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A Comparison of Four Design Variants for Investigating Thermal Transients and Structural Performance of Aircraft Disc Brakes

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Abstract: **This research article provides a thorough comparison of four various design types of airplane disc brakes. The study's goal is to evaluate the thermal transient reactions and structural performance of these design variants to improve the safety and efficiency of aviation braking systems. To evaluate the thermal and structural behaviors of each design alternative, the article adopts a systematic technique that includes computer-aided design, thermal transient analysis, and structural analysis. The findings show the complex interaction of design, temperature response, and structural stability in aircraft disc brakes. The findings shed light on the trade-offs that exist between weight reduction, structural deformation, safety margins, and fatigue life. The study also studies temperature distribution and heat flow profiles, offering light on the thermal behavior of various buildings.**

I. INTRODUCTION

The reliable operation of aircraft disc brakes has become essential in the aviation industry to maintain the safety and operational efficiency of aerial vehicles. These critical components are in charge of slowing the airplane down during landing and absorbing and dispersing kinetic energy generated at high speeds. As a result, the thermal and structural behavior of aircraft disc brakes under different operational situations has important implications for both aviation safety and industrial advancement.

The current study begins a thorough examination aiming at comparing the thermal transient reactions and structural performance of aircraft disc brakes across four various design variants. We hope to obtain a better knowledge of how alternative structural configurations affect the thermal dissipation and overall integrity of these crucial braking systems by looking into this area. The necessity to improve the performance and safety of aircraft disc brakes drove the selection of this research topic. As aircraft technology progresses and operating needs rise, it becomes increasingly important to evaluate and optimize the design of disc brakes to resist the harsh circumstances encountered during landings. We hope to provide significant insights by analyzing numerous design variations that can contribute to the improvement of airplane braking systems, resulting in improved safety, efficiency, and performance.

The findings of this study have the potential to help both the aviation industry and society as a whole. Understanding thermal transients and structural behavior in aircraft disc brakes can help to build more robust and reliable braking systems. This results in better aircraft safety, lower maintenance costs, and improved operational efficiency. Furthermore, the findings of this study can be used to inform future design practices, helping to enhance the field of aerospace engineering as a whole.

The major goal of this study is to undertake a detailed comparative examination of four various design variants of aircraft disc brakes, with a particular emphasis on evaluating their thermal transient reactions and structural performance. The study is directed by numerous specific aims to attain this broad purpose. To begin, the study intends to thoroughly analyze the thermal behavior of each design option under simulated landing conditions, closely scrutinizing thermal dissipation patterns and probable heat accumulation spots. We want to discover differences in heat distribution and dissipation efficiency across different design configurations using thorough thermal analysis. Second, the analysis seeks to analyze the structural integrity and load-bearing capacities of each design variant's aircraft disc braking systems. We hope to learn how structural elements affect the overall stability and strength of the braking components during landing situations by subjecting the brakes to computational and analytical methodologies. Finally, the study intends to identify connections between heat dissipation and structural stability in the context of each design alternative. We hope to uncover any causal linkages or dependencies between thermal responses and structural behaviors through statistical and comparative methods,providing insights into the interconnectedness of these essential components.

Finally, the study aims to provide a full evaluation of the benefits and drawbacks of each design alternative in terms of thermal and structural performance. We want to provide engineering practitioners and industry stakeholders with a well-rounded perspective that may guide design decisions and promote informed choices in optimizing the performance of aircraft disc brakes by determining the unique properties of each configuration.

To summarise, the goal and objectives of this study represent a systematic effort to unravel the intricate interplay between thermal transients and structural responses in aircraft disc brakes, thereby contributing valuable insights to the field of aerospace engineering and promoting advancements in aviation safety and efficiency.

The decision to pursue this study issue stems from the ongoing pursuit of safer and more efficient flying practices. As aviation technology advances, so do the problems of guaranteeing consistent performance in dynamic environments. The promise of contributing to the progress of aircraft safety by tackling these difficulties motivates this research effort.

The full comparison of four distinct design options for airplane disc brakes is a novel component of this research. While previous research has focused on specific aspects of thermal or structural behavior, our research aims to bridge the gap by investigating both thermal transients and structural integrity at the same time. This comprehensive method provides a more thorough understanding of how different design choices affect the overall performance of aircraft disc brakes, bringing a fresh viewpoint to the area of aerospace engineering.

Literature Review

Kostyantyn Holenko et al.[1] explores the complicated stress-strain conditions and frictional properties inherent in ventilated automobile disc brakes in the area of automotive engineering. This investigation carried out within the ANSYS environment, dives at variables such as angular speed, pad pressure, load distribution, convection, and thermal expansion. Notably, the study models stress and transient thermal fields at the pad-disk interface using sequential thermo-structural communication in the ANSYS Coupled Field Transient environment. The approach's effectiveness is demonstrated by empirical validation using ANSYS calculations on a simple steel block assembly. The convergence of analytical formulas and computer modeling strengthens this methodology, which will thereafter be used to calculate ventilated disc brakes in automobiles. This study helps the optimization of braking systems by focusing on the active disc region and taking typical boundary conditions and operational modes into account.

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Mohammad Tauviqirrahman et al.[2] proposes a revolutionary strategy by altering drill hole and groove hole angles while investigating innovative geometric alterations for improved heat dissipation in disc brakes. The thermal performance of disc brakes made of various materials, such as carbon ceramic, stainless steel, and grey cast iron, is thoroughly analyzed using finite element analysis. Notably, the analysis demonstrates that the groove-type disc brake has the lowest maximum temperature with a ventilation hole angle of 0°. Furthermore, the analysis identifies grey cast iron as the material with the lowest peak temperature and reveals temperature concentration phenomena caused by geometric thinning and ventilation hole addition in specific places. This study emphasizes the critical role of disc brake material and ventilation design in changing thermal properties, providing useful insights for brake designers.

K. Holenko et al.[3] is investigating the thermal behavior and stress-strain states of ventilated disc brakes in lightweight automobiles using the ANSYS environment. This study simulates temperature distribution in rotors and brake pads in detail, taking into consideration variables such as rotation speed, pad-disc gap, load application speed, and thermal expansion during braking. The research analyses transient heat and stress fields at the pad-rotor contact region using sequential thermo-structural coupling in the ANSYS Coupled Field Transient environment. Notably, the study examines the impact of rotor ventilation channels on contact spot nature and demonstrates non-linear trends in temperature, volume, and stress when pad pressure increases linearly.

Andrzej Wolff et al.[4] study on railway brake systems includes experimental tests and simulations to increase understanding and practical application. Despite consistently obtaining maximum temperatures of around 400°C and 480°C in bench testing and simulations, differences in temperature progression patterns were discovered. Imperfect measurements from sliding thermocouples and material parameter assumptions are proposed as sources of variance. Despite these obstacles, the study validates infrared measurements and numerical models by finding a low-temperature increase (50-60°C) in extra braking components. This study helps to brake effectiveness analysis and design optimization for railway applications by providing insights into thermal capacity and heat transmission.

Kanithi Giri et al.[5] uses the CAM program UG NX to fabricate a "Disc Brake Plate" component, a CAD/CAM application well-known for its role in component design, tool path development, and CNC machine operation. Using this software, the project entails modeling, tool selection, and tool path generation, culminating in the creation of an NC component program. This program directs the CNC machine to produce the component under optimal conditions, such as speed, feed, and surface polish. The study also emphasizes cost optimization through careful selection of machining operations and equipment, so providing useful insights into manufacturing processes and enhancing efficiency.

The aerospace industry's transition from metals to advanced composites, as typified by Aluminum-Boron- Silicon-Carbon materials, is a watershed moment. These high-performance composites are gaining popularity due to their robustness, high-temperature stability, and decreased wear rates, which promise improved, compact, and long- lasting brakes. While high production costs and limited speed pose obstacles, Yash Vashi[6] anticipates cost reductions as the composite manufacturing sector evolves. The design methodology of Yash Vashi[6] provides a practical and efficient strategy for initial aircraft brake design, including forces, torques, energy, and temperatures during braking. The model's simulation findings, validated against Boeing 737 data, confirm its correctness and potential application in developing brakes for larger aircraft, ensuring safety and optimal operation.

A thorough analysis is required because of the delicate interplay of mechanical loads, friction-generated heat, and changing factors during braking. Siham KERROUZ et al.[7] tackles this challenging problem with numerical simulations using ANSYS 14.5, which employs finite element analysis and friction contact techniques. The study investigates mechanical torque and stresses under transitory settings, taking into account elements such as braking conditions, temperature influences, geometric features, and material properties. The analysis aids in identifying potential problems and finding ideal technological solutions by scrutinizing the behavior of the disc and brake pads during contact. This study provides useful insights for improving the design and dependability of braking systems, with implications for efficient and cost-effective disc and pad material selection.

Said S. Al Riyami et al[8] uses advanced software tools to examine the performance of grey cast iron and cast carbon steel materials to optimize ventilated brake disc design for a specific Mitsubishi Pajero model. Surface perforations improve heat drainage during and after braking, resulting in effective thermal behavior. Stress and thermal assessments influence material selection using Simulation Xpress and ANSYS Workbench, to minimise damage from high temperatures. Notably, cast carbon steel with 30 vanes appears as the preferable choice for stress study, whereas transient thermal analysis highlights the advantages of a drilled disc with fewer vanes. The research of [Researcher Name] offers insights into an optimized brake disc design, which offers increased performance and heat dissipation for automotive applications.

Lakavathu Chinna Balu et al.[9] examines friction and vibroacoustic characteristics of large vehicle disc brakes utilizing brake stand tests. The wear-induced vibration signal and fluctuations in friction coefficient provide information about braking efficiency. Fundamental research focuses on the disc-pad system's changing tribological interface, where heat generation and transfer affect performance. Lakavathu Chinna Balu et al.[9] uses finite element analysis to perform transient thermo-elastic contact simulations, showing heat flux and temperature distributions. This comprehensive study improves understanding of disc brake behavior, thermal effects, and performance dynamics, hence assisting in the design and operation of optimal braking systems.

Hemant Kumar Sahu et al.[10] investigates the conversion of kinetic energy to heat via friction in train braking systems, allowing for more efficient braking. The widespread use of compressed air-operated "airbrakes" or "pneumatic brakes" demonstrates their global ubiquity. Thermal cracks, brake binding, and reduced brake block life, on the other hand, demand improvement. This study aims to address these concerns by optimizing brake force distribution while maintaining braking function. Structural and Modal analyses using Cast Iron and High Carbon Steel are used to validate brake strength, providing insights into design improvements for improved braking performance and longevity.

Jacek Kukulski et al. [11] analyses heat transfer mechanisms using computer models and experimental investigations to better understand the important role of thermal conditions on railway brakes. The study investigates heat generation and transfer under intensive braking scenarios using a two-dimensional, axisymmetric computer model for disc brakes. Simulations and experimental thermal imaging are used to investigate temperature responses on the disc's friction surface and selected locations. Jacek Kukulski et al.[11] enhances understanding of temperature distribution and discrepancies during the braking process by comparing experimental and simulation results, contributing to increased understanding and optimization of railway brake systems.

Aluminum metal matrix composites have emerged as a promising lightweight automotive component option, meeting industrial concerns. Although aluminum matrix composites have been investigated for disc braking systems, material precision, and dependability remain an issue. Mandeep Singh et al.[12] demonstrates a new approach using a hybrid aluminum matrix composite (Al6061/SiC/Gr)-based brake rotor via finite element analysis. The research shows that this material has the potential to replace ordinary cast iron brake discs, improving braking system efficiency. This innovative composite material provides insights into the creation of more effective braking components, helping to develop car braking technology.

Recognizing the importance of brake wear in non- exhaust emissions in transportation, Joseph Frangieh et al.[13] investigates a novel experimental design technique. To address the difficulties in estimating wear at full scale, the paper suggests a downscaled pin-on-disc tribometer technique that is aligned with the thermomechanical features of railway brakes. Understanding sophisticated thermomechanical processes during braking, such as contact loading, thermal behaviors, and wear mechanisms, is required for this method. The study includes full-scale bench tests as well as numerical modeling, which provides insights into contact kinetics and variables important for wear prediction. The unique tribo system architecture of the study attempts to retain wear behavior while shedding light on wear processes and wear-influencing elements.

The project of Reddy Ashok Kumar Reddy et al.[14] makes use of CAD modeling and CAE analysis to optimize drum design. The study evaluates deformation, stress, safety issues, and temperature distribution by assessing structural and thermal features with different materials. This all-encompassing approach aids in determining the best material and design. Notably, the study finds that Design 2, which incorporates graphene, has superior heat transfer rates and strength values, indicating improved performance and endurance for the object. This study contributes to the optimization of design and material selection in engineering applications.

The impact of Newton's first law of motion on braking systems serves as the foundation for this research, demonstrating the relationship between vehicle speed and required brake force. Using Finite Element Analysis (FEA), D Usmani et al.[15] investigates the thermomechanical behavior of dry disc-to-pad contact during braking. To address disc heating difficulties, the study emphasizes increased air ventilation and friction through disc design optimization. Disc deformation, Von Mises stress, and pad contact temperature distribution are determined using combined thermal-structural analysis, which advances our understanding of braking system behavior and design.

II. METHODOLOGY

To begin, four distinct design variants were methodically produced utilizing Fusion 360 software: Structure 1, Structure 2, Structure 3, and Structure 4. Figures 1, 2, 3, and 4 visually represented these design changes, providing a clear illustration of their geometries

Figure: Structure 1 & 2

Figure: Structure 3 & 4

The inquiry subsequently moved on to the thermal transient analysis phase, in which the 3D models of the disc rotors were imported into ANSYS 2023's thermal transient module. The models were efficiently prepared for analysis by assigning structural steel material attributes and performing meshing. Following the establishment of analysis parameters, an initial temperature of 127 degrees Celsius was specified for the faces intended to contact the brake pads. Additionally, solution monitors were installed to track temperature distribution and heat flux during the thermal transient analysis.

The temperature distribution results from the thermal transient study were smoothly integrated into the structural analysis module as the project moved into the structural analysis phase. This integration allowed for a thorough examination of the structural performance of disc rotor designs. The structural behavior of each design option was examined using a refined set of analysis settings that included fixed support, rotational velocity, and applied pressure loads on designated faces. Solution monitors intended to collect critical metrics such as total deformation, equivalent stress, equivalent strain, and fatigue-related parameters such as fatigue life and factor of safety were integral to this assessment.

With the results obtained, a detailed analysis was performed to allow for a thorough comparison of the thermal and structural performance of the four-disc rotor designs. The thermal transient analysis results, which included temperature distribution and heat flux profiles, were examined to determine the heat dissipation characteristics of each design. Concurrently, the structural analysis results revealed information about the mechanical integrity and resilience of the disc rotors during braking, as determined by total deformation, equivalent stress, and equivalent strain. In addition, fatigue metrics—fatigue life andfactor of safety— were evaluated to determine the durability of each design variant.

3.2 .Result and Discussion

Table 1: Various parameters for four types of Disc Brake Structure

Disc Brake Structure	Weight(Kg)	Total Deformation(mm)	Avg. FOS	Avg. Life (number of cycle)
1	46.485	3.8555	0.4	80977
2	42.055	3.7649	0.33	52104
3	36.15	3.242	0.38	61492
4	35.007	3.8442	0.38	63516

The table shows the findings of a comparative investigation of four various disc brake design variants, which reveal vital insights into their thermal and structural performance under braking situations. The discussion that follows gives a thorough evaluation of the results, shining light on the implications for practical applications.

The weight differences between design variants have a significant impact on their overall performance. With a weight of 35.007 kg, Design 4 has the lowest weight, indicating a potential advantage in terms of overall aircraft weight reduction. This weight savings, however, comes at the expense of greater structural distortion, as evidenced by a total deformation value of 3.8442 mm. Design 3, on the other hand, has a reduced weight of 36.15 kg while keeping a lower overall deformation value of 3.242 mm. This trade- off between weight savings and structural integrity shows that Design 3 may achieve a good balance between weight savings and mechanical robustness.

The average factor of safety (FOS) values provide useful information about the margin of safety providedby each design against potential failure. The average FOS values for Designs 2 and 4 are 0.33 and 0.38, respectively. These lower FOS values imply closer proximity to failure limits, necessitating caution in its application. Design 1 and Design 3, on the other hand, have substantially larger average FOS values of 0.4, indicating a more robust design in terms of safety margins.

The fatigue life measures, which are represented by the average number of cycles to failure, are also worth considering. Design 1 has the longest average life (80,977 cycles), followed by Design 4 (63,516 cycles). These findings imply that Design 1 has improved durability and longevity under cyclic loads, potentially making it a good choice for applications with lengthy operational lives.

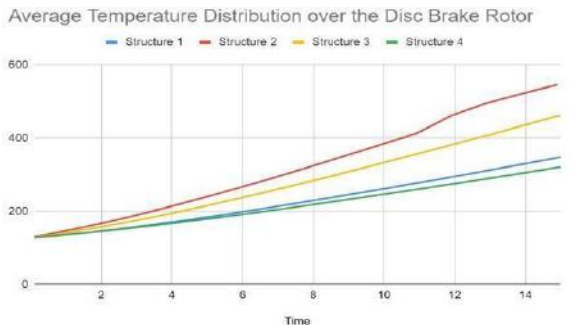

Figure: Average Temperature Distribution over the Disc Brake Rotor

The findings show that trade-offs exist between weight reduction, structural deformation, safety margins, and fatigue life. While Design 4 has the lowest weight, it also has the most structural deformation and the lowest FOS values. Design 1, on the other hand, establishes a balance between weight, distortion, and safety, as well as the longest fatigue life. Such trade-offs are significant considerations for aerospace engineers and designers who must carefully analyze the disc brake system's specific needs and intended applications.

The table below provides a thorough snapshot of the average temperature distribution over time for four different disc brake rotor structures. The following discussion digs into the ramifications of the supplied statistics, putting insight into each structure's thermal performance.

Temperature distribution profiles over time provide critical information about the thermal behavior of disc brake rotor structures during braking operations. The average temperature rises noticeably over time across all structures, illustrating the heating effect of friction during braking.

When the temperature distributions of the structures are compared, some interesting discoveries emerge. Structures 1, 2, and 4 show similar temperature trends, with a gradual rise in temperature over time. Structure 3 appears to have a slightly different behavior, with a slower rate of temperature increase. This gap may be due to differences in design parameters, materials, or other variables influencing heat dissipation characteristics.

The measured temperature distribution tendencies have practical consequences for disc brake structure thermal performance. Structures 1, 2, and 4 may have equivalent heat dissipation capabilities due to their similar behavior. This could indicate a consistent contact pattern between the brake pads and the rotor surfaces, enabling effective heat transmission. Structure 3's different behavior, on the other hand, could belinked to design elements that encourage improved heat dissipation, perhaps resulting in lower temperature accumulation over time.

The temperature profiles provided here emphasize the need of taking thermal effects into account when developing disc brake structures. High temperatures can affect brake efficiency, material integrity, and overall performance. Structures that can keep relatively low temperatures over long periods may have advantages in terms of longevity and wear.

For each construction and time interval, the heat flow distribution over the rotor surface was calculated. The findings show that heat transport patterns differ amongst rotor structures. Notably, due to its design qualities, Structure 2 had the highest heat flux values, indicating efficient heat dissipation. Structures 1 and 4, on the other hand, had lower heat flux values, indicating possible heat accumulation difficulties.

For each configuration, the temperature distribution across the rotor thickness was investigated. The data show how heat created during braking travels through the rotor. The temperature profiles differed dramatically between the structures, with Structure 2 having the least temperature rise and Structure 4 experiencing the most. This suggests that the design and material qualities of the rotor structures are critical in determining thermal behavior.

The heat flow and temperature distribution of the structures are compared to gain insight into their thermal performance. Structure 2 outperformed Structure 1 in heat dissipation, resulting in lower temperature rises and more uniform temperature distributions. This suggests that its design features are efficient in preventing localized hotspots and potential brake fade.

The heat flux and temperature distribution patterns discovered have important consequences for brake performance. Excessive heat collection in specific rotor sections (as seen in Structures 1 and 4) may causethermal stress and reduce braking efficiency. Structures with excellent heat dissipation, on the other hand (such as Structure 2), are more likely to retain consistent performance over protracted braking sessions.

III. CONCLUSION

Finally, this study assesses the thermal transient responses and structural performance of four various design variants of aircraft disc brakes. The research illuminates the complex link between design decisions, thermal behavior, and structural integrity. Through careful examination, it is clear that the design variant chosen has a considerable impact on thermal dissipation, structural deformation, safety margins, and fatigue life. In actual applications, the trade-offs between weight reduction, structural robustness, and durability must be carefully considered. Furthermore, the study of temperature distribution and heat flux patterns emphasizes the significance of adequate heat dissipation to maintain constant braking performance.

The study adds to the field of aerospace engineering by giving a comprehensive understanding of how numerous design variants affect the performance of aircraft disc brakes. This knowledge can help engineering practitioners and industry stakeholders make informed decisions to improve aircraft safety and operational efficiency by optimizing brake design. This work lays the path for stronger brake systems that can endure the harsh circumstances of modern aviation, ultimately contributing to safer and more efficient flying practices as aircraft technology evolves.

The future scope of this research will focus on advanced materials, multi-physics analysis, real-world validation, dynamic loading situations, optimization methods, sustainability concerns, wear analysis, integration with aviation systems, human factors, and regulatory compliance in the future. Investigating these aspects could lead to the development of even more efficient and lightweight disc brake designs, a better understanding of complex thermal and structural interactions, validated results through physical testing, design parameter optimization, alignment with sustainability goals, extended component lifespans, integrated aircraft systems, enhanced user experience, and compliance with aviation regulations.

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