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Integrated Maintainability in the Structural and System Design of Fixed-Wing UAVs

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Abstract
This paper introduces an overall design approach to a fixed-wing unmanned aerial vehicle (UAV) with an emphasis on the incorporation of maintainability into structural and system-level designs. Conceptual design was established using CAD software, following which aerodynamic performance was analyzed by external flow simulations based on the finite volume method. The outcome of the above analyses was used to finalize the external shape, resulting in detailed structural and layout designs. Mechanical behavior of critical structural components was analyzed through finite element analysis (FEA) to determine stress distribution, deformation, and vibration characteristics under simulated operational loading conditions.

A distinctive feature of this research is the prioritization of maintainability as a primary design criterion from the outset. The inner arrangement of components; batteries, electric ducted fan motors, avionics, and control surfaces, was carefully planned to provide maintainability access for both personnel and tools. Sensor and control systems were also embedded with the aim of facilitating condition-based and predictive maintenance over UAV's operational life. This involved choosing sensor points of attachment and providing access to areas expected to need regular inspection, adjustment, or replacement.

The completed UAV prototype optimizes aerodynamics, structural strength, and maintainability. The design strategy not only satisfies performance and production demand but also helps to reduce maintenance downtime and lifecycle costs. This maintainability-driven design philosophy serves to increase the UAV's viability for actual world deployment in environments in which reliability, serviceability, and operational readiness are vital.

Keywords: Aircraft Aerodynamics, Finite Element Analysis, Maintainability, On Board Maintenance.

1. Introduction

Aircraft maintenance is often inefficient due to fixed schedules that ignore real-time system conditions, leading to repeated failures, high costs, long downtimes, and operational disruptions—posing major concerns for aviation stakeholders focused on safety and efficiency [1].

The aviation sector, which has high economic stakes and sophisticated supporting infrastructure, is progressively calling for maintenance strategies that guarantee quick turnaround times, reduced costs, and higher system reliability. Optimization of maintainability; the simplicity and effectiveness with which maintenance activities can be carried out, continues to be a principal engineering goal in the design and maintenance of modern aircraft systems. Improved maintainability not only minimizes maintenance time and labor but also lowers the chances of faults occurring as a consequence of maintenance activities [2,3].

This research explores the maintainability characteristics of an electrically powered, fixed wing UAV that has been conceptually designed to capture realistic maintenance and operational constraints. Whereas most research efforts are concentrated on maintenance strategy and reliability modeling, this research differs by its focus on maintainability as a primary performance characteristic, with the objective of facilitating the creation of UAV systems that are not only operationally effective but also logistically sustainable. By examining design considerations that impact maintenance performance, this research supports the overall endeavor to reduce life-cycle costs and increase fleet availability in unmanned aviation systems [4].

2. Material and Method

This section details the step-by-step development of a fixed-wing UAV with health monitoring and predictive maintenance. Designed under 6 kg with dual EDFs, the UAV features a conventional layout. Structural analysis was done via FEA, and it was built using additive manufacturing. Sensors monitor key data for maintenance, while the aerodynamic design emphasizes low-speed stability and control using standard UAV design practices.

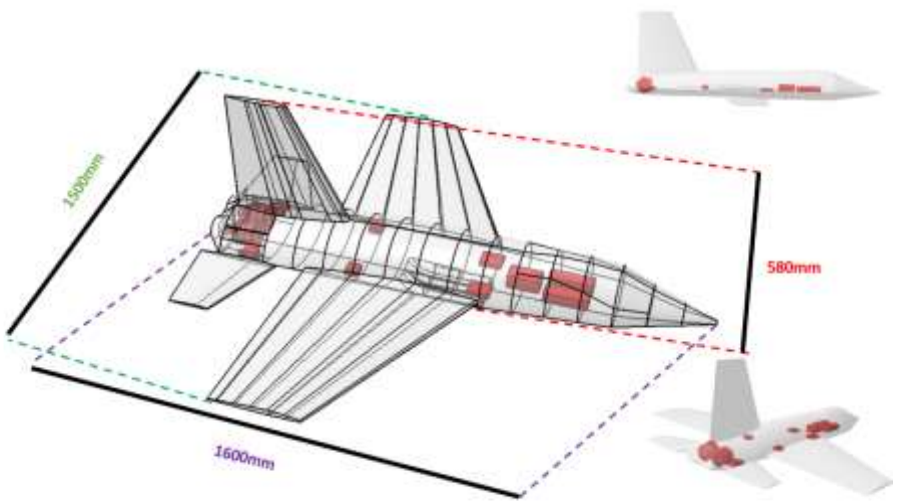

Figure 1: ANOYA UAV Conceptual Design

EDF motors were chosen for compactness, quietness, and light weight. Two rear-mounted EDFs enhance propulsion efficiency and internal volume and align thrust with the center of gravity. The prototype UAV was 3D-printed in PLA for quick development, with the aim to utilize stronger and lighter materials such as CFRPs and thermoplastics in the future to increase durability and minimize weight. Intake Geometry and installation illustrated in Figure 2.

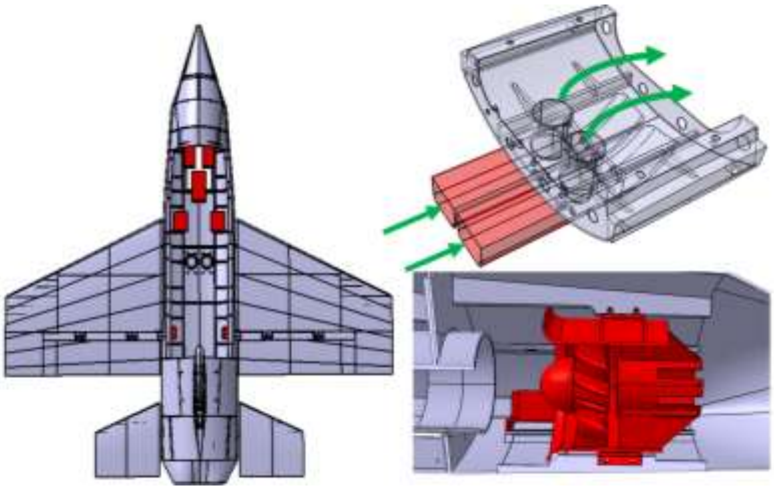

Figure 2: Internal Geometry and Air Intake Location of ANOYA

The UAV has a 1500 mm wingspan, 1200 mm length, and 0.3 m² wing area, designed for stable flight and balanced weight distribution. A centrally mounted battery and removable landing gear supports flight stability and ground testing. It achieves around 15 minutes of flight using a high-capacity LiPo battery.

The conceptual design phase defines the UAV's baseline geometry, considering trade-offs in manufacturability, weight, performance, durability, and maintainability. Structural analyses using ANSYS included static (70 N thrust), modal, and dynamic simulations to ensure deformation, resonance avoidance, and impact resistance, all within PLA material limits. Mesh refinement and element selection ensured accuracy in critical areas.

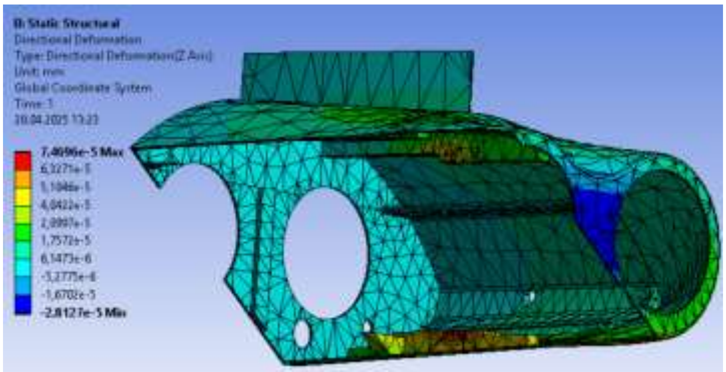

Figure 3: Rear Fuselage Meshing of ANOYA

The modal analysis of the UAV wing structure was conducted using ANSYS to identify natural frequencies and vibration modes (Figure 4). Second-order meshing was used for higher accuracy, and the wing root was fixed to simulate realistic constraints. The eigenvalue equation was solved for undamped free vibration, revealing six mode shapes. The lowest natural frequency was 87.021 Hz, involving both translational and torsional motion.

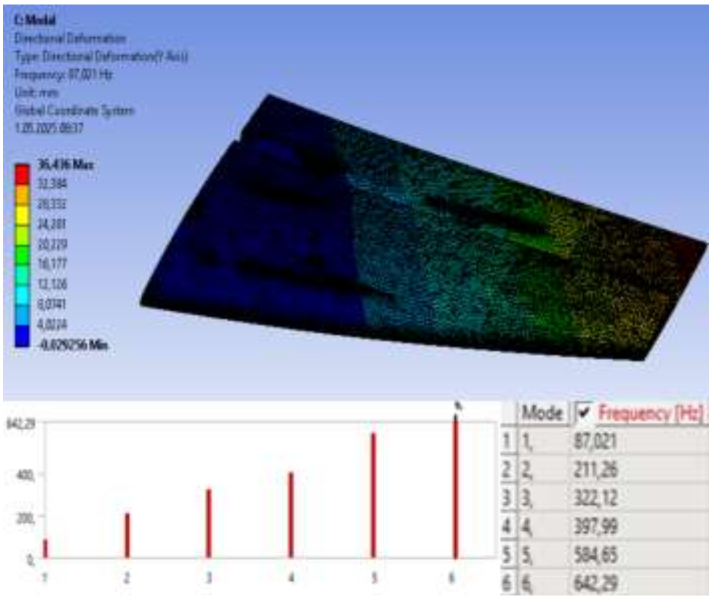

Figure 4: Modal Analysis of Wing Structure

The first simulation focused on the impact scenario of UAV which flight with 80 m/s velocity to a rigid wall (Figure 5). This scenario is an important impact scenario to observe overall behavior of the UAV about the directional, total deformation and equivalent stress. For this analysis, higher-order tetrahedral elements were used especially in the nose area to show improved stress wave resolution during to impact.

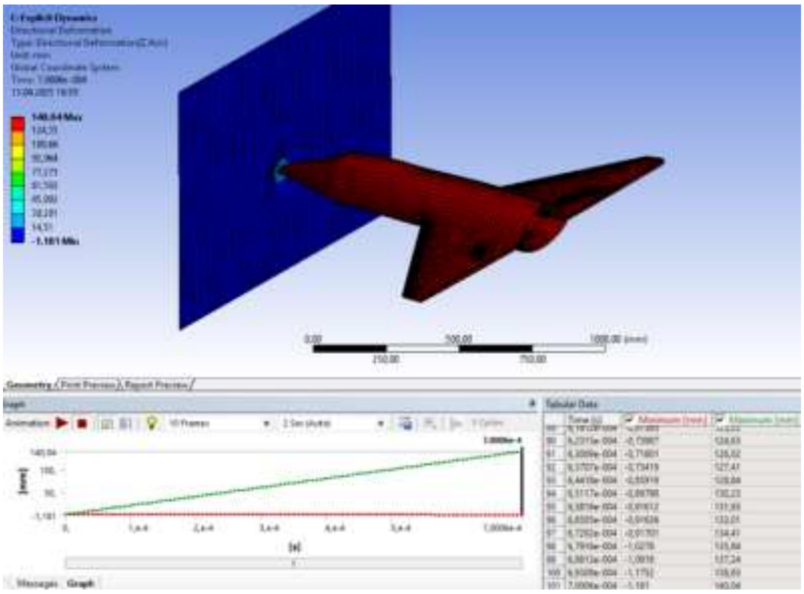

Figure 5: Equivalent Stress and Directional Deformation on Impact with a Wall

3. Results

In the result study, several finite-element and finite volume analyses were examined for structural and aerodynamic performance of the UAV and its components under different scenarios. The analytical results present insight into stress distributions, deformation results, and strain localizations of various components under static loading conditions. The maximum principal stress distribution in the nose structure of the aircraft (Figure 6) showed a peak value in the fuselage front of 2.519 MPa, reflecting a critical point in load transfer from the cockpit, due to both the geometry of the surface and its curvatures.

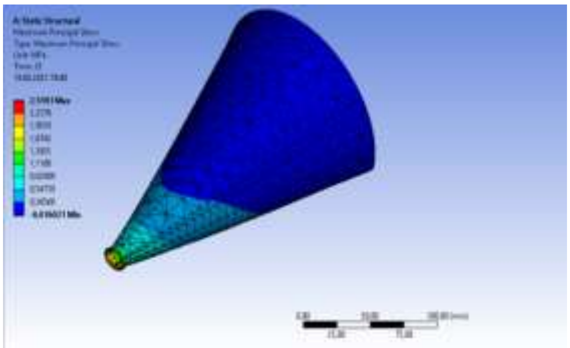

Figure 6: Maximum Principal Stress at Nose

Directional deformation reached 13.178 mm near mounting holes due to applied loads (Figure 7). Elastic strain peaked at 10.97 mm/mm around curvature transitions and bolt holes, indicating potential fatigue zones (Figure 8). Maximum principal stress was 12.385 MPa, concentrated at the upper flange and hole interfaces, suggesting a need for design reinforcement in these areas (Figure 9).

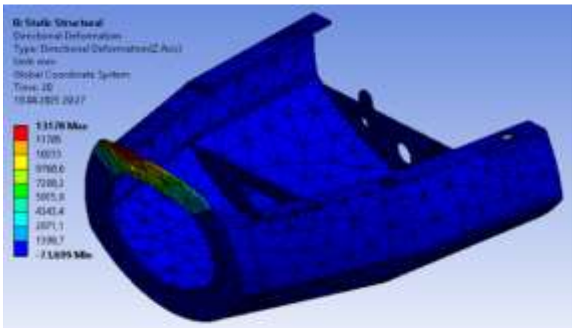

Figure 7: Directional Deformation Front Fuselage

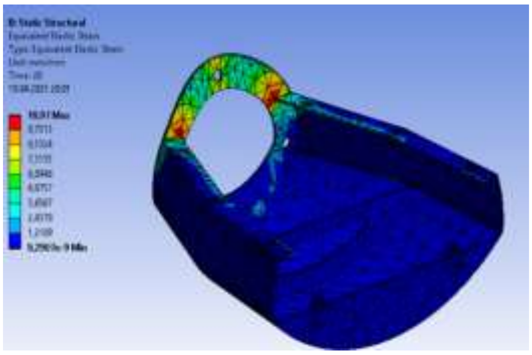

Figure 8: Equivalent Elastic Strain in Front Fuselage

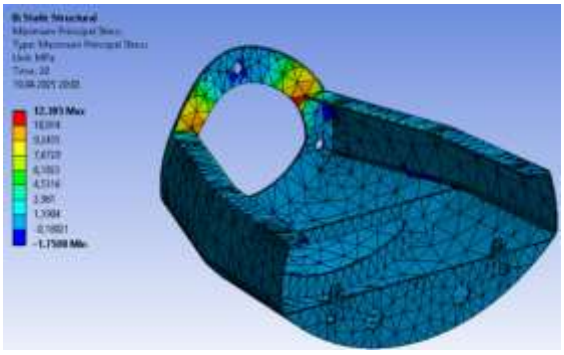

Figure 9: Maximum Principal Stress in Front Fuselage

4. Conclusion

This paper outlines a comprehensive design process for a fixed-wing UAV with a focus on maintainability, in addition to performance and durability, from the concept phase to prototyping. The configuration and internal layout of the UAV were intentionally developed to provide ready access, inspection, and repair, with the aim to minimize downtime and life-cycle costs.

Finite element analysis validated the structural soundness of the UAV in real-life scenarios, demonstrating effective stress distribution and sufficient resilience. In-built sensors facilitated condition-based maintenance, which improved reliability and field readiness.

The study demonstrates the feasibility of taking maintainability into consideration as a prime design factor, with the ANOYA UAV being a practical and sustainable prototype for future aerospace systems.

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