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Integrated approach of computational modal analysis and experimental modal analysis to thorough examination of the dynamic characteristics of aircraft structures

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Abstract: - This study investigates aircraft structural integrity using Experimental Modal Analysis (EMA) and integrates it with computational methods. The methodology combines advanced tools, including CatiaV5 for design, Hyper-Mesh for meshing, Nastran for computational analysis, and Sim Center 3D for precise accelerometer placement. This integrated approach thoroughly examines the dynamic characteristics of aircraft structures, focusing on natural frequencies, mode shapes, and damping ratios. Computational modal analysis of components like wings, fuselage, and vertical tails revealed critical modal parameters, which were validated through experimental modal analysis using impact hammers and accelerometers. The experimental results closely aligned with computational predictions, highlighting the accuracy of the approach. This study is an advancement in the aircraft structural analysis, reinforcing the reliability of modal analysis in aerospace engineering and offering a robust methodology for designing safer and more efficient aircraft.

Keywords: *Structural integrity, Experimental modelling, FEA analysis, Mode shape characteristics.*

1. Introduction

Designing an aircraft that is both structurally sound and safe is crucial to ensuring its performance and passenger safety. An aircraft's ability to withstand dynamic forces directly affects its operational efficiency and safety. One of the primary techniques used to assess and guarantee structural integrity is modal analysis. By identifying the natural frequencies, damping ratios, and mode shapes of an aircraft, modal analysis provides valuable insights into potential structural weaknesses and areas for improvement. In the aerospace industry, modal analysis is a key tool in the design process, helping to create aircraft that are not only reliable but also safe for passengers [1-2]. Aircraft structures encounter a wide range of challenges during operation, including varying environmental conditions, aerodynamic stresses, and operational loads. Understanding the dynamic behavior of these structures is essential for ensuring their reliability, safety, and optimal performance [3]. In this context, modal analysis plays a pivotal role by providing a detailed understanding of an aircraft's response to vibrations and dynamic forces [4]. This technique enables engineers to analyze the different vibrational modes of complex aircraft structures, allowing for informed design decisions, structural modifications, and maintenance strategies to enhance structural integrity and safety [5]. This analysis combines mathematical modeling and experimental model testing to identify dominant vibration modes and characteristics, optimizing design and ensuring structural integrity under various operating conditions. Modal analysis offers several methods, each tailored to the specific characteristics of the object under investigation. These methods include Experimental Modal Analysis (EMA), Operational Modal Analysis (OMA), and Computational Modal Analysis (CMA) [6-7]. Experimental Modal Analysis (EMA) is a

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technique used to determine the dynamic properties of a structure through physical measurements and testing. The process involves applying controlled external forces or excitations to induce vibrations in the structure. Sensors such as accelerometers, strain gauges, and displacement transducers are strategically placed on the structure to capture its response. The data collected through EMA provides valuable information on the natural frequencies, mode shapes, damping ratios, and modal masses of the structure. Signal processing techniques are then used to extract these modal parameters from the measured responses. EMA is particularly effective for analyzing complex structures where theoretical models may not fully capture all dynamic behaviors [8]. It allows for a more accurate representation of the structure's real-world performance, providing insights that are crucial for optimizing designs and ensuring safety. EMA is widely used across various industries, including aerospace, civil engineering, automotive, and mechanical engineering. It plays a crucial role in understanding how a structure behaves under different loading conditions, allowing engineers to optimize designs, identify potential issues, and validate theoretical models. However, the process of conducting EMA can be time-consuming, requires specialized equipment, and necessitates controlled testing environments, which can make it costly and sometimes difficult to execute [9]. In EMA, both the excitation force applied to the structure and the resulting structural response are measured simultaneously over time. The time-domain data is then converted to the frequency domain using a Fast Fourier Transform (FFT) algorithm. This transformation generates frequency response functions (FRFs) and other related functions that describe the relationship between the input force and the output response. These FRFs are then used to estimate the modal parameters—such as natural frequencies, damping ratios, and mode shapes—of the structure through advanced parameter estimation techniques [10]. In addition to EMA, Computational Modal Analysis (CMA) utilizes specialized software to create discretized models or meshes of physical structures within computer-aided design (CAD) programs. Finite Element Analysis (FEA) is then applied to simulate the behavior of these structures under various loads or boundary conditions. This process helps engineers identify regions of high stress or deflection that may require reinforcement. Modal analysis software can simulate a range of excitations, such as impact tests or shaker tests, to calculate the system's natural frequencies and mode shapes. Engineers can visualize animated mode shapes to pinpoint potential problem areas. The software also captures the structure's frequency response function (FRF), which acts as a "fingerprint" of its modal properties, providing a detailed representation of the dynamic behavior of the structure [11] [20 -22]. In aircraft engineering, modal analysis is a cornerstone technique, essential for understanding the complex dynamics of aircraft structures. It offers a comprehensive framework for predicting and analyzing structural behavior, which is crucial in ensuring the safety, performance, and longevity of aircraft [12-13]. The techniques used in modal analysis have evolved significantly over time, progressing from basic concepts to the sophisticated methods employed today. Modal analysis originated from the fundamental principles of vibration and structural mechanics. In its early stages, it relied on simplified mathematical models and empirical observations, which laid the groundwork for understanding structural dynamics [14]. With technological advancements, particularly in computational capabilities, the aviation industry has seen substantial changes. The advent of powerful computational tools has revolutionized modal analysis, enabling the use of more advanced simulation techniques. These tools allow engineers to predict complex structural responses, including intricate modal behaviors within aircraft structures. At the same time, experimental modal analysis has also evolved. Traditional experimental methods have been enhanced through the integration of cutting-edge sensor technologies and advanced signal processing techniques. This evolution has allowed experimental modal analysis to complement computational approaches, creating a synergistic relationship between the two. Together, computational and experimental methods provide engineers with a deeper and more comprehensive understanding of aircraft structural dynamics. Computational Modal Analysis (CMA), specifically, is used to study the dynamic behavior of structures using computational techniques. It involves determining the natural frequencies, mode shapes, and damping ratios of a structure to understand how it responds to dynamic loads [15]. The Finite Element Method (FEM) is a widely used technique in Computational Modal Analysis (CMA) for simulating the behavior of structures under varying conditions. This method involves discretizing a structure into smaller, manageable elements, and solving the governing equations of motion using specialized solvers. The Modal Superposition method combines the individual modal responses to derive the overall structural response. Numerical techniques, such as Lanczos, QR iteration, and subspace iteration, serve as Modal Analysis Solvers to extract modal parameters, including natural frequencies, mode shapes, and damping ratios. Advanced FEM software tools like ANSYS, Abaqus, and Nastran are essential for performing modal analysis on complex structures. These tools allow for detailed simulations that provide insights into the dynamic behavior of components under various conditions. To manage the complexity of large-scale models, model reduction techniques are applied. These methods simplify complex models without sacrificing essential dynamic information, making them invaluable in industries like aerospace, automotive, and civil engineering for design optimization and structural safety [23-32]. However, there are certain limitations. Computational costs can rise for large-scale models, model accuracy can be influenced by simplifications and assumptions, and challenges remain in accurately modeling nonlinear behavior [16-17]. In the aerospace industry, CATIA V5 is a powerful and versatile tool widely used for creating and analyzing 3D models of aircraft structures. It enables engineers to conduct detailed simulations and analyses of components, playing a vital role in the design and optimization process. CATIA V5 excels in geometric modeling, finite element pre-processing, and integrates seamlessly with other analysis tools, providing engineers with a comprehensive solution [18]. HyperMesh is another essential software tool in the Finite Element Analysis (FEA) workflow. It plays a crucial role in preparing models for simulation, especially in generating meshes and manipulating models for use in solvers like Nastran. By streamlining the pre-processing phase, HyperMesh simplifies the creation of precise and effective models for structural analysis [19]. NASTRAN, a robust FEA solver, is widely used across various industries for structural analysis. Particularly prevalent in the aerospace sector, NASTRAN is employed to perform static, dynamic, fatigue, and thermal analyses of aircraft components and systems. Its powerful capabilities make it an indispensable tool in ensuring the safety, performance, and reliability of complex structures.

This paper presents a novel integration of both experimental and computational approaches to modal analysis, aiming to enhance the understanding of aircraft structural dynamics. By combining Experimental Modal Analysis (EMA) with Computational Modal Analysis (CMA), this study provides a comprehensive assessment of aircraft components, such as the wings, fuselage, and vertical tail. The novelty lies in the seamless application of advanced tools, such as CatiaV5 for design, Hyper-Mesh for meshing, and Nastran for computational analysis, alongside precise experimental setups for real-world validation. This dual approach not only validates the computational models but also reveals new insights into the dynamic behavior of the aircraft under various operational conditions. The study's integration of these methodologies improves the accuracy of predictions and provides a deeper understanding of the vibrational characteristics essential for designing safer, more efficient aircraft.

2. Methodology

At the initial stage of our research initiative, significant effort was dedicated to designing the aircraft structure using CATIA V5, a leading computer-aided design (CAD) software. The focus of the research was on conceptualizing the overall shape and structure of the aircraft, with a strong emphasis on aerodynamic principles and structural requirements. We meticulously addressed key details, such as material specifications, structural components, and assembly methods, to refine the design. The result was a comprehensive 3D model that served as the foundation for subsequent analyses. Figure 1 shows the final 3D model of the design.

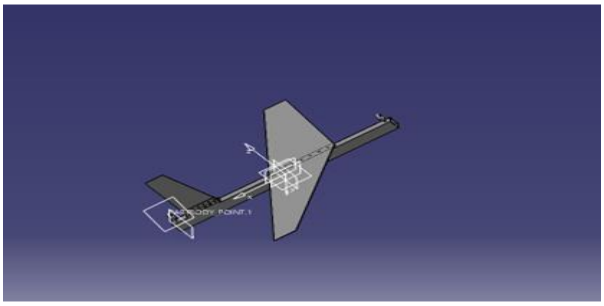

Figure 1: 3D Model of the Designed Aircraft Structure.

After completing the aircraft structure design, we used HyperMesh to create the finite element mesh for the model. This step required careful attention to detail, including selecting the appropriate element types and mesh density to ensure accuracy in the subsequent modal analysis. We also assigned material properties and applied realistic boundary conditions to simulate actual operational constraints. Figure 2 shows the model after meshing in HyperMesh. The meshed model was then exported to Nastran for modal analysis, where key parameters such as natural frequencies and mode shapes were calculated.

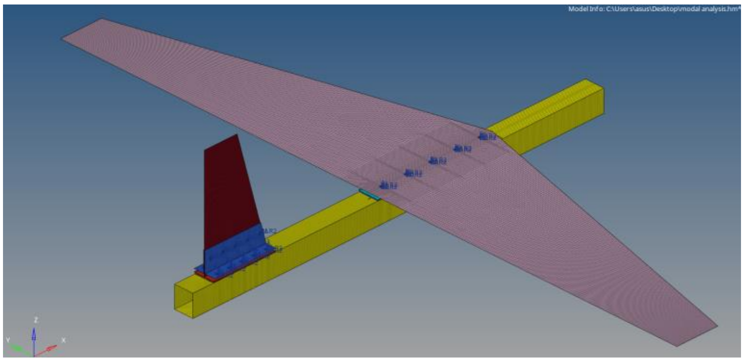

Figure 2: Meshed Model of the Aircraft Structure.

After completing the computational analysis, we used HyperView to interpret the results obtained from Nastran. We focused on analyzing the mode shapes and natural frequencies to better understand the dynamic behavior of the aircraft structure. With HyperView's advanced visualization tools, we graphically represented the mode shapes, offering a clear and intuitive view of the structural dynamics.

3. Experimental Setup

Figure 3 illustrates the experimental setup for the Experimental Modal Analysis, focusing on the dynamic response of the aircraft structure, particularly its behavior in the pitch direction. The aircraft, weighing 6.7 kilograms, is carefully suspended using bungee cords. This suspension method is specifically chosen to simulate a 'free-free boundary condition,' which is crucial for this experiment. This condition allows the aircraft to oscillate naturally, free from the constraints of rigid or fixed supports that would otherwise limit its movement.

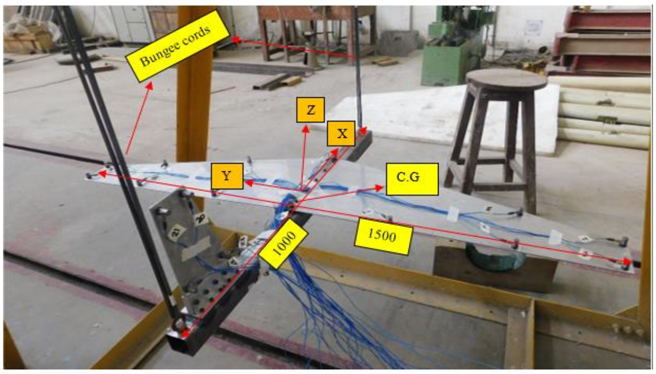

Figure 3: Experimental Modal Analysis Setup of Aircraft Structure.

The primary focus of this experiment is the pitch direction, which refers to the up-and-down movement of the aircraft's nose and tail. Pitch is a critical aspect of the aircraft's aerodynamic performance, influencing its stability and control during flight. Understanding the aircraft's behavior in this direction under various conditions is essential for assessing its overall flight capabilities and safety.

A key measurement in this setup is the suspension frequency, recorded at 0.40 Hz. This frequency is significant because it provides insights into the aircraft's natural frequency in the pitch direction. The natural frequency is a fundamental parameter that helps engineers and researchers understand how the aircraft might respond to aerodynamic forces during flight. By knowing the natural frequency, better-informed decisions can be made regarding the design and potential modifications of the aircraft, ultimately enhancing its performance and safety. Overall, this experimental setup provides crucial data and insights into the dynamic response of the aircraft, particularly in the pitch direction, which plays a key role in its aerodynamic efficiency and safety during flight.

4. Details of Instrumentation and Analysis

The instrumentation used in this study plays a critical role in accurately capturing the dynamic behavior of the aircraft during the experimental modal analysis. The key components of the setup include various sensors, data acquisition systems to measure and interpret the aircraft's response to external excitations.

I. PC-Based Data Acquisition System and Modal Analysis Software (Sim Center Impact Test Lab): Used to collect and process data from various sensors, enabling detailed modal analysis of the aircraft's dynamic response.
II. 28 ICP Accelerometers for pitch direction with a sensitivity of 100 mV/g. Calibration is due on 17-07-2023. The locations of these accelerometers are shown in Figure 3, and they were strategically placed to capture the aircraft's vibrations in key areas.
III. Instrumented Impact Hammer with a sensitivity of 2.15 mV/N: Used to provide controlled excitations to the structure, inducing vibrations and allowing for the measurement of the aircraft's response.

The details for the Accelerometer location and description are given Table 1

Table 1: Locations and Descriptions of Accelerometers.

Sr. No.	Accelerometer Location	Number and Type of Accelerometer
1.	Fuselage	5 tri-axial (X,Y,Z)
2.	Wing	14 uniaxial (Y)
3.	Vertical tail	4 uniaxial (Z)

5. Results and Discussions

5.1 Finite Element Analysis Results

The natural frequencies, mode shapes, and damping percentages of the aircraft structure were obtained using HyperMesh and HyperView. The results are presented in the figures below (4 to 24).

I. Wing: The mode shapes for the wing deformation, including symmetric, anti-symmetric, and torsional modes, are shown in Figures 4 to 8. These modes were obtained through computational modal analysis.

Figure 4: First Mode: Symmetrical bending.

Figure 5: Second Mode: Anti-Symmetrical bending.

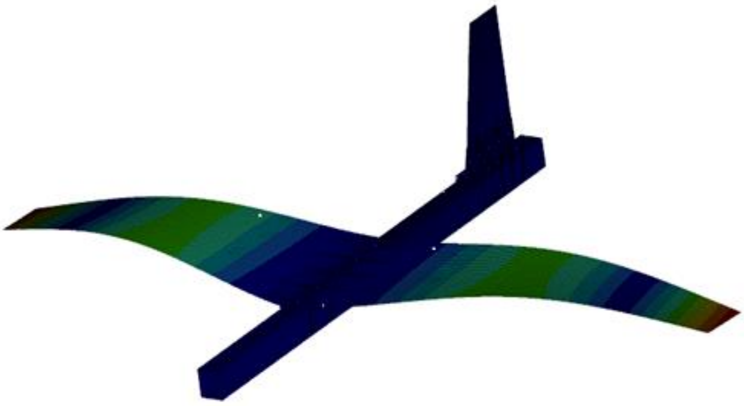

Figure 6: Third Mode: Symmetrical bending

Figure 7: Fourth Mode: Anti-Symmetrical bending

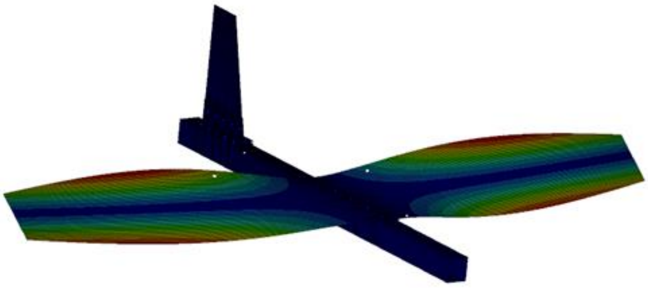

Figure 8: Fifth Mode: Simultaneous Bilateral Torsion (SB Torsion).

Figures 4 through 8 illustrate various modes of wing deformation, highlighting their implications on aircraft stability and control. Figure 4 demonstrates symmetrical bending about the longitudinal (X) axis, where both wing tips deflect upward in unison, forming a mirrored deformation pattern. In contrast, Figure 5 exhibits anti-symmetrical bending, as the wing tips bend in opposite directions, indicating a twisting dynamic that disrupts aerodynamic balance. Similarly, Figure 6 portrays another instance of symmetrical bending, with both wings adopting an upward concave curvature along the longitudinal axis, maintaining a uniform aerodynamic profile. Conversely, Figure 7 reveals anti-symmetrical bending, where the curvature of the left and right wings diverges, introducing destabilizing aerodynamic forces. Figure 8 presents a more complex deformation—Simultaneous Bilateral Torsion—where torsional forces act concurrently along both the longitudinal (X) and lateral (Y) axes, producing a multi-axis twist in the wing structure. While symmetrical bending has minimal impact on the aircraft's stability and control characteristics, anti-symmetrical bending can significantly impair flight performance, introducing asymmetries that adversely affect handling, maneuverability, and structural integrity.

II. Fuselage: The mode shapes for fuselage deformation, including longitudinal bending (Figure 9) and lateral bending (Figure 10), are shown, as obtained from the computational modal analysis.

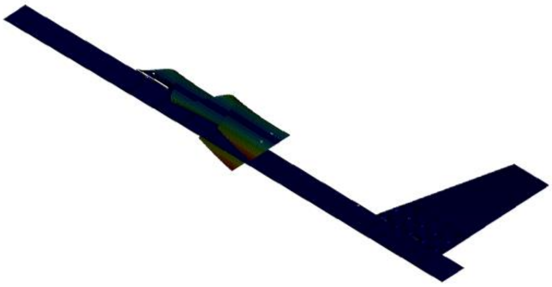

Figure 9: Sixth Mode: Longitudinal bending

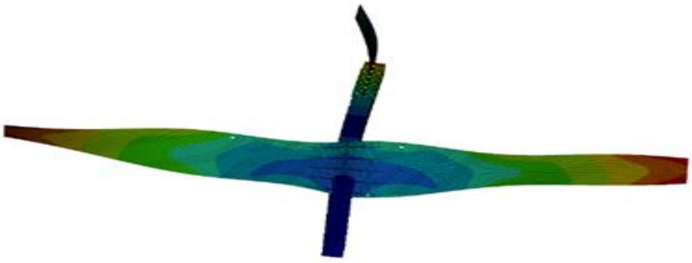

Figure 10: Seventh Mode: Lateral bending

Figures 9 and 10 showcase critical fuselage deformation modes that can severely affect an aircraft's structural integrity and flight performance. Figure 9 depicts longitudinal bending along the fuselage, a condition that disrupts the aircraft's aerodynamic alignment and undermines both safety and controllability. Such deformation is structurally unfavorable and can compromise flight dynamics if left unaddressed. Figure 10 presents lateral bending, where sideward flexing of the fuselage—especially when exceeding design tolerances—can escalate into a catastrophic failure scenario. These structural anomalies emphasize the importance of robust design, precise load distribution, and continuous monitoring to ensure the aircraft operates within safe deformation thresholds.

III. Vertical Tail: Figures 11 and 12 display the mode shapes of the vertical tail, showing bending and twisting behaviors, as obtained from the modal analysis.

Figure 11: Eighth Mode: Bending

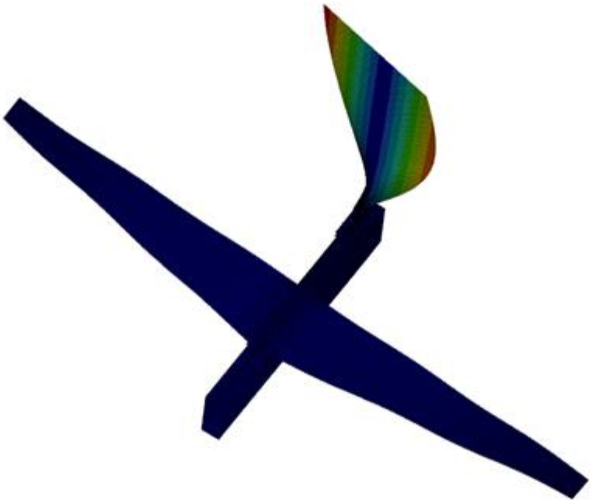

Figure 12: Ninth Mode: Twisting

Figures 11 and 12 highlight critical deformations in the tail section that adversely impact the aircraft's directional stability and control. Figure 11 illustrates tail bending, a structural distortion that can disrupt airflow over the vertical stabilizer, leading to compromised yaw stability. Figure 12 reveals tail twisting, a torsional deformation that alters control surface effectiveness, further diminishing the aircraft's ability to maintain steady directional control. Both conditions undermine the aerodynamic balance essential for stable flight, emphasizing the need for precise structural design and integrity in the tail assembly.

6. Experimental Results

6.1 Frequency Response

The Frequency Response obtained from the Experimental Modal Analysis using Sim Center Impact Test Lab software are shown in Figures 13 and 14. The peaks in these figures indicate the natural frequencies at specific points on the structure.

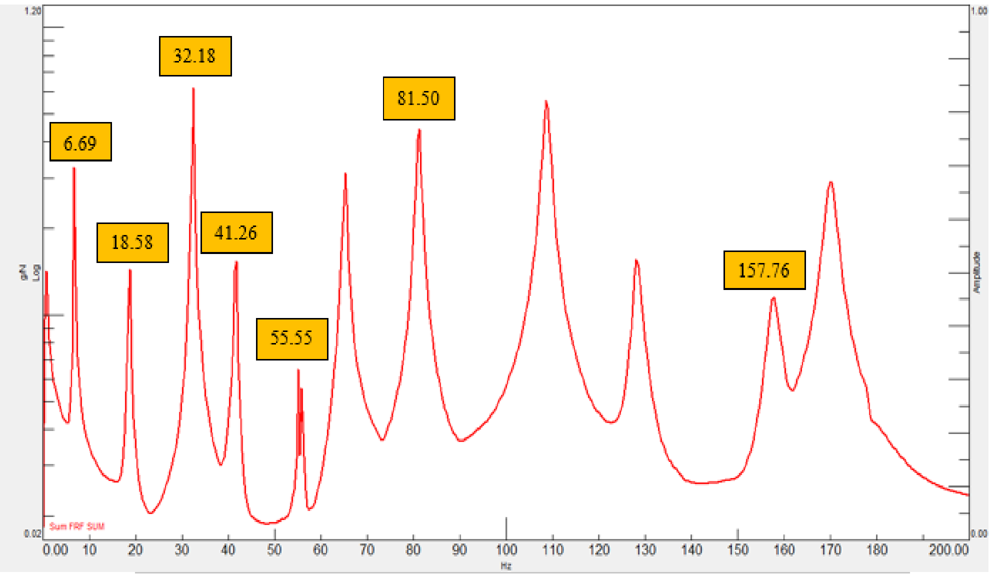

Figure 13: Frequency Response of the Airframe in Longitudinal Bending (XZ Plane).

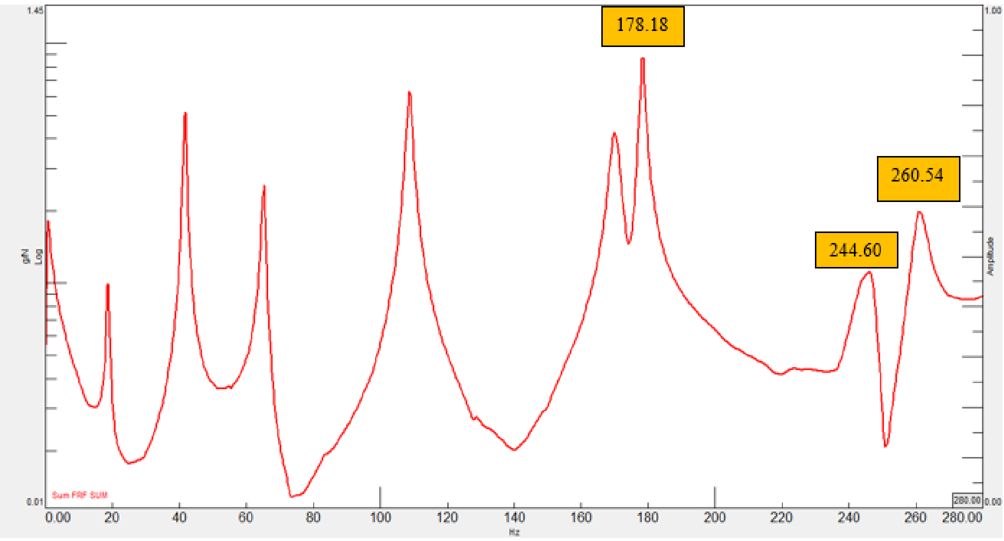

Figure 14: Frequency Response of the Airframe in Lateral Bending (XY Plane).

Figures 13 and 14 illustrate the frequency response functions (FRFs) obtained through Fast Fourier Transform (FFT), revealing the natural vibrational modes of the structure as detected by accelerometers. These plots highlight key resonant frequencies where the system exhibits amplified responses due to structural resonance. In Figure 13, the frequency spectrum extends up to 200 Hz, showing distinct peaks at 6.69 Hz, 18.58 Hz, 32.18 Hz, 41.26 Hz, 55.55 Hz, 81.50 Hz, and 157.76 Hz. These frequencies correspond to various global and localized mode shapes, with the lowest frequency likely representing the first bending mode of the structure, and the higher frequencies indicating more complex dynamic behavior such as torsion or coupled modes. Figure 14 extends the range up to 280 Hz and captures higher-frequency resonances at 178.18 Hz, 244.60 Hz, and 260.54 Hz, which suggest localized structural responses possibly involving stiffer components or control surfaces. The amplitude of each peak signifies the intensity of the structural response at that frequency, where sharper, more prominent peaks indicate well-defined modes.

Experimental Modal Analysis Results

I. Wing: The mode shapes for wing deformation, including symmetric, anti-symmetric, and torsional modes, obtained from the Experimental Modal Analysis, are shown in Figures 15-19 below. These mode shapes have been reconstructed to compare with the results obtained from computational analysis. The coordinates shown in the figures indicate the exact positions of the accelerometers used during the experimental measurements.

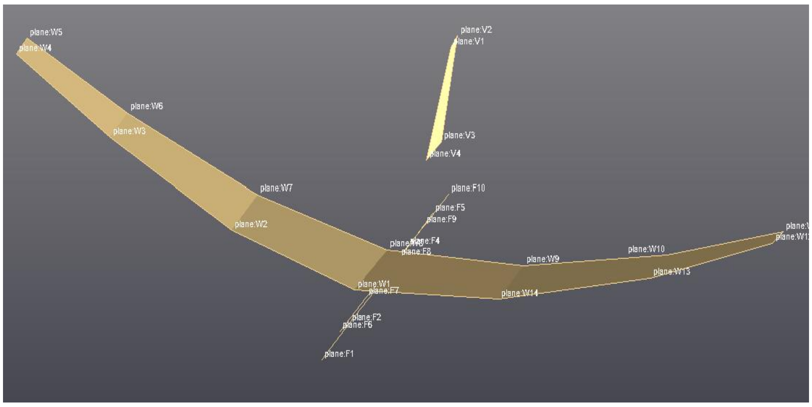

Figure 15: First Mode: Symmetrical bending

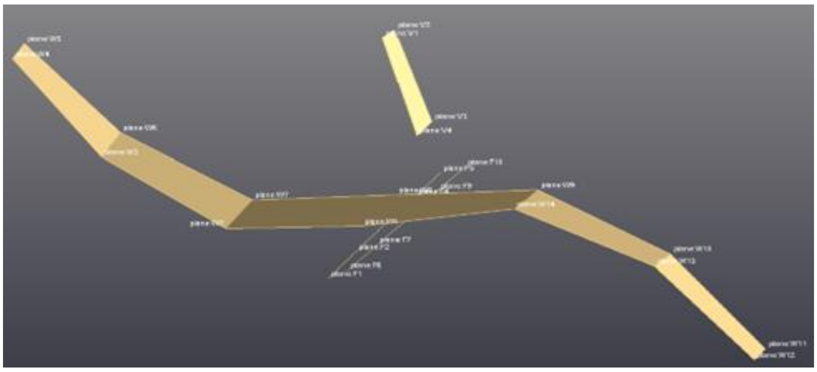

Figure 16: Second Mode: Anti-Symmetrical bending

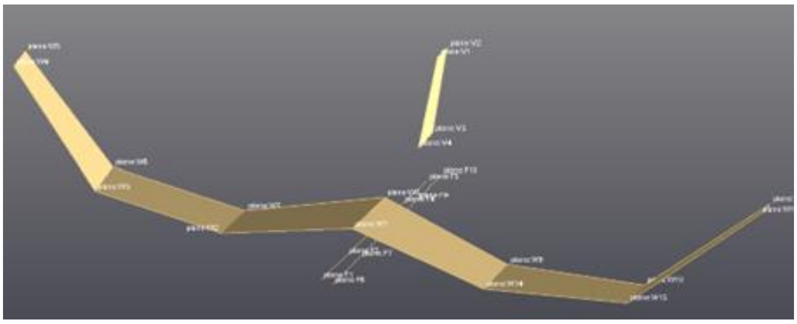

Figure 17: Third Mode: Symmetrical bending

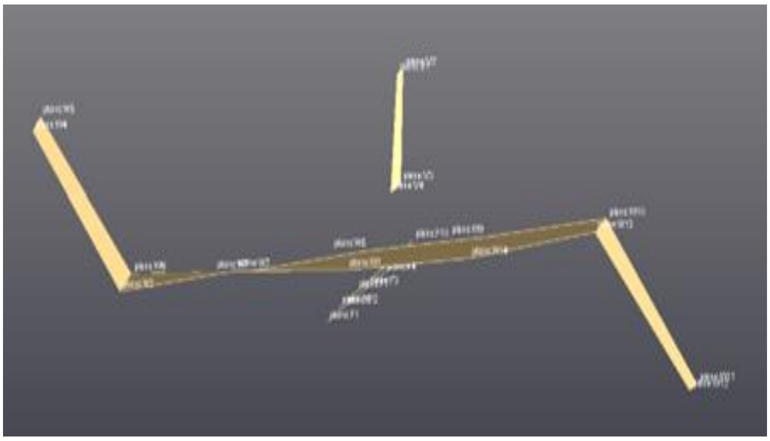

Figure 18: Fourth Mode: Anti-symmetrical bending

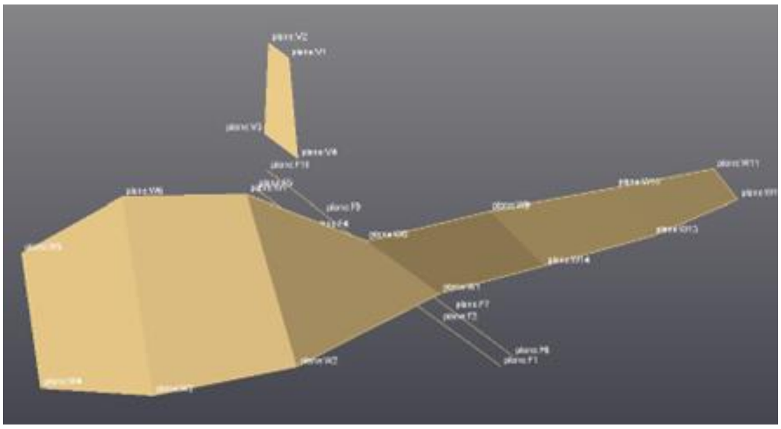

Figure 19: Fifth Mode: Simultaneous Bilateral Torsion

II. Fuselage: The mode shapes for fuselage deformation, including longitudinal bending (Figure 20) and lateral bending (Figure 21), obtained from the Experimental Modal Analysis, are shown below.

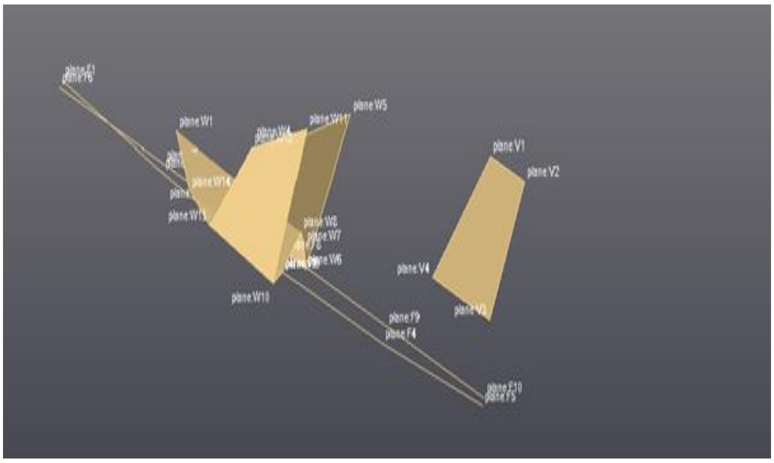

Figure 20: Sixth Mode: Longitudinal bending

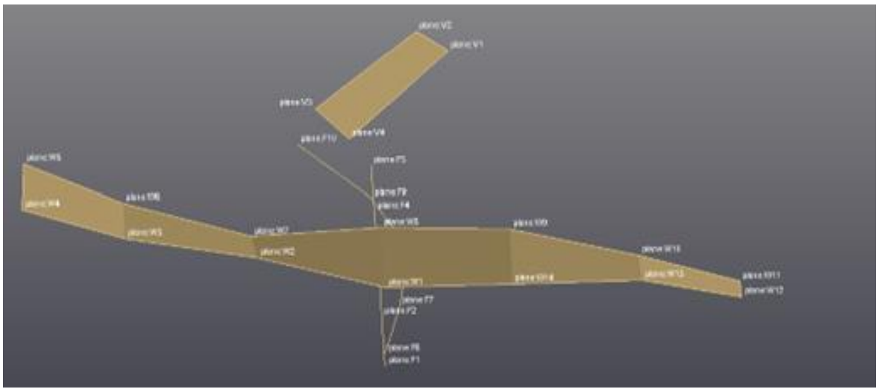

Figure 21: Seventh Mode: Lateral bending

iii. Vertical Tail: Figure 22, figure 23 and figure 24 show the mode shapes of the vertical tail from the experimentation and the bending and twisting can be seen.

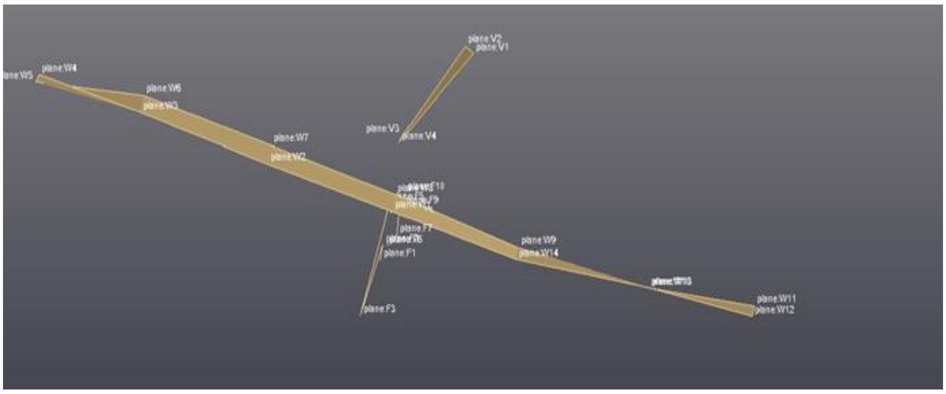

Figure 22: Eight Mode: Bending

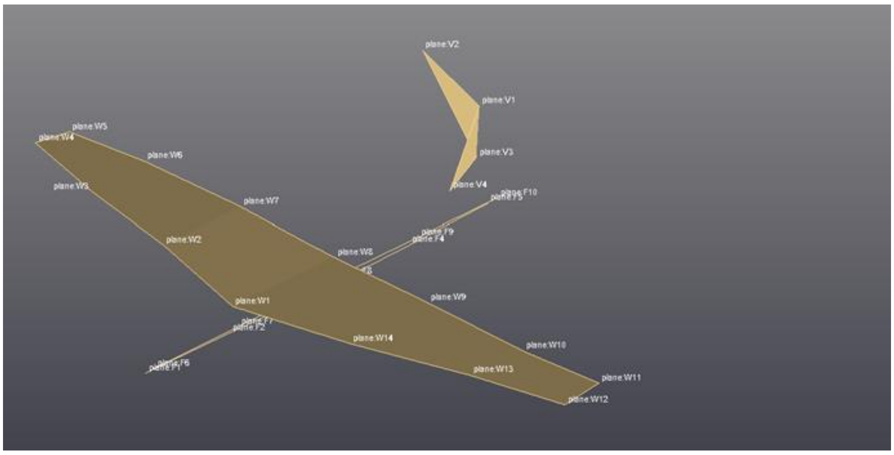

Figure 23: Ninth Mode: Twisting

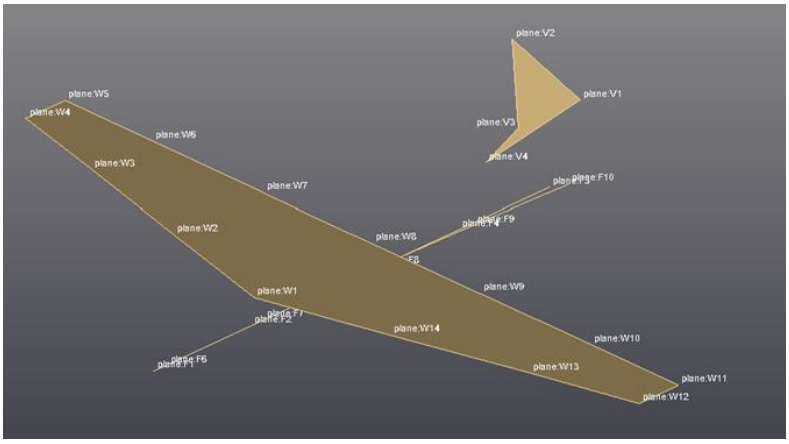

Figure 24: Ninth Mode: Twisting (Dominating frequency)

7. Comparison of Experimental and Computation Modal Analysis

Table 2: Comparison of Experimental and Computational Modal Analysis Results.

Sr. No.	**Model Description**	**Experimental frequency in (Hz) and modal damping (%) (6.7kg)**	**Computational Frequency in (Hz) (7.3kg)**
Wing			
1	Symmetrical 1st bending	6.69 (0.20%)	6.69
2	Anti-Symmetrical 1st bending	18.58 (0.60%)	18.98
3	Symmetrical 2nd bending	32.18 (0.50%)	32.46
4	Anti-symmetrical 2nd bending	41.26 (0.64%)	37.41
5	Torsion	55.55 (0.14%)	50.77
Fuselage			
6	Longitudinal 1st bending	157.76 (0.81%)	158.73
7	Lateral 1st bending	178.18 (0.31%)	180.79
Vertical Tail			
8	Bending	81.50 (1.07%)	90.79
9	Twisting	244.60 (0.58%)	265.62
		260.54 (0.82%) (Dominating frequency)	265.62

Table 2 presents a comparison between the results of Experimental Modal Analysis and Computational Modal Analysis for various vibration modes in different aircraft components i.e. wing, fuselage, and vertical tail. These results are crucial for understanding the dynamic behavior of the aircraft's structure under operational conditions.

For the wing, the 1st symmetrical bending mode shows an experimental frequency of 6.69 Hz with a damping ratio of 0.20%, which perfectly matches the computational frequency. In the 1st anti-symmetrical bending mode, however, there is a small discrepancy between the experimental result (18.58 Hz, 0.60% damping) and the computational frequency. The differences become more noticeable in the 2nd bending modes. For the symmetrical 2nd bending mode, the experimental frequency is 0.28 Hz lower than the computational result, while for the anti-symmetrical 2nd bending mode, the experimental frequency is 4.15 Hz higher than the computational value.

For torsion, the experimental analysis yields a frequency of 55.55 Hz with a very low damping ratio of 0.14%, while the computational analysis predicts a lower frequency of 50.77 Hz. This discrepancy could stem from variations in boundary conditions, material properties, or geometric details between the experimental model and the computational model.

For the fuselage, the longitudinal 1st bending mode shows a minor difference between the experimental result (157.76 Hz, 0.81% damping) and the computational frequency (158.73 Hz). The lateral 1st bending mode results are very close, with the computational frequency being slightly higher than the experimental value by 2.61 Hz.

Finally, for the vertical tail, the bending mode shows a more noticeable difference, with the computational frequency being 9.29 Hz higher than the experimental frequency. The twisting mode shows the largest frequency discrepancy of 5.02 Hz. The experimental analysis identifies the twisting frequency of 260.54 Hz as the dominant frequency, which may suggest that this mode is of particular importance or sensitivity under operational conditions.

Overall, while there are some differences between the experimental and computational results, the frequencies are relatively close, indicating that the computational model provides a good representation of the experimental set up. The damping ratios, available only for the experimental results, offer valuable insights into the energy dissipation characteristics of each mode. These are crucial for understanding the vibration behavior of the aircraft components and can help in design improvements for better performance and durability.

Conclusions

This comprehensive study delves into the intricate details of experimental modal analysis conducted on an aircraft structure, highlighting advanced methodologies used in Aerospace Engineering. By focusing on aircraft structural dynamics, the research integrates both experimental and computational approaches to offer a deeper understanding of the aircraft's vibrational characteristics and performance.

- The experimental modal analysis was meticulously executed with accelerometers placed on critical locations of the aircraft, including the wing, fuselage, and vertical tail.
- The data gathered provided valuable insights into the frequencies and damping of the aircraft, essential for assessing its structural integrity under various flight conditions.
- Computational Modal Analysis was conducted which is revealing a high degree of alignment with experimental results, particularly in the fundamental bending modes.
- The close correlation between experimental and computational results confirms the predictive accuracy and reliability of the computational model, while minor discrepancies offer opportunities for further refinement.
- The study underscores the importance of integrating experimental and computational modal analyses to optimize aircraft design and enhance safety and efficiency in aerospace engineering.

List of Abbreviations

CAD	Computer Aided Design
CMA	Computational Modal Analysis
Catia V5	Catia Version 5
EMA	Experimental Modal Analysis
FEA	Finite Element Method
FFT	Fast Fourier Analysis
g	Gram
Hz	Unit of Frequency
mV	milli volt
X	X Co-ordinate
Y	Y Co-ordinate
Z	Z Co-ordinate
3D	3- Dimensional

Declarations

Availability of data and material: Amity School of Engineering and Technology, Amity University Haryana, Gurugram,

Competing interest: Author declares that there is no competing interest

Funding: Not applicable

[1]**Author contribution:** conceptualization, methodology development and data analysis

[2]**Author contribution:** manuscript writing, results interpretation

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