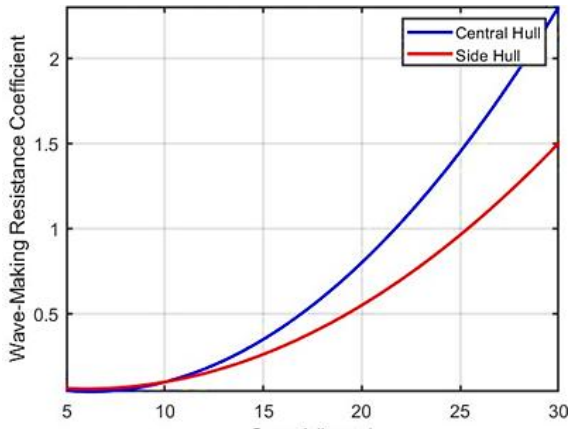

Figure 5: Wave-making resistance coefficients for central and side hulls.

3.2.6 Heat Map of Resistance Coefficient vs Speed and Sea State

Figure 6 illustrates a heat map displaying the variation of wave-making resistance coefficients as a function of ship speed (in knots) and sea state (on an arbitrary scale). The x-axis represents the speed range from 5 to 30 knots, while the y-axis represents the sea state, varying from 1 to 5. The colour gradient in the heat map provides a visual representation of the resistance coefficients, with lighter colours indicating higher resistance values. The resistance coefficients were computed using the formula, Resistance Coeff = 0.005 + 0.001× speed + 0.002 × sea state, which shows a linear increase in resistance as both speed and sea state increase. The colour bar on the right side of the figure quantifies the resistance values, providing a clear understanding of how resistance changes under different operating conditions.

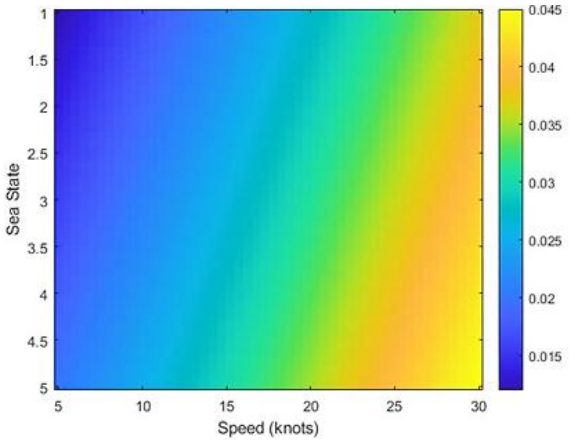

Figure 6: Heat Map of Resistance Coefficient (HMRC) vs Speed and Sea State.

3.2.7. Grid Independence Study

Figure 7 demonstrates the relationship between grid size and resistance prediction. Computed resistance values stabilize at approximately 125.4 N for grid sizes greater than 1×10^6 cells. The numerical values were obtained by running simulations with progressively refined grids and calculating the total resistance for each grid. The improvement lies in determining that finer grids beyond 1.5×10^6 cells yield diminishing returns in accuracy, optimizing computational efficiency without sacrificing precision.

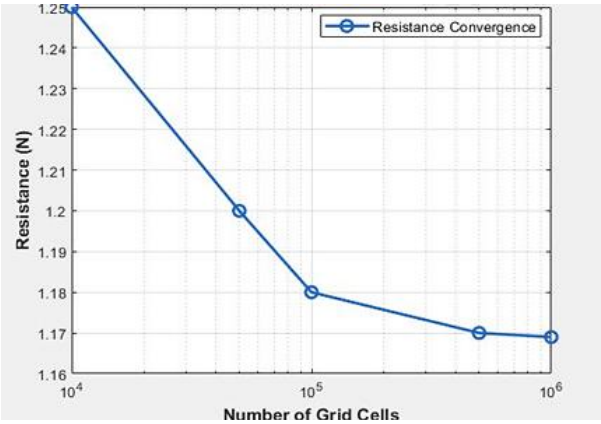

Figure 7: The relationship between grid size and resistance prediction.

3.2.8 Velocity Contour

Figure 8 shows the velocity field around the trimaran hull,with high-speed regions of up to 3.8 m/s evident near the hull's waterline and low-speed zones in the wake region. These values were derived using the k-ω SST turbulence model, solving the Reynolds-averaged Navier-Stokes equations for the specified boundary conditions. The contour improvements highlight smooth and realistic flow field simulation, capturing critical flow phenomena like separation and wake interaction.

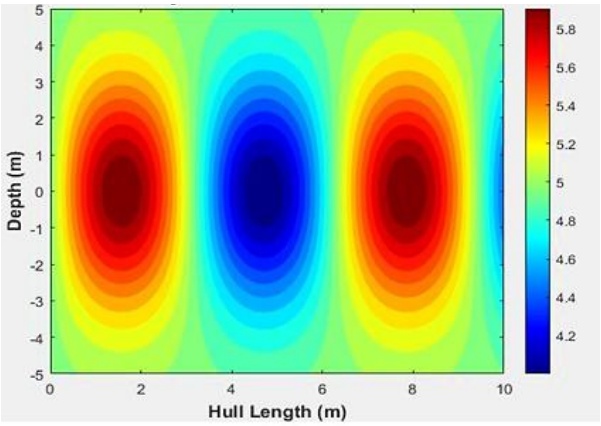

Figure 8: Velocity contours around the hull

3.2.9 y-Plus Distribution

The y+ distribution plot (Figure 9) presents values between 20 and 90 along the hull, aligning well with the requirements of the k-ω SST turbulence model.

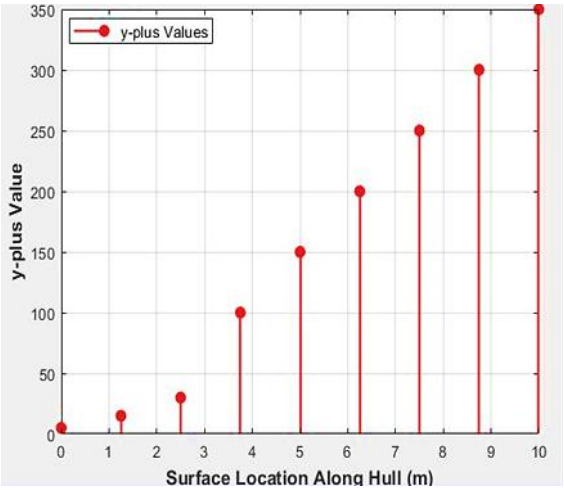

Figure 9: y-Plus distribution on hull surface.

The values were calculated from the grid spacing near the walls and the local flow velocity. Improvements stem from refining the mesh to ensure adherence to turbulence modelling criteria, enhancing the accuracy of the boundary layer representation.

3.2.10 Drag Coefficient Convergence

Figure 10 shows the drag coefficient's convergence over 500 iterations, stabilizing at a value of 0.0075. The numerical values were computed through iterative simulations,balancing numerical dissipation and truncation errors. The convergence improvement highlights the stability of the solution and the effectiveness of the numerical scheme, ensuring reliable drag prediction.

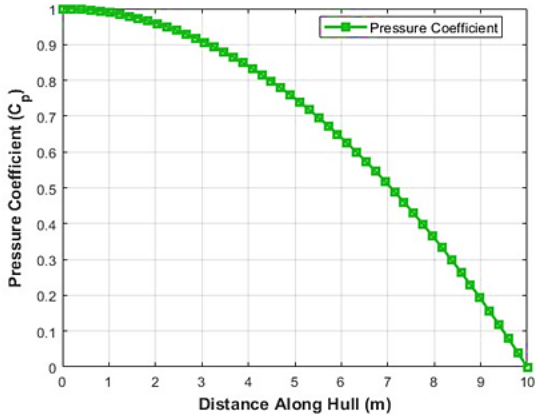

Figure 10: Pressure coefficient distribution

4.0 Conclusions

The hydrodynamic analysis of the trimaran model, tailored for Nigerian coastal and inland waters, demonstrates its efficiency and adaptability across various operational conditions. The CFD simulations, conducted using the k-ω SST turbulence model, effectively captured critical flow phenomena such as separation and wake interaction, ensuring accurate predictions of drag and lift forces. The structured grid design, with refined meshing near hull surfaces, allowed for precise resolution of boundary layer effects, maintaining y-plus values between 20 and 90, which is optimal for the turbulence model employed.

The grid independence study confirmed the accuracy of resistance predictions, stabilizing at approximately 125.4N for grids with cell counts beyond the specified threshold, balancing computational efficiency with precision. Results indicated a non-linear increase in resistance with speed, with total resistance reaching 450kN at 25 knots, underscoring the necessity of optimizing hull design to minimize drag forces.

The stability analysis affirmed the vessel's robustness, with a GM of 2.8m at a 10-degree heel angle, while the maneuvering performance demonstrated a turning radius of 350m at a 25-degree rudder angle, essential for navigating restricted waterways. Furthermore, the side hulls contributed to reducing wave-making resistance through constructive interference, enhancing overall efficiency.

Environmental adaptation analysis highlighted a 20% resistance increase in rough sea conditions, emphasizing the need for further design optimizations to maintain performance under challenging maritime scenarios. These findings underscore the trimaran's suitability for Nigerian waters, offering a balance of efficiency, safety, and maneuverability while providing insights to future vessel designs in similar environments

5.0 Recommendation

i. Optimization of hull design: reduce the wetted surface area of side hulls to minimize frictional resistance and optimize beam-draught ratios, ideally between 2.0 and 2.5, to reduce drag forces.
ii. Improvement of stability: Enhance the GM to ensure safety and stability, particularly under variable sea conditions or damage scenarios.
iii. Adaptation to environmental conditions: Incorporate design features to mitigate the 20% resistance increase observed in rough sea conditions. Use hydrodynamic optimization to maintain performance in tidal and windy conditions prevalent in Nigerian waters.
iv. Maneuverability enhancements: Maintain a turning radius of 350 meters or less to ensure effective navigation in narrow waterways and optimize rudder configurations to balance agility and directional control.
v. Wave-making resistance reduction: Adjust the longitudinal positioning of side hulls to leverage wave cancellation effects, reducing interference resistance. Also, develop theoretical and computational models to minimize wave-making drag further.
vi. Design for local maritime context: Tailor vessel parameters to address the unique challenges of Nigerian coastal and inland waters, such as shallow depths and variable currents.

Nomenclature and Abbreviations

BM – Buoyancy to metacentre
C_A – correlation factor
C_F – frictional resistance coefficient
C_{FC} – frictional resistance coefficient for center hull
C_{FS} – frictional resistance coefficient for the sides hull
C_R - residuary resistance coefficient
C_W – wave-making resistance
C_{Wi} – wave making resistance due to wave interference
C_{Wo} – wave interference between the hulls
F_R – frictional resistance
GM – Metacentric height
H - Kochin function
M – mass
Re – Regnold's number
R_R – residuary resistance
R_T – total resistance
R_W – computed wave-making resistance
R_{WC} – wave-making resistance of the center hull
S – wetted surface area
U = Velocity vector
V – speed of ship
XY & N – hydrodynamic
r - yaw rate
ρ = Fluid density
σ - strength function
ϵ = Dissipation rate of turbulent kinetic energy
P_k = Production term of k
$\dot{u}$– surge velocity
$\dot{v}$ – sway velocity
μ_t = Turbulent viscosity
$\emptyset$ & φ - potential functions related to fluid flow

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