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Design and Analysis of Vtol Uav with Fixed & Rotary Wings for Image Transmission

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Abstract: The increased demand for UAVs has motivated vertical take-off and landing configurations that can handle operation within constrained environments. Even though fixed-wing UAVs provide good aerodynamic efficiency and longer endurance, rotary-wing platforms have the ability to hover; combining these advantages into one remains a key design challenge. This paper presents the design and aerodynamic analysis of a hybrid VTOL UAV using a simulation-driven approach. A symmetric NACA 0012 airfoil is chosen to obtain stable and predictable aerodynamic performance over a wide range of angles of attack, considering the transition conditions of VTOL. Wing and airframe geometries are designed using CAD to ensure proper integration of components with structural feasibility. A pressure distribution analysis, velocity fields, and lift-drag characteristics are studied in ANSYS Fluent under subsonic flow conditions. A deformation, stress, and strain analysis is performed to analyze the response of the structure. Results show stable aerodynamic behavior and acceptable structural response, which is a validated design framework for VTOL UAV configurations.

Keywords: *VTOL UAV, NACA 0012, Aerodynamic Analysis, ANSYS Fluent, CAD Modeling, Fixed and Rotary Wing*

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I. INTRODUCTION

Unmanned aerial vehicles (UAVs) are increasingly deployed in applications requiring mobility, flexibility, and efficient operation in constrained environments, such as surveillance, reconnaissance, and infrastructure monitoring. Fixed-wing UAVs offer superior aerodynamic efficiency and endurance, whereas rotary-wing platforms provide vertical take-off, landing, and hovering capabilities. However, neither configuration alone fully satisfies the combined requirements of compact operation and efficient forward flight.

Vertical Take-Off and Landing (VTOL) UAVs address this limitation by integrating fixed-wing and rotary-wing concepts. Nevertheless, the aerodynamic design of VTOL UAVs presents significant challenges due to complex flow behavior, wide variations in angle of attack, and structural loading during different operational modes. In particular, airfoil selection and wing design play a critical role in ensuring stability and predictable aerodynamic performance.

This paper investigates the design and aerodynamic analysis of a hybrid VTOL UAV employing a NACA 0012 symmetric airfoil. The UAV geometry is developed using computer-aided design (CAD) tools, and aerodynamic characteristics are evaluated through computational fluid dynamics (CFD) simulations in ANSYS Fluent. Pressure distribution, velocity contours, lift–drag behavior, and structural response are analyzed under subsonic conditions. The results provide a simulation-validated design framework that supports the aerodynamic feasibility of VTOL UAV configurations and contributes to ongoing research in hybrid UAV systems.

➢ *Operational Advantages of VTOL UAVs*

The operational utility of Unmanned Aerial Vehicles (UAVs) is largely determined by their aerodynamic configuration. Fixed-wing UAVs demonstrate superior aerodynamic efficiency, enabling high forward flight speeds and long endurance missions with reduced fuel consumption. These characteristics make fixed-wing platforms suitable for surveillance over wide areas, high-altitude reconnaissance, and applications where extended

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range is prioritized. However, their dependency on runways or catapult-based launch systems, as well as the need for recovery areas, significantly limits deployment in confined or inaccessible environments. In contrast, rotary-wing UAVs provide hovering capability, vertical take-off and landing, and exceptional maneuverability in restricted operational zones. These attributes allow them to conduct missions such as low-altitude monitoring, close-range inspection, and tactical reconnaissance in urban or naval environments. Nevertheless, rotary-wing configurations are constrained by relatively lower endurance, reduced forward flight efficiency, and limited payload capacity compared to fixed- wing systems, thereby restricting their effectiveness in long-range or high-speed missions. Vertical Take-Off and Landing (VTOL) UAVs combine the complementary features of both fixed-wing and rotary-wing architecture. By enabling vertical take-off and landing without runways, VTOL UAVs extend operational flexibility to locations where infrastructure is limited or absent. Once airborne, the ability to transition into fixed-wing mode enhances endurance, increases cruise speed, and improves aerodynamic efficiency, overcoming the endurance and range limitations of rotary-wing systems. Furthermore, the capacity to hover provides advantages in surveillance, target acquisition, and payload delivery, enabling operations in dynamic or confined environments where fixed-wing UAVs are impractical.

➢ *Technology Advancements*

The rapid advancement of aerospace technology has significantly enhanced the performance and reliability of Vertical Take-Off and Landing (VTOL) Unmanned Aerial Vehicles (UAVs). One of the most notable developments is the improvement of propulsion systems, particularly the use of hybrid-electric and distributed propulsion architectures. These systems enable VTOL UAVs to achieve efficient hovering during take-off and landing while transitioning smoothly into fixed-wing flight for longer endurance missions. This advancement addresses the traditional limitations of rotary-wing UAVs by extending range and payload capability without sacrificing vertical flight flexibility. Another key technological improvement lies in the area of flight control and autonomy. Modern VTOL UAVs are now equipped with advanced algorithms that support autonomous take-off, landing, and transition between hover and cruise modes. Through sensor fusion and real-time control, these systems provide stable flight even in turbulent or unpredictable conditions. This automation reduces operator workload and enhances the precision of mission execution. Additionally, advancements in lightweight composite materials and aerodynamic design optimization have contributed to improved structural efficiency. By reducing overall weight while maintaining strength, VTOL UAVs can now carry larger payloads and operate for longer durations. Computational tools such as CFD have also enabled more accurate predictions of aerodynamic performance, resulting in optimized wing and fuselage designs for hybrid configurations.

Furthermore, communication and data-handling technologies have advanced significantly. VTOL UAVs can now transmit high-resolution imagery, live video, and sensor data to ground stations in real-time, supporting immediate decision-making in surveillance and reconnaissance operations. These capabilities enhance situational awareness and improve the effectiveness of both defense and civilian missions.

Collectively, these advancements have transformed VTOL UAVs into versatile platforms that bridge the gap between fixed-wing endurance and rotary-wing maneuverability, making them a critical asset for modern aerial applications.

➢ *Objective*

- To design and analyze a hybrid Vertical Take-Off and Landing (VTOL) UAV integrating fixed-wing and rotary-wing configurations to achieve combined hovering capability and efficient forward-flight aerodynamics.
- To perform aerodynamic analysis of the selected NACA 0012 symmetric airfoil and evaluate its lift, drag, pressure distribution, and flow behavior under subsonic operating conditions using computational simulations.
- To develop a detailed CAD model of the VTOL UAV, including the wing, fuselage, and propulsion layout, ensuring proper geometric integration and mass distribution suitable for VTOL operation.
- To conduct Computational Fluid Dynamics (CFD) simulations using ANSYS Fluent to analyze pressure contours, velocity fields, lift–drag characteristics, and flow stability around the wing section.
- To evaluate the structural response of the wing under aerodynamic loading, including deformation, stress, and strain analysis, to assess structural feasibility using simulation-based methods.
- To study the aerodynamic suitability of symmetric airfoils for VTOL UAV applications, particularly in conditions involving varying angles of attack and transition-related flow behavior.
- To establish a simulation-driven design framework that supports the aerodynamic and structural feasibility of VTOL UAV configurations and can serve as a foundation for future experimental validation and prototype development.

II. LITERATURE REVIEW

- Mukhti et al. (2021) presented a conceptual design and aerodynamic study of a fixed-wing VTOL UAV, emphasizing the importance of airfoil selection and thrust-to-weight ratio in achieving stable transition behavior. Their work highlighted that symmetric airfoils provide predictable aerodynamic performance under varying angles of attack, making them suitable for VTOL configurations where attitude changes are frequent. This finding directly supports the selection of the NACA 0012 airfoil in the present study.

- Musonda and Mweene (2020) analyzed the aerodynamic characteristics of a fixed-wing VTOL UAV using ANSYS Fluent. Their study demonstrated that CFD-based pressure and velocity analysis is effective in evaluating lift and drag behavior under subsonic conditions. While the work validated aerodynamic feasibility, it did not consider the use of symmetric airfoils specifically optimized for VTOL transition phases. The current study extends this approach by employing a NACA 0012 airfoil and integrating CAD-based structural evaluation.

- Mazhar and Khan (2010) performed finite element analysis on UAV wing structures to assess deformation and stress under aerodynamic loading. Their results emphasized the importance of evaluating structural integrity alongside aerodynamic performance. However, the study did not combine CFD-derived pressure loads with structural simulations. In the present work, aerodynamic pressure results from CFD are directly applied to structural analysis for realistic load assessment.

- Zhang et al. (2022) presented a comprehensive review of hybrid VTOL UAV configurations, highlighting challenges related to aerodynamic interference, stability, and control during transition phases. Although the study provided valuable system-level insights, it lacked detailed airfoil-level aerodynamic and structural analysis. This research addresses that gap through simulation-based evaluation of a VTOL UAV wing using a symmetric airfoil.

III. METHODOLOGY

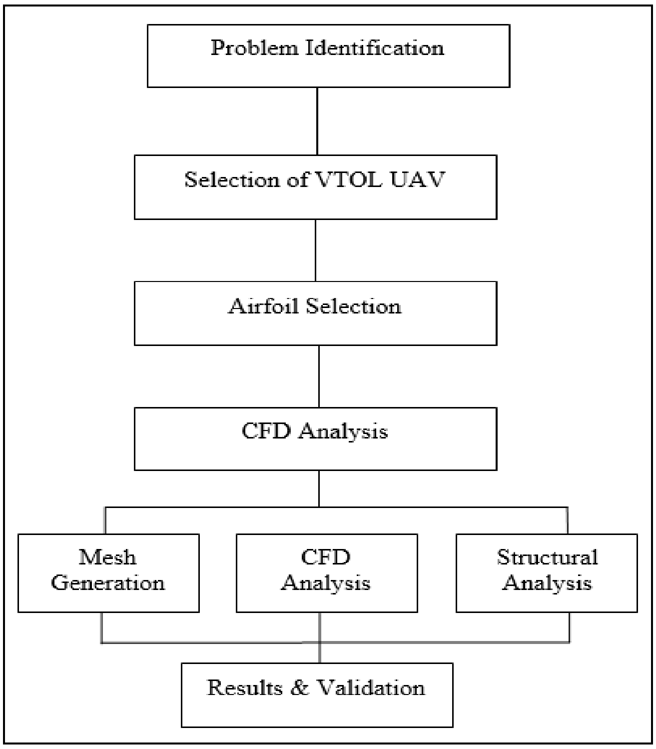

Fig 1 Design Methodology

➤ *Conceptual Design*

The preliminary design phase defines the overall configuration and functional arrangement of the hybrid VTOL unmanned aerial vehicle. At this stage, the main focus was to bring together fixed-wing and rotary-wing capabilities in a single platform with minimum impact on aerodynamic stability and geometric simplicity. The hybrid configuration was selected to enable vertical take-off and landing capability along with efficient forward-flight performance.

Key design considerations include aerodynamic efficiency, structural feasibility, and suitability for surveillance-oriented missions. The fixed wing will provide lift in forward flight, and the rotary-wing system will provide vertical lift in take-off, landing, and hovering. Symmetric geometry with evenly distributed mass aims at minimal aerodynamic asymmetry to reduce the complexity of control requirements. This conceptual layout establishes the relative positions of wing, fuselage, and rotary propulsion units, thus forming the basis of the subsequent detailed design and analysis.

➤ *Airfoil Selection*

Airfoil selection plays a critical role in determining the aerodynamic performance and stability of a VTOL UAV, particularly under varying angles of attack encountered during transition phases. In this study, the NACA 0012 symmetric airfoil was selected for the main wing. The NACA 0012 airfoil features zero camber and a thickness-to-chord ratio of 12%, resulting in a neutral pitching moment and predictable lift behavior. These characteristics make it well-suited for VTOL applications where flow conditions can vary significantly. Unlike cambered airfoils, symmetric airfoils provide balanced aerodynamic performance in both positive and negative angles of attack, which is advantageous during vertical-to-horizontal transition. Additionally, the NACA 0012 airfoil has been extensively studied in existing literature and exhibits reliable performance at low to moderate Reynolds numbers typical of small-scale UAV operations. Its well-documented aerodynamic characteristics enable accurate computational analysis and validation, making it an appropriate choice for a simulation-driven design study.

➤ *CAD Modelling*

The geometric modeling of the VTOL UAV was carried out using computer-aided design (CAD) tools to accurately represent aerodynamic surfaces and structural layout. The CAD model serves as the foundation for both aerodynamic and structural simulations and ensures consistency across all analysis stages. The wing was modeled using the NACA 0012 airfoil profile, generated from standard airfoil coordinate equations to preserve geometric accuracy. Based on validated design references for hybrid VTOL UAVs, the wing was designed with a total wingspan of 2000 mm. A tapered planform was adopted, with a root chord length of 300 mm and a tip chord length of 240 mm, resulting in a taper ratio of 0.8. The corresponding mean aerodynamic chord (MAC) was approximately 270 mm, which serves as the reference length for aerodynamic calculations.

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The wing geometry resulted in a total wing area of approximately 0.54 m² and an aspect ratio of about 7.4, values that fall within the recommended range for efficient low-speed UAV operation. No geometric sweep was applied, and the wing was modeled as a straight, symmetric lifting surface to maintain predictable aerodynamic behavior. The fuselage was designed as a streamlined structure to minimize drag while providing adequate volume for onboard systems. Mounting provisions for rotary-wing propulsion units were incorporated into the CAD model to represent the hybrid VTOL configuration. All components were assembled virtually to verify alignment, clearance, and geometric compatibility prior to simulation.

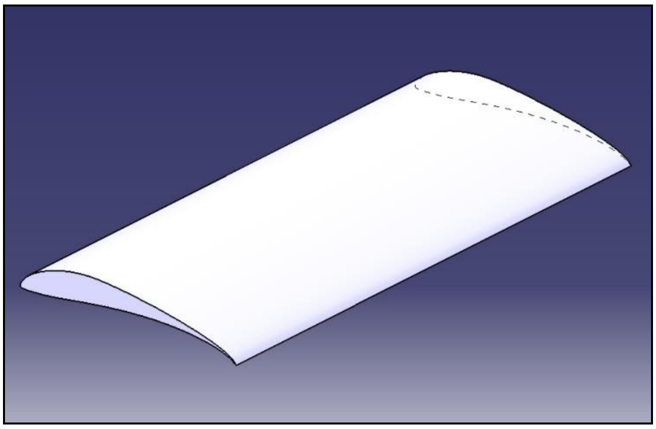

Fig 2 NACA 0012 Airfoil CAD Model

IV. CFD ANALYSIS

The CFD analysis was conducted to study the aerodynamic performance of the wing, which was designed with the selected NACA 0012 airfoil. The process of analysis was carried out in a three-dimensional and steady-state approach by using ANSYS Fluent. The intention of the conducted CFD investigation was to explore the pressure distribution, velocity fields, and the aerodynamic forces, and study the behavior of flow over the wing in subsonic operating conditions.

➢ *Geometry and Mesh*

The three-dimensional wing geometry generated during the CAD modeling stage was imported into ANSYS Fluent for aerodynamic analysis. A tetrahedral mesh was generated to discretize the computational domain. The final mesh consisted of approximately 732,435 cells, 1,494,663 faces, and 137,413 nodes, ensuring adequate spatial resolution for capturing aerodynamic phenomena.

Mesh quality was assessed using orthogonal quality and aspect ratio metrics. The minimum orthogonal quality achieved was 0.14, and the maximum aspect ratio was approximately 20, which falls within acceptable limits for external aerodynamic simulations. Local mesh refinement was applied near the wing surface to accurately capture boundary-layer effects and pressure gradients. A histogram of orthogonal quality confirmed that most of the elements were concentrated in the higher-quality range, contributing to numerical stability

➢ *Physical Model & Material Properties*

The simulations were performed using a pressure-based solver with double-precision formulation. The flow was modeled as steady-state**,** three-dimensional**,** and turbulent. The standard k–ε turbulence model with standard wall functions was employed due to its robustness and suitability for external aerodynamic flows at moderate Reynolds numbers.

Air was selected as the working fluid with a density of 1.225 kg/m³ and dynamic viscosity of 1.7894 × 10^{-5} kg/(ms). The wing material was defined as aluminum with a density of 2719 kg/m³, which was later used for structural analysis coupling.

➢ *Boundary Conditions*

A velocity inlet boundary condition was applied at the inlet with a flow velocity of 120 km/h, representing subsonic operating conditions. The turbulence intensity was set to 5%, with a turbulence viscosity ratio of 10, reflecting realistic atmospheric turbulence levels for UAV operations.

A pressure outlet boundary condition with zero-gauge pressure was imposed at the outlet. No-slip wall conditions were applied to the wing surface to simulate viscous flow behavior. Wall roughness was neglected, assuming a smooth aerodynamic surface. All boundary conditions were defined in an absolute reference frame.

➢ *Solver Settings*

The pressure–velocity coupling was handled using the coupled scheme. Spatial discretization was performed using second-order schemes for pressure and momentum equations to improve solution accuracy. Turbulent kinetic energy and dissipation rate equations were discretized using first-order upwind schemes for numerical stability.

Explicit relaxation factors were applied for momentum and pressure equations. Convergence criteria were monitored using residuals for continuity, velocity components, turbulent kinetic energy, and dissipation rate. The solver was executed until residuals stabilized and aerodynamic coefficients showed convergence trends.

➢ *Flow Visualization*

Pressure vector analysis was carried out to examine the combined magnitude and direction of pressure forces acting on the NACA 0012 wing model under subsonic flow conditions. Unlike scalar pressure contours, pressure vectors provide insight into how pressure forces are distributed spatially and how they influence the resultant aerodynamic loading on the wing surface.

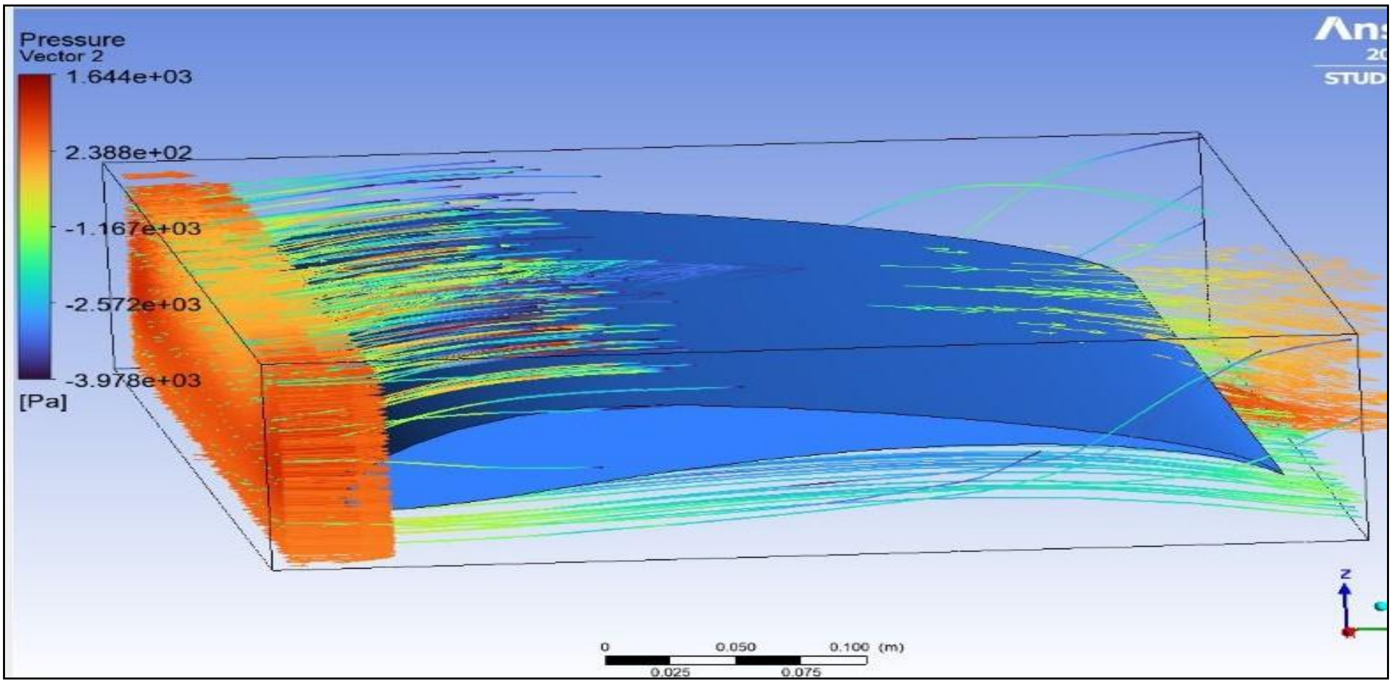

Fig 3 Pressure Vector Distribution Over the NACA 0012 Wing Under Subsonic Flow Conditions.

Figure Fig illustrates the pressure vector distribution around the three-dimensional NACA 0012 wing. Regions of high-pressure magnitude are observed near the leading-edge stagnation zone on the lower surface, where the incoming flow decelerates, resulting in increased static pressure. The vectors in this region are oriented predominantly normal to the wing surface, indicating strong pressure forces contributing to lift generation.

On the upper surface of the wing, the pressure vectors exhibit lower magnitudes and are aligned along the surface curvature, corresponding to accelerated flow and reduced static pressure. This pressure differential between the upper and lower surfaces confirms effective lift generation in accordance with classical aerodynamic theory. The smooth variation of vector direction along the chord indicates attached flow without abrupt pressure reversal, suggesting the absence of flow separation under the simulated operating condition.

Spanwise pressure vector uniformity is also observed across the wing, indicating consistent aerodynamic loading along the span. This behavior is desirable for VTOL UAV wing applications, as it minimizes localized stress concentrations and improves structural reliability. The gradual reduction in vector magnitude toward the trailing edge reflects pressure recovery and stable wake formation.

The pressure vector magnitudes obtained from the simulation fall within the expected range for subsonic UAV wing operation and are consistent with pressure contour results presented earlier. These pressure vectors were subsequently used as input loads for structural analysis, enabling evaluation of deformation, stress, and strain induced by aerodynamic forces.

Overall, the pressure vector analysis validates the aerodynamic effectiveness of the NACA 0012 airfoil for VTOL UAV applications and demonstrates stable pressure force distribution suitable for further aero-structural assessment.

➢ *Velocity Magnitude Contour Analysis*

Velocity magnitude contours were analyzed to understand the acceleration and distribution of flow around the NACA 0012 wing under subsonic operating conditions. Figure Fig presents the contours of velocity magnitude over the three-dimensional wing surface.

The results show a clear increase in velocity over the upper surface of the wing compared to the lower surface. This acceleration of flow over the upper surface corresponds to a reduction in static pressure, which directly contributes to lift generation as explained by Bernoulli's principle. Regions near the leading-edge exhibit moderate velocity gradients, indicating smooth flow attachment without abrupt acceleration or stagnation beyond the leading-edge region.

Along the spanwise direction, the velocity magnitude remains relatively uniform, suggesting consistent aerodynamic loading across the wingspan. No large regions of velocity deficit or recirculation are observed near the trailing edge, indicating stable flow behavior and the absence of large-scale flow separation at the analyzed condition. These results confirm that the NACA 0012 airfoil maintains attached flow and favorable aerodynamic characteristics under the simulated operating regime.

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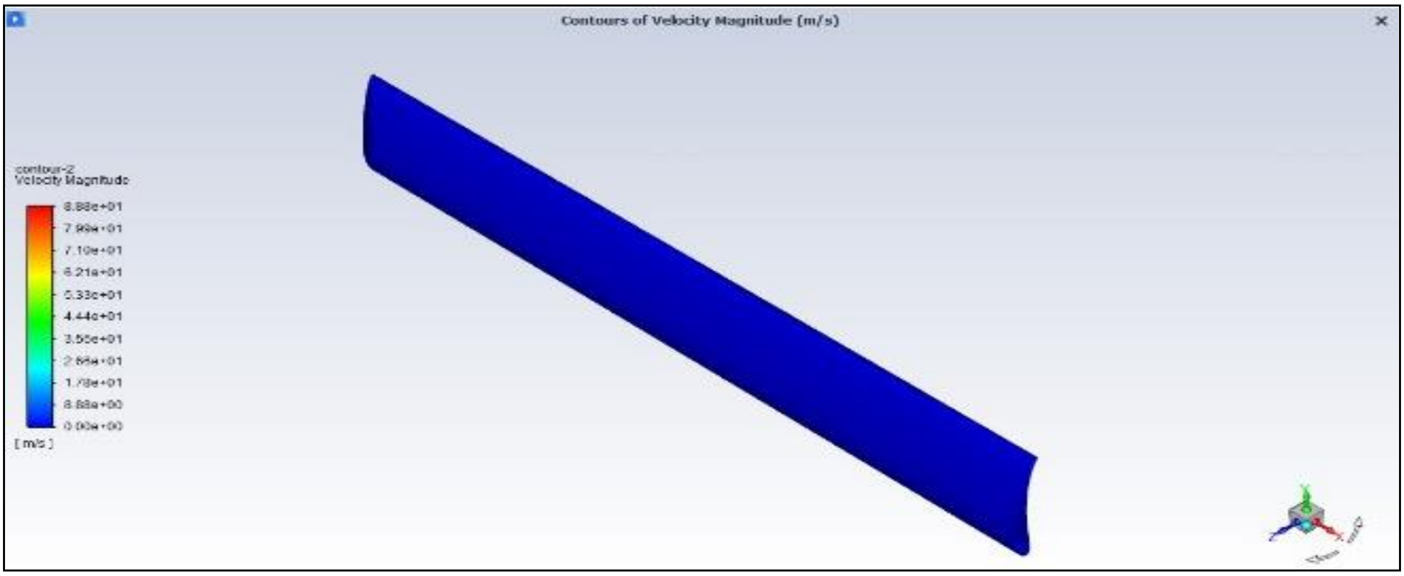

Fig 4 Velocity Magnitude Contour Around the NACA 0012 Airfoil Wing.

➢ *Velocity Vector in X- Direction*

The velocity vectors resolved in the X-direction were examined to evaluate the primary flow alignment with respect to the freestream. Figure Fig illustrates the X-component velocity vectors colored by velocity magnitude.

The vectors are predominantly aligned along the chordwise direction, indicating that the flow remains largely parallel to the wing surface. Higher X-direction velocity components are observed over the upper surface, particularly near the mid-chord region, which corresponds to flow acceleration due to airfoil curvature. This behavior confirms efficient momentum transfer and dominant streamwise flow, which is essential for lift generation and aerodynamic efficiency.

Minimal disturbances or flow reversal are observed in the X-direction, further confirming the absence of separation or adverse pressure gradients severe enough to disrupt the main flow.

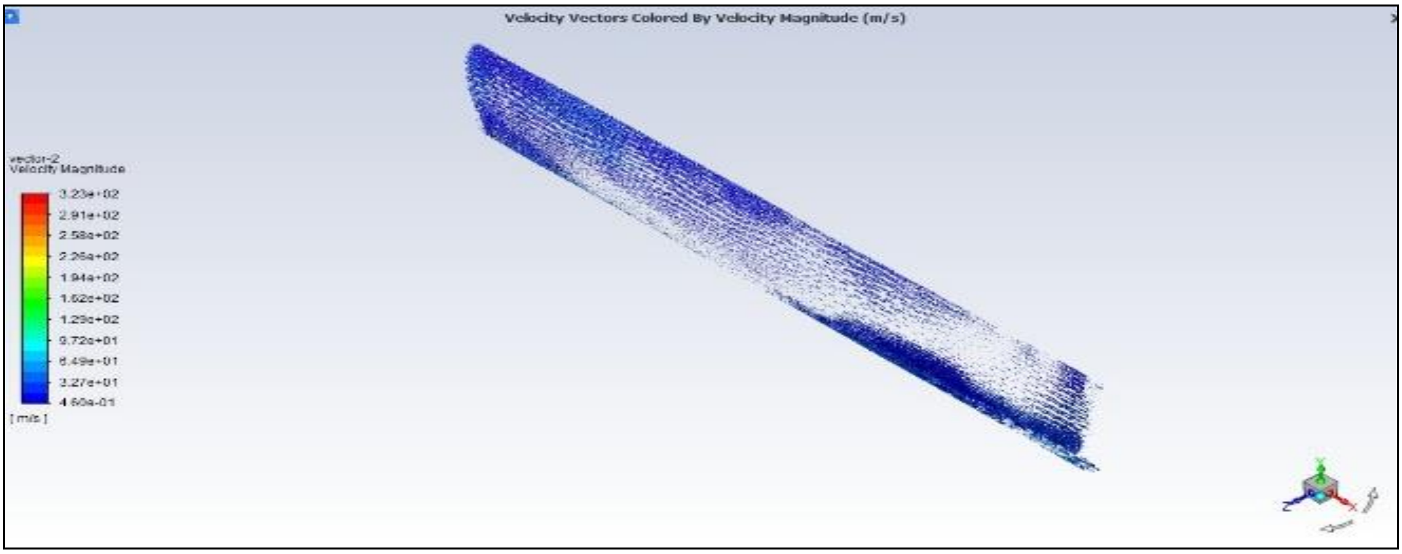

Fig 5 Velocity Vector Distribution in the X-direction for the NACA 0012 Wing.

➢ *Velocity Vector Analysis in Y-Direction*

The Y-direction velocity vectors, representing the spanwise flow component, are shown in Figure Fig . Analysis of the Y-velocity component is important for identifying spanwise flow, crossflow effects, and potential aerodynamic inefficiencies.

The results indicate relatively low velocity magnitudes in the Y-direction across most of the wing surface. This suggests that spanwise flow is minimal and that the wing experiences predominantly two-dimensional flow behavior along most of its span. Limited Y-direction velocity is observed near the wing tips, which is expected due to three-dimensional effects and the formation of tip vortices.

The controlled magnitude of spanwise velocity indicates reduced aerodynamic losses and uniform lift distribution, which is beneficial for both aerodynamic performance and structural loading.

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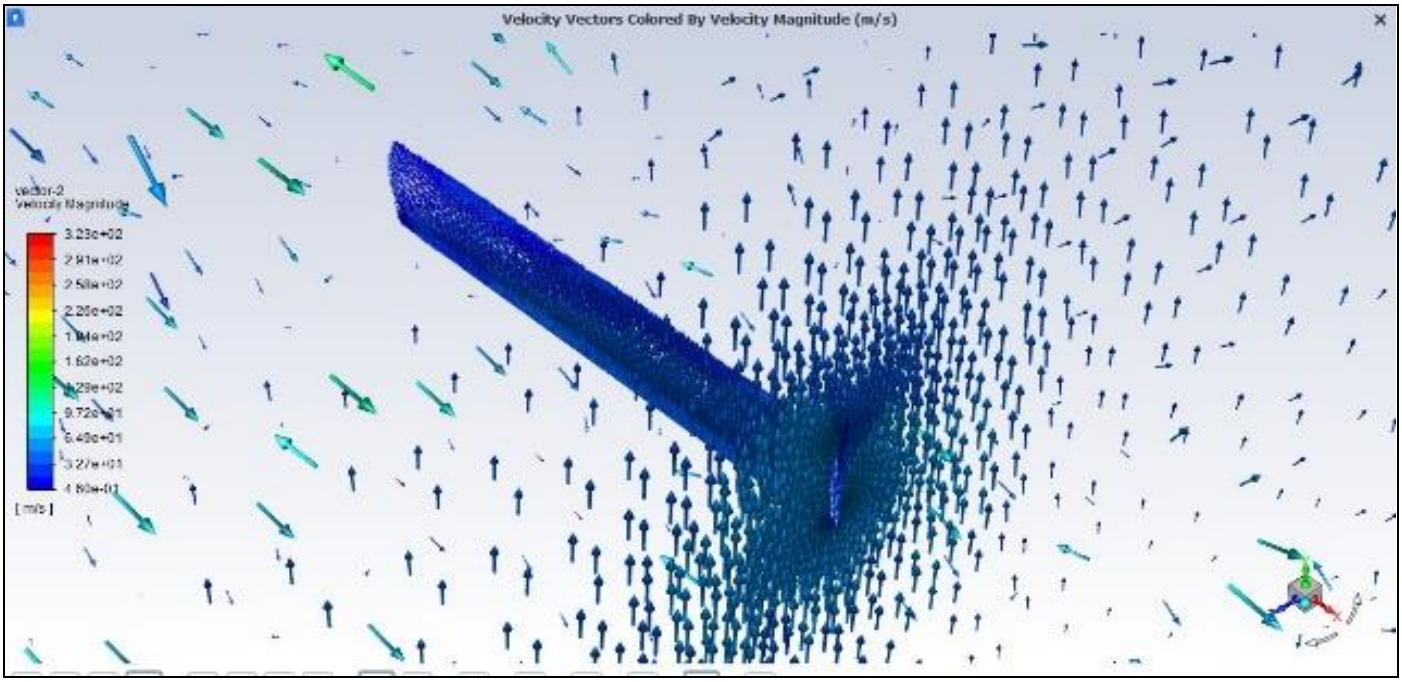

Fig 6 Velocity Vector Distribution in the Y-direction for the NACA 0012 Wing.

➢ *Velocity Vector in Z-Direction*

The Z-direction velocity vectors, representing the vertical flow component, are presented in Figure Fig. This component provides insight into upwash and downwash behavior associated with lift generation. The Z-direction vectors show upward flow deflection below the wing and downward deflection above the wing, particularly near the trailing edge. This behavior is characteristic of lifting surfaces and confirms that the wing induces a downward momentum change in the airflow, consistent with Newton's third law of motion. The magnitude of Z-direction velocity increases gradually toward the trailing edge, indicating smooth wake development and stable downwash formation. No abrupt changes or oscillatory patterns are observed, further supporting the conclusion that the flow remains attached and aerodynamically stable under the simulated conditions.

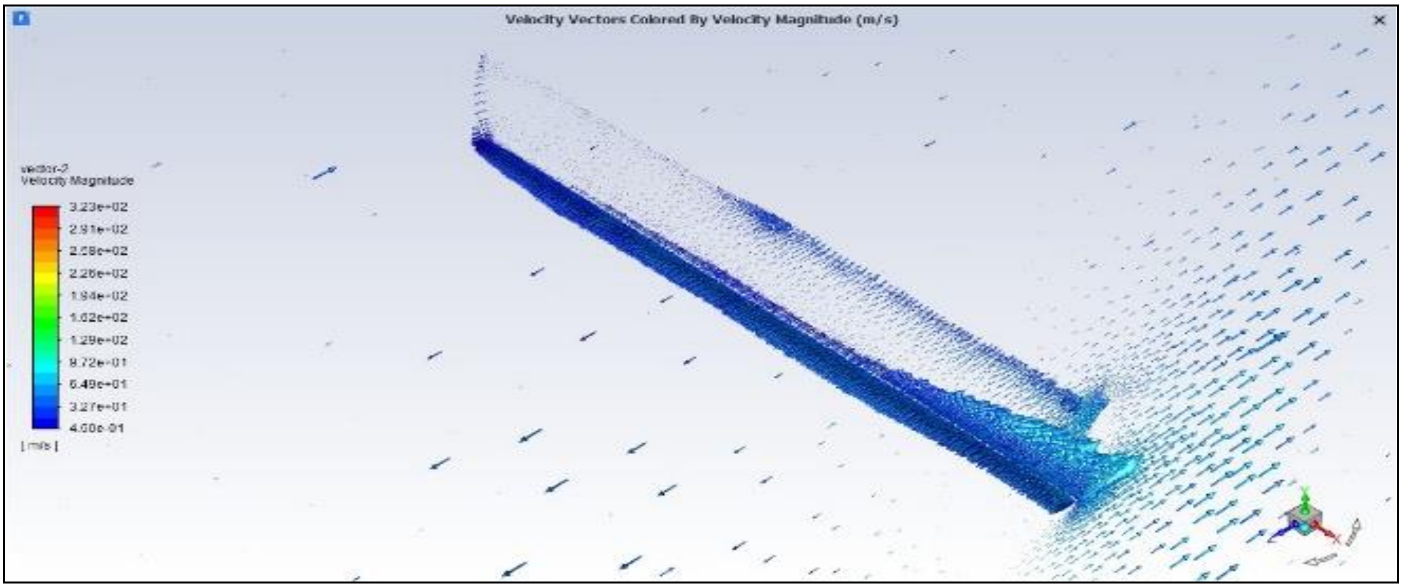

Fig 7 Velocity Vector Distribution in the Z-direction for the NACA 0012 Wing.

V. STRUCTURAL ANALYSIS

In addition to aerodynamic performance evaluation, a structural integrity assessment of the NACA 0012 airfoil wing was carried out. This analysis was performed to ensure that the wing structure can safely withstand aerodynamic loads encountered during operation without excessive deformation or structural failure. The pressure loads obtained from the CFD analysis were mapped onto the structural model to perform a one-way fluid–structure interaction (FSI) study.

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➢ *Elastic Strain Distribution*

Figure Fig illustrates the equivalent elastic strain distribution on the wing surface under aerodynamic loading conditions. The results show that the maximum elastic strain is approximately 5.92×10^{-5}, while the minimum strain value is around 1.82×10^{-5}, with an average strain of approximately 3.43×10^{-5}. The regions of higher strain concentration are observed near the root section of the wing, which is expected due to higher bending moments generated by lift forces. The strain values remain well within the allowable limits of typical aerospace structural materials such as aluminum alloys and composite laminates. This indicates that the wing structure experiences elastic deformation only, with no onset of plastic deformation, ensuring structural safety under the analyzed load conditions.

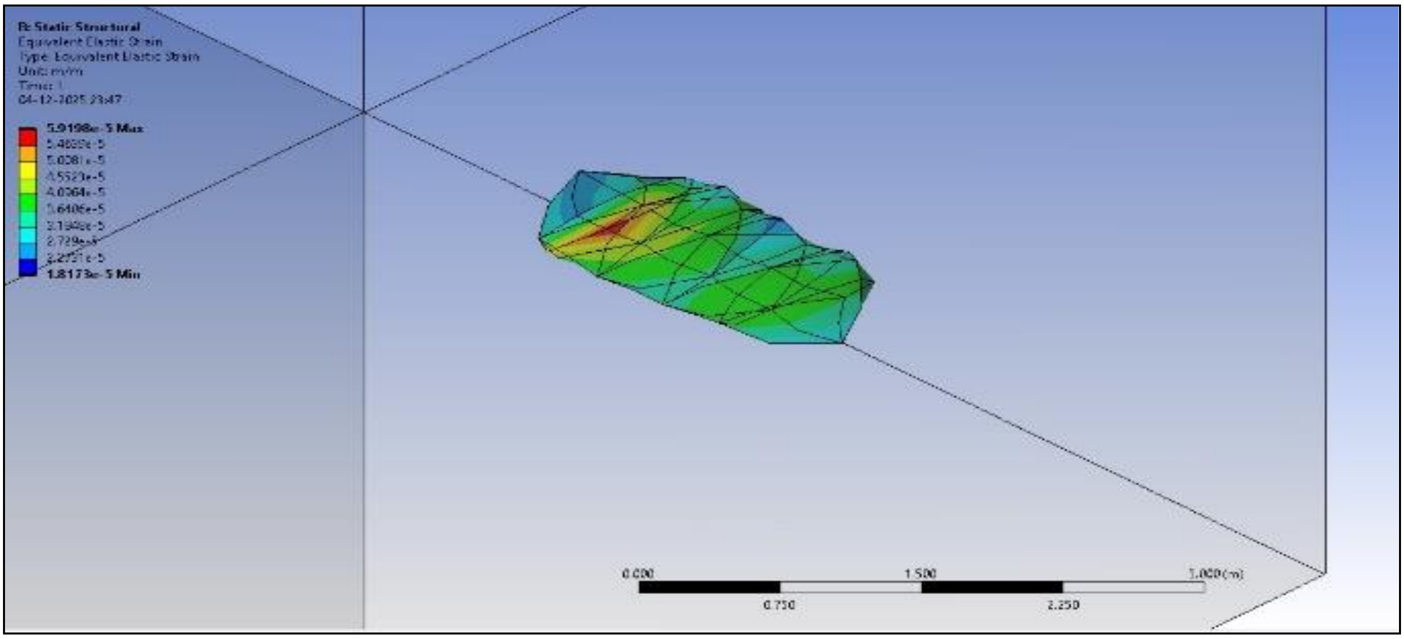

Fig 8 Equivalent Elastic Strain Distribution on the NACA 0012 Wing.

➢ *Elastic Stress Distribution*

Figure Fig presents the equivalent (von Mises) stress distribution obtained from the static structural analysis.

The maximum von Mises stress developed in the wing structure is approximately 7.43 MPa, while the minimum stress is around 0.74 MPa, with an average stress value of approximately 3.35 MPa. These stress levels are significantly lower than the yield strength of commonly used UAV wing materials, such as aluminum alloys (≈250 MPa) or carbon fiber reinforced polymers. The stress contours indicate that the highest stress concentrations occur at the wing root region, which is structurally critical due to load transfer to the fuselage. The stress distribution along the span shows a gradual reduction toward the wing tip, consistent with expected aerodynamic loading behavior.

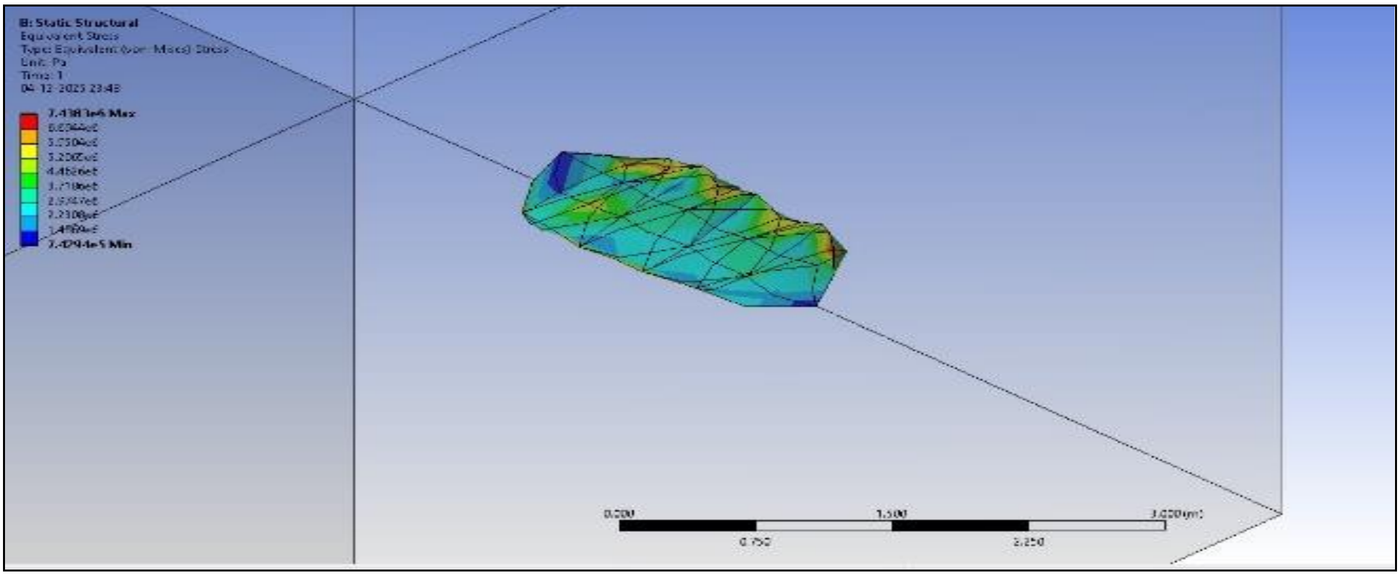

Fig 9 Equivalent Elastic Strain Distribution on the NACA 0012 Wing.

VI. RESULTS AND CONCLUSION

The aerodynamic and structural analyses conducted on the NACA 0012 airfoil wing using ANSYS provide valuable insight into the performance of the proposed VTOL UAV wing configuration. The pressure contour and pressure vector results reveal a clear pressure differential between the lower and upper wing surfaces, confirming effective lift generation under subsonic operating conditions. High pressure is observed near the leading edge on the lower surface, while lower pressure dominates the upper surface, indicating stable aerodynamic behavior with no significant flow separation. Velocity magnitude contours show accelerated airflow over the upper surface of the wing, contributing to reduced static pressure and enhanced lift. The velocity distribution remains uniform along the span, suggesting consistent aerodynamic loading. Directional velocity analysis indicates that the flow is predominantly aligned with the freestream direction, while vertical velocity components reflect lift-producing flow curvature around the airfoil. Minimal spanwise velocity components suggest limited three-dimensional flow effects and reduced aerodynamic losses.

Structural analysis results demonstrate low elastic strain and von Mises stress levels across the wing structure, with maximum values occurring near the wing root due to bending loads. These values remain well within the elastic limits of typical lightweight aerospace materials, confirming structural safety. Overall, the results validate the aerodynamic efficiency and structural feasibility of the NACA 0012 airfoil wing for VTOL UAV applications and support its integration into a hybrid UAV platform.

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