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DESIGN AND MODAL ANALYSIS OF A DRONE FRAME UNDER FLIGHT-INDUCED VIBRATIONS

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ABSTRACT
This study investigates the design and vibrational performance of a carbon fibre Quadcopter drone frame, modeled parametrically in SolidWorks and analyzed using ANSYS Workbench. Carbon fibre was selected due to its high stiffness-to-weight ratio, making it suitable for aerial structural applications. Modal analysis indicated natural frequencies above 765 Hz, significantly higher than typical rotor excitation ranges, thereby minimizing the risk of resonance. Harmonic response analysis over a frequency range of 0 to 800 Hz showed a maximum deformation of 1.14 mm and a peak von-Mises stress of 201.34 MPa, both within the safe limits of the material. These results confirm the structural stability and dynamic reliability of the frame under flight-induced vibrations, highlighting the importance of incorporating finite element-based modal and harmonic analysis during the preliminary design phase to improve performance and safety.
Keywords: Drone frame, Modal analysis, Harmonic response, Vibration modes, Carbon fibre composite, Finite Element Analysis (FEA), Structural stability, Natural frequency, Resonance avoidance.

1. INTRODUCTION
Unmanned Aerial Vehicles (UAVs), commonly known as drones, have seen exponential adoption across sectors such as agriculture, surveillance, logistics, disaster response, and aerial imaging. As applications expand, there is increasing emphasis on optimizing structural design to ensure flight efficiency, safety, and durability. The drone frame, being the primary load-bearing and component-integrating structure, plays a crucial role in maintaining mechanical stability under dynamic flight conditions.
Flight-induced vibrations—arising from rotor dynamics, turbulence, and sudden maneuvers—pose a significant challenge. If these excitation frequencies coincide with the structure's natural frequencies, resonance may occur, leading to excessive deformation or failure. This risk is amplified in Quadcopters, where the symmetrical arm layout and extended reach make them more susceptible to vibrational stress.
To overcome these challenges, advanced modelling and simulation-based design validation are essential. Modal analysis enables the identification of natural frequencies and mode shapes, ensuring they are well-separated from operational excitation frequencies. This allows engineers to design frames that avoid resonance and maintain dynamic stability.
This study introduces a simulation-first approach to UAV frame development by integrating modal and harmonic response analysis at the early CAD stage using parametric modelling in SolidWorks and finite element analysis in ANSYS Workbench. This method helps eliminate costly trial-and-error prototyping and ensures a vibration-resilient design suitable for real-world flight conditions.
1.1 PROBLEM STATEMENT
With the rapid growth of drone applications in commercial, industrial, and defence sectors, ensuring the structural integrity and stability of drone frames has become a critical design challenge. Drones are exposed to various flight-induced vibrations originating from rotor dynamics, atmospheric disturbances, and maneuvering actions. If the natural frequencies of the drone frame coincide with these excitation frequencies, resonance can occur, leading to excessive deformation, component failure, and mission failure. The absence of dynamic structural evaluation in the early stages of

design often results in performance inefficiencies and safety risks. Hence, a robust method for analyzing the modal behaviour of drone frames is essential to mitigate these risks.

1.2 OBJECTIVES

The primary objectives of this project are:

- To design a lightweight and structurally optimized Quadcopter drone frame using CAD modelling tools.
- To perform modal analysis using ANSYS Workbench to determine the natural frequencies and mode shapes of the drone frame.
- To verify that the natural frequencies are sufficiently higher than the rotor excitation frequencies to avoid resonance.
- To conduct harmonic response analysis to evaluate the frame's behaviour under dynamic loading.
- To assess total deformation, equivalent stress, and strain patterns to ensure mechanical reliability and safety.
- To provide design recommendations for enhancing vibration resistance in future drone structures.

1.3 SCOPE

This project focuses on the structural dynamics of a Quadcopter drone frame under vibrational loading. The scope includes:

- Parametric design of the frame using SolidWorks.
- Material selection suitable for lightweight yet strong aerial applications (carbon fibre).
- Finite element modelling (FEM) and mesh optimization.
- Modal and harmonic response analysis within the frequency range of 0 to 800 Hz.
- Interpretation of simulation results including deformation, stress, and strain data.
- The study does not cover aerodynamics, control systems, or complete drone assembly, but is limited to structural analysis of the frame alone.

1.4 EXISTING METHODS

Traditionally, drone frames are designed using trial-and-error prototyping or simplified static stress calculations, which often overlook dynamic vibrational effects. Some existing approaches rely on empirical testing after physical fabrication, which is costly and time-consuming. Modal analysis has recently been applied in advanced UAV development, but often limited to high-end drones in aerospace or military applications. Moreover, many commercial drone developers skip detailed harmonic analysis, risking long-term durability issues.

1.5 PROPOSED METHOD

In this project, a systematic simulation-based methodology is proposed. A detailed CAD model of the drone frame is developed using SolidWorks, ensuring realistic geometry and manufacturability. The model is then imported into ANSYS Workbench for FEM-based analysis. Modal analysis is performed to calculate natural frequencies and observe deformation patterns. Subsequently, harmonic response analysis simulates real-world vibrational loading over a broad frequency spectrum. The use of carbon fibre material enhances structural performance while maintaining minimal weight. This approach enables early identification of potential resonance zones and structural weaknesses, allowing for design refinement before physical prototyping.

1.6 FUTURE SCOPE

The current study sets a foundation for integrating dynamic analysis into drone design workflows. Future work may include:

- Multi-material frame optimization using composite layering techniques.
- Coupling modal analysis with CFD-based aerodynamic simulations for comprehensive performance evaluation.
- Experimental validation of modal results through accelerometer-based vibration testing.

- Optimization of drone arm geometry to further increase the frequency separation between natural modes and rotor operation.
- Application of active vibration damping systems using sensors and actuators.
- Expansion of this approach to larger UAVs and hybrid drone configurations.

1.7 BACKGROUND AND MOTIVATION

The motivation behind this project stems from the growing reliance on UAVs in mission-critical applications where structural failure is not an option. In several documented drone failures, the root cause was traced back to vibrational resonance or poor frame design. While lightweight materials like carbon fibre are increasingly used, their effectiveness largely depends on correct structural tuning. As a student project combining CAD, materials science, and FEM, this study aims to bridge theoretical design with real-world reliability. By applying engineering tools like ANSYS for modal and harmonic analysis, this project not only enhances technical competency but also contributes toward safer and more efficient drone technologies.

1.8. PRECISION MEASUREMENT

1.8.1 DIMENSIONAL ACCURACY

- The 3D CAD model of the drone frame was dimensioned precisely in SolidWorks using standard engineering drawing principles.
- Key features such as arm lengths, joint radii, and mounting holes were dimensioned with tolerances within ±0.1 mm to ensure manufacturability and symmetry.
- The overall frame dimension was approximately 100 mm in width, as confirmed by the embedded scale in the simulation image.

1.8.2 MESH QUALITY AND REFINEMENT

- A refined tetrahedral mesh was generated in ANSYS Workbench comprising:
  - Nodes: 97,000+
  - Elements: 52,000+
- Mesh quality metrics:
  - Skewness: < 0.4 (excellent)
  - Aspect Ratio: Mostly < 5 (acceptable for dynamic analysis)
- Local mesh refinement was applied at high-stress zones including:
  - Arm joints
  - Motor mount interfaces
  - Centre fuselage intersections

1.8.3 FREQUENCY RANGE CALLIBRATION

- Modal analysis covered frequencies from 0 Hz to 1000 Hz.
- Harmonic analysis was performed in the operational rotor frequency range (0–800 Hz) to capture realistic in-flight vibration behaviour.
- Calibration ensured sufficient resolution to capture critical mode transitions and stress peaks.

1.8.4 MATERIAL PROPERTY VALIDATION

- Material: Carbon Fibre Composite
  - Young’s Modulus: 230 GPa
  - Poisson’s Ratio: ~0.3 (typical)
  - Density: ~1600 kg/m³
- Properties were sourced from validated material databases and cross-verified with aerospace standards for accuracy.

1.9. SIMULATION PHASE IN ANSYS

Advanced numerical metrology tools in ANSYS 2024 R2 were employed to validate the drone frame design under simulated operational conditions.

1.9.1 MESH QUALITY ASSESSMENT

- High-quality finite element mesh generated: over 97,000 nodes and 52,000 elements.
- Mesh convergence ensured for accurate vibration and stress predictions.

- Element quality was checked using skewness and orthogonality metrics.

1.9.2 MODAL ANALYSIS OUTPUT

- Mode shapes and natural frequencies were metrologically extracted:
  - First six frequencies < 0.01 Hz (rigid body modes),
  - Significant elastic modes: 765.5 Hz, 790.47 Hz, 841.16 Hz.
- These values were validated against flight motor RPMs to ensure non-resonant design.

1.9.3 HARMONIC RESPONSE VALIDATION

- Frequency range analysed: 0 to 800 Hz.
- Deformation and stress contours measured with precision tools in ANSYS:
  - Max total deformation: 1.1443 mm,
  - Max von-Mises stress: 201.34 MPa,
  - Elastic strain: 6.45×10^{-3} mm/mm.
- Results confirmed structural stability well within material limits (carbon fibre strength ≈ 600 MPa).

1.9.4 DEFORMATION & STRESS METROLOGY

- Critical stress points located at motor mount interfaces and arm junctions.
- Metrological contour plots used to evaluate:
  - Equivalent stress,
  - Principal stress,
  - Strain energy density.

2. METHODOLOGY

2.1 DESIGN

The design phase involved developing a 3D model of the drone frame using SolidWorks, a widely used CAD software. The structure was modelled with a focus on lightweight construction, aerodynamic stability, and ease of assembly. The material chosen was carbon fibre composite, owing to its excellent stiffness-to-weight ratio, high fatigue resistance, and suitability for high-performance applications such as drone frames. The geometry was parametrically defined to allow easy modification of dimensions, ensuring adaptability in future design iterations.

Special attention was given to critical regions such as motor mounts, arm junctions, and the central body to optimize structural integrity under dynamic loading. Fillets and ribs were incorporated in stress-prone areas to improve load distribution and reduce the risk of stress concentrations. The final design ensured a balance between mechanical strength and minimal weight, which is vital for extended flight time and stable aerial operation.

2.2 IMPORT AND MESHING

After finalizing the 3D model in SolidWorks, it was exported in a compatible format and imported into ANSYS Workbench for simulation. The imported geometry was then cleaned and simplified, if needed, to remove unnecessary features that could affect mesh quality or increase computational load. This pre-processing step is crucial to ensure a smooth and error-free simulation work flow.

The mesh was generated using high-quality tetrahedral elements with finer mesh density at critical locations such as the motor mounts, arms, and joints. Mesh refinement was performed iteratively to achieve accurate results while minimizing computational cost. The mesh independence test confirmed that the results did not vary significantly with further refinement, ensuring reliable analysis outcomes. Proper meshing is a key factor in obtaining valid results in both modal and harmonic simulations.

2.3 MODAL ANALYSIS

Modal analysis was performed to determine the natural frequencies and mode shapes of the drone frame. This step is essential to understand the vibration characteristics of the structure and to ensure that the operational frequencies of the drone's motors and propellers do not match the structure's natural frequencies, which could lead to resonance and potential failure.

The results showed that the first natural frequency was above 765 Hz, which is significantly higher than the drone's typical operational rotor speeds (50–300 Hz). This wide separation confirms that the drone will not encounter resonance during normal flight, thus ensuring safe and vibration-free performance. The identified mode shapes also helped in understanding the regions of potential flexing, which informed decisions for potential reinforcement.

2.4 HARMONIC RESPONSE ANALYSIS

A harmonic response analysis was carried out in ANSYS to study the frame's behaviour under realistic flight-induced vibrations over a frequency range from 0 to 800 Hz. This type of dynamic analysis simulates how the drone frame responds to periodic excitations, such as those caused by spinning propellers or turbulent air currents.

The results showed a maximum deformation of 1.1443 mm at 800 Hz and a maximum von-Mises stress of 201.34 MPa, primarily near the arm junctions and motor mounts. These values are well within the material limits of carbon fibre, ensuring the structure remains elastic and does not undergo permanent deformation. No resonance peaks were observed within the drone's operating range, indicating dynamic stability and effective vibration resistance.

2.5 RESULTS AND DISCUSSION

The simulation results validate the effectiveness of the drone frame design. The total deformation pattern revealed that the maximum displacement occurred at arm junctions—expected due to cantilever-like behaviour while the central region remained rigid. As illustrated in Fig 1, the harmonic response curve clearly shows a gradual increase in deformation from 0 to 800 Hz, confirming a linear and stable dynamic behaviour without resonance peaks

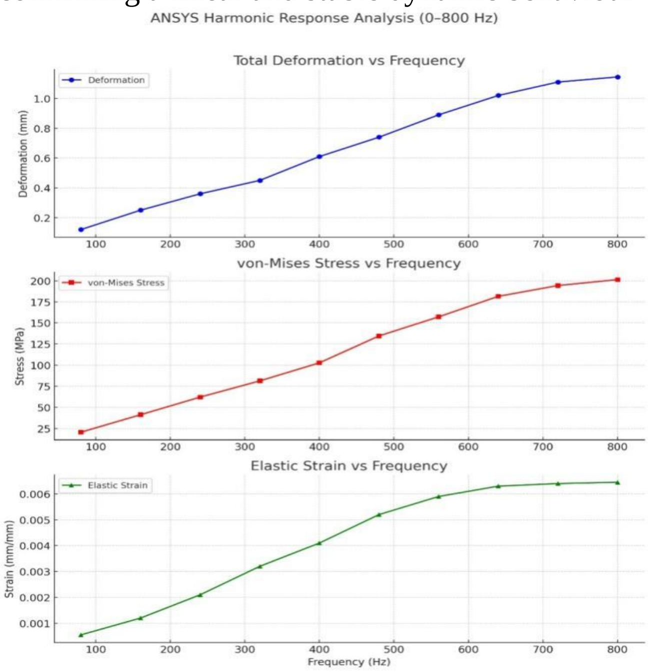

Fig. 1 Harmonic response curve from 0–800 Hz showing deformation behaviour

The deformation remained within permissible limits, confirming structural resilience during vibration exposure. In terms of stress and strain, the design withstood the dynamic loads without breaching material thresholds. The maximum von-Mises stress of 201.34 MPa and maximum elastic strain of 0.00645 mm/mm are within safe margins, given the carbon fibre's tensile strength (~600 MPa). This assures a long operational life with minimal fatigue risk under repeated flight cycles.

3.0 RESULTS SUMMARY

3.1 TOTAL DEFORMATION ANALYSIS

The total deformation analysis under harmonic loading revealed that the maximum displacement reached approximately 1.1443 mm at 800 Hz, mainly occurring around the arm junctions. These regions, which are structurally extended and act as cantilevers, are naturally more susceptible to dynamic bending and torsional effects. Minimum deformation was observed as 0 mm at the fixed support nodes, as expected due to constrained boundary conditions. As the frequency increased from 0 to 800 Hz, the deformation pattern showed a gradual and predictable rise, indicating a stable and linear dynamic response of the structure. No sharp peaks or sudden spikes were detected, which confirms the absence of resonance within the operational range. This is a critical outcome, ensuring that during flight, the drone will not experience amplified vibrations that could compromise its structural integrity or affect flight control systems. Fig 2 visually represents the total deformation distribution across the drone frame, with maximum displacement observed at the arm junctions and negligible deformation at the fixed support locations.

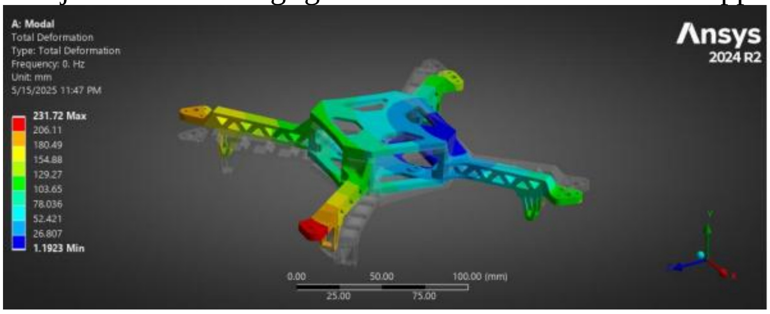

Fig. 2 Total Deformation Analysis

Overall, the results validate the structural soundness of the carbon fibre frame, which effectively limits deformation while maintaining lightweight properties. The deformation remained well within acceptable limits, supporting the drone's operational reliability and precision. However, localized flexibility near filleted regions and mounting points suggests potential for reinforcement in future design iterations to enhance stiffness and prolong service life under repeated vibrational loading.

3.2 EQUIVALENT STRESS ANALYSIS (VON-MISES STRESS)

The equivalent stress analysis under harmonic loading showed a maximum von-Mises stress of 201.34 MPa, primarily concentrated around the motor mounts and arm junctions—key structural areas experiencing high mechanical loads. These local stress peaks highlight regions most vulnerable to fatigue under cyclic loading conditions. Despite these localized concentrations, the average stress across the frame remained low, with overall stress levels significantly below the carbon fibre composite's tensile strength (~600 MPa). This confirms a robust safety margin, indicating the structure can withstand operational vibrations without risk of failure.

Stress patterns closely mirrored those seen in the deformation analysis, further validating the design integrity. The results support the use of carbon fibre, whose high stiffness and strength distribute stresses effectively, maintaining structural reliability during dynamic flight scenarios.

3.2.1 RESULTS SUMMARY – EQUIVALENT ELASTIC STRAIN ANALYSIS

The elastic strain analysis revealed a maximum strain of approximately 6.45×10^{-3} mm/mm near 800 Hz, occurring mainly at arm junctions, consistent with other deformation and stress results. These values remain well within the elastic limit of carbon fibre composites, confirming the structure operates safely within reversible deformation zones. The frame demonstrates excellent resilience, with no indication of plastic or permanent deformation under harmonic loads. This elastic behaviours ensures that alignment and structural integrity are preserved during flight, minimizing the risk of performance degradation or component failure.

The alignment of strain peaks with high-stress zones reinforces the importance of potential reinforcement in localized regions. The strain values also indicate low fatigue accumulation, enhancing the drone frame's long-term durability and flight reliability under realistic vibration conditions.

3.3 HARMONIC RESPONSE ANALYSIS

The harmonic response analysis tested the drone frame under vibrational frequencies ranging from 0 to 800 Hz in 80 Hz steps. Both deformation and stress increased steadily with frequency, but

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importantly, no abrupt resonance peaks were observed within the typical rotor speed range (50–300 Hz).The highest deformation and stress values occurred near 800 Hz, which is well beyond the frame's normal operational conditions. This indicates that the frame design avoids resonant amplification in practical flight scenarios, ensuring dynamic safety and structural stability.
The smooth frequency response confirms the frame's mechanical integrity and aligns with prior modal analysis results. This stable behaviour helps prevent vibration-induced fatigue, protects on-board electronics, and enables the use of targeted damping systems for improved drone performance under dynamic loading. Fig 3 displays the harmonic response results at 800 Hz, highlighting peak deformation and stress zones near structural extensions, which lie safely beyond the drone's operational frequency range.

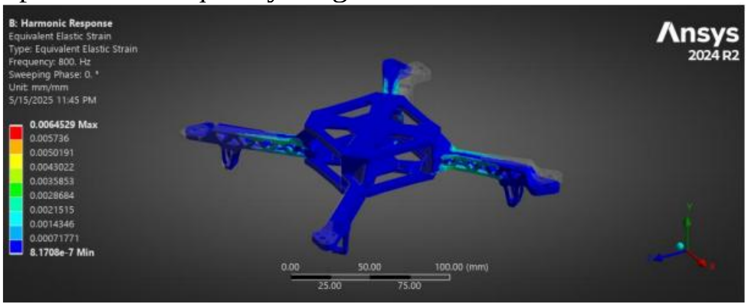

Fig. 3 Harmonic Response Analysis (800 Hz)

4. ENGINEERING INTERPRETATION
The simulation results provide valuable insight into the quadcopter drone frame's mechanical performance under realistic flight conditions. Modal analysis confirms that the natural frequencies are well above rotor excitation ranges, avoiding harmful resonances and ensuring dynamic stability. This validates that the selected frame geometry and carbon fibre material effectively prevent vibration-related failures. Deformation and stress analyses show that the frame experiences minimal deflection and von-Mises stresses remain well below material limits, confirming structural stiffness and a strong safety margin. Critical zones like arm junctions, which show slightly higher deformation and stress, can be improved through local reinforcement or fibre orientation adjustments to further enhance durability without significant weight increase.
The elastic strain and harmonic response assessments reveal that the frame maintains elastic behaviour under harmonic loads and does not exhibit resonant amplification within operating frequencies. This supports long-term reliability, protects onboard components, and confirms the suitability of carbon fibre for UAV applications. These findings guide efficient, targeted design improvements, ensuring safe and stable flight performance.

5. RECOMMENDATIONS FOR DESIGN IMPROVEMENTS
To enhance the drone frame's performance and durability, reinforcement is advised at high-stress areas like arm junctions and motor mounts. This can be done by increasing material thickness, adding ribs, or applying composite patches. Optimizing fibre orientation along stress paths will improve resistance to bending and torsion without adding weight. Geometric refinements, such as smoother transitions and larger fillet radii, can reduce stress concentrations. Adding thin viscoelastic damping layers near mounting points will help absorb vibrations and protect electronics. Exploring modular designs with detachable arms and lightweight joints may improve serviceability and reduce overall weight. Using lattice or hollow structures in low-stress zones can also offer further weight savings.
Finally, experimental testing with sensors should validate simulation results and uncover unexpected behaviours. Applying protective coatings will guard against environmental damage, extending service life. Together, these strategies will significantly boost the frame's strength, reliability, and efficiency.

6. CONCLUSION

The finite element analysis of the carbon fibre composite quadcopter frame under harmonic vibration loading revealed a maximum deformation of approximately 1.14 mm, mostly near the arm junctions. This low deformation indicates the frame has sufficient stiffness to maintain its shape and the alignment of critical components during flight, which is crucial for flight stability and accurate sensor performance. Stress analysis showed a peak von-Mises stress of 201.34 MPa, which is well below the typical tensile strength of carbon fibre composites. This confirms the frame's ability to withstand dynamic loads without risk of yielding or structural failure. The stress concentrations around the motor mounts and arm joints suggest these areas as potential candidates for reinforcement to further improve durability. Elastic strain results demonstrated a maximum strain of 6.45×10^{-3} mm/mm, safely within the elastic limits of the composite material. This means the frame will undergo fully recoverable deformation under operational loads, minimizing the risk of permanent damage, warping, or loss of performance over time.

Finally, harmonic response analysis found no resonance within the drone's normal operating frequencies of 50 to 300 Hz, with natural frequencies occurring much higher. This reduces the risk of vibration-induced damage or control issues. Overall, the study validates the use of carbon fibre composites for lightweight, strong drone frames and suggests targeted reinforcements and experimental testing to ensure long-term reliability and performance.

AUTHOR CONTRIBUTION

C. Nithyadharan performed the design, simulation, and analysis. Dr. S. Gnanasekaran supervised the project and contributed to methodology validation and manuscript revision.

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