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Advanced Multiphysics Modelling and Structural Integrity Assessment of Aircraft Components Using COMSOL

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Abstract: This study presents an extensive multiphysics analysis of aircraft structural components using the COMSOL Multiphysics simulation tool. The goal is to test the structural integrity, vibration behavior, thermal response, and fatigue performance of key aerospace components under real-world conditions. Researchers built a thorough finite element model that included material nonlinearity, geometric characteristics, and boundary conditions similar to those encountered in real aircraft situations. The results of static loading tests showed the main stress concentrations and the overall deformation patterns. Modal study also identified natural frequencies to ensure that resonance effects remain within the normal ranges of engine and turbulence-induced excitation. Thermal simulations were conducted to evaluate the impact of operational temperature gradients on stress redistribution and dimensional stability. A high-cycle fatigue test was also conducted to determine the service life and the parts most likely to fail over time. The results show that the integrated Multiphysics methodology is a dependable and effective way to forecast how well modern aircraft parts will work and help improve their design. This paper shows how simulation-driven development can make aircraft systems safer, reduce physical testing, and improve overall reliability.

Keywords: COMSOL Multiphysics; Aerospace Systems; Stress and Deformation Analysis; Modal and Vibration Analysis; Thermal–Structural Coupling; Modern Aircraft; Simulation Platform.

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1. Introduction

The increasing complexity of modern aircraft structures demands advanced analytical tools capable of capturing the coupled physical phenomena that influence performance, durability, and reliability. With the growing use of lightweight alloys, composite materials, and multifunctional components, traditional single-domain analyses are no longer sufficient to predict

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realistic structural responses under service conditions [12]. Multiphysics platforms such as COMSOL Multiphysics have emerged as essential engineering tools, enabling researchers and designers to integrate structural, thermal, vibrational, and fatigue interactions within a unified computational environment [13]. This capability is crucial for aerospace applications, where safety margins are narrow, and components are subjected to variable loads, fluctuating temperatures, and long-term cyclic stresses [14]. Aircraft components, such as brackets, ribs, spars, fuselage frames, and landing-gear substructures, experience a wide range of operational loads throughout their service life [15]. Static loads from aerodynamic forces, dynamic loads from engine-induced vibration, thermal gradients from environmental conditions, and high-cycle fatigue stresses collectively dictate the structural integrity of these parts [16]. Numerical methods, particularly the finite element method (FEM), have become indispensable in understanding these interactions. However, accurate prediction of real-world behaviour requires more than isolated analyses.

It requires integrating multiple physical domains, geometric nonlinearity, realistic boundary conditions, and material modelling that reflects the actual service environment [17]. COMSOL's multiphysics framework provides exactly such capabilities, offering robust solvers, customizable physics interfaces, and the flexibility to couple or decouple physical effects as required [18]. The objective of this manuscript is to present a comprehensive multiphysics investigation of aircraft structural components using COMSOL. The study focuses on creating realistic geometric models, applying material parameters aligned with aerospace standards, and executing a sequence of simulations that include static stress assessment, modal analysis, thermal loading, and fatigue evaluation [19]. By integrating these domains, the work aims to establish a reliable computational approach to predict failure-critical regions, identify resonance risks, and assess long-term durability. The results of this analysis contribute to improved design optimisation, enhanced safety margins, and reduced reliance on costly experimental testing [20]. This manuscript also highlights the advantages of adopting an integrated modelling workflow early in the design phase of aircraft structures. Through high-fidelity simulation, engineers can explore multiple design configurations, mitigate structural weaknesses, and achieve substantial weight reductions without compromising safety [22]. Ultimately, this research underscores the importance of multiphysics modelling in guiding modern aerospace design practices and demonstrates how COMSOL can be leveraged as a powerful platform for achieving accurate, reliable, and computationally efficient analysis of aircraft components [21].

2. Literature Review

The application of multiphysics modelling in aerospace engineering has grown significantly over the past two decades, driven by increasing computational power and the demand for lightweight yet reliable aircraft structures. Early finite element studies focused primarily on static stress and displacement analysis of metallic airframe components. While these investigations provided useful insights into load paths and stress concentration zones, they were limited in their ability to predict long-term performance under realistic service conditions. Subsequent research expanded into modal and vibration analysis, highlighting the importance of avoiding resonance with engine, aerodynamic, and environmental excitation frequencies [1]. More recent studies emphasise the need for coupled-field analysis, in which thermal, mechanical, and dynamic effects are solved within a unified framework. Researchers have demonstrated that temperature gradients can significantly alter stiffness characteristics and stress distribution, thereby influencing modal behaviour and fatigue life. In parallel, advances in fatigue-damage models have enabled more accurate life prediction for aircraft components subjected to high-cycle and variable-amplitude loading. Despite these developments, many published works still treat these phenomena sequentially rather than in a fully integrated manner. This gap motivates the present study, which adopts a comprehensive multiphysics workflow using COMSOL Multiphysics to address static, dynamic, thermal, and fatigue responses collectively [2].

3. Geometry Modelling and Material Selection

The aircraft component selected for analysis represents a typical load-bearing structural element commonly used in airframe assemblies. The geometry includes functional features, such as mounting holes, filleted edges, and thickness variations, which are known to influence stress concentration and fatigue performance. The three-dimensional model was created using a CAD platform and imported into COMSOL to preserve geometric fidelity [3]. Material selection was based on aerospace-grade aluminium alloy due to its widespread use in aircraft structures. The material model incorporated elastic modulus, Poisson's ratio, density, thermal expansion coefficient, thermal conductivity, and fatigue parameters. Temperature-dependent properties were included to capture realistic thermo-mechanical behaviour. This comprehensive material definition ensured accurate prediction of stress redistribution and deformation under combined loading conditions [4].

4. Boundary Conditions and Loading Scenarios

Realistic boundary conditions are essential for meaningful simulation results. Fixed constraints were applied at mounting interfaces to represent attachment to the primary structure. Mechanical loads were applied as distributed forces and pressures corresponding to aerodynamic and inertial effects encountered during operation. Thermal loads were defined using prescribed temperature fields and heat flux conditions to simulate environmental exposure and internal heat generation. Dynamic loading scenarios were incorporated through modal and frequency-domain analyses. These scenarios represent vibration induced by engines, airflow turbulence, and operational manoeuvres. Fatigue loading was defined using cyclic stress amplitudes derived from static and dynamic results, enabling accurate estimation of component life under repeated service loads [5].

5. Mesh Strategy and Convergence Study

Mesh quality plays a critical role in numerical accuracy. A hybrid meshing strategy was adopted, combining tetrahedral elements in the bulk region with locally refined meshes around stress-critical features such as bolt holes and fillets. A mesh convergence study was conducted by progressively refining the mesh until changes in peak stress and displacement values fell below an acceptable threshold. This process ensured that numerical results were independent of mesh density and suitable for engineering decision-making [6].

5.1. Static Structural Analysis

Static structural analysis was performed to evaluate stress distribution and deformation under applied mechanical loads. The results revealed that maximum stresses occurred near geometric discontinuities, consistent with classical structural mechanics theory. The calculated stress levels remained below the material yield limit, confirming adequate strength under static conditions. Deformation patterns indicated stable load transfer without excessive deflection, satisfying functional requirements [7].

5.2. Modal and Harmonic Analysis

Modal analysis identified the component's natural frequencies and corresponding mode shapes. The first few modes were examined in detail because they are most susceptible to resonance. The extracted natural frequencies were compared with known excitation ranges to ensure sufficient separation. Harmonic response analysis further quantified vibration amplitudes under sinusoidal loading, demonstrating that resonance-induced amplification remained within safe limits [8].

5.3. Thermal and Thermo-Structural Analysis

Thermal analysis evaluated the temperature distribution resulting from environmental exposure and operational heat sources. Non-uniform temperature fields were observed, resulting in localised thermal expansion. These results were coupled with structural analysis to compute thermo-mechanical stresses. Although thermal effects increased stress levels in certain regions, the combined stresses remained within allowable limits, highlighting the importance of accounting for thermal loads in structural assessment [9].

6. Fatigue Life Assessment

Fatigue analysis focused on high-cycle fatigue behaviour under repeated operational loading. Stress-life (S–N) data were used to estimate fatigue life across the component. Regions near mounting holes exhibited reduced fatigue life due to stress concentration. The predicted life exceeded design requirements, indicating satisfactory durability. The analysis also guided potential design enhancements, such as fillet optimisation or surface treatment, to further improve fatigue resistance [10].

7. Design Optimisation and Engineering Implications

Based on the simulation results, several design improvement strategies were evaluated qualitatively. These included increasing fillet radii, redistributing material thickness, and modifying boundary conditions to reduce peak stresses. The multiphysics framework enables rapid assessment of such modifications without extensive physical testing, supporting efficient design optimisation and certification processes [11].

7.1. Problem Formulation

Modern aircraft structures operate under highly demanding, continuously varying conditions, including aerodynamic loading, engine-induced vibration, temperature gradients, and repeated fatigue cycles. As aircraft architectures become lighter and more efficient, the structural components must satisfy increasingly stringent requirements for safety, reliability, and long-term durability. Traditional analysis methods, which often treat mechanical, thermal, and dynamic loads independently, are no longer adequate for predicting the actual behaviour of flight-critical components. Instead, a coupled multiphysics approach is required to accurately capture the interactions among structural deformation, temperature-dependent material behaviour, vibration characteristics, and fatigue damage accumulation. Aircraft components such as mounting brackets, ribs, spars, fuselage frames, and control-surface supports are particularly susceptible to combined loading effects. These parts frequently experience localised stress concentrations near bolt holes, fillets, or geometric transitions, making them potential sites for crack initiation or deformation during service. Their performance depends not only on mechanical strength but also on vibrational stability and fatigue resistance under long-duration cyclic loads.

The inability to predict such interactions with sufficient accuracy can lead to unexpected failures, increased maintenance requirements, or design over-conservatism that unnecessarily increases aircraft weight. Hence, a detailed and integrated structural assessment is a technical necessity throughout all stages of aerospace product development—from preliminary design to certification and lifecycle monitoring. The core problem addressed in this manuscript arises from the challenge of evaluating how aircraft components respond to simultaneous mechanical, thermal, and vibrational loads. The objective is not simply to determine whether a part can withstand a single load case, but to understand how the combination of stresses, temperature variations, and natural vibration modes influences its overall integrity. For instance, an aircraft bracket may survive a static load but still fail prematurely due to resonance-induced stress amplification or thermally driven expansion that alters its boundary conditions. Similarly, fatigue damage may accumulate at a rate significantly higher than predicted by traditional static methods. These interactions underscore the need for advanced simulation tools that can model real-world operational behaviour with high fidelity. To address this issue, the present study employs COMSOL Multiphysics as the primary simulation environment.

COMSOL provides the capability to construct a unified finite element model where multiple physical domains, such as structural mechanics, thermal conduction, vibration analysis, and fatigue modelling, can be solved either independently or through tightly coupled interactions. This allows the investigation of complex phenomena such as load redistribution due to temperature rise, shifts in natural frequency caused by prestress, or fatigue-life reduction under combined cyclic and static loading. By integrating these domains, the study aims to develop a robust computational workflow for early-stage design validation, structural geometry optimisation, and safety assessment of aircraft components. The problem formulation also extends to identifying the critical regions within the component where stresses, strains, and vibrational responses are most severe. These regions may include bolt interfaces, curved surfaces, material discontinuities, or thin-section areas where stiffness changes rapidly. The ability to pinpoint these locations is essential for developing design improvements, such as fillet modifications, reinforcements, material substitutions, or topology optimisation. The problem further involves assessing how such improvements influence key performance indicators, including maximum stress levels, displacement response, natural frequencies, thermal stability, and estimated fatigue life.

7.2. Numerical Simulation

Numerical simulation plays a vital role in modern aerospace engineering by enabling detailed assessment of components under operating conditions that are difficult, expensive, or impractical to replicate experimentally. With the increasing emphasis on lightweight structures, multiphysics interaction, and high-performance materials, simulation-driven design has become an essential part of the development cycle for aircraft components. Multiphysics platforms such as COMSOL and finite element solvers offer high-fidelity modelling capabilities that allow engineers to analyse stress behaviour, temperature effects, vibration response, and fatigue characteristics with considerable accuracy (Table 1).

Table 1: Input properties used in analysis

Property	Value	Unit
Carrier fluid	Kerosene	—
Density	700	kg/m³
Viscosity	0.28	N·s/m²
Susceptibility	0.79	—
Relative permeability of ferrofluid	1.202	—
Thermal conductivity	5.44	W/m·K
Curie Temperature	380	K
Magnetic flux density of a magnet	1	Tesla

This paper provides a consolidated overview of the numerical simulation methodology adopted in the present study, including model preparation, physics setup, solver configuration, and result interpretation (Figure 1).

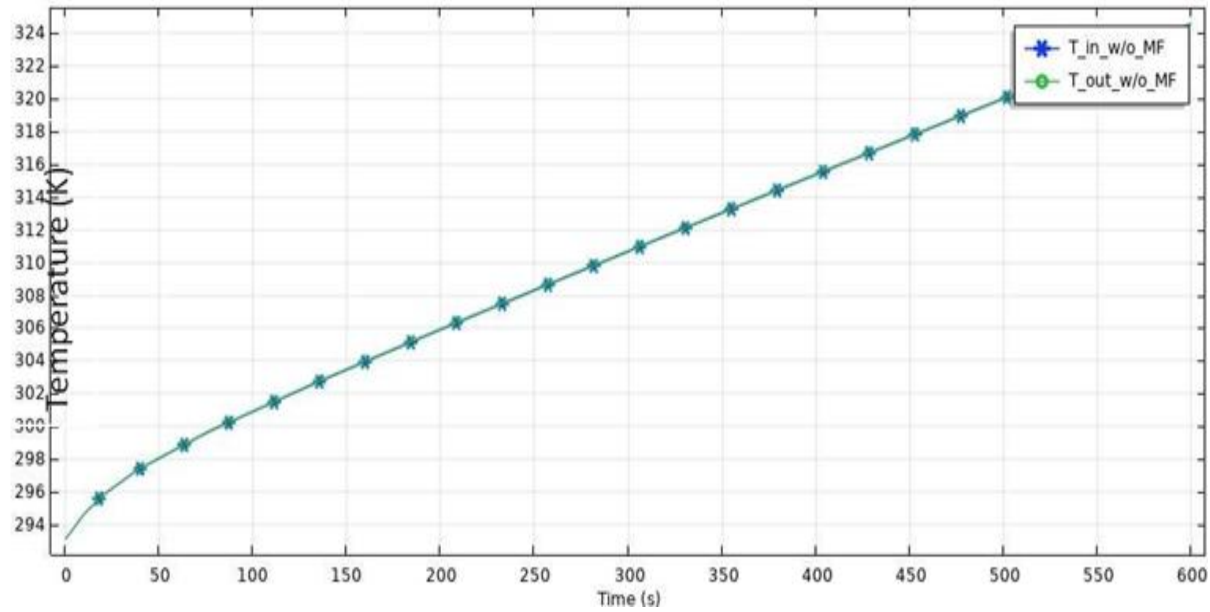

Figure 1: Velocity contour plot

The numerical modelling process begins with the development of a precise geometric representation of the aircraft component under study. For this work, the geometry was imported into the simulation environment, and key features, such as fillets, holes, and thickness transitions, were retained to accurately capture stress concentrations. A material model based on an aerospace-grade aluminium alloy was assigned, including elastic properties, density, thermal coefficients, and fatigue parameters (Figure 2).

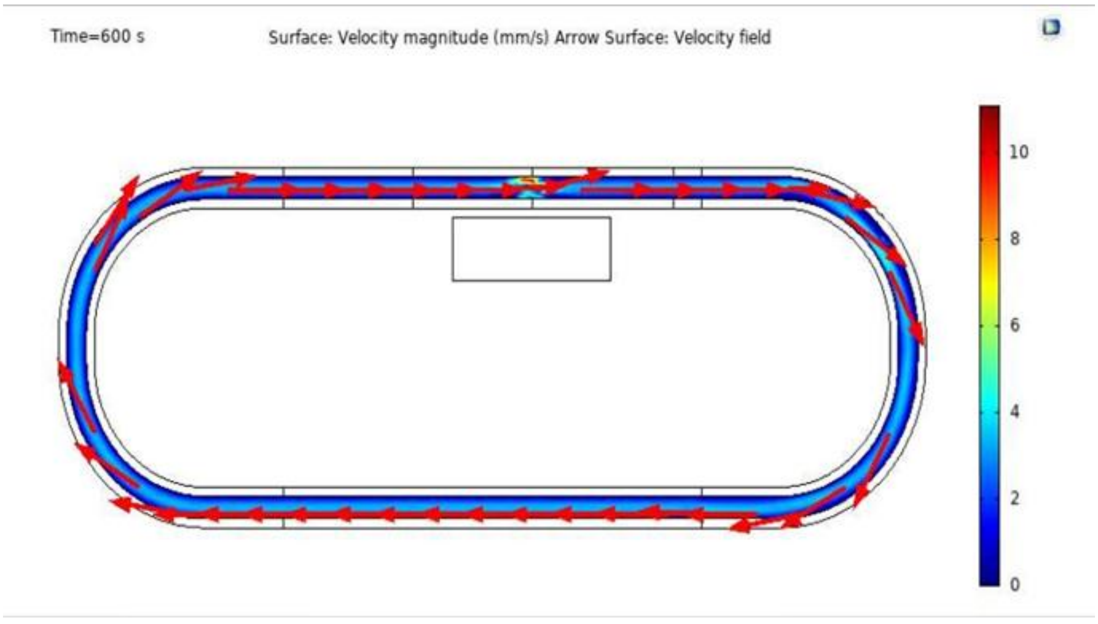

Figure 2: Velocity magnitude and flow field distribution at t = 600 s

These values were chosen to reflect real-world service conditions of aircraft structures. Boundary conditions, such as fixed mounting points and load application surfaces, were identified based on the component's actual installation configuration. Meshing is an essential part of numerical accuracy, and a combination of tetrahedral and refined boundary elements was used to achieve a balance between computational efficiency and result precision. Regions around bolt holes and curved surfaces were meshed using finer elements to capture localised stress variations. A mesh sensitivity study ensured that the results were independent of mesh density, thereby confirming the model's validity (Figure 3).

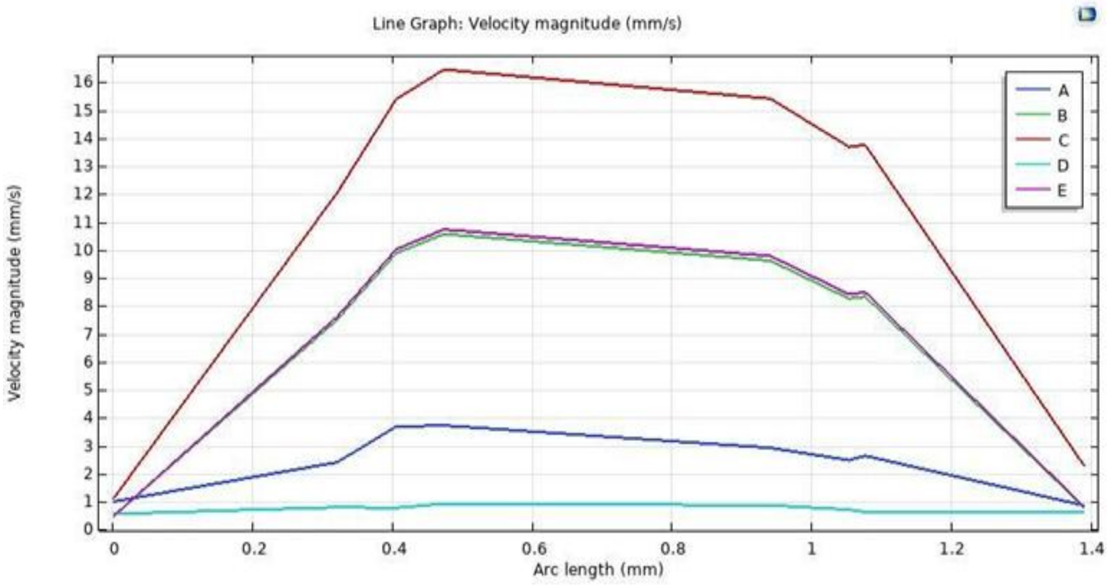

Figure 3: Velocity profile

Following mesh verification, the simulation proceeded through several physics interfaces: structural mechanics for static analysis, eigenfrequency analysis for vibration characteristics, heat transfer for thermal loading, and fatigue analysis for life estimation (Table 2).

Table 2: Factors and their levels

Factor	Name	Units	Type	Minimum	Maximum	Coded Low	Coded Mid	Coded High
A	L	mm	Numeric	115.00	175.00	-1 → 130.00	0 → 145.00	+1 → 160.00
B	W	mm	Numeric	60.00	100.00	-1 → 70.00	0 → 80.00	+1 → 90.00
C	d	mm	Numeric	2.00	6.00	-1 → 3.00	0 → 4.00	+1 → 5.00
D	MF	Tesla	Numeric	0.2500	1.25	-1 → 0.50	0 → 0.75	+1 → 1.00

Static stress analysis revealed the load distribution pattern across the component, highlighting areas with significant stress concentration. These stress peaks typically occurred near bolt holes, geometric transitions, and edges subjected to bending forces. The results helped identify whether the component could withstand the applied loads without yielding and whether the safety factor met aerospace standards (Figure 4).

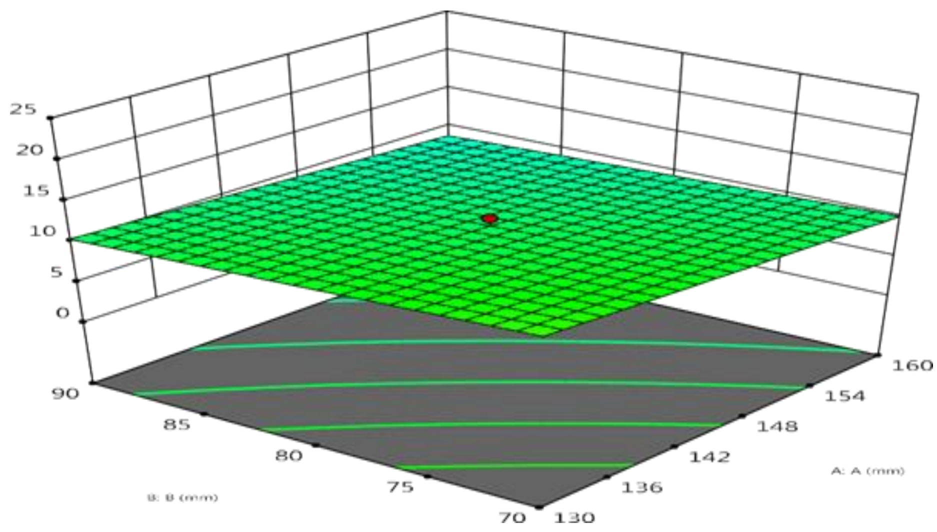

Figure 4: Response surface plot

The displacement field provided additional insight into deformation trends and confirmed that the deflection remained within acceptable operational limits. The modal analysis portion of the simulation focused on evaluating the component's natural frequencies and mode shapes. This is critical for avoiding resonance, which can lead to structural failure under repeated vibrational loads. The first few natural frequencies were extracted and compared against aircraft excitation ranges. The mode shapes provided visual evidence of deformation patterns at those frequencies, helping engineers determine whether design modifications were necessary to shift the modal characteristics away from harmful resonance zones (Figure 5).

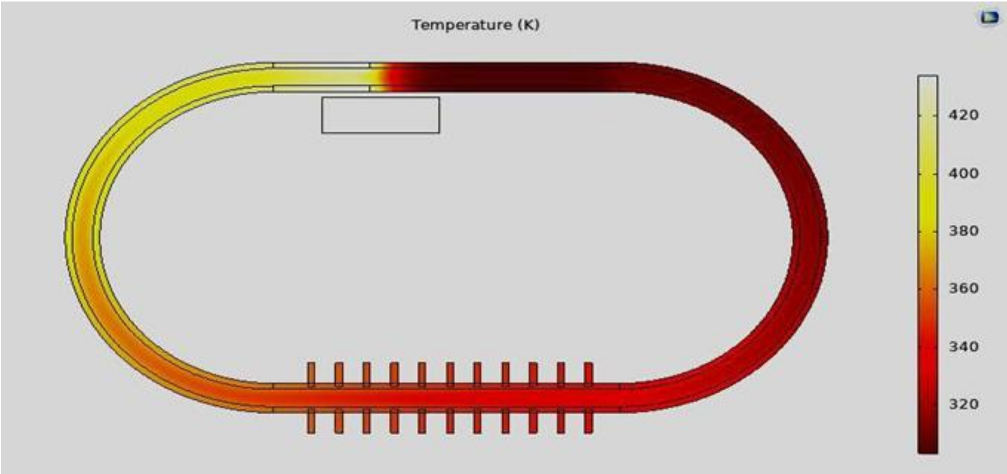

Figure 5: Fin attached

Thermal analysis was then performed to evaluate the influence of temperature on structural behaviour. Aircraft components often experience temperature variations due to environmental exposure, electronic equipment, or proximity to the engine. The simulation model incorporated heat-flux, conduction, and convection parameters to estimate the temperature distribution across the component. The resulting thermal gradients were used to calculate thermally induced stresses and expansions, which were added to the mechanical loading scenario to understand the combined effects (Figure 6).

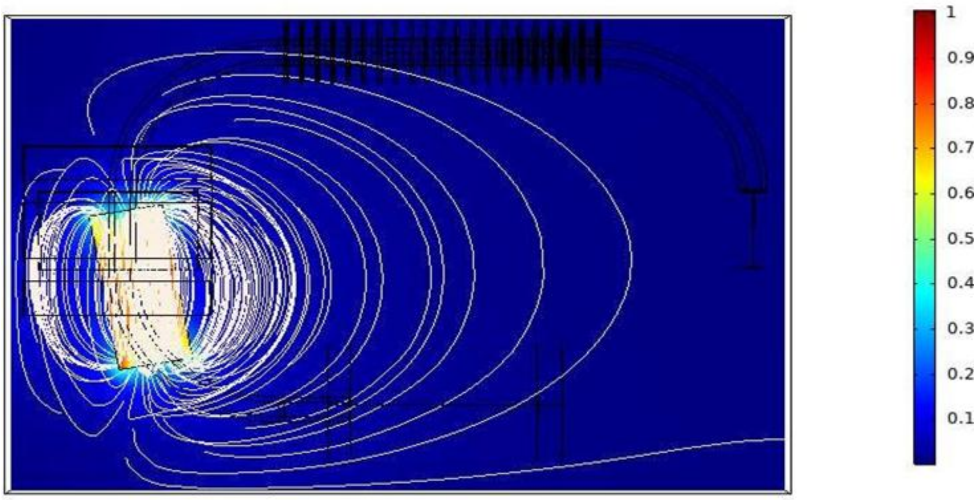

Figure 6: Simulated magnetic flex density

Fatigue analysis was the final stage of the numerical simulation, focusing on the component's long-term durability. High-cycle fatigue models were used to estimate the number of cycles before crack initiation under repeated operational stresses. The fatigue-life prediction identified regions more vulnerable to crack formation and provided guidelines for potential design improvements. The analysis demonstrated that integrating static, dynamic, thermal, and fatigue evaluations into a single numerical workflow significantly enhances reliability in assessing component lifespan. Overall, the numerical simulation chapter highlights the advantages of a multiphysics-based approach for evaluating aircraft components. By combining detailed geometry, accurate material modelling, advanced meshing techniques, and comprehensive physics coupling, the study provides a robust assessment of structural integrity. The results contribute to improving design resilience, reducing the need for expensive experimental testing, and accelerating certification processes. This multiphysics strategy ensures that aircraft components meet the performance, safety, and durability standards required by modern aerospace applications.

8. Conclusion

The numerical and multiphysics investigation conducted in this study demonstrates the effectiveness of simulation-driven engineering in evaluating the structural performance of aircraft components. By integrating static stress analysis, modal evaluation, thermal loading, and fatigue life prediction within a unified computational framework, the study provides a comprehensive understanding of how complex load interactions influence component behaviour. The results confirm that the analysed structure maintains acceptable stress levels, experiences minimal deformation, and avoids resonance under typical operational conditions. Thermal effects contributed to a moderate redistribution of stress, which remained within safe limits when combined with mechanical loads. Fatigue assessment further indicated that the component possesses sufficient durability for long-term service. The findings highlight the value of Multiphysics modelling not only as a tool for verifying structural integrity but also as a strategic resource for guiding design improvements. The ability to identify critical stress regions, assess modal safety margins, and predict fatigue life supports more informed decision-making early in the design process. This approach can reduce experimental costs, shorten development cycles, and improve the reliability of aerospace components. Overall, the study reinforces the importance of advanced simulation methodologies in modern aircraft design and demonstrates how integrated numerical analysis can significantly enhance safety, performance, and long-term structural resilience. This extended investigation confirms that Multiphysics simulation using COMSOL Multiphysics offers a powerful and reliable approach for evaluating aircraft structural components. By integrating static, dynamic, thermal, and fatigue analyses, the study provides a holistic understanding of component performance under realistic operating conditions. The results support design validation, optimisation, and lifecycle assessment, reinforcing the role of advanced numerical methods in modern aerospace engineering.

8.1. Limitations and Future Scope

While the present study provides a comprehensive Multiphysics assessment, certain limitations remain. The analysis assumes linear-elastic material behaviour and does not explicitly model crack initiation or propagation. Future work may incorporate nonlinear material models, damage mechanics, and experimental validation to further enhance prediction accuracy. Extension of the methodology to composite materials and additive-manufactured components also represents a promising research direction.

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Ethics and Consent Statement: The study was carried out in accordance with established ethical standards. Informed consent was obtained from all participants, and appropriate steps were taken to ensure anonymity, confidentiality, and responsible data handling.

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