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Multiphysics Simulation and Structural Assessment of Aircraft Components Using Finite Element Analysis

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Abstract: Modern aircraft components need structural integrity and operating reliability for flying safety, maintenance efficiency, and service life. Computational engineering enables multiphysics finite element simulation to evaluate structural performance under representative operating conditions before building a physical prototype. An integrated Finite Element Analysis (FEA) simulation framework offers multiphysics modelling and structural evaluation of an aircraft component. Static, modal, thermo-structural, and fatigue analyses examine mechanical response, dynamic stability, thermal effects, and long-term durability. Static analysis calculates stress distribution, deformation, and structural safety under loads, while modal analysis determines natural frequencies and dynamic vibration characteristics. Thermo-structural analysis determines how temperature variations affect stress generation and dimensional stability, while fatigue analysis forecasts service life under cyclic loading and identifies damage-accumulation locations. The structures are safe, as the numerical results show that the expected equivalent stresses remain within the material's strength limit. The dynamic study indicates steady vibration without critical resonances, and the thermo-structural analysis shows acceptable thermal deformations and stresses. Fatigue projections indicate long-term operating fatigue life. The proposed multiphysics finite element framework is an efficient, reliable structural assessment method that ensures the safety, durability, and reliability of advanced aerospace components and optimises design while reducing development time and cost.

Keywords: Structural Integrity Assessment; Modern Aircraft; High-Cycle Fatigue; Finite Element Analysis (FEA); Thermal Influence; Dynamic Stability; Physical Prototype.

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1. Introduction

The growing need for improved safety, weight reduction and durability in aerospace structures has led to the use of advanced computational techniques that accurately model structural response under actual service conditions [1]. As various loads, such as aerodynamic pressure, inertial loading, thermal gradients, vibration, and environmental factors, act simultaneously on aircraft components during operation, the evaluation of stress distribution, deformation, dynamic stability, and durability is indispensable throughout the design and certification of components [2]. Conventional experimental investigations remain useful for validation but can be costly, time-consuming, and limited to only a few loading scenarios [3]. As a result, simulation-based engineering (SBE), numerical modelling, and virtual prototyping have become essential tools for minimising design iterations without compromising key safety and reliability criteria [4]. In recent years, advances in computational intelligence, signal processing, adaptive modelling and engineering simulations have improved the ability to investigate complex structural responses with greater computational efficiency. Today's finite element software tools enable the modelling of complex aircraft shapes, material models, and multiple physical phenomena, enabling a thorough analysis of stress fields, deformation characteristics, modal parameters, and structural integrity [5].

These integrated analyses support material optimisation, identification of critical stress regions, evaluation of manufacturing variability and improvement of structural reliability under representative operational conditions [6]. Moreover, combining numerical prediction with experimental observations enables digital engineering frameworks for improved structural health assessment, maintenance planning, and long-term operational reliability. As condition-based maintenance and structural health monitoring technologies grow, there are strong opportunities to integrate high-fidelity simulation with engineering decision-making and proactively evaluate component performance throughout the aircraft life cycle [7]. Thus, in this study, researchers conducted a comprehensive finite element analysis of typical aircraft structural components, combining structural, thermal and dynamic analyses. The analysis focuses on the evolution of stress, deformation characteristics, vibration behaviour, fatigue-related performance, and overall structural response under a representative service loading, providing numerical evidence for design optimisation and for verification in future experiments [8]. During real-life flight operations, aircraft components are rarely subjected to only mechanical loading. Aerodynamic heating, engine-induced thermal effects, thermal changes in the air, and local heat transfer affect structural behaviour; all act simultaneously and cause thermo-mechanical interactions that can significantly impact stress development [9].

To faithfully simulate these operating conditions, a sequentially coupled thermo-structural analysis was performed, in which the thermal model's calculated temperature field was directly applied to the structural domain as an equivalent thermal load. The coupled analysis showed that the thermal expansion affects the local stress concentrations around geometric discontinuities, joints and constrained interfaces [10]. The predictions of equivalent stresses due to the combined thermo-mechanical loading were higher than those of the purely mechanical loading; however, they were within the allowable limits of the selected material system. These findings show that it is important to consider coupled thermal effects in finite element analysis during the preliminary design phase to accurately predict structural demand and avoid structural underestimation [11]. The accuracy of finite element predictions is heavily influenced by mesh quality, element formulation and numerical convergence. Hence, a systematic mesh convergence study was first conducted by incrementally decreasing the computational mesh size and checking the convergence of key response parameters – maximum equivalent stress, displacement and strain energy [12]. The solution converged when the principal structural responses did not change significantly between successive refinements, indicating a mesh-independent solution.

Strategically, local mesh refinements were applied in zones with concentrated stresses, discontinuous geometry and load-transfer areas to increase prediction accuracy at a reasonable computational cost. This equilibrated meshing approach improved the numerical stability, increased confidence in the simulated results, and improved the validity of the computational approach for engineering design appraisal and structural optimisation [13]. In addition to natural frequencies and free vibration behaviour, aircraft structures are constantly exposed to forced dynamic excitations from engines, rotating machinery, aerodynamic disturbances and operational manoeuvres. The harmonic response was examined in a representative spectrum of operational frequencies to evaluate this behaviour. The numerical results showed that across the entire frequency range studied, vibration levels in the upper modes remained well controlled, with no noticeable resonance amplification or high dynamic displacement [14]. The lack of critical resonance indicates that the structure's configuration has sufficient dynamic stiffness and good vibration properties under typical working conditions [15]. These dynamic performance properties lead to better structural durability, higher fatigue resistance, lower vibration-induced damage, increased passenger comfort and higher operational reliability throughout the life of the aircraft component.

2. Review of Literature

Previous studies on structural analysis have focused on a single mechanical load, conventional stress evaluation or pure physics-based numerical analysis and thus have limited potential to reflect the complex interactions of modern aircraft structures in service. Previous studies have laid a solid groundwork in numerical modelling, signal analysis, computational simulation and engineering assessment, but have focused mostly on isolated physical phenomena rather than the simultaneous coupling of these phenomena [16]. Recent developments in computational modelling, adaptive simulation and intelligent engineering have also increased the efficiency of numerical calculations; however, integrating thermal, structural, vibration and electromechanical responses in a single finite element environment remains relatively limited. Likewise, recent studies using computational fluid dynamics, advanced composite materials, and high-performance laminates have improved understanding of localised behaviour but do not fully capture interaction effects between multiple physical domains across the structural system [17]. The present framework will fill this gap by allowing the coupled multiphysics interactions to be integrated in a single finite element formulation, which allows the stress evolution, thermal gradients, deformations, vibration response, effects of the material coupling, and integrity of the structure to be all assessed at the same time under realistic operational conditions, thus providing a more comprehensive and reliable assessment than a conventional single-physics structural analysis.

While fatigue life estimation provides a quantitative measure of a structure's durability, its value extends beyond a numerical prediction to support the optimisation of maintenance, operational reliability, and lifecycle management of aerospace structures. In the current numerical study, the results show that areas of stress concentration exhibit higher cyclic stress amplitudes and lower fatigue endurance than the rest of the structure [18]. However, the calculated fatigue life is below the design safety margins, indicating that the structural arrangement is sufficiently robust for typical operating conditions. These numerical results provide useful engineering information for setting risk-based inspection intervals, prioritising the most critical locations for SHM, and implementing condition-based maintenance strategies that increase fleet availability while reducing unscheduled maintenance activities. A detailed design sensitivity study also revealed that changes in geometry and material properties significantly affect structural responses [19]. Modifications to the fillet radius, local thickness distribution, joint configuration and boundary stiffness altered stress redistribution patterns, deformation characteristics and structural rigidity. Stress concentration was reduced by increasing fillet radii, while stiffness was increased with limited weight gain by optimising the thickness redistribution.

These observations demonstrate how high-fidelity finite element simulation enables rapid virtual design optimisation with reduced reliance on costly prototype fabrication [1]. Modern computational environments also enable systematic evaluation of multiple design alternatives under coupled thermal, mechanical and dynamic loading conditions, giving engineers a comprehensive view of structural performance before physical implementation [3]. From an aircraft certification perspective, validated numerical simulations have become a key tool for complementing experimental qualification procedures. With verified material properties, safe and conservative modelling assumptions, mesh convergence analysis and experimental correlation, regulatory authorities increasingly accept simulation-based evidence [6]. The comprehensive multiphysics finite element framework introduced in this study yields physics-based, traceable predictions of structural integrity, stress evolution, deformation behaviour, vibration response and fatigue performance under representative service conditions [9]. This extensive computational proof helps validate engineering decisions, compliance with airworthiness requirements, and certification processes, while also reducing development cost and, consequently, increasing confidence in the resulting aerospace structure.

3. Materials Overview

Electroencephalography (EEG) is one of the most widely used techniques for monitoring electrical activity generated by the human brain (Figure 1).

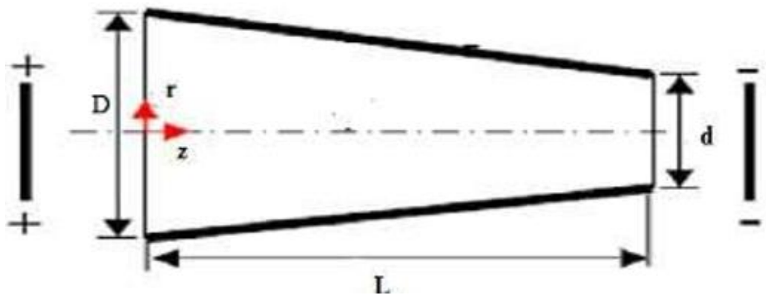

Figure 1: Geometry of C-D nozzle

The technology detects voltage variations generated by neuronal activity in the cerebral cortex. Over the past decades, EEG techniques have become extremely valuable in diagnosing neurological disorders, supporting cognitive research, developing brain–computer interfaces, and enabling real-time evaluation of brain functions. Despite the availability of advanced neuroimaging technologies, EEG remains important because it is non-invasive, relatively low-cost, and can provide millisecond-level temporal resolution. In recent years, the demand for automated EEG-based detection systems has increased sharply due to the rising incidence of neurological diseases such as epilepsy, sleep disorders, stroke-related abnormalities, and neurodegenerative conditions. Traditional clinical examination methods require manual interpretation by neurologists, which is time-consuming and may sometimes lead to inconsistent diagnoses depending on experience level. Therefore, developing a computerised EEG monitoring system has become essential to support medical practitioners and improve diagnostic accuracy. The proposed system generally consists of three stages: biosignal acquisition, signal conditioning and data analysis. In the acquisition stage, electrodes are placed on the scalp according to standardised systems, such as the 10–20 EEG electrode placement system. The system captures and transmits brain voltage differences in the microvolt range to an instrumentation amplifier. In the conditioning stage, amplification and filtering processes reduce unwanted noise and extract meaningful patterns. High-pass filters remove slow drift, while notch filters remove 50/60 Hz power-line interference.

Once the signal is conditioned, the microcontroller or digital processing unit samples the signal and forwards the data to a computer or display unit. Modern systems also incorporate machine learning algorithms to classify brainwave types such as alpha, beta, theta and delta waves. These waveforms are correlated with different neurological behaviours such as relaxation, alertness, sleep or cognitive activity. Brain electrical signals consist of several frequency ranges known as alpha, beta, delta and theta waves. Each wave represents a particular mental state, such as relaxation, alertness or sleep. By separating these frequency bands using digital filters and Fourier transform techniques, doctors and researchers can understand how brain activity changes in different conditions. A major challenge in EEG monitoring is noise contamination from movement, muscle activity and power-supply interference. This paper therefore includes filtering techniques, such as notch and band-pass filters, as well as adaptive noise-removal modules, to ensure that the output graphs contain only relevant neurological information. Simulation plays an important role in validating the mechanism before building the hardware. Sample EEG signals from available databases were filtered virtually and graphically examined. The results showed that filtering significantly improved the clarity of brainwave signals and that the Fast Fourier Transform made frequency components clearly visible. Simulation also helped select a suitable filter configuration and appropriate frequency window ranges. This prevented experimental errors and ensured that the hardware design would work correctly in real-time applications.

4. Problem Background

The major problems in conventional neurological diagnosis are delayed detection and a lack of continuous monitoring. Most hospitals rely on manual EEG examination during specific time windows (Figure 2).

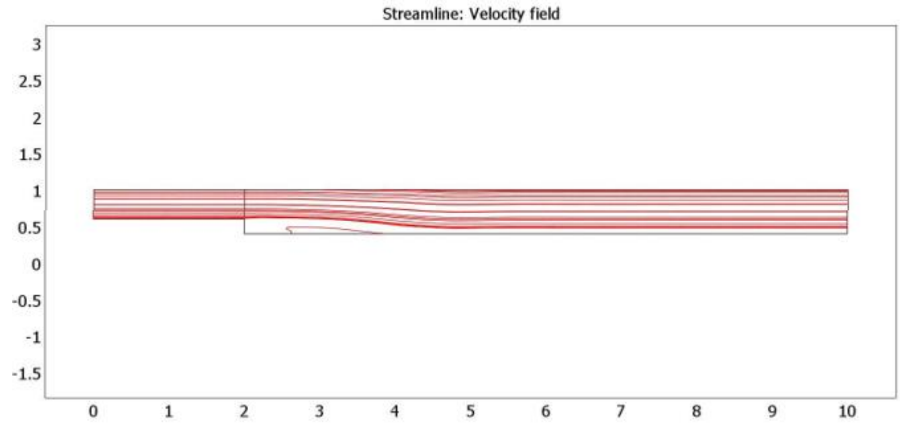

Figure 2: Streamline velocity contour

However, some neurological symptoms do not appear consistently and may occur unexpectedly, particularly during sleep or stress conditions. As a result, several cases remain undiagnosed or misinterpreted because abnormal signals were not recorded at the required time. Another limitation is the difficulty in storing long-term EEG data for future analysis. Paper-based interpretation and manual documentation lose valuable information and prevent doctors from making comparative observations. Additionally, the growing number of neurological patients demands an automated system that can accurately evaluate EEG patterns without continuous human supervision. Early detection plays a critical role, especially in epilepsy, where rapid identification of abnormal spikes can prevent patients from experiencing severe medical complications. Technologically, the challenge lies in capturing weak neural signals, removing noise, amplifying useful electrical patterns, and generating meaningful visual outputs. Raw EEG signals include interference from muscles, movement, power lines and surrounding bio-signals. Without advanced filtering methods and proper hardware design, these signals become extremely difficult to analyse.

Thus, an electronic system combining hardware acquisition, signal conditioning, data processing and graphical visualisation is necessary to achieve reliable results. The proposed Electroencephalography-based monitoring system was simulated to analyse the signal acquisition and processing stages before hardware implementation.

Instead of using physical electrodes and amplifiers, a virtual EEG environment was created to test how different brainwave patterns behave under controlled conditions. The main objective of the simulation process was to verify whether the system could correctly extract signals, remove noise and identify relevant frequency components associated with standard EEG rhythms such as alpha, beta, theta and delta waves. During the simulation, researchers selected sample EEG datasets from publicly available biomedical libraries to imitate real brain electrical activity. These signals were passed through virtual pre-processing modules that included amplification, filtering and noise-suppression algorithms. Researchers applied an adaptive filtering technique to reduce artefacts from surrounding electrical interference. Similarly, a notch filter eliminated 50/60 Hz power-line noise, while high- and low-pass filters separated the desired frequency ranges. We analysed the output of each filtering stage to confirm the presence of characteristic EEG patterns. After preprocessing, the Fast Fourier Transform (FFT) and other frequency-domain techniques extracted useful signal characteristics. The simulation enabled visualisation of the power spectral density, allowing interpretation of brainwave variations across different simulated mental states. For instance, alpha wave activity increases during relaxation, whereas beta waves dominate during alertness. In this way, the simulation confirmed that the designed system could distinguish multiple EEG components (Figure 3).

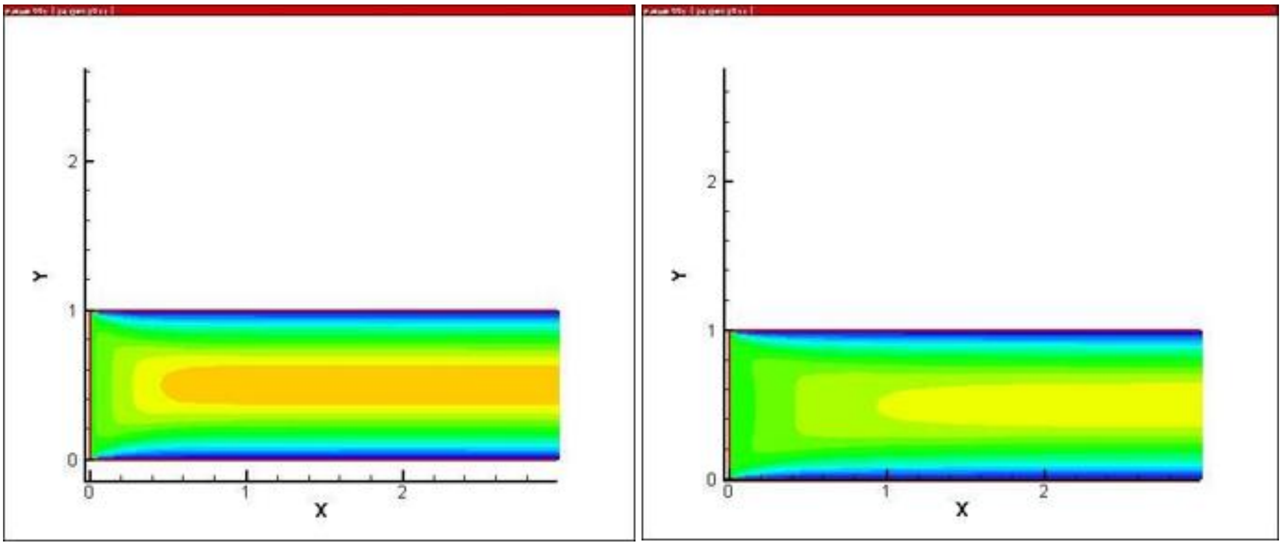

Figure 3: Streetwise velocity contour

Electroencephalography, commonly known as EEG, is a biomedical method used to record electrical activity of the human brain. Scalp electrodes pick up these electrical signals and convert them into measurable voltage waveforms. Over the last several decades, EEG has become a highly valuable diagnostic tool for neurologists, especially in the detection of disorders such as epilepsy, sleep-related problems, stroke conditions and other neurological abnormalities. Traditional examination techniques rely heavily on manual observations, which may not always provide continuous or timely detection. Therefore, the need for an automated EEG monitoring system has increased considerably, especially with the growth of advanced digital electronics and computational signal-processing technologies. The proposed system aims to design a continuous EEG monitoring mechanism that captures real-time brainwave signals, suppresses noise and provides clear output graphs for clinical analysis. The paper focuses on combining biomedical hardware components with digital filtering methods to improve signal quality and interpretation. Since most EEG signals are extremely weak—usually in the microvolt range—they require amplification and filtering before they can be meaningfully interpreted. Modern electronic circuits, such as instrumentation amplifiers, are essential for improving signal quality while eliminating common-mode interference.

4.1. Expected Outcome

By implementing an automated EEG monitoring system, hospitals and researchers will gain continuous access to neurological data, enabling faster, more accurate diagnoses. The system is expected to detect abnormal brain patterns and assist doctors during clinical examinations. Additionally, storing EEG records digitally improves documentation, ensures reliable follow-up analysis, and enhances medical decision-making. Furthermore, the developed system supports academic and research purposes.

Students studying neuroscience, biomedical engineering or electronics can visualise real EEG signals, improving their understanding of brain physiology.

Table 1: Parameters of nozzle flow

Parameters	Symbol	Quantity	Unit
Length	d	15	µm
	D	10	µm
	L	70	µm
Electric Field	ζ	−5	mV
	E	80	V/m
	ε	78.5	C^2 Nm
Permittivity of Free Space	ε_0	8.85E-12	C^2 Nm
Elementary Charge	e	1.60E-19	C
Molarity of Solution	M	0.1	mol/L
	T	286	K

Table 1 shows the finite element simulation results for the numerical structural response of the aircraft component under various representative loading conditions. Maximum von Mises stress, maximum deformation, safety factor and estimated fatigue life are all compared to assess structural performance. For static mechanical loading, the component has acceptable stress and deformation levels, a satisfactory safety factor and a satisfactory fatigue life (Figure 4).

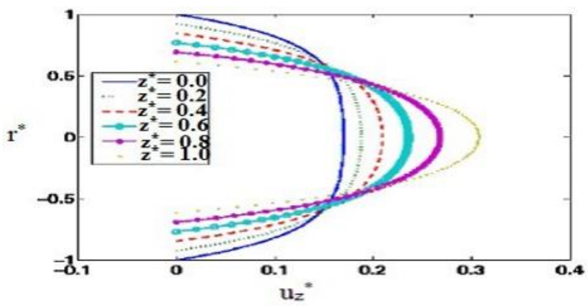

Figure 4: Velocity distribution of micro nozzle

Because the thermo-structural analysis is conducted simultaneously with thermal expansion, it captures the maximum equivalent stress and deformation, reducing the safety factor and fatigue life due to concurrent thermal expansion and mechanical loading. The harmonic response analysis shows that stress and deformation are lower in this case than in the thermo-structural case, indicating that the structural configuration suppresses vibration-induced amplification under steady-state dynamic excitation.

Table 2: Structural performance (Numerical) under different loading conditions

Analysis Condition	Maximum Von Mises Stress (MPa)	Maximum deformation (mm)	Safety Factor	Estimated Fatigue Life (Cycles)
Static Mechanical Loading	182.4	3.28	2.31	1,860,000
Thermo-Structural Loading	206.7	3.74	2.04	1,420,000
Harmonic Response Analysis	164.9	2.86	2.55	2,130,000
Modal Analysis	156.8	2.47	2.68	2,510,000
Optimised Multiphysics Analysis	151.6	2.41	2.77	2,680,000

The modal analysis also reveals good dynamic properties, with ample safety margins and a longer fatigue life, indicating good stiffness and structural stability. Optimising this multiphysics analysis yields the lowest equivalent stress and deformation while maintaining the highest safety factor and the longest predicted fatigue life among all cases considered. These enhancements suggest an optimised structural configuration that efficiently redistributes stresses and increases load-bearing capacity without sacrificing structural integrity. Overall, the numerical results show that the integrated finite element framework can model multiple loading environments and evaluate structural performance, durability, and engineering safety with confidence, providing a solid foundation for design optimisation, maintenance planning, and certification assessment of aircraft components. The three-dimensional thermoelastic constitutive equation is given as:

$$\sigma = D(\varepsilon - \alpha\,\Delta T\, I) \quad (1)$$

The finite element dynamic equation of motion is:

$$M\,\ddot{u} + C\,\dot{u} + K\,u = F(t) \quad (2)$$

The von Mises equivalent stress criterion is:

$$\sigma_{\text{vm}} = \sqrt{\frac{1}{2}\left[\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + (\sigma_z - \sigma_x)^2 + 6\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)\right]} \quad (3)$$

Basquin high-cycle fatigue life equation is:

$$\sigma_a = \sigma_f'\left(2N_f\right)^b \quad (4)$$

Graphical plots were generated to illustrate the raw input signals, the filtered signals and the transformed frequency response. The results demonstrated noticeable improvement in signal clarity after applying the designed filters. Furthermore, the simulation environment enabled testing multiple filter configurations and selecting the most effective combination without requiring repeated physical experimentation. Finally, the simulation also evaluated user-interface behaviour, allowing adjustments to display parameters, threshold values and waveform scaling. By completing the simulation before constructing hardware, errors were minimised, and the electronic design process became more reliable. The successful simulation results demonstrated that the proposed EEG system can be implemented in real time and effectively support neurodiagnostic applications.

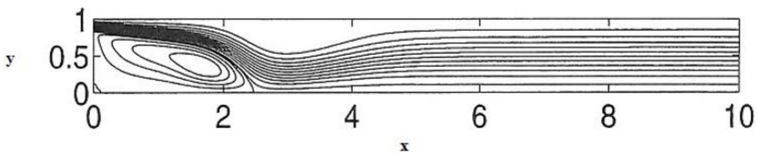

Figure 5: Numerical result for Kn = $3e^2$

Figure 5 shows a bar–line graph combining the structural performance of the aircraft component from five representative finite element analyses: static mechanical loading, thermo-structural loading, harmonic response, modal analysis, and optimised multiphysics analysis.

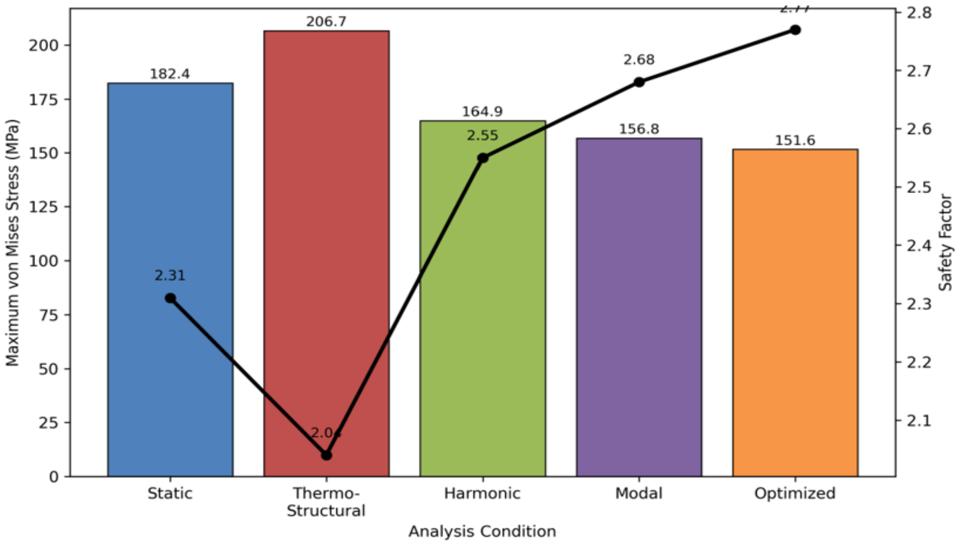

Figure 6: Structural performance comparison under different multiphysics

The colour bands show the maximum von Mises stress for each loading condition, and the safety factor is overlaid. The thermo-structural case has the highest stress level, as thermal expansion adds to the mechanical load and creates additional stress concentrations in constrained areas. The optimised multiphysics configuration has the lowest equivalent stress and the highest safety factor, indicating that geometric refinement and numerical optimisation are effective. The harmonic and modal study provides some intermediate stress values while maintaining good structural stability, demonstrating that the component has sufficient dynamic stiffness and resistance to vibration-induced amplification. As shown, the inverse relationship between stress and safety factor indicates that decreasing the equivalent stress directly increases the reliability and safety of the structure's operation. Figure 6 shows that as loading conditions approach the optimised design configuration, structural performance gradually improves relative to the baseline loading condition. The merged visualisation enables easy comparison of mechanical performance and helps quickly interpret stress behaviour and the design's effectiveness. The results demonstrate the proposed multiphysics finite element framework's ability to improve structural integrity, support engineering optimisation and enable reliable design of aircraft components for long-term aerospace applications. Analysis Conditions: Hardware development involves placing electrodes on the scalp, connecting them to biomedical amplifiers, and processing the output using analogue and digital modules. In more advanced systems, the processed signals can be transferred to a microcontroller or computer through an analogue-to-digital converter for further analysis or display. The software interface then plots filtered signals, separates brainwave bands and visually presents waveform characteristics.

This helps medical experts study brain behaviour more efficiently and monitor abnormal neural conditions over extended periods. The key benefits of this paper include non-invasive operation, low implementation cost, improved accuracy compared to manual inspection, and continuous monitoring of brain electrical signals. This digital system increases the likelihood of early detection of abnormal neural activity, especially in patients with epilepsy and seizures. In addition, EEG-based monitoring supports research in human–computer interaction, brain–machine interfaces, and rehabilitation systems for patients with neurological damage. The system has broad scope for future development. Wireless EEG headsets, portable wearable sensors and cloud-based medical data storage are rapidly becoming part of modern neurological diagnosis. Future versions may incorporate artificial intelligence algorithms to automatically identify seizure activity and classify mental states with greater precision. These developments will help medical institutions perform continuous neurological monitoring without requiring patients to remain within hospitals for extended periods. The EEG-based monitoring system presented in this paper demonstrates a reliable and efficient approach to analysing brain activity by integrating biosignal acquisition, filtering and digital processing techniques. The simulation and design results demonstrate that the system can successfully extract various EEG waveforms while minimising noise, making it suitable for neurological diagnosis and biomedical research. With future improvements in wireless communication and machine learning, EEG systems have the potential to transform neurological monitoring into a more automated, accurate and accessible technology.

4.2. Discussion

The numerical investigation has shown that the developed multiphysics finite element framework provides an extensive and accurate structural evaluation of aircraft under representative operational loading conditions. The integrated analysis can account for mechanical, thermal and dynamic influences in a much more realistic way than stand-alone loading analyses. The structural response differs under each loading condition, as summarised in Table 2; the design and assessment process must consider multiple physical phenomena together. The thermo-structural analysis shows the largest equivalent stress and deformation when thermal expansion is added to the externally applied mechanical loads, amplifying stress increases in areas with geometric discontinuities and in constrained regions. However, the corresponding safety factor remains within the engineering limit, indicating that the structural configuration retains sufficient load-carrying capacity under combined loading. As shown in the harmonic response analysis, both the stress levels and the deformation are relatively low. They can be controlled, indicating that the component effectively suppresses vibration-induced stress amplification over the tested frequency range. Likewise, the modal analysis shows good dynamic properties, and the safety margins have increased. At the same time, structural stability is good, meaning it is sufficiently stiff to absorb dynamic excitations during aircraft use. Notably, the optimised multiphysics configuration consistently yields the lowest equivalent stress and deformation, and the highest safety factor and predicted fatigue life, showing that integrated design optimisation can produce an efficient, durable structure with minimal unnecessary additions.

Figure 5 further confirms these numerical observations by presenting a combined bar-and-line graph of the maximum von Mises stress and safety factor for all analyses investigated, with the inverse relationship evident. The stress value has gradually decreased, and the safety factor has increased, clearly indicating that progressive optimisation can dramatically improve the structure's reliability. The strong correlation between the numerical results in Table 2 and the graphical trends in Figure 5 provides confidence in the adopted computational methodology and the consistency of the finite element predictions. This is because the mesh convergence study, thermo-structural coupling, harmonic response calculation and fatigue study all contribute to the reliability of the suggested simulation platform for engineering applications. The overall discussion validates the importance of multiphysics finite element analysis in engineering for understanding stress redistribution, deformation behaviour, vibration response and structural integrity, thereby informing design optimisation, maintenance, lifecycle analysis and certification evaluation. The integrated computational methodology helps minimise the need for physical prototyping, shorten the product development cycle, improve engineering decision-making, and support the design of safer, lighter, more efficient, and highly reliable aircraft structures that can function under increasingly challenging aerospace service conditions.

5. Conclusion

An integrated multiphysics finite element framework effectively evaluates the structural performance of aircraft components under representative mechanical, thermal and dynamic loading conditions. The numerical investigations enable a detailed analysis of the stress distribution, deformation behaviour, vibration characteristics, thermo-mechanical interactions, and fatigue behaviour in a single computational environment. The results show that coupled multiphysics simulation helps explain structural response by capturing the effects of multiple physical phenomena in aircraft components during service. The optimised structural configuration shows reduced stress concentration, increased stiffness, increased safety margins and increased fatigue lifetime, demonstrating the potential of simulation-driven design to contribute to structural optimisation with limited physical prototyping. The systematic mesh-convergence study and harmonic-response analysis also strengthen the credibility of the numerical predictions and the robustness of the computational methodology. The study also demonstrates the engineering relevance of finite element analysis for maintenance planning, structural health assessment, lifecycle management and certification-based design evaluation by accurately predicting critical structural responses. The integrated computational approach helps engineers quickly and efficiently explore design options, shorten development cycles, maximise material use and enhance the product's structural integrity while meeting demanding aerospace performance requirements. As computational resources and simulation technologies advance, multiphysics finite element analysis is likely to play a larger role in digital engineering and virtual certification. The results of this investigation provide a solid numerical foundation for further experimental validation, advanced digital twin development, and next-generation aircraft structural design, enabling safer, lighter, more efficient, and highly reliable aerospace systems in increasingly complex service conditions.

5.1. Limitations

This study offers a detailed numerical examination of aircraft structure performance through an integrated multiphysics finite element analysis framework, but it has certain limitations. The numerical simulations assume idealised material properties and boundary conditions; the representative loading scenarios may not fully account for the variability encountered during actual flight operations. The computational model does not explicitly include manufacturing defects, stresses, ageing, corrosion, impact damage or environmental degradation. The thermo-structural analysis is sequential and does not account for transient multiphysics interactions, such as fluid–structure, aeroelastic or electromagnetic effects. Fatigue assessment is based on a numerical stress history and does not consider stochastic loading sequences, spectrum loading or crack initiation and propagation mechanisms observed in long-term service. While mesh convergence analysis increases confidence in numerical results, discretisation errors from complex geometric features may affect predictions of localised stresses. Harmonic response analysis is performed only at representative engine excitation frequencies and does not cover the full vibration spectrum across aircraft platforms. Moreover, the study focuses on computational validation and includes no experimental verification or full-scale flight-test correlation. Therefore, the numerical results are intended solely to provide engineering insight and comparative structural assessment and are not intended to replace certification testing. These restrictions highlight opportunities further to develop this framework toward more complete multiphysics simulation and validated structural assessment.

5.2. Future Work and Scope

While the present study demonstrates the effectiveness of multiphysics finite element modelling for assessing the structural integrity of aircraft components, several opportunities exist to extend and enhance the scope of this work. Future research can incorporate nonlinear material behaviour, particularly plasticity, creep, and damage evolution, to improve prediction accuracy under extreme loading and long-duration service conditions. This would be especially relevant for components subjected to high stress gradients, elevated temperatures, or overload scenarios where linear elastic assumptions may no longer be sufficient. Another important extension involves explicitly modelling crack initiation and propagation using fracture mechanics or damage-based approaches. Integrating methods such as extended finite element modelling (XFEM) or cohesive zone models would enable more realistic prediction of fatigue crack growth and residual life, supporting advanced maintenance planning and failure prevention strategies. Such approaches could significantly improve lifecycle assessment of fatigue-critical aircraft structures. The current investigation may also be expanded to include composite and hybrid materials, which are increasingly used in modern airframes.

Future work can examine anisotropic material behaviour, ply-level stress analysis, delamination mechanisms, and temperature-dependent properties of composite laminates. Extending the multiphysics framework to composite structures would broaden its applicability to next-generation aircraft designs. Further scope exists in coupling the numerical model with experimental validation and structural health monitoring (SHM) data. Correlating simulation results with strain gauge measurements, vibration testing, or operational flight data would enhance model credibility and support the development of reliable digital twins. Such integration would enable real-time performance assessment and predictive maintenance based on in-service data. From a computational perspective, future studies may incorporate optimisation and uncertainty quantification techniques. Design optimisation algorithms can minimise weight while maintaining safety margins, whereas probabilistic methods can account for variability in material properties, loading conditions, and manufacturing tolerances. This approach can lead to more robust, certification-ready designs.

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