

# CONCEPTUAL DESIGN, AND FEA -BASED STRUCTURAL ANALYSIS OF UNMANNED AERIAL VEHICLE FOR SURVEILLANCE APPLICATIONS

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## ABSTRACT

*Unmanned Aerial Vehicles (UAVs) have become important platforms for surveillance because they can perform monitoring tasks with improved operational safety, flexibility, and efficiency. This paper presents the design and simulation-based analysis of a fixed-wing UAV intended for surveillance missions. A conceptual comparison of drone configurations was first carried out, and the fixed-wing configuration was selected because of its superior endurance, aerodynamic efficiency, and suitability for long-range operation. The UAV geometry was developed using calculated aerodynamic design parameters, and the Eppler 387 airfoil was selected for efficient low-speed aerodynamic behavior. Computational Fluid Dynamics (CFD) analysis was conducted to evaluate lift, drag, pressure distribution, velocity behaviour, and aerodynamic moment over different angles of attack, while structural and modal analyses were performed in ANSYS to assess deformation, stress, strain, and vibration response for multiple composite materials [cite:1]. The results indicate that Kevlar 149 fiber epoxy provides the best overall structural stability, lower deformation, and improved vibration resistance among the studied materials, making it suitable for fixed-wing surveillance UAV applications.*

**Keyword:** UAV, fixed-wing drone, surveillance, CFD, structural analysis, modal analysis, composite materials

## 1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have become an effective solution for modern surveillance because they can monitor large or inaccessible areas with better flexibility, lower operational risk, and improved real-time data collection than many conventional systems. Progress in lightweight materials, embedded control, communication systems, and aerodynamic design has expanded UAV use in defence, disaster response, infrastructure inspection, environmental monitoring, and traffic observation. Among the major UAV categories, fixed-wing platforms are especially suitable for surveillance missions because they provide longer endurance, wider coverage, and better energy efficiency than hovering-based configurations. These characteristics make fixed-wing UAVs attractive for missions that demand stable flight over long distances and continuous sensing capability.

To identify the most appropriate configuration for surveillance applications, the study compared multi-rotor, single-rotor, and fixed-wing drones using parameters such as long-range mapping, surveillance capability, cost, weight efficiency, manufacturability, endurance, payload capacity, manoeuvrability, and maintenance simplicity. The decision-matrix evaluation showed that the fixed-wing platform achieved the highest overall score of 49, compared with 40 for the single-rotor type and 39 for the multi-rotor type, mainly because of its stronger endurance, energy efficiency, aerodynamic performance, and operational range. Based on this selection, the work focuses on the design and analysis of a fixed-wing UAV for surveillance applications, with emphasis on aerodynamic behavior, structural integrity, and vibration stability under operating conditions.

## 2. LITERATURE REVIEW

Maciej Milewski et al. investigated the structural dynamics of composite UAV wings using finite

element modeling and experimental modal analysis techniques. The study focused on predicting natural frequencies and vibration characteristics of lightweight UAV structures. Composite layers with different fiber orientations and thickness values were analyzed using ANSYS ACP software. Experimental testing was carried out using shaker excitation methods to validate the simulation results. The work identified the influence of simplified FEM assumptions on vibration accuracy. The study concluded that improved composite modeling increases structural reliability and modal prediction accuracy in UAV applications [1].

J. Simsiriwong and R.W. Sullivan performed experimental vibration analysis on carbon composite UAV wings to determine modal characteristics under different mounting conditions. Accelerometers and shaker-based excitation systems were used to evaluate the dynamic response behavior. Carbon composite structures fabricated with prepreg laminates were analyzed under free-free and fixed support conditions. The study compared wing vibration responses under varying structural configurations. Experimental observations showed that support conditions strongly affect modal frequencies and damping behavior. The authors concluded that modal testing is essential for lightweight UAV structural validation [2].

Artur Kierzkowski et al. carried out sensitivity analysis on UAV composite wing structures considering laminate orientation and material property variations. The work focused on improving wing stiffness while reducing structural weight. Finite element analysis was used to evaluate deformation and natural frequency behavior under aerodynamic loads. Different laminate stacking sequences were compared for performance optimization. Results indicated that fiber orientation significantly influences modal and structural performance. The study concluded that optimized laminate configurations improve UAV aerodynamic stability and structural efficiency [3].

B. Herrmann et al. developed nonlinear system identification methods for fixed-wing UAVs with flexible structural behavior. The authors integrated aerodynamic modeling with structural dynamics to predict UAV flight characteristics accurately. The study investigated distributed aerodynamics and wing flexibility under various

flight conditions. Numerical simulations demonstrated the influence of structural flexibility on control stability. The work emphasized the need for coupling aerodynamic and structural analysis in UAV design. The researchers concluded that nonlinear modeling improves flight prediction and guidance accuracy [4].

Jakub Wróbel et al. conducted experimental modal analysis of lightweight UAV composite structures using impact hammer testing methods. The study evaluated vibration modes and natural frequencies for composite wing configurations. Carbon fiber reinforced structures with foam cores were experimentally tested under different support conditions. The work analyzed the effect of accelerometer placement and fixture conditions on modal results. Experimental observations validated finite element predictions successfully. The study concluded that modal testing improves UAV structural reliability and vibration safety [5].

V. Raja et al. investigated structural performance of rotary-wing UAVs using conventional and hybrid composite materials. Finite element analysis was used to evaluate stress, strain, and deformation under aerodynamic loading conditions. Different composite laminates were compared to improve load carrying capability and stiffness. The study found that hybrid composites reduced structural weight while maintaining strength requirements. Numerical simulations showed improved structural stability for composite UAV frames. The authors concluded that composite materials are highly suitable for advanced UAV applications [6].

### 3. METHODOLOGY

The methodology adopted in this study was organized into six stages: conceptual design selection, preliminary aerodynamic sizing, three-dimensional CAD modeling, CFD-based aerodynamic analysis, structural analysis, and modal analysis of a fixed-wing UAV intended for surveillance applications. A comparative decision matrix was first used to evaluate multi-rotor, single-rotor, and fixed-wing configurations using long-range mapping capability, surveillance suitability, cost, weight efficiency, manufacturability, flight endurance, energy efficiency, payload capacity, maneuverability, and maintenance simplicity as the selection criteria. Based on this evaluation, the fixed-wing configuration obtained the highest overall score of

49 and was selected for detailed investigation because of its superior endurance, aerodynamic efficiency, and large-area surveillance capability.

Following configuration selection, the principal geometric parameters of the UAV were estimated using standard preliminary design relations and mission-based assumptions. The gross weight was assumed as 4 kg and the aspect ratio was taken as 8 during the initial sizing stage. From these calculations, the wing chord length, wingspan, wing area, and fuselage length were determined as 0.306 m, 2.449 m, 0.75 m<sup>2</sup>, and 1.836 m, respectively, while the Eppler 387 airfoil was selected because of its favorable low-speed lift characteristics for surveillance flight. The battery requirement was estimated as 0.5 kW, and these dimensions were used to define the baseline UAV geometry for further analysis.

The three-dimensional model of the UAV was developed in CATIA by importing the Eppler 387 airfoil coordinates, generating the wing profile, and extruding it along the calculated span. The fuselage and tail sections were then modeled using the calculated dimensions and assembled into a complete fixed-wing configuration suitable for simulation. CATIA surface and solid modeling tools were used to ensure geometric continuity and aerodynamic smoothness before exporting the model to ANSYS Workbench for further analysis.

Aerodynamic analysis was carried out in ANSYS using Computational Fluid Dynamics to determine airflow behavior, lift, drag, pressure distribution, velocity contours, and aerodynamic moment under steady-flight conditions. A computational fluid domain was created around the UAV, and the geometry was discretized using a finite-volume mesh with local refinement in regions expected to exhibit strong flow gradients. A mesh convergence study was conducted to ensure numerical accuracy, and the results indicated that convergence was achieved at approximately 260000 cells. The CFD simulations were performed at a flight velocity of 25 m/s, and the resulting aerodynamic pressure loads were extracted for subsequent structural analysis.

Structural analysis was performed in ANSYS Mechanical to evaluate stress, strain, and total deformation under aerodynamic loading. The imported UAV geometry was cleaned, meshed, and assigned a uniform shell thickness of 5 mm

throughout the structure. Five candidate composite materials, namely Kevlar 149 fiber epoxy, carbon fiber epoxy, Glass-E fiber epoxy, Glass-S fiber epoxy, and Technora fiber epoxy, were defined by their mechanical properties and applied to the same UAV model for comparison. The aerodynamic pressure obtained from CFD at 25 m/s was applied as the external load, while the bottom edge regions and rear end of the model were constrained to represent structural support conditions during loading.

Modal analysis was then conducted to determine the natural frequencies and vibration mode shapes of the UAV for the same material set. In this stage, the UAV was analyzed under free-free space conditions without external constraints in order to capture its inherent dynamic characteristics during flight. The ANSYS modal solver was used to obtain the first several natural frequencies and corresponding mode shapes, enabling comparison of vibration resistance and stiffness among the selected composite materials. Finally, the aerodynamic, structural, and modal results were integrated to identify the most suitable lightweight material and design configuration for a stable, efficient, and vibration-resistant fixed-wing surveillance UAV.

## 4. AUTHOR WORK

### 4.1 Design calculations

For effective UAV design, several key parameters such as the drone's length, height, and maximum operating speed must also be determined. These parameters directly influence the aerodynamic efficiency, propulsion requirements, and maneuverability of the UAV. For instance, the maximum speed is an important factor in ensuring that the drone can quickly reach disaster or rescue locations. Thus, all these design considerations collectively contribute to improving the reliability and performance of UAVs used in search and rescue operations.

The gross weight of the drone can be expressed as:

$$W_{\text{gross}} = W_{\text{payload}} + W_{\text{battery load}} + W_{\text{own weight}} + W_{\text{crew weight}}$$

An airfoil is the cross-sectional profile of a wing that plays a significant role in generating aerodynamic forces when air flows around it during flight. The geometry of the airfoil directly

affects the production of lift and the reduction of drag, both of which are essential for maintaining stable and efficient flight in aerial vehicles such as drones. In the case of Unmanned Aerial Vehicles (UAVs), especially those operating at low speeds, the selection of a suitable airfoil greatly influences flight performance, stability, and maneuverability.

For low-speed UAV applications, specialized airfoils are often selected to provide higher lift at reduced velocities. These airfoils are particularly important for drones involved in operations such as surveillance, mapping, and search and rescue missions, where steady flight and efficient low-speed performance are required. The design of such airfoils focuses on improving aerodynamic efficiency while minimizing the risk of flow separation and stall at higher angles of attack.

Choosing the most appropriate airfoil for a drone depends on several operational requirements. Parameters such as payload capacity, flight altitude, mission objectives, endurance, and overall drone weight all affect the airfoil selection process. To simplify this process, engineers frequently refer to established airfoil databases containing experimentally tested and validated profiles under various aerodynamic conditions. These references provide useful baseline information for identifying airfoils suitable for specific UAV applications.

After selecting potential airfoils, their aerodynamic characteristics must be carefully evaluated. This evaluation commonly involves studying drag polar curves, which illustrate the relationship between lift and drag, as well as analyzing lift coefficients at different angles of attack. Such analyses help determine the efficiency and stability of the airfoil under expected flight conditions. In addition, previous research studies and technical literature related to UAV airfoil performance provide valuable guidance in selecting the most effective design.

The identification of the maximum lift coefficient (CL) and drag coefficient (CD) is an important part of the airfoil selection process, as these parameters directly influence the flight capability and efficiency of the UAV. In this work, a fixed-wing drone configuration is selected for search and rescue applications because of its ease of operation, compact structure, and efficient flight characteristics. Initially, the drone payload and gross weight are assumed to be 4 kg. Furthermore,

several operating assumptions, including flight altitude, wind load, and flight speed, are considered during the preliminary design stage.

### Top of Form

After estimating the total weight of the drone and considering the wind loading conditions, the swept area of the UAV can be determined. The swept area is generally calculated using the relationship between the drone's weight and the wind speed acting on the aircraft. This parameter plays an important role in evaluating the aerodynamic behavior and flight stability of the drone.

In fixed-wing UAV design, the aspect ratio is typically assumed to be 8 during the initial design phase. The aspect ratio is defined as the ratio of the wing span (width) to the wing chord length. This parameter significantly affects the aerodynamic efficiency, lift generation, and drag characteristics of the drone.

$$AR = 8$$

$$AR = \frac{b}{c}$$

$$b = 8 \times c$$

$$s = b \times c$$

$$= 8 \times c \times c$$

$$s = 8c^2$$

$$\text{chord} = 0.306$$

$$\text{Span} = 2.449$$

$$\text{area} = 0.75$$

$$AR = 8$$

$$\text{Cross Section} = \text{Epplar 387}$$

$$\text{Wing in } C_e = 0^\circ$$

$$c = \sqrt{\frac{0.75}{8}} = 0.3061 \quad (1)$$

$$b = 8 \times c$$

$$= 8 \times 0.3061$$

$$= 2.449m$$

From the calculations performed, the wing chord length was determined to be 0.306 m, the

wingspan was calculated as 2.449 m, and the total wing area was found to be 0.75 m<sup>2</sup>. In the present study, the wing cross-sectional profile selected for the UAV is the Eppler 387 airfoil. The design analysis is carried out by considering the lift characteristics of the airfoil at an angle of attack of 0°.

Battery selection is another important aspect in the design of a fixed-wing drone, as it directly influences flight endurance and overall system performance. To estimate the required battery size, the average battery weight-to-power ratio (W/P) obtained from previous research studies is considered during the design process.

$$w/p = 6.8kg/kw$$

$$p = \frac{4}{8} = 0.5kw$$

The battery size is calculated as 0.5kW. The length and diameter of the fuselage is calculated depends up on the fuselage ratio (FR). The fuselage ratio is taken from the previous research which is 0.75. To calculate the fuselage length, wingspan length is required.

$$weight \leq 4kg$$

$$\leq 1kg$$

$$FR = L_f / d_f \quad (2)$$

$$\frac{L_f}{b} = 0.75$$

$$L_f = 1.836m$$

Finally, the fuselage length was determined to be 1.836 m. After completing all the design calculations and defining the specifications of the fixed-wing drone, a detailed three-dimensional model of the UAV is developed using the surface and part design modules available in CATIA. The 3D model plays a vital role in visualizing the overall structure and preparing the design for further aerodynamic evaluation.

Subsequently, Computational Fluid Dynamics (CFD) analysis is carried out using ANSYS software to study the aerodynamic behavior of the drone. This analysis helps in examining important aerodynamic parameters such as airflow distribution, lift generation, and drag characteristics. The results obtained from the CFD

simulation are used to improve and optimize the UAV design for enhanced aerodynamic performance and operational efficiency. Once the design achieves satisfactory aerodynamic characteristics, the development process proceeds to the manufacturing stage to produce the final fixed-wing drone prototype.

#### 4.2 3D Modelling of Fixed-Wing UAV Using CATIA

The three-dimensional model of the fixed-wing UAV was developed using CATIA software based on the calculated design parameters obtained from the preliminary aerodynamic design stage. Initially, the coordinate points of the selected Eppler 387 airfoil were imported into the software environment to generate the wing profile geometry accurately. The maximum airfoil length was considered as the calculated wing chord length of the UAV. Using the imported airfoil coordinate points, the wing cross-sectional profile was created in the sketching module of the software. Accurate airfoil modeling is important because the aerodynamic characteristics of the UAV mainly depend on the wing profile geometry and its lift generation capability.

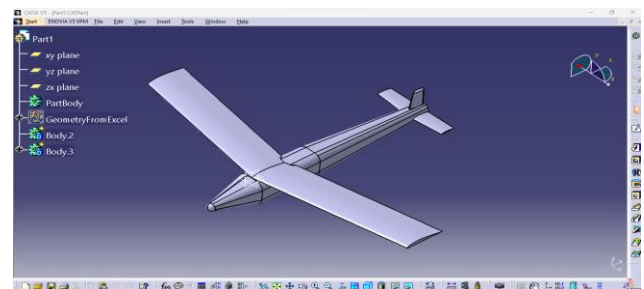


Fig. 4.1 design of fixed-wing drones

After generating the airfoil profile, the wing model was created by extruding the airfoil section along the calculated wingspan direction. The extrusion process was carried out according to the calculated wingspan dimension of 2.449 m to obtain the complete wing geometry. Similarly, the fuselage model was developed based on the calculated fuselage length and diameter values obtained from the fuselage ratio calculations. The fuselage structure was designed to accommodate the battery system, payload components, control electronics, and aerodynamic requirements of the surveillance UAV. Proper fuselage design is essential to achieve structural balance, aerodynamic stability, and efficient integration of all UAV components during flight operations.

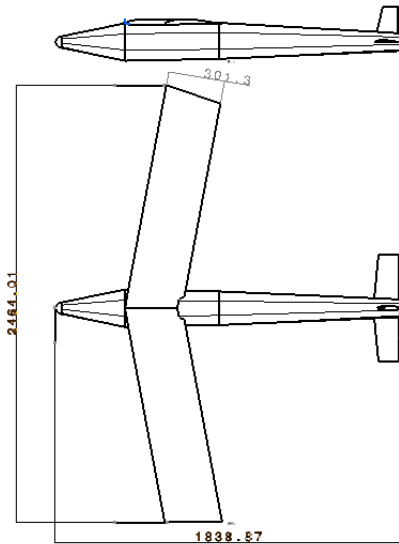


Fig. 4.2 Dimensions for fixed-wing drone.

To generate the complete UAV configuration, the Multi-Section Solid command available in CATIA was used for creating smooth and continuous three-dimensional surfaces between different sectional profiles. This command helped in developing the aerodynamic body shape of the UAV with improved surface continuity and structural appearance. The wing, fuselage, and tail sections were assembled properly to obtain the final UAV model suitable for aerodynamic and structural analysis. The developed three-dimensional model and detailed dimensional specifications of the UAV are presented above for further CFD, structural, and modal analysis studies.

### 4.3 Analysis on drone

Ansys, Inc. is a leading software company known for developing advanced engineering simulation and modeling tools used in computer-aided engineering applications. One of its most widely used platforms, Ansys Workbench, provides an integrated environment for computer-aided design (CAD) and simulation activities. The software features an intuitive graphical user interface that improves workflow efficiency and enables smooth interaction between different simulation modules. It simplifies complex engineering operations by providing convenient access to preprocessing, solving, and post-processing tools, making simulation setup and result evaluation more efficient across various engineering disciplines.

The Workbench platform also includes powerful CAD modeling tools such as SpaceClaim and DesignModeler, which allow users to create, edit, and modify complex geometrical structures with high accuracy. ANSYS supports a broad range of engineering simulations, including electrical analysis, acoustic studies, fluid flow investigations through Computational Fluid Dynamics (CFD), and structural evaluations using Finite Element Analysis (FEA). Specialized modules are available for different applications; for example, CFD tools are used for airflow and fluid behavior analysis, while the CFX module is particularly effective for turbo machinery simulations.

In addition, the Mechanical module is widely utilized for analyzing stress distribution, vibration characteristics, deformation, and thermal effects in engineering components. One of the key advantages of ANSYS Workbench is its ability to import external CAD geometries and perform detailed simulations within a unified environment. This integrated approach enables engineers and researchers to thoroughly validate, optimize, and improve their designs before the manufacturing stage, thereby enhancing overall performance and reliability.

### 4.3.1 Working procedure of simulation

This study utilizes visual representations to examine the behavior and performance characteristics of fixed-wing drones. Through the analysis of graphical and image-based data, the research investigates the aerodynamic behavior of the drone and its response to different forces encountered during flight operations.

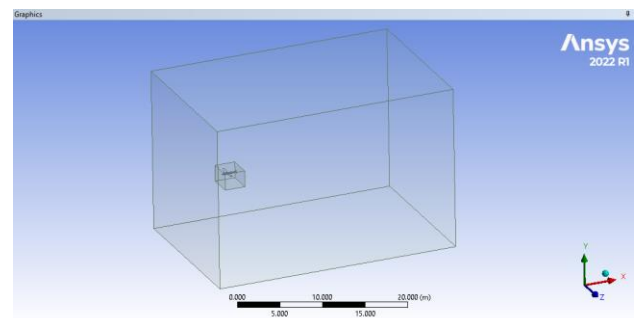


Fig. 4.3 domain for fixed-wing drone.

### 4.3.2 Application of Meshing Techniques

After completing the geometry creation, the next stage in the CFD analysis involves generating the mesh using simulation software. Meshing refers to the process of dividing the entire computational

domain into numerous small and discrete elements that enable numerical simulation of airflow around the drone. The accuracy and reliability of the CFD results largely depend on the quality of the mesh generated. Therefore, a finer and more refined mesh is generally applied in regions where high flow gradients and complex aerodynamic interactions occur to accurately capture the aerodynamic forces acting on the UAV.

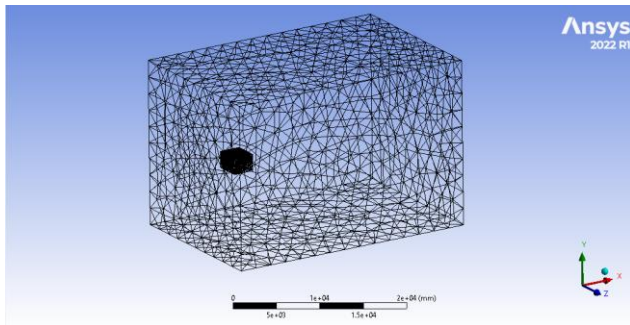


Fig: 4.4 Finite volume model for fluid domain

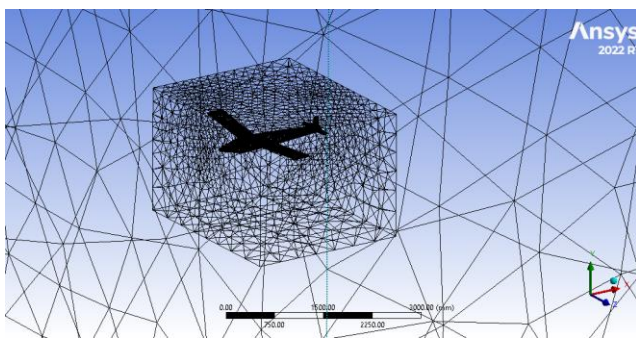


Fig: 4.5 Detail mesh view of fixed-wing drones

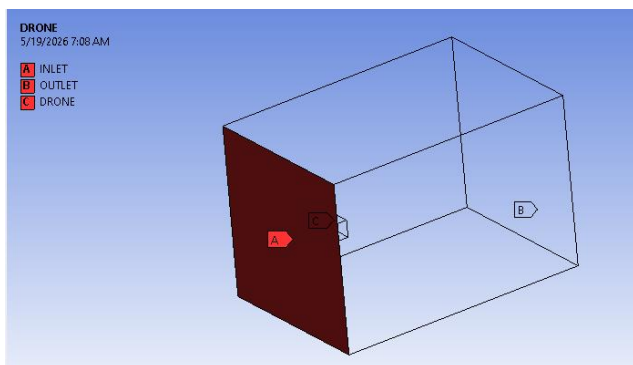


Fig: 4.6 boundary conditions for fixed-wing drones.

#### 4.3.3 Selection of Analysis Type

The simulation study can be performed as either a transient analysis or a steady-state analysis depending on the objectives of the investigation. A transient analysis considers the variation of physical conditions with respect to time, making it

suitable for studying dynamic events such as drone takeoff, launch, or maneuvering conditions. In contrast, a steady-state analysis assumes that the operating conditions remain constant over time, which is generally appropriate for evaluating stable flight conditions such as cruising. The selection of the analysis type depends on the specific performance characteristics of the drone that need to be examined.

#### 4.3.4 Assignment of Material Properties to Cell Zones

After defining the material properties, these characteristics are assigned to the corresponding cell zones within the computational mesh. This step ensures that each section of the drone model behaves according to its actual material properties during the simulation. Assigning the correct material characteristics to different regions of the model enables accurate evaluation of structural and aerodynamic performance across various components of the UAV.

#### 4.3.5 Application of Boundary Conditions

Boundary conditions are applied at the inlet and outlet regions to replicate the actual operating environment of the drone. These conditions include parameters such as atmospheric pressure, temperature, airflow velocity, and flow direction. Proper definition of inlet and outlet conditions is essential for accurately simulating the aerodynamic behavior of the UAV and predicting its performance under realistic flight conditions.

#### 4.3.6 Performing the Simulation Analysis

Once all simulation parameters are specified, the CFD analysis is executed. During this stage, the software numerically computes the airflow behavior around the drone based on the generated geometry, computational mesh, assigned material properties, and applied boundary conditions. Since aerodynamic simulations involve highly complex calculations, advanced computational resources may be required to efficiently process the analysis.

#### 4.4 Convergence Study

Convergence analysis is an important procedure in Computational Fluid Dynamics (CFD) simulations, particularly in aerofoil design and aerodynamic evaluation. It ensures that the simulation results obtained are stable, accurate, and reliable for predicting aerofoil performance.

The convergence process involves iterative refinement of the computational mesh and adjustment of simulation parameters to improve solution accuracy and numerical stability.

During aerofoil development, engineers perform multiple simulation iterations to progressively achieve a more precise representation of aerodynamic behavior. Each iteration contributes to refining important aerodynamic characteristics such as lift, drag, airflow distribution, and overall aerodynamic efficiency. As the solution gradually converges, the calculated performance parameters become increasingly accurate and dependable.

The convergence process is further strengthened by validating simulation results against experimental data, such as wind tunnel testing, or by comparing them with theoretical predictions. Such validation confirms the accuracy and reliability of the aerofoil model. The primary objective of this detailed computational approach is to develop an aerofoil configuration that provides maximum aerodynamic efficiency while satisfying the required design and operational conditions. Parameters such as aerofoil shape, size, and angle of interaction with airflow are carefully optimized to achieve the desired performance. Therefore, convergence studies play a major role in identifying the most effective aerofoil design for applications involving aerodynamic systems, including UAVs and fixed-wing drones.

#### 4.5 Velocity and Pressure Analysis of Fixed-Wing Drones

The aerodynamic behavior of fixed-wing drones involves complex interactions between airflow and wing geometry. During flight, the airflow velocity around the drone wings changes continuously depending on the wing shape and flight conditions. In many cases, the wing design incorporates a curved or cambered profile that enhances lift generation. Increased wing camber improves the lift coefficient, enabling the drone to maintain stable flight and achieve better maneuverability.

As air flows over the wing surfaces, differences in velocity are created between the upper and lower sections of the wing. The airflow over the upper surface generally moves faster than the airflow beneath the wing, producing a pressure difference that generates lift. This aerodynamic phenomenon

allows the drone to remain airborne and perform climbing or maneuvering operations effectively.

Pressure distribution across the wing surfaces is another critical factor influencing flight performance. Due to the aerodynamic profile of the wings, lower pressure is generated on the upper surface, while relatively higher pressure exists on the lower surface. This behavior follows the principles of Bernoulli's theorem, which relates fluid velocity to pressure variation. The resulting pressure difference between the two wing surfaces is responsible for lift generation and stable flight operation.

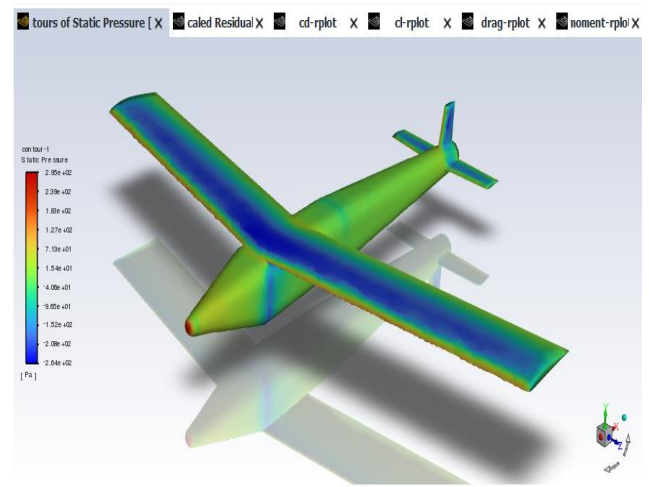


Fig. 4.7 the pressure distribution of pressure on fixed-wing drone.

Figure 4.7 illustrates the pressure distribution over the drone structure using a color-contour representation. Regions marked in red indicate areas experiencing maximum pressure, whereas blue-colored regions represent minimum pressure zones. For the fixed-wing drone analyzed in this study, the leading edge of the wing experiences the highest pressure, reaching approximately 2900 Pa. Conversely, the minimum pressure recorded is about -2640 Pa. These pressure variations demonstrate the significant aerodynamic forces acting on the drone during flight.

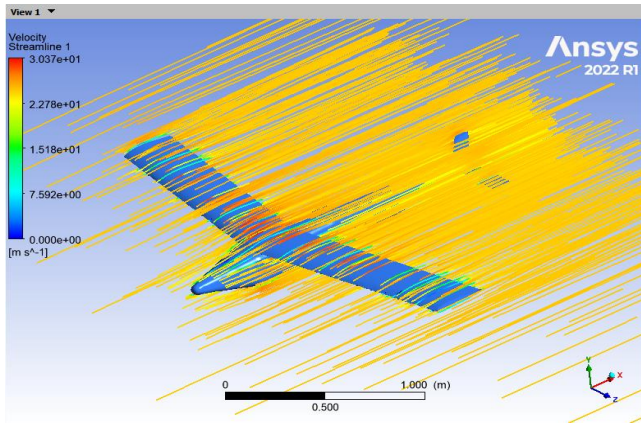


Fig. 4.8 velocity distribution of pressure on fixed-wing drone

Figure 4.8 presents the airflow velocity distribution around the drone. Higher airflow velocities are observed near the wing tips, represented by red color contours, while lower velocities are found in the central regions between the wings, shown in blue. The velocity distribution clearly demonstrates the variation of airflow patterns across different sections of the drone.

The airflow around the fixed-wing drone also exhibits moderate turbulence in certain regions due to aerodynamic resistance and flow interaction with the drone structure. However, as the airflow approaches the trailing edge of the wings, turbulence gradually decreases and the flow becomes smoother and more streamlined. The velocity analysis indicates that the airflow ranges from 0.00 m/s in stagnant regions to a maximum velocity of approximately 30.37 m/s, highlighting the dynamic aerodynamic behavior surrounding the drone during operation.

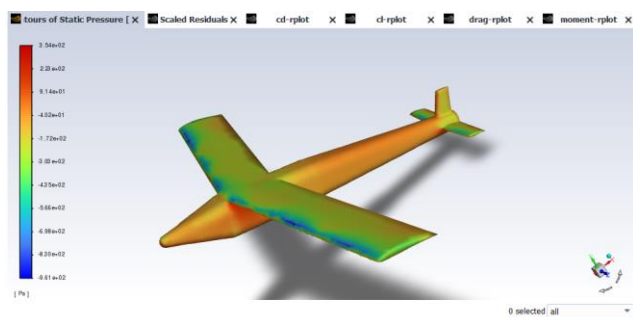


Fig: 4.9 Pressure distribution at 18 AOA

Figure 4.9 illustrates the pressure distribution over the structure at an angle of attack (AOA) of 18°. The pressure contours are represented using a color scale, where red regions indicate areas subjected to maximum pressure and blue regions represent zones of minimum pressure. The

variation in colors demonstrates the significant changes in pressure experienced across the surface of the structure during flight conditions. For the fixed-wing drone considered in this study, the highest pressure is concentrated near the leading edge of the wing, reaching approximately 354 Pa. In contrast, the minimum pressure recorded is about -961 Pa, indicating the presence of strong aerodynamic pressure differences over the wing surfaces. These pressure variations play an important role in lift generation and overall aerodynamic performance. The figure provides a clear understanding of the complex pressure behavior acting on the drone at higher angles of attack.

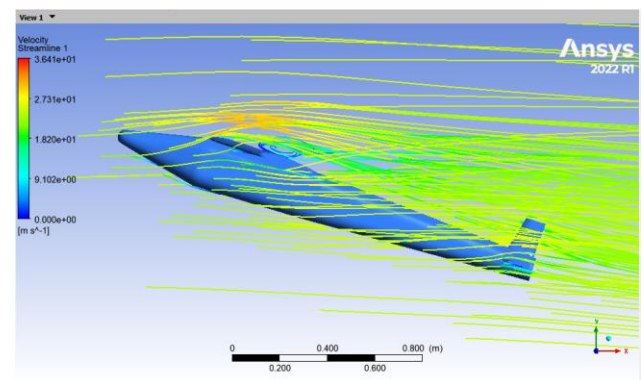


Fig: 4.10 velocity streamline distribution at 18 AOA

Figure 4.10 presents the airflow velocity distribution around the fixed-wing drone at an 18° angle of attack. The velocity contours are represented using different color intensities, where bright red shades correspond to regions of high airflow velocity, particularly near the wing tips, while blue shades indicate areas of lower velocity located mainly between the wings. The visualization demonstrates the variation of airflow speed across the drone structure and highlights the aerodynamic interactions occurring during flight. Airflow around the drone experiences regions of acceleration and deceleration, along with moderate turbulence caused by the interaction between the airflow and the drone surfaces. As the airflow progresses toward the trailing edge, the turbulence gradually decreases and the flow becomes smoother and more streamlined. The analysis shows that the airflow velocity ranges from 0.00 m/s in stagnant regions to a maximum velocity of approximately 36.4 m/s. These observations emphasize the complex aerodynamic characteristics associated with fixed-wing drones and provide valuable insights

into their flight behavior and performance at higher angles of attack.

#### **4.6 Structural Analysis of Fixed-Wing UAV Using ANSYS**

Structural analysis is an important stage in the design and development of an Unmanned Aerial Vehicle (UAV) because the drone structure is continuously subjected to aerodynamic forces, vibration loads, payload loads, and operational stresses during flight conditions. A properly designed UAV structure should possess sufficient strength, stiffness, and stability to withstand these loading conditions without failure. Structural analysis helps in determining important parameters such as stress distribution, strain behavior, deformation, and safety of the UAV components. It also helps in identifying weak regions in the structure that may experience excessive deformation or stress concentration during operation.

In fixed-wing UAVs, aerodynamic pressure generated during flight produces lift and drag forces on the wings and fuselage structure. These forces can result in structural deformation and vibration, affecting flight stability and aerodynamic performance. Therefore, structural analysis is essential to evaluate the capability of the UAV structure to resist aerodynamic loads safely. The use of lightweight composite materials such as Kevlar 149 fiber epoxy, Technora fiber epoxy, Glass-E fiber epoxy, Glass-S fiber epoxy, and Carbon fiber epoxy requires detailed structural evaluation because each material possesses different mechanical properties and stiffness characteristics. By performing structural analysis, the most suitable material with minimum stress, strain, and deformation can be selected for the UAV structure.

### **5. RESULTS AND DISCUSSIONS**

#### **5.1 Introduction**

This chapter presents the detailed results obtained from the aerodynamic, structural, and modal analysis of the fixed-wing Unmanned Aerial Vehicle (UAV) developed for surveillance applications. The UAV model was designed using calculated aerodynamic parameters and modeled in CATIA software. The aerodynamic analysis was carried out using Computational Fluid Dynamics (CFD) techniques to evaluate the flow behavior, lift characteristics, drag characteristics,

aerodynamic moment, and stall behavior of the UAV under different angles of attack. The structural and modal analyses were performed using ANSYS software to investigate the deformation behavior, stress distribution, strain characteristics, and vibration response of different composite material configurations.

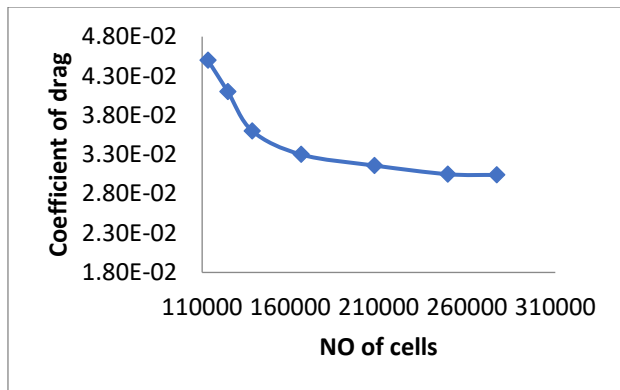
The CFD analysis was conducted by considering airflow conditions suitable for surveillance flight operations. Important aerodynamic parameters such as coefficient of lift, coefficient of drag, lift force, drag force, and aerodynamic moment were evaluated for different angles of attack to understand the aerodynamic performance of the UAV. Mesh convergence analysis was also performed to ensure the accuracy and reliability of the numerical simulation results. The aerodynamic behavior of the UAV was studied carefully to identify the stall condition and determine the optimum operating range for stable flight performance. The obtained CFD results provide important information regarding the aerodynamic efficiency, stability, and operational capability of the fixed-wing UAV.

The structural and modal analyses were carried out by considering different lightweight composite materials including Kevlar149 fiber epoxy, Technora fiber epoxy, Glass-E fiber epoxy, Glass-S fiber epoxy, and Carbon fiber epoxy. Structural analysis was performed by applying aerodynamic pressure loads obtained from CFD analysis to evaluate the deformation, stress, and strain behavior of the UAV structure. Modal analysis was conducted under free-free space conditions to determine the natural frequencies and vibration mode shapes of the UAV model. The obtained results were compared to identify the most suitable material for the fixed-wing UAV structure based on aerodynamic efficiency, structural stability, stiffness, and vibration resistance characteristics. The detailed results and corresponding discussions are presented in the following sections.

#### **5.2 Mesh Convergence for Coefficient of Drag**

Mesh convergence analysis is an important procedure in the computational evaluation of the drag coefficient for a fixed-wing drone with a vertical launch system. The objective of this process is to refine the computational mesh progressively until the calculated drag coefficient reaches a stable and consistent value. Once

convergence is achieved, further refinement of the mesh produces only negligible changes in the results, confirming the reliability and accuracy of the simulation.

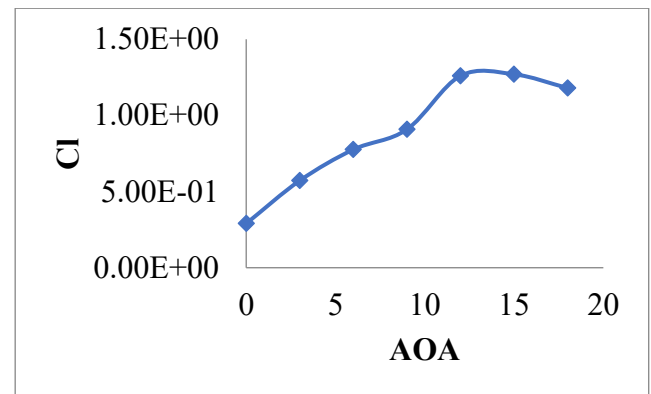


Graph 5.1 drag coefficient for fixed-wing drone

A finer computational mesh improves the capability of the CFD model to capture detailed aerodynamic flow behavior around the drone surfaces, particularly in regions with complex airflow patterns. Accurate prediction of these flow characteristics is essential for evaluating the aerodynamic performance and efficiency of the drone during vertical takeoff and forward flight operations. However, increasing mesh density also increases computational time and resource requirements. Therefore, the mesh convergence study aims to identify an optimal mesh size that provides accurate results while maintaining reasonable computational cost. By systematically varying the number of mesh cells and analyzing the resulting drag coefficient values, engineers can verify that the numerical solution closely represents real aerodynamic conditions. This approach ensures dependable simulation outcomes that support effective drone design and performance optimization. Figure shows the relationship between the number of computational cells and the corresponding drag coefficient values. As the number of cells increases, noticeable variations in the drag coefficient are observed initially. However, after reaching approximately 260,000 cells, the drag coefficient values become nearly constant, indicating convergence of the numerical solution. This stabilization suggests that the selected mesh density is sufficient for obtaining accurate and reliable drag coefficient predictions without requiring additional mesh refinement.

### 5.3 AOA vs coefficient of lift

The relationship between the angle of attack (AOA) and the coefficient of lift plays a significant role in determining the aerodynamic performance of a fixed-wing drone equipped with a vertical launch system. As the angle of attack increases, the lift coefficient also increases initially, resulting in greater lift generation that supports efficient takeoff and climbing performance. However, when the angle of attack exceeds a certain critical limit, airflow separation occurs over the wing surface, leading to a sudden reduction in lift and the onset of aerodynamic stall. Therefore, understanding the relationship between AOA and lift coefficient is essential for achieving stable and efficient flight performance.



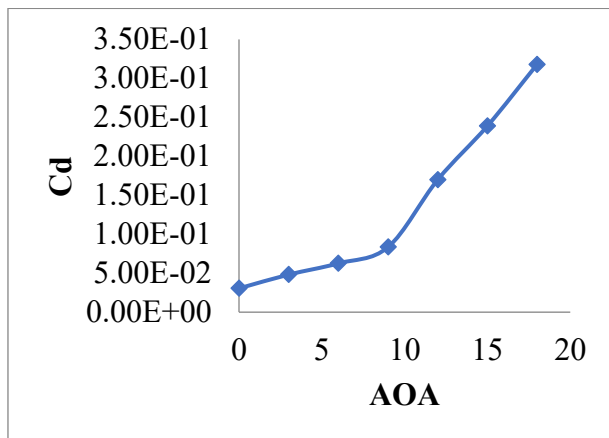
Graph 5.2 AOA vs lift coefficient

Figure illustrates the variation of the lift coefficient with respect to the angle of attack for the fixed-wing drone. At lower angles of attack, the lift coefficient increases almost linearly as the wing interacts more effectively with the incoming airflow. This trend continues until the critical angle of attack is reached. Beyond this point, the lift coefficient begins to decrease due to disruption of the smooth airflow over the wing surfaces. The separation of airflow reduces the aerodynamic efficiency of the wing and causes a stall condition, resulting in a significant loss of lift. The critical angle of attack is an important aerodynamic parameter because it defines the boundary between stable lift generation and aerodynamic stall. Maintaining the angle of attack below this critical limit is necessary to ensure controlled and stable flight operation. This concept is particularly important in the design and development of fixed-wing drones, as it directly influences flight safety, maneuverability, and overall aerodynamic efficiency. Similar aerodynamic principles can also be observed in bird flight, where birds naturally

adjust their wing orientation to maximize lift while avoiding stall conditions. Therefore, the relationship between angle of attack and lift coefficient serves as a valuable reference for both UAV aerodynamic design and the study of natural flight mechanisms.

#### 5.4 AOA vs drag coefficient

The relationship between the angle of attack (AOA) and the drag coefficient is an important factor in determining the aerodynamic efficiency of a fixed-wing drone equipped with a vertical launch system. As the angle of attack increases, the wings generate greater lift; however, this also results in an increase in aerodynamic drag. The drag coefficient represents the resistance encountered by the drone while moving through the air and directly affects the power consumption, endurance, and overall flight efficiency of the UAV. Therefore, understanding the variation of drag with respect to angle of attack is essential for optimizing drone performance and minimizing energy loss during flight.



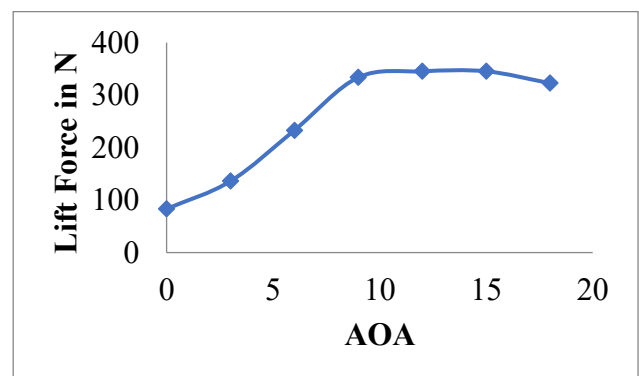
Graph 5.3 AOA vs drag coefficient

Figure illustrates the relationship between the angle of attack and the drag coefficient for the fixed-wing drone. The graph shows that the drag coefficient increases as the angle of attack increases, indicating a corresponding rise in aerodynamic drag acting on the drone. Initially, this increase follows a nearly linear trend, demonstrating that higher wing inclination produces greater resistance to airflow. This behavior continues up to the critical angle of attack. Under normal aerodynamic conditions, exceeding the critical angle of attack generally leads to airflow separation and stall, which may alter the drag behavior. However, the results

shown in Figure indicate that the drag coefficient continues to increase even beyond the critical angle without any noticeable reduction. This continuous rise in drag suggests that the drone experiences significant aerodynamic resistance at higher angles of attack, which can negatively affect flight efficiency, maneuverability, and energy consumption. The analysis of the AOA–drag coefficient relationship is highly important in the aerodynamic design of fixed-wing drones. Understanding this behavior helps engineers optimize wing geometry and aerodynamic characteristics to reduce drag while maintaining sufficient lift. Such optimization improves flight stability, operational efficiency, and overall drone performance. Similar aerodynamic principles are also observed in natural flight systems such as birds, where wing positioning is continuously adjusted to achieve an effective balance between lift and drag during flight.

#### 5.5 AOA vs lift force

The angle of attack (AOA) is a major aerodynamic parameter that significantly affects the lift force generated by fixed-wing drones, especially those equipped with vertical launch systems. As the angle of attack increases, the lift force generated by the wings also increases initially, improving the drone's ability to achieve takeoff and climb efficiently. However, when the angle of attack exceeds a critical limit, airflow separation occurs over the wing surface, causing a sudden reduction in lift and leading to stall conditions. Therefore, proper control of the angle of attack is essential to ensure stable flight, smooth transition from vertical launch to forward flight, and safe operation under varying atmospheric conditions.



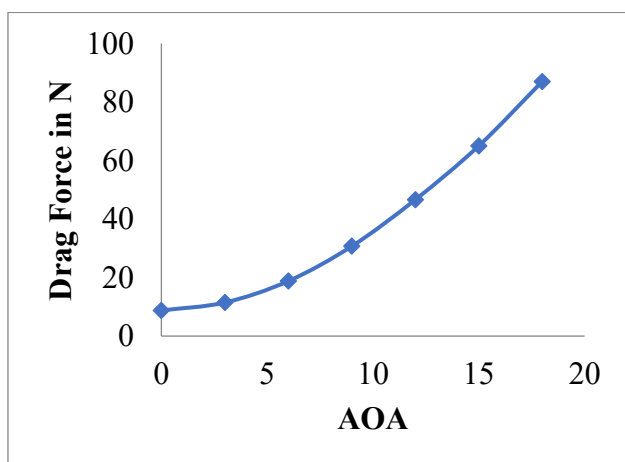
Graph 5.4 AOA vs lift force

Understanding the relationship between angle of attack and lift force is important in the aerodynamic design and operation of UAVs, as it

directly influences flight stability, efficiency, and safety. Maintaining the angle of attack within the optimal operating range allows the drone to generate sufficient lift while avoiding aerodynamic instability. Figure illustrates the variation of lift force with respect to the angle of attack for the fixed-wing drone. The graph shows that the lift force increases progressively as the angle of attack increases. This trend continues up to a specific critical point, beyond which no significant increase in lift is observed. The results indicate that the optimal aerodynamic performance is achieved only within a certain range of angle of attack values. According to the analysis, the critical angle of attack occurs at approximately  $9^\circ$ . At this point, the lift curve begins to level off, indicating the onset of stall conditions. Beyond the stall angle, the wing loses aerodynamic efficiency and cannot generate additional lift effectively. This information is highly valuable for drone design and flight control, emphasizing the importance of operating the UAV within the recommended angle of attack range to maintain stable and efficient flight performance.

### 5.6 AOA vs drag force

The relationship between the angle of attack (AOA) and drag force is an important aerodynamic consideration for fixed-wing drones equipped with vertical launch systems. As the angle of attack increases, the lift generated by the wings initially improves, which supports efficient vertical takeoff and climbing performance. However, increasing the AOA also causes a rise in aerodynamic drag. Beyond a certain critical limit, the drag force increases significantly, which can reduce flight efficiency, increase power consumption, and negatively affect the stability of the drone during ascent and forward flight operations.

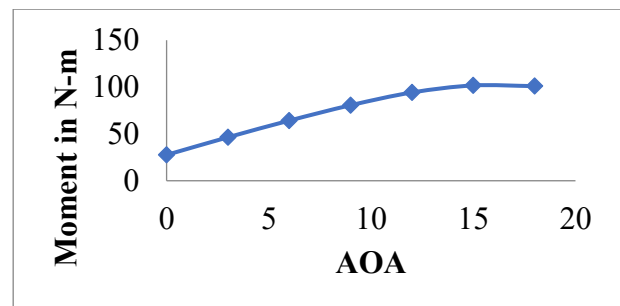


Graph 5.5 AOA vs drag force

Figure illustrates the variation of drag force with respect to the angle of attack for the fixed-wing drone. The graph clearly shows that drag force increases progressively as the angle of attack rises. This trend continues until the drone reaches the critical or stall angle, where aerodynamic behavior changes considerably. Detailed analysis of Figure 25 indicates a continuous increase in drag force with increasing AOA values. The rise in drag becomes more significant at higher angles of attack due to greater airflow resistance and increased flow separation around the wing surfaces. As the drone approaches the stall angle, the aerodynamic efficiency decreases, resulting in higher energy requirements and reduced flight performance. This relationship between angle of attack and drag force is highly important in UAV aerodynamic design and flight control. Understanding these aerodynamic characteristics helps engineers optimize wing geometry and operating conditions to achieve a balance between lift generation and drag reduction. Proper management of the angle of attack is therefore essential for maintaining flight stability, improving operational efficiency, and ensuring safe performance of fixed-wing drones.

### 5.7 AOA vs moment

The angle of attack (AOA) is one of the most important aerodynamic parameters affecting the flight performance of fixed-wing drones. It is defined as the angle formed between the incoming airflow and the chord line of the wing. Proper adjustment of the angle of attack enables the drone to generate sufficient lift while maintaining flight stability and aerodynamic efficiency. Effective control of the AOA is therefore essential for smooth operation, stable maneuvering, and efficient flight performance.



Graph 5.6 AOA vs moment

Another significant aerodynamic parameter is the moment or aerodynamic torque acting on the drone. The aerodynamic moment influences the pitch, roll, and yaw motions of the UAV, thereby affecting its overall stability and controllability during flight. Proper management of these moments is necessary to achieve accurate maneuvering and balanced flight characteristics. Consequently, maintaining an appropriate relationship between the angle of attack and aerodynamic moment is critical in the design and operation of fixed-wing drones. Figure illustrates the relationship between the angle of attack and the aerodynamic moment generated on the drone. The graph indicates that the aerodynamic moment increases progressively as the angle of attack increases. This behavior suggests that higher AOAs create greater aerodynamic forces on the wing surfaces, leading to increased resistance and moment generation. Further analysis of the graph reveals that this increasing trend continues up to an angle of attack of approximately 15°. Beyond this point, the aerodynamic moment begins to decrease, indicating a change in the airflow behavior around the wings. This reduction suggests the presence of a critical aerodynamic condition where flow separation and stall effects begin to influence the stability and control characteristics of the drone. Understanding this relationship is important for optimizing UAV aerodynamic design and ensuring stable flight operation under different flight conditions.

### 5.8 Structural analysis results

Material	Deformation in mm	Stress in Mpa	Strain
Kevlar149 fiber epoxy	0.186	0.901	5.04E-06
Technora fiber epoxy	0.47	0.901	1.28E-05
Glass-E fiber epoxy	0.438	0.901	1.18E-05
Glass-S fiber epoxy	0.378	0.901	1.02E-05
Carbon fiber epoxy	0.237	0.901	6.44E-06

Table 5.1: Structural analysis results.

The structural deformation results obtained for different composite materials are presented in Table. From the analysis, the Kevlar149 fiber epoxy material exhibited the minimum deformation value of 0.186 mm, indicating better

structural stiffness and resistance to aerodynamic bending loads. In comparison, Technora fiber epoxy showed the maximum deformation of 0.47 mm, which is approximately 152.68% higher than the Kevlar material. Similarly, Glass-E fiber epoxy produced a deformation of 0.438 mm, which is about 135.48% higher than Kevlar, while Glass-S fiber epoxy showed 0.378 mm deformation, which is approximately 103.22% greater than Kevlar. Carbon fiber epoxy exhibited a deformation value of 0.237 mm, which is only about 27.41% higher than Kevlar material. From the deformation analysis, it is evident that Kevlar149 fiber epoxy provides the best stiffness characteristics and minimum structural displacement among all considered materials.

The stress analysis results indicate that all the composite materials developed the same maximum bending stress value of 0.901 MPa under the applied aerodynamic loading conditions. The maximum stress concentration was observed near the wing-fuselage connection region because aerodynamic loads from the wings are transferred through this support area into the fuselage structure. Since all materials exhibited identical stress values, the percentage variation in stress between the materials is negligible. Furthermore, the obtained stress values are significantly lower than the allowable yield strength of all considered composite materials, confirming that the UAV structure remains within safe operating limits under the applied dynamic pressure loading conditions. Therefore, all the selected composite materials are structurally safe for the present UAV application from the stress analysis perspective.

The strain analysis results show that Kevlar149 fiber epoxy produced the minimum strain value of  $5.04 \times 10^{-6}$ , indicating superior stiffness and better resistance to structural deformation. Technora fiber epoxy exhibited the maximum strain value of  $1.28 \times 10^{-5}$ , which is approximately 153.97% higher than Kevlar material. Glass-E fiber epoxy produced a strain value of  $1.18 \times 10^{-5}$ , which is around 134.13% greater than Kevlar, while Glass-S fiber epoxy developed a strain value of  $1.02 \times 10^{-5}$ , approximately 102.38% higher than Kevlar material. Carbon fiber epoxy showed a strain value of  $6.44 \times 10^{-6}$ , which is about 27.78% higher than Kevlar. From the strain analysis results, Kevlar149 fiber epoxy demonstrated the lowest strain and highest

structural rigidity among all the analyzed composite materials. Therefore, considering both deformation and strain behavior, Kevlar149 fiber epoxy is identified as the most suitable material for the fixed-wing UAV structure.

### 5.9 Frequency analysis results

Material	1st frequency	2nd frequency	3rd frequency	4th frequency	5th frequency
Kevlar149 fiber epoxy	28.955	88.031	157.83	170.85	231.38
Technora fiber epoxy	18.621	56.612	101.05	109.87	148.8
Glass-E fiber epoxy	14.353	43.638	78.238	84.69	114.7
Glass-S fiber epoxy	15.445	46.956	84.188	91.132	123.42
Carbon fiber epoxy	24.545	74.623	133.79	144.83	196.14

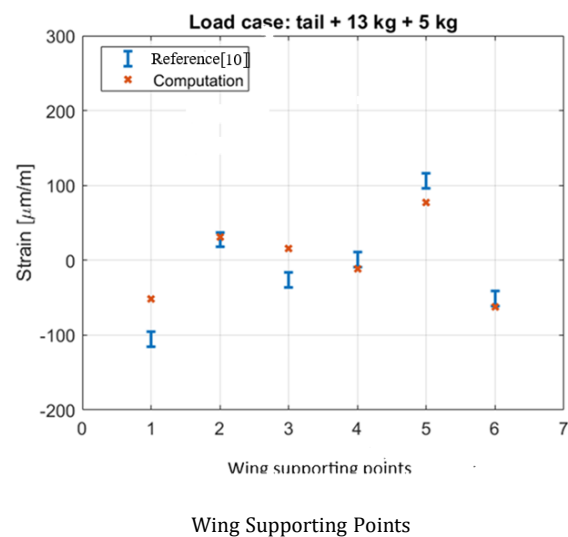
Table 5.2: frequency readings for different materials.

The modal analysis results obtained for different composite materials are presented in Table. The natural frequency of a structure represents its vibration response under free vibration conditions, and higher natural frequencies generally indicate greater structural stiffness and better resistance to resonance. Resonance occurs when the excitation frequency during operation becomes equal to the natural frequency of the structure, leading to excessive vibration and possible structural instability. Therefore, materials with higher natural frequencies are preferred for UAV structures because they provide improved dynamic stability and reduced resonance effects during flight operation. Among all the analyzed materials, Kevlar149 fiber epoxy exhibited the highest natural frequency values in all vibration modes, indicating superior stiffness and vibration resistance characteristics.

In the first vibration mode, Kevlar149 fiber epoxy produced the highest natural frequency of 28.955 Hz, while Glass-E fiber epoxy exhibited the lowest frequency of 14.353 Hz. The first mode frequency of Kevlar is approximately 101.73% higher than

Glass-E fiber epoxy and about 55.50% higher than Technora fiber epoxy. Similarly, in the second vibration mode, Kevlar showed a frequency of 88.031 Hz, which is around 101.72% higher than Glass-E material and approximately 17.97% higher than carbon fiber epoxy. In the third mode, Kevlar produced 157.83 Hz, which is nearly 101.73% greater than Glass-E composite material. The fourth and fifth mode frequencies of Kevlar material were observed as 170.85 Hz and 231.38 Hz respectively, which are also significantly higher than all other composite materials considered in the analysis. These higher frequency values indicate that Kevlar material possesses better stiffness and improved resistance to vibration deformation.

The overall modal analysis results clearly indicate that Kevlar149 fiber epoxy provides the best dynamic performance among all the considered composite materials. Higher natural frequency values reduce the possibility of resonance during UAV operation and improve structural vibration stability. Although carbon fiber epoxy also exhibited comparatively high frequency values, its frequencies were lower than those of Kevlar material in all vibration modes. Glass-E and Glass-S composite materials showed lower frequency values, indicating comparatively lower stiffness characteristics. Technora fiber epoxy also produced lower natural frequencies compared to Kevlar material. Therefore, based on the modal analysis results, Kevlar149 fiber epoxy is identified as the most suitable material for the fixed-wing UAV structure due to its higher stiffness, improved vibration resistance, and superior dynamic stability characteristics.



The present investigation using finite element analysis in ANSYS is validated against experimental data taken from reference [10]. Based on the presented results, it can be observed that the numerical models show a high degree of agreement with the experimental data. The maximum stress calculated using the FEA model deviates by less than 13% compared to the experimentally obtained values, indicating relatively small error and high model precision. Similarly, the deformation at maximum stress show deviations of 17.8%, further confirming the reliability of the numerical analysis. The small deviations between the numerical and experimental results can be attributed to various factors, including idealization in the numerical model, variations in material properties, and the accuracy of experimental measurements. Based on these results, it can be concluded that the applied numerical models are valid and capable of representing real conditions with satisfactory accuracy. This comparison allows for additional verification and calibration of the models, achieving greater precision in future analyses and applied research.

## 6. CONCLUSION

In the present study, a fixed-wing Unmanned Aerial Vehicle (UAV) for surveillance applications was successfully designed and analyzed using aerodynamic, structural, and modal analysis techniques. Based on the decision matrix analysis, the fixed-wing drone was selected due to its superior aerodynamic efficiency, higher endurance, and better surveillance capability. The UAV parameters were calculated with an aspect ratio of 8, resulting in a wingspan of 2.449 m, chord length of 0.306 m, and wing area of 0.75 m<sup>2</sup>. The UAV model was developed in CATIA and CFD analysis was performed at 25 m/s velocity. The aerodynamic analysis indicated that the stall angle occurred at approximately 9°, and mesh convergence was achieved at nearly 260000 cells, ensuring accurate simulation results.

Structural and modal analyses were carried out in ANSYS using different composite materials with 5 mm shell thickness. Among all materials, Kevlar149 fiber epoxy showed the best structural performance with minimum deformation of 0.186 mm and minimum strain of  $5.04 \times 10^{-6}$ , while all materials developed the same stress value of 0.901 MPa. Compared to Kevlar material, Technora fiber epoxy showed approximately

152.68% higher deformation and 153.97% higher strain. Modal analysis results also confirmed that Kevlar material exhibited the highest natural frequencies, indicating superior stiffness and better vibration resistance. Therefore, Kevlar149 fiber epoxy was identified as the most suitable material for the fixed-wing surveillance UAV due to its improved structural stability, lower deformation, and higher dynamic performance.

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