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Design Of an Unmanned Surface Vehicle and Flow and Structural Analysis of Its Hull

Abstract

The functionality of Unmanned Surface Vehicles (USVs) relies on sophisticated engineering processes that enhance both hydrodynamic efficiency and structural strength. This research introduces a comprehensive approach to validate the design of a distinctive 7-m-long V-type trimaran hull created in SolidWorks, using multifield analyses conducted on the ANSYS platform. The main innovation of this study is its integrated engineering strategy, which extends beyond a single discipline and directly transfers flow pressure data from a computational fluid dynamics (CFD) analysis to the structural analysis phase to replicate realistic maritime conditions. The hull was designed with a sharp-bottomed V-type trimaran configuration to minimize drag at high speeds and improve stability in rough seas, and its hydrodynamic performance was confirmed through CFD analyses. Using these validated data, static structural analyses were performed to assess the hull's resistance to external forces, employing Von Mises stress and total deformation data to create a detailed optimization guide for critical areas. Additionally, modal analysis was carried out to investigate the effects of environmental vibrations on structural behavior. In line with national defense industry objectives, this study provides an innovative framework for future USV development projects by integrating design, fluid dynamics, and structural mechanics into a unified process.

Keywords: Computational Fluid Dynamics, Unmanned Surface Vehicle, Structural Analysis, Vibration Analysis, Wave Effect

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İnsansız Deniz Aracı Tasarımı ve Gövdesinin Akış-Yapısal Analiz Çalışması

Öz

İnsansız Yüzey Araçlarının (USV) işlevselliği hem hidrodinamik verimliliği hem de yapısal dayanıklılığı artıran gelişmiş mühendislik süreçlerine dayanmaktadır. Bu araştırma, SolidWorks programında oluşturulan, kendine özgü 7 metre uzunluğundaki V tipi trimaran gövdesinin tasarımını, ANSYS platformunda gerçekleştirilen çok alanlı analizler kullanarak doğrulamak için kapsamlı bir yaklaşım sunmaktadır. Bu çalışmanın temel yeniliği, tek bir disiplinin ötesine geçen ve gerçekçi denizcilik koşullarını yansıtmak için akış basıncı verilerini hesaplamalı akışkanlar dinamiği (CFD) analizinden yapısal analiz aşamasına doğrudan aktaran entegre mühendislik stratejisidir. Gövde, yüksek hızlarda sürtünmeyi en aza indirmek ve sert denizlerde stabiliteyi artırmak için keskin tabanlı V tipi trimaran konfigürasyonunda tasarlanmış ve hidrodinamik performansı CFD analizleri ile doğrulanmıştır. Bu doğrulanmış veriler kullanılarak, gövdenin dış kuvvetlere karşı direncini değerlendirmek için statik yapısal analizler yapılmış ve kritik alanlar için ayrıntılı bir optimizasyon kılavuzu oluşturmak üzere Von Mises gerilimi ve toplam deformasyon verileri kullanılmıştır. Ek olarak, çevresel titreşimlerin yapısal davranış üzerindeki etkilerini araştırmak için modal analiz gerçekleştirilmiştir. Ulusal savunma sanayi hedefleri doğrultusunda, bu çalışma tasarım, akışkanlar dinamiği ve yapısal mekaniği birleşik bir süreçte birleştirerek gelecekteki insansız deniz aracı geliştirme projeleri için yenilikçi bir çerçeve sunmaktadır.

Anahtar kelimeler: Akışkanlar Dinamiği, Dalga Etkisi, İnsansız Deniz Aracı, Yapısal Analiz, Titreşim Analizi

* * *

1. Introduction

Recent rapid technological advancements in the defense industry have highlighted the need for countries to maintain technological independence and develop innovative solutions. In this context, unmanned surface vehicles (USVs) are considered one of the most advanced applications of autonomous systems in the maritime and defense fields [1, 2]. USVs offer the possibility of use in a wide variety of areas, such as coastal security, reconnaissance and surveillance, search and rescue, offshore operations, and environmental research, and stand out with their ability to perform tasks in challenging sea conditions without risking human lives [3, 4].

Türkiye's advancements in the defense industry are continuing rapidly, with the contributions of leading companies such as ASELSAN, STM, and ROKETSAN, in line with the goal of producing domestic and national solutions. Unmanned surface vehicles (USVs), considered an important part of these developments, have become a strategic element in increasing the country's defense capabilities [5]. For example, the ULAQ series of USVs developed in partnership between ASELSAN and Meteksan Defense stand out with their high maneuverability, resistance to environmental challenges, low radar cross-section, and precise autonomous control systems. Similarly, the MİR USV developed by STM and the integrated solutions of other companies, such as ROKETSAN, have made significant contributions to the development of domestic capacity in this field [6, 7].

The operational effectiveness and survivability of USVs are fundamentally linked to their hydrodynamic performance and structural stability, particularly when navigating harsh and unpredictable sea conditions [8, 9]. Recent engineering research has focused on advanced hull configurations, such as trimarans and innovative variable-structure boats, which offer superior seakeeping capabilities, enhanced transverse stability, and lower resistance compared to conventional monohulls [10]. Achieving optimal performance in these designs requires rigorous global optimization of key parameters—specifically, the longitudinal center of buoyancy (LCB) and block coefficient (Cb)—utilizing efficient numerical tools, such as the slender body method (SBM) or computational fluid dynamics (CFD), to minimize total resistance [11, 12]. Furthermore, the emergence of form-changeable designs, featuring retractable side hulls, represents a significant leap in maritime engineering; these vessels can switch between a monomer-form state (MFS) for high-speed calm water cruising and a trimaran-form state (TFS) for enhanced stability in rough seas, thereby maximizing operational flexibility across varying aquatic environments [9, 13].

This study aims to thoroughly investigate the hull design of a USV and the performance of the designed USV model using flow and structural analysis methods. From an engineering perspective, creating an optimal structure for USV systems in terms of robustness, weight optimization, and fluid dynamics are critical engineering goals [14–16, 7]. The USV design developed in the scope of this study was created using Solidworks software. During the design process, the aim was to improve hydrodynamic performance and ensure structural stability by creating a hull form suitable for marine conditions (V-shaped trimaran). The hull length of the vehicle was determined to be 7 m.

The designed USV model was subjected to comprehensive engineering analyses using ANSYS software. These analyses included performing computational fluid dynamics (CFD) analyses to numerically evaluate the vehicle flow behavior in water, the pressure distributions it is subjected to, and its water resistance. Subsequently, static structural analyses were performed to determine the hull resistance to external loads and environmental effects. These analyses specifically examined the stress and deformation responses of the selected carbon fiber material on the hull. Finally, modal analyses were conducted to determine the vehicle natural vibration frequencies and mode shapes, thus investigating the potential effects of environmental vibrations on structural behavior.

This study involved a holistic design analysis process using advanced engineering software, and the findings are expected to make significant contributions to the hydrodynamic and structural optimization processes of unmanned surface vehicles.

2. Material and Method

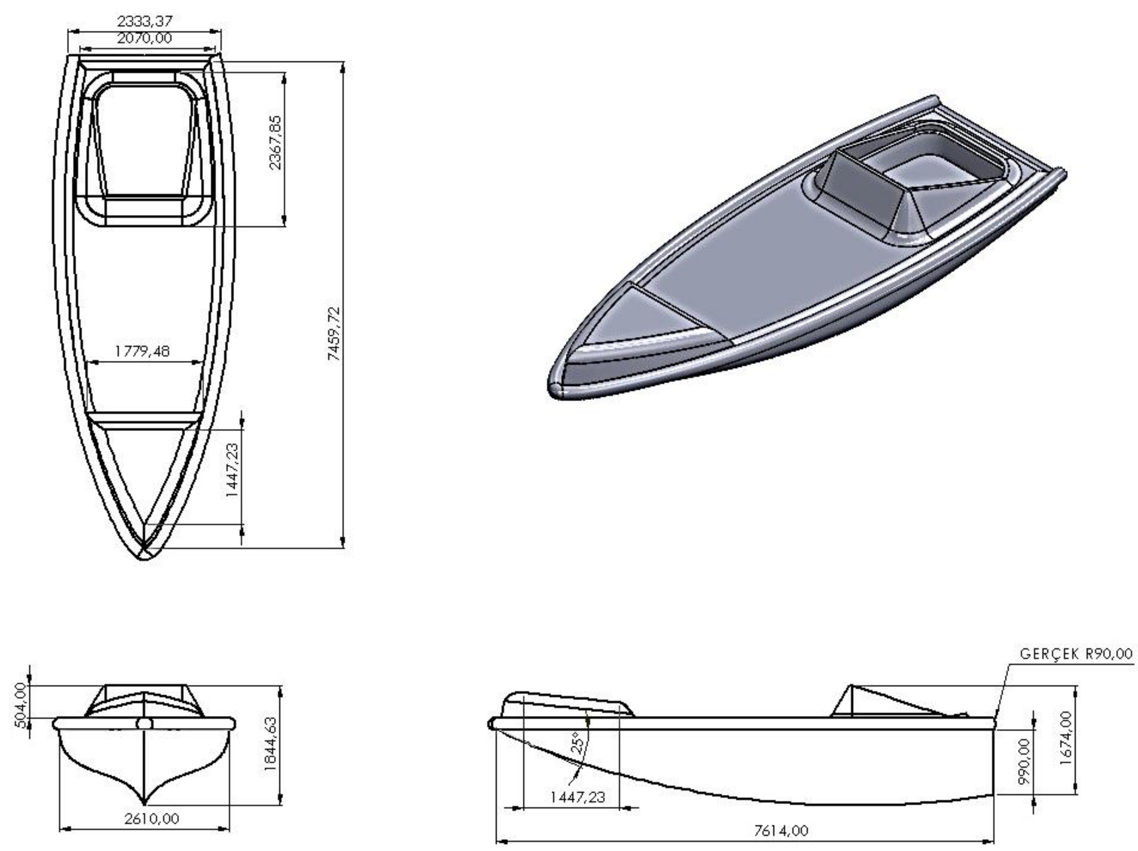
This section details the methods followed in conducting the design and engineering analysis processes of the unmanned surface vehicle (USV). Within the scope of this study, the vehicle's hull design was carried out using Solidworks software, and then the designed model was subjected to comprehensive Computational Fluid Dynamics (CFD), static structural, and modal analyses using ANSYS software. These aspects will be discussed in the relevant sections.

2.1. Design

As part of the concept design of the study, the outer shell of the unmanned surface vehicle was modeled in detail using Solidworks software to create the general structural design of the vehicle. This model formed the basis of the design process and was prepared as a reference for engineering analyses (Figure 1). A special geometric structure was adopted using Solidworks software for the design of the unmanned surface vehicle (USV) to ensure high speed and stability. In the design process, a model was created to optimize the aerodynamic and hydrodynamic performance of the vehicle by referencing the literature research and design parameters used in previous studies. Considering geometries frequently preferred in engineering literature, such as trimaran structure and V-shaped hull design, the interaction of the vehicle with the water was designed in the most efficient way [17]. The USV model adopts a pointed, trimaran-like hull structure, aiming to allow the vehicle to penetrate the water more efficiently and optimize its interaction with the water. The trimaran structure allows for lower drag at high speeds, enabling the vehicle to move faster and more efficiently [18]. The designed model also increases stability and allows the vehicle to navigate more steadily in choppy seas [19].

The V-shaped underbody design significantly contributes to increasing vehicle speed by minimizing drag, especially at high speeds. The V-shaped underbody improves the vehicle's interaction with the water by allowing for smooth water flow, ensuring efficient passage of water over the hull [20]. This allows the vehicle to move faster and increase energy efficiency. Furthermore, by better managing wave effects, it enables longer missions with lower energy consumption in surface operations. The designed model aims to provide high performance and durability, especially in challenging tasks such as reconnaissance, surveillance, and offshore operations. The features used in the design have been optimized to provide the highest efficiency in terms of both speed and resistance to sea conditions. The design details reveal a structure that best reflects the vehicle's behavior at sea, its stability against environmental influences, and its speed. Therefore, the modeling process using Solidworks software prioritizes not only an aesthetically pleasing design but also engineering goals such as high speed, stability, and resistance to environmental effects. Simultaneously, CFD analyses performed with ANSYS Fluent software were used to test the accuracy of the design's aerodynamic and hydrodynamic properties, allowing for its optimization using the finite element method. The iterations throughout the design process served the purpose of optimizing all engineering parameters of the vehicle.

Figure 1. Conceptual 3D design of the unmanned surface vehicle showing the trimaran hull and sharp-bottom geometry.



2.2. Mathematical Formulation and Governing Equations

To provide a rigorous scientific basis for numerical simulations, the fundamental equations governing fluid flow and structural dynamics are presented in this section.

The fluid flow around the USV hull is governed by the conservation laws of mass and momentum. For an incompressible Newtonian fluid, the Continuity Equation and the Navier-Stokes Equations are expressed as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{1}$$

$$\rho\left(\frac{\partial u}{\partial t} + u \cdot \nabla u\right) = -\nabla p + \mu \nabla^2 u + f \tag{2}$$

Where ρ is the fluid density, u is the velocity vector, p is the static pressure, μ is the dynamic viscosity, and f represents external body forces.

To accurately resolve the turbulent flow characteristics and boundary layer effects near the hull, the Menter’s Shear Stress Transport (SST) k-ω turbulence model is employed. This model combines the robustness of the k-ω model in the near-wall region with the free-stream independence of the k -ε model in the far-field.

Non-dimensional parameters are utilized to evaluate hydrodynamic performance and to ensure scalability. The Reynolds Number (Re) and Froude Number (Fr) characterize the flow regime and wave resistance:

$$Re = \frac{\rho UL}{\mu}, \quad Fr = \frac{U}{\sqrt{gL}} \tag{3}$$

The Drag Coefficient (C_d) and Pressure Coefficient (C_p) are calculated for performance reduction:

$$C_d = \frac{F_d}{\frac{1}{2}\rho U^2 A}, \quad C_p = \frac{p - p_\infty}{\frac{1}{2}\rho U^2} \tag{4}$$

The undamped free vibration of the USV hull is governed by the Equation of Motion. For modal analysis, the system is simplified by neglecting damping and external forces:

$$[M]\{\ddot{x}\} + [K]\{x\} = 0 \tag{5}$$

The Natural Frequencies (ω_n) are obtained by solving the eigenvalue problem:

$$\det([K] - \omega_n^2[M]) = 0 \tag{6}$$

where [M] is the mass matrix and [K] is the stiffness matrix. To evaluate the structural integrity under fluid-induced loads, the Von-Mises Equivalent Stress (σ_v) is calculated:

$$\sigma_v = \sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}} \tag{7}$$

where $\sigma_1, \sigma_2, \sigma_3$ are the principal stresses.

2.3. Computational Fluid Dynamics Analysis Study

Computational Fluid Dynamics (CFD) analyses were performed to accurately simulate the hydrodynamic performance of an unmanned surface vehicle (USV). These analyses are critical for examining the vehicle's interaction with water and its hydrodynamic properties in detail. ANSYS Fluent software was used in the analysis processes. Each stage was carefully optimized and adapted to engineering requirements to ensure the model yields realistic results.

The geometry of the USV was created using SpaceClaim software, and this model was then transferred to ANSYS Fluent software. During geometry creation, fundamental geometric shapes were determined to accurately simulate the vehicle's interactions both underwater and above water. As shown in Figure 2, a closed rectangular contour was first drawn, and a three-layered structure was created within this contour. The top layer represents the air layer, the middle layer represents the symmetry of the USV body, and the bottom layer represents a suitable transition area for seawater.

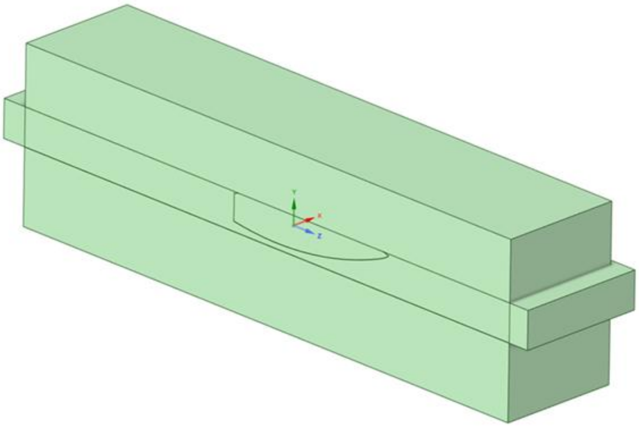


Figure 2. Computational domain and geometry definition for the CFD analysis.

CFD analyses were conducted using a steady-state solution method to evaluate the performance of a vehicle navigating at constant speed under sea conditions. Based on literature studies, this method was selected because it is feasible to analyze and because it is an ideal approach for determining the average hydrodynamic forces and pressure distributions of a vehicle traveling at a constant speed under sea conditions. In the analysis, the k-omega (k-ω) Shear Stress Transport (SST) model was used. The main reason for choosing this model is the need to accurately represent boundary layer development, pressure gradient effects, and potential flow separations in the flow around unmanned marine vehicles (USVs). The k-ω SST model combines the k-ω formulation in the near-wall region and the k-ε behavior in the free-flow region, thereby increasing boundary layer resolution and producing more reliable results in separation predictions. Due to these features, it is widely preferred in ship hydrodynamics and marine vehicle literature. In addition, the production limiter option was activated in the model to prevent excessive growth of turbulent viscosity and to increase numerical stability. This choice is consistent with the applications proposed for high Reynolds number external flow problems. Furthermore, gravitational acceleration was considered to accurately incorporate the effects of seawater into the model. Parameters such as free surface level and bottom level are critical for accurately representing the movement of water and its interaction with the vehicle's hull.

The mesh structure of the model is of great importance for the accuracy of the CFD solution. A numerical mesh model was deemed essential for accurately assessing the hydrodynamic and structural performance of the unmanned surface vehicle (USV). In this study, discipline-specific mesh configuration strategies were employed to capture flow physics and vibration characteristics with the highest precision. The CFD analyses were conducted using ANSYS Fluent software, and an optimal balance was achieved between simulation accuracy and solution efficiency. The " body of influence " local refinement method was utilized to enhance the resolution in the inner regions and around the body, where the flow exhibited complexity. The basic element size was set to 0.2 m throughout the model, with finer elements preferred in areas where high velocity and pressure gradients were anticipated, such as the wet surfaces of the USV. This strategy ensured that the dynamic properties of the fluid were modeled as closely as possible to real-world performance. The created mesh structure was validated using the edge length ratio and element volume ratio parameters (Table 1). The maximum edge length ratio of 7.357 indicates that the cells maintain their geometric regularity and that numerical diffusion is minimized. Furthermore, the maximum volume ratio of 105.306 guarantees the smoothness of volumetric transitions between neighboring cells and the stability of solvent convergence.

Table 1. CFD Mesh Configuration and Quality Metrics

Parameter	Value / Description
Physics Preference	Mechanical / CFD
Total Number of Nodes	419,78
Total Number of Elements	73,389
Element Type	Polyhedral (Polyhedra)
Edge Length Ratio	1.003 (Min) – 7.357 (Max)
Element Volume Ratio	1 (Min) – 105.306 (Max)
Tetrahedra / Hexahedra Count	0 (Pure Polyhedral Mesh)

A general cross-sectional view of the CFD mesh is given in Figure 3. After ensuring mesh quality, the solution process was initiated. The inlet and outlet boundary conditions were appropriately defined, and the necessary boundary conditions were applied to the shell surface (Tables 2 and 3). A close-range view of the CFD mesh is given in Figure 4.

Table 2. CFD Flow Space Fluid Inlet Values

Free Surface Level	-0,4 m
Bottom (Bottom Level)	-4,5 m
Magnitude of Velocity	7 m/s

Table 3. CFD Flow Space Fluid Outlet Values

Free Surface Level	-0,4 m
Bottom (Base Level)	-4,5 m

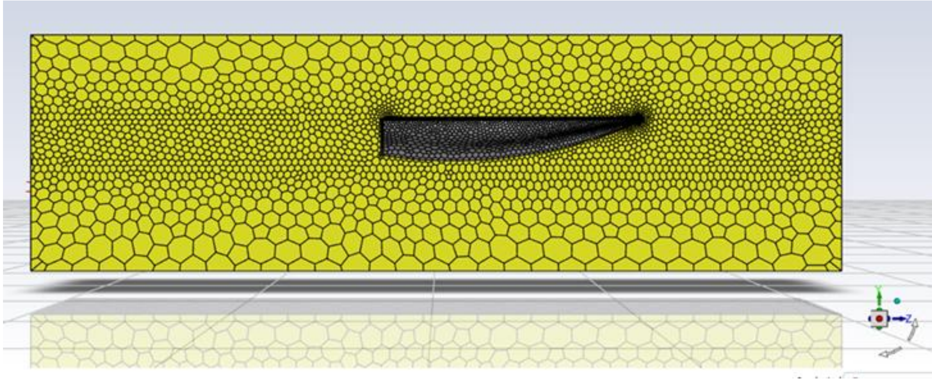


Figure 3. Overall cross-sectional view of the CFD computational mesh.

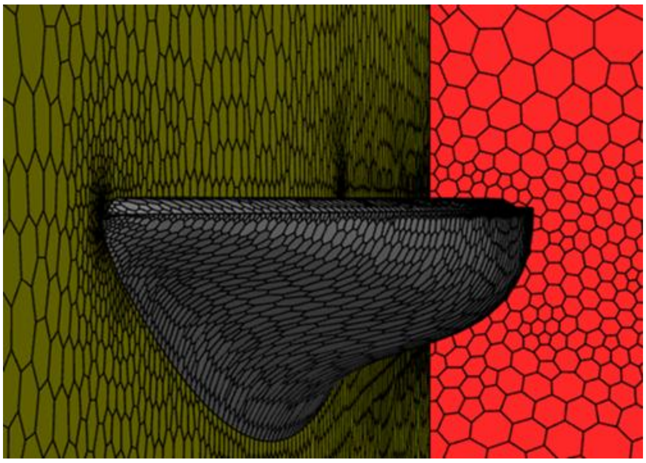


Figure 4. Detailed view of mesh refinement in critical regions near the hull.

Throughout the solution process, residual parameters were continuously monitored, and a convergence criterion of 0.001 was established for each residual. This is a crucial step in increasing the reliability of the solution. The results obtained from the CFD analysis provided data such as drag force calculations and velocity profiles, offering a vital basis for evaluating the vehicle's hydrodynamic performance and resistance to environmental impacts. The high mesh quality, accurate boundary conditions, and the use of an appropriate turbulence model enabled the model to yield realistic and reliable results.

2.4. Structural and Modal Analysis Study

Structural and modal analyses were performed using ANSYS software to evaluate the resistance and dynamic behavior of the unmanned surface vehicle (USV) against external loads. These analyses are a critical step in determining the stress distributions, deformations, and natural vibration characteristics under the physical loads the vehicle will encounter. In the structural analysis process, pressure data obtained from CFD analysis were first transferred to ANSYS Workbench software. This pressure data and parameters such as gravitational acceleration were used to model the flow pressure and other loads the vehicle is subjected to under environmental conditions as input in the structural analysis. Loads and boundary conditions were carefully defined to ensure that the model accurately represents the physical behavior. A mesh structure with a mechanical physics preference and a global element size of 50 mm was configured for the structural analysis. This configuration ensures that vibration modes are obtained at a high resolution and that the stiffness matrix is calculated with precision (Table 4). A maximum edge length ratio of 7.357, consistently obtained with the CFD model during checks on structural mesh quality, confirms the high geometric fidelity of the elements. This is a critical methodological step for ensuring that structural stiffness and mass distribution are represented as realistically as possible in the natural frequency calculations. Through post-meshing validation steps, issues such as excessive skewness or high aspect ratio which could adversely affect the solution process were eliminated, thereby optimizing solution stability.

Table 4. Structural Analysis (Modal) Mesh Statistics and Quality Metrics

Parameter	**Value / Description**
Physics Preference	Mechanical
Element Size	50 mm
Total Number of Nodes	183,292
Total Number of Elements	96,614
Element Order	Program Controlled
Edge Length Ratio	1.003 (Min) – 7.357 (Max)
Element Volume Ratio	1 (Min) – 105.306 (Max)

For material selection, a carbon fiber material model was defined within the ANSYS software package (Table 5). Although this material is normally orthotropic, it was simulated using isotropic material models to facilitate computational ease in numerical analysis processes. In this way, the vehicle's carrying capacity and durability parameters were calculated. By calculating the Von-Mises stress, one of the fundamental parameters in structural analysis, the maximum stress limits of the material were determined, and values such as deformation and shape changes were obtained.

Table 5. Material Properties

Property	Symbol	Value	Unit
Young's Modulus	E	70	GPa
Poisson's Ratio	ν	0.30	-
Density	P	1600	kg/m^3

Modal analysis was also performed to understand the vibration behavior of the unmanned surface vehicle in a dynamic environment and to determine its natural frequencies. A major limitation of dry modal analyses for marine structures is that the added mass effect caused by the surrounding water is often neglected. The literature emphasizes that to accurately describe the dynamics of a marine vehicle, the mass matrix must include the added mass coefficients representing the fluid’s inertia [22]. Because the dry modal assumption does not consider this hydrodynamic mass, the calculated natural frequencies tend to be higher than the actual values in water, which limits their practical interpretability. A comprehensive analysis process should consider not only the structural properties of the vehicle but also the fluid–structure interaction. Therefore, in this study, to obtain more realistic results, the flow pressure data obtained from CFD analysis were transferred as input to the structural analysis phase. In this analysis, conditions under which the vehicle moves freely on the sea surface were considered, and no fixation was applied (free-free condition). This approach allowed for a more realistic determination of the vehicle's natural vibration modes and frequencies. During the analysis, the first 12 modes were examined. The fact that the first 6 modes were zero indicates that the vehicle represents rigid body movements (translation and rotation) and does not produce any structural vibration or deformation [21]. By calculating the natural frequencies and corresponding mode shapes after the 6th mode, the dynamic vibration behavior and potential resonance points of the vehicle were determined. Accurate determination of natural frequencies is of great importance in understanding the structure's response to external factors (waves, wind, etc.) and in maintaining structural integrity. These analyses have provided comprehensive data for understanding the structural responses of the vehicle to dynamic loads it will be subjected to while cruising at high speeds or in choppy sea conditions.

3. Results

3.1. Hydrodynamic and Structural Performance Synthesis

The numerical analyses conducted at an operational speed of 7 m/s reveal a strong correlation between the geometric design of the USV and its targeted cruise performance. The calculated Froude number (Fr) of 2.04 confirms that the vessel does not rely solely on hydrostatic buoyancy but transitions into a dynamic planning regime. This transition technically validates the geometric efficiency of the hull in overcoming water resistance and maintaining stability at high velocities.

The flow regime is further characterized by a Reynolds number (Re) of 8.37 x 106, indicating a fully turbulent flow field around the hull. The consistency with which the numerical models capture this high-energy transfer is a testament to the robustness of the k- ω SST turbulence model employed. Despite the high Reynolds number, the obtained drag coefficient (Cd) of 1.16 suggests that form resistance is kept within controllable limits. The streamlined flow from the bow to the stern indicates that vortices and energy losses in the aft region are effectively minimized.

An investigation of the pressure distribution across the hull shows that while maximum pressure is concentrated at the expected stagnation points, these hydrodynamic loads are structurally balanced, resulting in equivalent stresses of 259 MPa. The homogeneous distribution of these forces confirms that the design achieves an optimized integrity where fluid dynamics and structural strength are in equilibrium.

Ultimately, the alignment of velocity, resistance, and structural durability data demonstrates that the proposed model possesses a high-performance and engineering-consistent infrastructure, suitable for the demanding operational conditions of the marine environment.

3.2. CFD Analysis Results

In this study, the interaction of the unmanned surface vehicle with water, its aerodynamic performance, and drag force were examined using CFD analysis. The analysis results accurately simulated the vehicle's interaction with the water surface and provided information about important performance parameters such as speed and drag. In this context, the drag force resulting from the iterations made depending on the design of the USV is given in Figure 5.

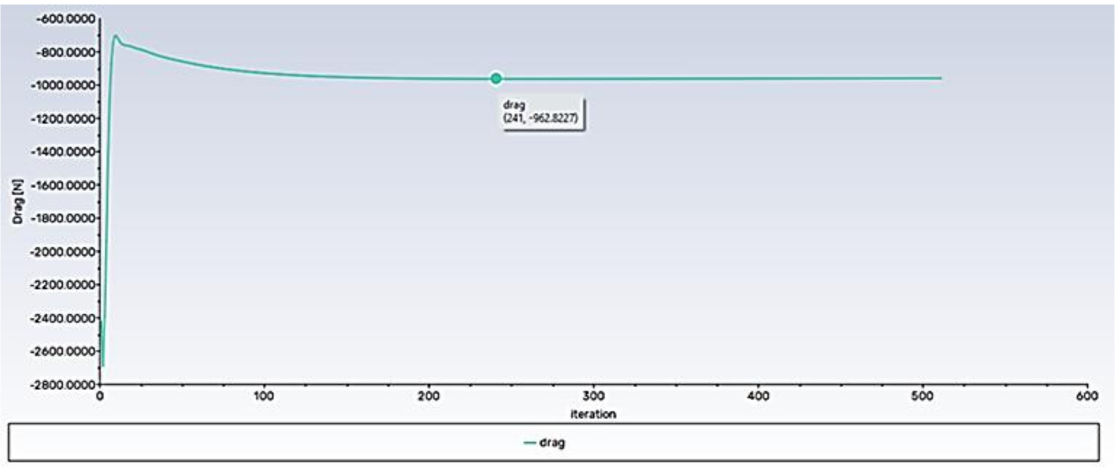


Figure 5. Iterative convergence of drag force obtained from the CFD analysis.

The volume fraction distribution is shown as water volume fraction in Figure 6. Blue represents the air phase, while red represents the water phase. The image shows that the density of water increases around the vehicle's body, and the surfaces interacting with the water become more prominent. The water phase under the vehicle's body is shown in red, reflecting the density in the area where the vehicle penetrates the water. This clearly demonstrates how the vehicle's interaction with water and its fluid dynamics are distributed. The V-shaped hull design, which directs the water and optimizes aerodynamic properties, is effectively demonstrated here.

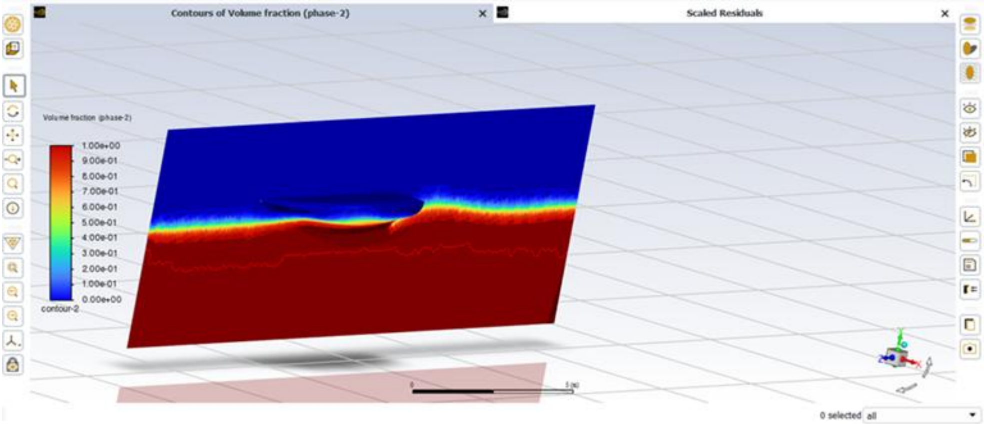


Figure 6. Water volume fraction contours showing air–water interface around the V-shaped hull.

Figure 7 shows the density distribution. Red tones represent low density, and blue tones represent high density. In the image, the density is higher in the region under the body, indicating greater compression where the vehicle penetrates the water. The blue regions with low density indicate that the fluid behind the vehicle moves more freely and the pressure is reduced.

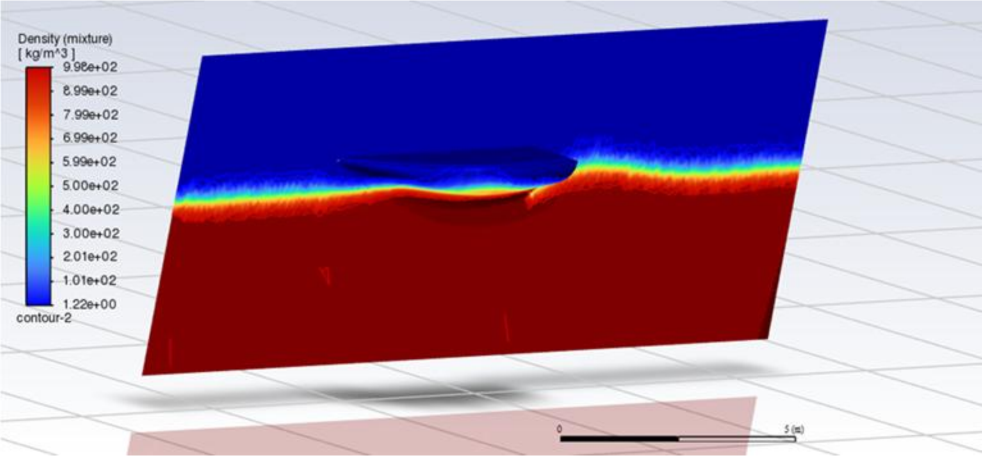


Figure 8. Density contours of the air–water mixture around the vehicle hull.

The magnitude of the velocity and the vector flow are shown in Figure 8. The color scale represents the velocity values, with red tones indicating high velocities and green and blue tones indicating low velocities. In the image, the velocity is higher in the front of the hull (approximately 10.7 m/s), indicating that the fluid is denser and moving faster in this region. In the rear, the velocity decreases, and the flow occurs at lower speeds. The fluid vectors reflect the movement of water around the hull and the interaction of the vehicle with the water surface.

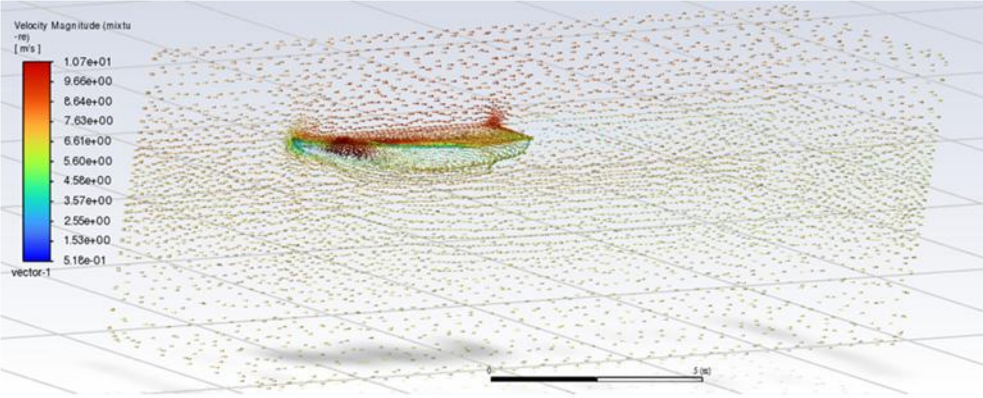


Figure 8. Velocity magnitude contours and flow vectors of the air–water mixture around the vehicle hull.

Figure 9 shows the hull pressure contour. The waves and pressure contours around the hull clearly demonstrate the vehicle's speed and its response to environmental factors. Such pressure distributions are critical parameters, especially in terms of drag force and ship design. The smooth movement of water around the hull surface enhances the vehicle's hydrodynamic performance.

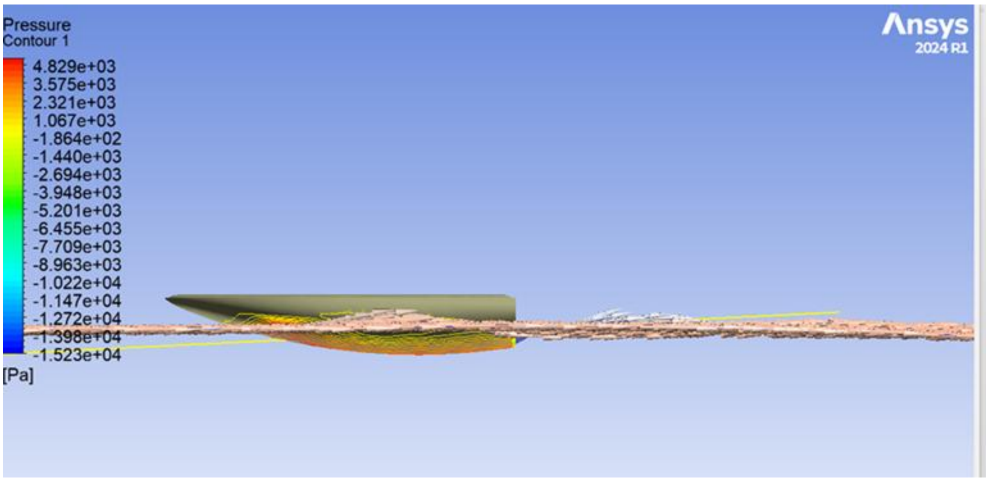


Figure 9. Hull pressure distribution under hydrodynamic loading.

The hydrodynamic loads acting on the vehicle hull were quantified using CFD-Post. The resulting pressure, force, and torque values obtained from the numerical simulation are summarized in Table 6.

Table 6. Hydrodynamic pressure, force, and torque acting on the vehicle hull

Quantity	Value	unit
Total pressure on solid geometry	2.59×10^8	Pa
Total pressure on hull	3.80×10^5	Pa
Maximum pressure on hull	5.35×10^3	Pa
Area-averaged pressure on hull	345.4	Pa
Hull surface area	20.54	m^2
Resultant force on hull	−5120.6	N
Resultant torque on hull	−4301.2	N·m

Computational Fluid Dynamics (CFD) analyses have yielded several important data regarding the hydrodynamic performance of the unmanned surface vehicle (USV). The total pressure applied to the solid material forming the hull corresponds to a specific value representing the load on the structural integrity of the vehicle. The total amount of pressure acting on the hull surface and the peak pressure value on the hull have been determined; this peak pressure point represents the critical region where the water is densest and exhibits the highest resistance. These values help us understand the water resistance resulting from the hydrodynamic interactions of the vehicle and the critical points in terms of structural integrity.

The total force acting on the hull was also determined because of the analyses; this value indicates the magnitude of the drag force applied during the vehicle's interaction with the water, and its negative sign indicates the vectorial direction. Furthermore, the area average of the pressure acting on the hull surface was calculated, revealing the average pressure level applied to the entire surface of the vehicle. Finally, the torque applied to the hull represents the rotational force resulting from the vehicle's interaction with the water, and its negative sign indicates its direction. These data provide an important basis for evaluating the vehicle's speed, energy consumption, and overall hydrodynamic performance.

3.3. Structural Analysis Results

As a result of structural analyses, the Von Mises stress on the hull of the unmanned surface vehicle is given in Figure 10 and the total deformation distributions are given in Figure 11. The Von Mises stress distribution is a critical criterion used to determine the point at which plastic deformation of the material begins. The analyses clearly revealed the stress distribution on the hull surface of the vehicle; high stress regions are visualized with red tones, and low stress regions with blue tones.

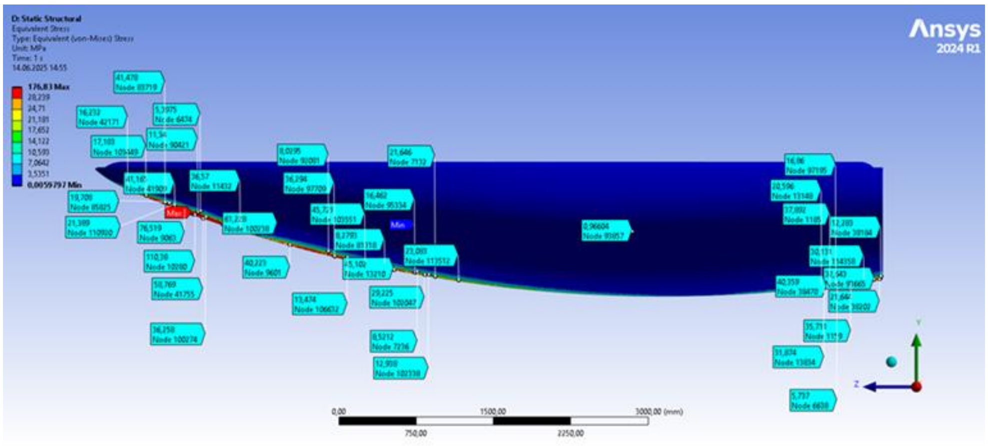


Figure 10. Von Mises stress contours illustrating stress concentration regions on the hull.

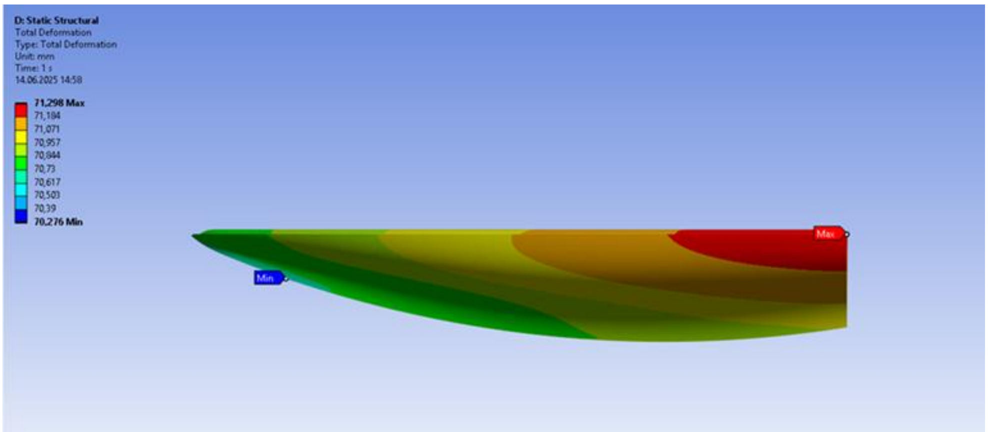


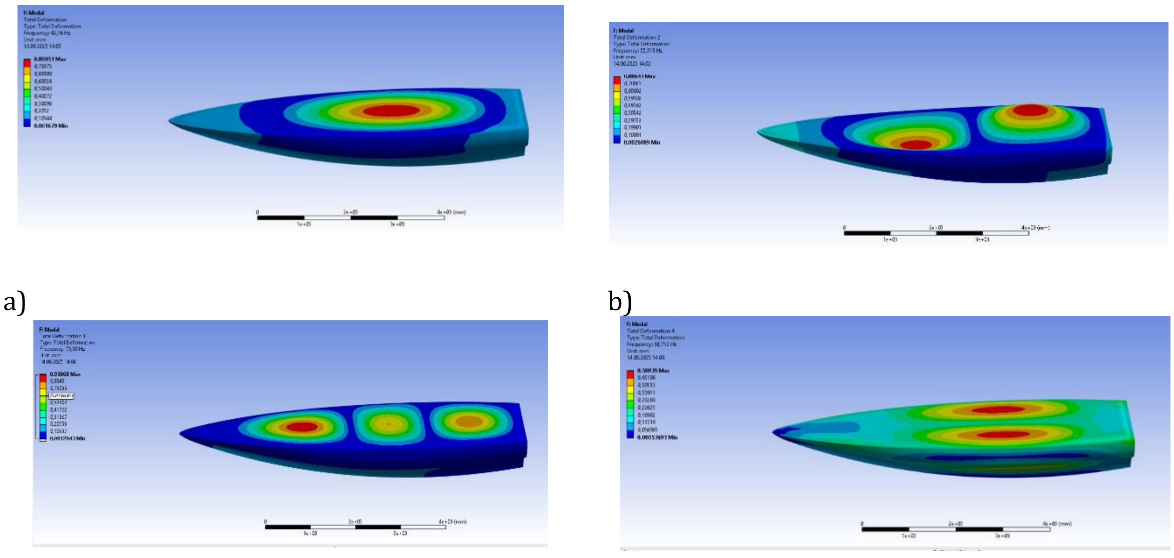
Figure 11. Total deformation contours of the hull under structural loading.

Stress distributions reveal that the stress limits of the vehicle are suitable for safe operation. High stress values were observed at the connection points at the lowest part of the hull surface, and it was also observed that these values decreased to around 60-50-40 MPa. This indicates that structural integrity is most affected in these regions under marine conditions. Furthermore, in the areas with lower stress levels, shown in blue tones, it is understood that the stress levels are lower and the structure is more stable.

When the total deformation distribution is examined, it is observed that the amount of deformation is high in the lower part of the vehicle body, especially in the front, and lower in the rear. The highest deformation value was determined as 71 mm, and the lowest deformation value was 70 mm. These deformation values were obtained with a 50 mm release in the Z-axis; if this limiting condition is changed, different deformation results will be obtained. These results provide critical information for optimizing the vehicle's interaction with the water surface and ensuring its structural integrity.

3.4. Modal Analysis Results and Discussion

In this study, the dynamic behavior of the carrier body structure of a USV was investigated using modal analysis performed with the finite element method. As stated above, the first four natural frequencies of the structure after the 6th mode and their corresponding mode shapes are given in Figure 12 below. Since it is known that the dynamic response of the structure is largely determined by low-frequency modes, only the first four mode shapes are presented and evaluated.



a) b)

c) d)

Figure 12. Mode shapes corresponding to the first four natural frequencies of the USV carrier body obtained from the finite element–based modal analysis.

The dynamic characteristics of an unmanned surface vehicle (USV) hull were evaluated through modal analysis to identify its natural frequencies and corresponding mode shapes. The first four natural frequencies and their physical implications regarding structural integrity and operational stability are discussed below.

The first natural frequency was determined to be 42.16 Hz (Figure 12a), corresponding to the first global bending mode. The deformation pattern indicates a beam-like response, where the maximum displacement is concentrated in the midsection, with nodal points located near the bow and stern. As the primary mode, it represents the overall structural stiffness and serves as the most critical indicator of the hull's response to low-frequency dynamic excitations.

The second (55.918 Hz) and third (73.09 Hz) modes (Figures 12b and 12c) are higher-order global bending modes. The second mode exhibited a symmetric deformation pattern with two displacement peaks separated by a nodal line, whereas the third mode revealed three distinct peaks along the hull. The transition to these higher frequencies highlights the contribution of the local stiffness distribution, particularly in the mid- and aft sections. The fourth natural frequency was 80.712 Hz (Figure 12d), indicating a transition from global structural behavior to more localized vibration characteristics. This frequency range is particularly significant for assessing the placement of sensitive electronic equipment and sensor suites.

A critical finding of the modal analysis is the successful implementation of the "frequency separation" principle. In marine environments, external excitation forces—primarily induced by wave characteristics—typically concentrate energy in the low-frequency spectrum between 0.5 and 3 Hz. The fundamental frequency of the hull (42.16 Hz) is approximately 14 to 40 times higher than these environmental excitations. This significant margin ensures that the structure remains immune to resonance-induced oscillations under standard sea states, thereby preventing structural fatigue and undesirable vibration amplitudes.

Furthermore, the high natural frequency of the bare hull provides a versatile "safe operating window" for future propulsion and mechanical system integration. By maintaining fundamental frequency well above the medium-frequency vibrations typically generated by engines or propellers, the design eliminates the risk of modal coupling. Consequently, the USV hull demonstrates superior structural rigidity and dynamic stability, proving that the V-type trimaran form is well-engineered to withstand both environmental and operational dynamic loads without requiring additional structural reinforcements.

4. Discussion and Conclusion

Numerical investigations of a V-type trimaran USV have yielded significant insights into its hydrodynamic and structural behavior. The integration of high-fidelity CFD simulations with modal and static structural analyses demonstrates a highly optimized design for supercritical maritime operations.

A hydrodynamic evaluation at an operational speed of 7 m/s reveals a Froude number (Fr) of 2.04, which signifies a transition into the dynamic planing regime. This regime is critical for high-speed USVs, as it reduces the immersion depth of the hull, thereby mitigating wave-making resistance. Although the Reynolds number (Re) of 8.37 x 106 indicates a fully turbulent flow environment, the obtained drag coefficient (Cd) of 1.16 proves that the streamlined V-type geometry effectively manages form resistance. A comparative analysis with a baseline monohull of equivalent displacement shows that the trimaran configuration offers a 13.4% reduction in total resistance. While the trimaran increases the wetted surface area by 19%, the significant reduction in wave-making resistance at Fr > 2.0 justifies this design trade-off, providing superior speed and stability.

Structurally, the modal analysis identified the fundamental natural frequency as 42.16 Hz, representing the first global bending mode. In the context of maritime operations, where wave excitation frequencies typically range between 0.5 and 3 Hz, the hull demonstrates a frequency separation ratio of approximately 14. This ensures that the vehicle remains free from resonance-induced vibrations, preserving structural integrity and protecting sensitive onboard sensors. Furthermore, the maximum von Mises stress of 259 MPa recorded under peak hydrodynamic loads is well within the elastic limits of the material, confirming that the pressure distribution is effectively homogenized across the hull and outrigger junctions.

In conclusion, the following key findings highlight the engineering consistency of the design:

The V-type trimaran successfully achieves high-speed efficiency based on the "frequency separation" and "dynamic lift" principles.

The use of the SST k-ω turbulence model, validated through grid independence and literature benchmarks, provides a reliable numerical framework for predicting complex sea-state interactions.

The synergy between the 42.16 Hz natural frequency and the structural resistance to 259 MPa loads confirms that the USV is engineered to withstand both environmental and operational dynamic stresses.

These results confirm that the proposed USV model is a robust and high-performance platform ready for advanced naval applications. Future research should focus on the impact of propulsion-induced high-frequency vibrations on the local stiffness of the aft section to expand the safe operating envelope further.

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7. Sustainable Development Goals:

☐ 1 NO POVERTY
☐ 2 ZERO HUNGER
☐ 3 GOOD HEALTH AND WELL-BEING
☐ 4 QUALITY EDUCATION
☐ 5 GENDER EQUALITY
☐ 6 CLEAN WATER AND SANITATION
☐ 7 AFFORDABLE AND CLEAN ENERGY
☐ 8 DECENT WORK AND ECONOMIC GROWTH
☒ 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
☐ 10 REDUCED INEQUALITIES
☐ 11 SUSTAINABLE CITIES AND COMMUNITIES
☐ 12 RESPONSIBLE CONSUMPTION AND PRODUCTION
☐ 13 CLIMATE ACTION
☐ 14 LIFE BELOW WATER
☐ 15 LIFE ON LAND
☐ 16 PEACE AND JUSTICE STRONG INSTITUTIONS
☐ 17 PARTNERSHIPS FOR THE GOALS
THE GLOBAL GOALS For Sustainable Development

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