Computational Aeroacoustics Analysis and the Impact of Acoustic Materials on Aircraft Noise Reduction

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Abstract. As the aviation industry continues to pursue sustainable, eco-friendly solutions, aeroacoustic analysis has become essential for achieving noise-reduction objectives. At the core of efforts to meet sustainability goals, aeroacoustic analysis is key to minimizing aircraft noise, enhancing passenger comfort, and reducing impact on surrounding communities. This paper explores the complex interactions between aerodynamic flow fields and structural vibrations that contribute to noise emissions. By leveraging advanced computational fluid dynamics and structural finite element analysis, the research aims to accurately predict noise propagation and identify key noise sources. The study examines the effectiveness of various acoustic materials, such as wood, aluminum, titanium, and steel, complementing traditional sound insulation methods to mitigate aircraft noise pollution. The insights gained from this aeroacoustic analysis will enhance the design of quieter aircraft, helping to address environmental concerns and meet stringent regulatory standards. Ultimately, this research supports the aviation industry's ongoing efforts to develop aircraft that are not only more efficient and sustainable but also less disruptive to the environment and communities.

1 Introduction

Sustainability goals across various sectors, including aviation, focus on minimizing environmental impacts and promoting eco-friendly practices [1-6]. Aircraft noise is a significant environmental hazard for communities near airports and along aircraft routes [7-9]. When operational, an aircraft's primary noise sources include its engine, airframe, and landing gear [10,11]. Engine noise originates from various sources, including combustion, fan blades, rotors, gearboxes, and exhaust turbulence [12]. For instance, jet engines generate high-frequency noise due to exhaust turbulence and fan operations [13,14]. In contrast, airframe and landing gear noise are dominated by lower-frequency components caused by airflow interactions during flight and landing [15,16]. Exposure to aircraft noise adversely impacts human health in multiple ways [17,18]. According to global standards set by the European Commission and the World Health Organization (WHO), prolonged noise exposure can lead to cardiovascular diseases, sleep disturbances, stress-related disorders, and other adverse health outcomes [19,20]. Aeroacoustic analysis plays a pivotal role in understanding and addressing the challenges posed by aircraft noise [21]. Advanced software tools, such as ANSYS Fluent, enable detailed simulations of noise sources and their propagation through the atmosphere, thereby aiding in optimizing aircraft design to mitigate noise emissions [22]. Acoustic materials are another critical component of noise reduction strategies. These materials can effectively absorb sound energy, and advancements in computational modeling facilitate the development of novel acoustic materials with enhanced properties [23]. Integrating these materials into components such as engine nacelles, high-lift devices, and landing gear reduces noise without compromising aerodynamic performance [24]. The present study focuses on modeling the acoustic properties of acoustic materials using ANSYS tools. Simulations will be performed to analyze noise transmission through the aircraft wing structure, enabling a simulation-based comparison of materials [25]. The findings will help optimize material selection to achieve the desired noise-reduction levels while maintaining performance standards.

2 Literature Review

2.1 Aeroacoustics of Flight Vehicles

Aircraft noise became a topic of intense research interest in the 1970s, following earlier investigations in the late 1960s focused on developing ultra-quiet military surveillance aircraft [26]. Early studies identified airframe noise, including contributions from flaps, trailing edges, and landing gear, as a significant challenge to meeting noise certification standards [27]. This led to the emergence of two primary research approaches. The first, the whole aircraft approach, aimed to correlate overall noise levels with various aircraft parameters, such as speed and wing aspect ratio. The second approach, known as the component source approach, focused on analyzing individual noise sources and their interactions. These two methods provided complementary perspectives on understanding and mitigating aircraft noise [28].

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Traditionally, noise measurements were conducted through full-scale testing in anechoic chambers and wind tunnels. Over time, computational aeroacoustics (CAA) techniques, such as the Ffowcs Williams-Hawkings equation, were developed to model noise sources and predict their propagation [29]. These computational methods integrate computational fluid dynamics (CFD) simulations with acoustic analysis, enabling the capture of intricate interactions among noise-generating mechanisms. Noise generation can be quantified by calculating the rate of pressure change over a surface, as pressure variations are typical markers of sound waves [30]. Airflow dynamics inherently produce sound, with vortex shedding, high-pressure gradients, and turbulent flow separation contributing significantly to noise. These effects are most pronounced near the leading edges of aircraft components [31]. A clear understanding of these phenomena enables engineers to model and effectively reduce aeroacoustic consequences.

Modern noise formation and propagation research employs advanced computational techniques such as ANSYS Fluent and detached eddy simulation (DES). These methods provide exceptionally detailed insights into aeroacoustic phenomena while significantly reducing costs compared to experimental procedures [32]. Using contour plots to visualize pressure fluctuation rates, researchers can identify noise sources and assess their effects on the auditory environment. Such computational approaches have become indispensable in aeroacoustic studies, offering engineers the tools to model and mitigate noise generation and propagation efficiently [33].

2.2 Sources of Aircraft Noise

The noise generated by an aircraft (*see* Fig.1) is broadly classified into two primary forms. The first and most significant type is engine noise, followed by airframe noise. Both are essential to an aircraft's overall acoustic signature [34]. The relative importance of these noise types varies across different phases of flight, including take-off, cruise, and landing.

Engine noise originates from the propulsion system and remains significant, even during increased thrust phases such as takeoff and climb. Jet exhaust noise is generated when the jet exhaust mixes with surrounding air at high velocity, with noise intensity directly proportional to the jet speed, making it the dominant noise source during takeoff [35]. In turbofan engines, fan and compressor noise result from air flowing through the fan blades, generating noise from pressure fluctuations. Additionally, combustion noise, produced by chemical reactions in the combustion chamber, generates intense sound waves that contribute to the overall noise signature of internal combustion engines. However, recent advancements in propulsion technologies, such as high-bypass-ratio turbofan engines, have significantly reduced engine noise compared to past decades [36].

Airframe noise occurs during flight phases such as approach and landing, when low altitude and high thrust amplify aerodynamic forces. Deploying high-lift devices, such as flaps and slats, generates noise by promoting turbulent airflow [24]. The extended landing gear produces turbulent vortices and unsteady pressure variations, contributing to significant sound [28]. Additionally, interactions between airflow and pressure perturbations on the wing and the fuselage generate sound, contributing to the airframe's overall noise profile [25].

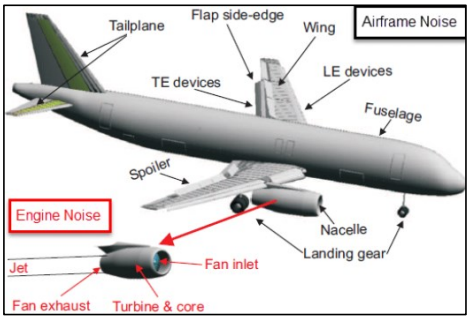

Fig. 1. Sources of Aircraft Noise [30]

3 Role of Material Properties in Noise Mitigation

The properties of a material are crucial in determining how sound is generated and transmitted, especially in relation to vibrations and pressure changes caused by airflow interacting with aircraft panels. These interactions can produce a variety of noises, ranging from low-frequency hums to high-pitched whines. A material's acoustic impedance, which measures its resistance to sound transmission, plays a key role in either amplifying or attenuating these noises. Additionally, the material's density influences its ability to absorb or reflect sound waves, further affecting the overall noise profile.

i. Density

Sounds are less intense in low-density materials because they have a reduced ability to transmit vibrations. This reduced vibratory response means that they absorb or dissipate sound energy more effectively, making them particularly effective in controlling noise, especially from wind-induced vibrations. In applications such as soundproofing or noise reduction in wind-related environments, low-density materials help minimize the intensity of unwanted noise by dampening the vibrations that would otherwise propagate through denser materials [9].

ii. Damping Properties

Materials with high damping capacity are particularly effective at absorbing or dissipating vibrational energy, reducing the mechanical energy converted into sound. These materials can significantly attenuate noise by minimizing the vibrations that would otherwise propagate through the structure. In applications like aerospace engineering, the leading edge of an airfoil is subject to high turbulence and aerodynamic forces, [33], making it a prime location where materials with high damping properties can be especially beneficial. These materials help mitigate noise at the leading edge, where turbulent airflow can generate unwanted sound waves, thereby improving overall acoustic performance and reducing noise levels in flight [34].

iii. Stiffness

High structural stiffness, while crucial for supporting aerodynamic loads and ensuring structural integrity under stress, can inadvertently enhance noise transmission. This is because stiffer materials or structures are less able to absorb or dissipate vibrations. Instead, they tend to transmit vibrations more efficiently, thereby increasing the amount of mechanical energy converted into sound [35]. In contexts such as aircraft or automotive design, where minimizing noise is critical to both performance and comfort, the challenge lies in balancing structural stiffness with the need for noise reduction. While stiffness provides the necessary strength and stability, it can also amplify unwanted noise if not carefully managed [36].

iv. Acoustic Impedance

A material's acoustic impedance determines how sound waves interact with its surface. Materials with impedance values close to that of air are excellent at minimizing sound reflection and propagation [37]. The appropriate ratio of various materials will be used to evaluate how well noise reduction works. Structural strength is often subordinated to acoustic performance, particularly in components subjected to turbulent airflow, such as high-lift devices and leading edges [38]. To determine the best solution for combined structural and acoustic requirements, engineers can now assess material behavior under aerodynamic conditions using advanced computational techniques [39]. This requires investment in developing metering advances and producing green composites that support noise absorption and sustainability [40-42]. With the growing trend toward addressing environmental needs, such applications are revolutionizing noise-mitigation techniques for future generations, resulting in quieter, more efficient aircraft [43-45].

4 Methodology

4.1. Computational Approach

The primary objective of the computational analytic approach was to model and evaluate the aeroacoustic performance of four distinct materials, steel, titanium, aluminum alloy, and wood, under conditions characterized by a Mach number of 0.8. The study aimed to investigate the noise-source characteristics of these materials and demonstrate their significance for noise reduction. To achieve this, the ANSYS Fluent solver was utilized at PC Lab at Amity University Dubai as the computational tool, enabling detailed simulation and analysis of these materials' acoustic behaviors and aerodynamic interactions. This approach underscores the potential influence of material properties on the overall effectiveness of noise mitigation strategies in relevant applications.

4.2 Geometry

The aeroacoustic simulation domain has been set up in ANSYS Fluent under appropriate conditions to closely represent the combined effects of the flow and the NACA 23012 aerofoil. The domain has been modeled as rectangular and closed to simulate a real-world environment, so that later boundary conditions would not affect the aerofoil behavior. The aerofoil was centered within the enclosure to give enough space for sound reflection outside the test object. The dimensions of the enclosure were carefully chosen to estimate the cost with computing and to simulate as best as possible what happens at the end of the leading and associated slits. This spatial distribution has enabled the study of the generation and propagation of noise. Figures 1 and 2 present the structured geometry for this study, including the enclosure and coordinate axes for precision simulation.

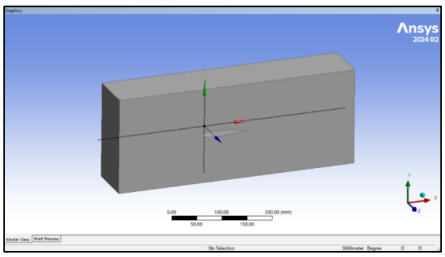

Fig. 2. Geometry in the domain and the meshed model

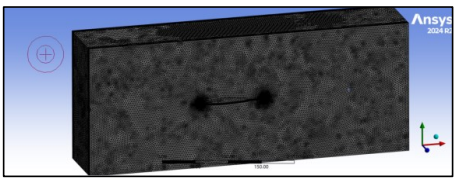

Fig. 3. Meshed model

4.3 Setup Environment

This analysis employs a DES, a reliable computational method for capturing complex turbulent flow and aeroacoustics interactions. DES combines the strengths of the RANS (Reynolds-Averaged Navier-Stokes) and LES (Large Eddy Simulation) approaches: RANS efficiently models large-scale flow structures, while LES provides detailed simulations of transient, unsteady flow phenomena, reducing computational costs. This hybrid capability makes DES ideal for accurately simulating the generation and propagation of aeroacoustic noise. In this paper, the inlet Mach number was maintained at 0.8 throughout the simulation, creating a controlled test environment to evaluate material behaviour. The setup enabled the assessment of how variations in material density, stiffness, and damping characteristics affect acoustic performance. As a result, the study provided a detailed understanding of the mechanisms of noise generation and the acoustic behaviour of materials under different flow conditions. The main module tasks in Figure 4 configure and analyse all fluid dynamics simulations.

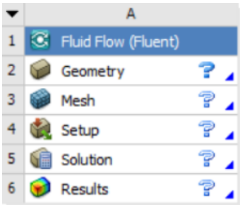

Fig. 4. Main module tasks

5 Materials and Their Properties

The materials selected for this research, wood, aluminum, titanium, and steel, possess mechanical properties that directly impact their acoustic behavior and noise reduction effectiveness under aeroacoustics conditions. Table 1 presents a detailed overview of each material's characteristics, including the mechanical and material properties, based on the specified criteria.

Wood stands out for its low density (700 kg/m^3) and high damping factor (0.05). These characteristics make it an effective material for absorbing vibrations and reducing noise generation. It's relatively low Young's Modulus (10 GPa) indicates flexibility, which could contribute to dissipating energy from acoustic waves. However, its mechanical strength is significantly lower than that of metals, potentially limiting its application in high-stress environments. With a relatively high Poisson's ratio (0.35) compared to metals, wood may exhibit a more flexible vibration behavior and better damping characteristics. It absorbs vibrations more efficiently, helping reduce overall noise generated by structural vibrations.

Aluminum is a lightweight metal (2700 kg/m^3) with moderate stiffness (70 GPa) and a relatively low damping factor (0.02). Its higher density than wood could result in greater acoustic energy transmission, making it less effective in noise absorption. However, its low weight and good mechanical strength balance make it a common choice for aerospace applications where material durability and weight savings are critical. Aluminum has a slightly lower Poisson's ratio

(0.33) than wood, but it still has enough elasticity to support good vibration transmission. It has a relatively low damping factor, so although it might not dampen vibrations as effectively as wood, it still offers a reasonable balance of stiffness and flexibility for some acoustic applications.

Titanium is known for its high strength-to-weight ratio and excellent corrosion resistance. Its relatively high density (4500 kg/m^3) and stiffness (116 GPa) contribute to the efficient transmission of acoustic waves, resulting in less natural damping. The low damping factor (0.01) further highlights its limitations in passive noise reduction. However, its superior mechanical properties make it suitable for high-performance applications where structural integrity is paramount. Titanium's Poisson ratio (0.34) is similar to aluminum's, but its higher stiffness (due to higher Young's modulus) leads to stronger vibrations and higher acoustic emissions. It transmits sound waves more efficiently, resulting in greater acoustic energy, especially at higher frequencies.

Steel is this study's densest (7850 kg/m^3) and stiffest material, with a very high Young's Modulus (200 GPa). This gives it exceptional strength and the ability to withstand extreme mechanical loads. However, its low damping factor (0.01) suggests poor noise absorption, making it less effective for applications that prioritize aeroacoustic noise reduction. Steel's higher density also means greater acoustic wave transmission, increasing the potential for noise propagation. Steel has the lowest Poisson's ratio (0.29) in this set, indicating it is more rigid and less elastic in lateral deformation. While this contributes to its high stiffness and strength, steel is less effective at damping vibrations, leading to stronger transmission of both vibrations and sound waves and louder noise emissions.

Table 1. Properties of the materials selected [42]

Materials	Density (kg/m^3)	Young's Modulus (GPa)	Poisson Ratio	Damping Factor
Wood	700	10	0.35	0.05
Aluminum	2700	70	0.33	0.02
Titanium	4500	116	0.34	0.01
Steel	7850	200	0.29	0.01

6 Results

The simulation results reveal significant variations in noise generation across the four materials studied: wood, aluminum alloy, titanium, and steel. This demonstrates the impact of their distinct mechanical and damping properties on acoustic performance. A contour plot of the aerodynamic airfoil's surface depicting the RMS pressure change rate further illustrates the distribution and strength of acoustic sources along the airfoil. This visualization provides valuable insights into how material properties influence aeroacoustic behavior.

6.1 Wood

The analysis revealed that wood outperformed the other materials in minimizing noise levels, making it the most acoustically efficient option. This superior performance is primarily due to its low density and high damping factor, which enable it to effectively absorb and dissipate acoustic energy. Notably, near the airfoil's leading edge, a critical region for noise generation, wood demonstrated exceptional acoustic absorption capabilities. Its ability to mitigate pressure fluctuations and reduce sound emissions in this region highlights its effectiveness in suppressing aeroacoustic noise, further emphasizing its potential for noise-sensitive applications. In Figure 5, the maximum value of 1.79e+06 Pa/s can be observed for the material wood.

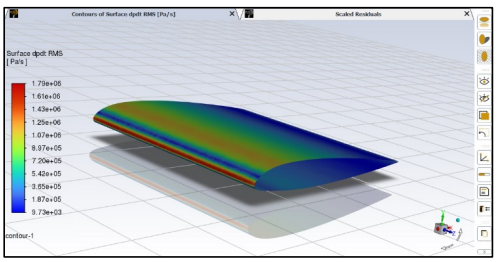

Fig. 5. Aeroacoustics performance of wood-based airfoil

6.2 Aluminium Alloy

The analysis indicated that the aluminum alloy produced moderate noise levels, placing it between wood and denser materials in terms of acoustic performance. Due to its higher density than wood, a noticeable noise peak was observed near the airfoil's leading edge, where turbulent flow interactions are most intense. The increased density of aluminum contributed to higher vibrational responses, resulting in reduced energy absorption and greater noise propagation. While aluminum's acoustic performance is less effective than wood, it still offers a balanced trade-off between structural

strength and moderate noise suppression. In Figure 6, the maximum value of 1.93e+06 Pa/s can be observed for the aluminum material.

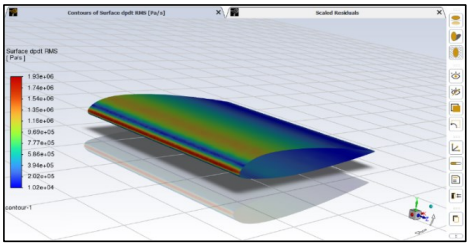

Fig. 6. Aeroacoustics performance of aluminum-based airfoil

6.3 Titanium

Titanium exhibited higher noise levels than aluminum, with a significant concentration of noise near the airfoil's leading edge that diminished only minimally toward the trailing edge. This behavior is attributed mainly to titanium's high density and stiffness. While these properties enhance structural integrity and resistance to deformation, they hinder the material's ability to effectively absorb and dissipate acoustic energy. Instead, the increased stiffness facilitates the propagation of vibrational energy, amplifying noise generation and reducing attenuation across the airfoil surface. Consequently, titanium's acoustic performance highlights the trade-off between structural robustness and noise mitigation. In Figure 7, the maximum value of 1.21e+06 Pa/s is observed for the titanium material.

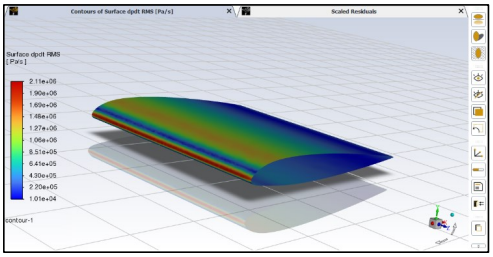

Fig. 7. Aeroacoustics performance of titanium-based airfoil

6.4 Steel

Steel exhibited the highest noise levels among the materials evaluated, making it the least effective in terms of acoustic performance. This outcome is primarily attributed to its exceptionally high density, significant rigidity, and notably low damping factor. These properties severely limit steel's ability to absorb and dissipate acoustic energy, leading to minimal vibration attenuation. Instead, the material facilitates stronger acoustic interactions, amplifying pressure fluctuations and sound wave propagation across the airfoil surface. Consequently, steel generates elevated noise levels near-critical regions, such as the leading edge, and maintains significant noise emissions throughout the airfoil, underscoring its limitations for noise-reduction applications. In Figure 6, the maximum value of 2.36 Pa/s is observed for steel.

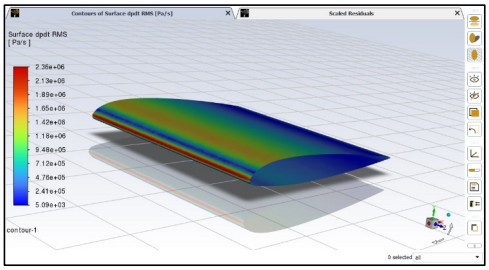

Fig. 6. Aeroacoustics performance of steel-based airfoil

7 Discussion

The aircraft wing's leading edge was identified as the most prominent source of aeroacoustic noise across all analyzed materials. This noise primarily arises from turbulence, high-pressure gradients, and vortex shedding during airflow interaction with the leading edge. As air interacts with this critical region, it experiences significant pressure fluctuations, generating intense sound waves. Materials with high rigidity and poor damping properties exacerbate this issue by efficiently transmitting vibrations, further amplifying noise levels. Additionally, airflow and material surface interactions contribute to the generation of secondary noise. Among the materials tested, wood emerged as one of the most effective for noise reduction. Its low density and superior damping properties enable it to dissipate acoustic energy efficiently, particularly at the leading edge where noise generation is most intense. This highlights the importance of material selection in minimizing aeroacoustic noise, with wood a promising candidate for such applications. The study underscores the critical need to integrate material properties with aerodynamic design when developing aircraft wings. Optimizing this synergy is essential to mitigating noise generation in high-impact regions, such as the leading edge. By prioritizing materials with favorable acoustic characteristics, such as wood, designers can significantly reduce aeroacoustic emissions and enhance the overall performance of aircraft designs.

The future of aeroacoustics analysis in the aerospace industry is poised to leverage cutting-edge technology and advanced materials to achieve more efficient noise reduction while complying with stringent environmental and regulatory standards. Future research should focus on developing superior acoustic materials and refining their integration with existing aerodynamic structures to balance noise control and overall performance [46]. One promising avenue is the exploration of manufactured metamaterials, which offer the potential for highly customizable sound absorption and noise reduction capabilities. Investigating how metamaterials interact with airflow and how they can be integrated into critical aerospace components such as engine nacelles, leading and trailing edges, and landing gear assemblies will be key to advancing noise reduction efforts [47]. In addition, bio-composites and sustainable composites are gaining significant attention due to their potential to provide sound absorption for cabin acoustics while helping the aviation industry meet environmental goals [48]. These lightweight, eco-friendly materials, made from natural fibers or bio-resins, could revolutionize noise-reduction strategies while reducing the environmental impact of aerospace manufacturing [49]. Another critical area for future research is the integration of computational and experimental validation techniques. While tools like ANSYS provide valuable insights into noise propagation and material interactions, experimental validation is essential for confirming performance. Future studies should combine computational simulations with real-world testing, such as wind tunnel experiments and anechoic chamber assessments, to improve the accuracy of noise predictions and material performance evaluations. In a world increasingly shaped by artificial intelligence (AI) and machine learning, the ability to analyze large datasets from simulations and experiments more rapidly will enable the prediction of optimal material configurations, leading to more efficient designs [49]. Innovations in micro-perforated panels and hybrid materials that combine multiple acoustic properties could offer further opportunities to reduce in-cabin noise without significantly increasing weight, making this another promising area for future research [50-52]. Finally, the ongoing collaboration among aerospace engineers, materials scientists, and environmental experts is crucial to advancing simultaneously noise reduction, aerodynamic efficiency, and sustainability [53-57]. By working together, these multidisciplinary teams can drive the development of innovative solutions that create environmentally friendly, quiet, and high-performing aircraft.

9 Conclusion

A computational approach was utilized to analyze noise generation on an aerofoil, providing valuable insights into the role of material properties in aeroacoustic performance. The comparative study emphasizes the significant impact of density and damping on material selection for noise-sensitive applications. For example, wood, with its high damping factor and low density, is highly effective at reducing noise. In contrast, materials with high stiffness and density, such as steel, tend to amplify noise because they are poor at dissipating acoustic energy. The results underscore the importance of selecting the right materials to optimize aeroacoustic performance, particularly in components such as airfoils and other aerospace structures, where minimizing noise emissions is crucial. These findings highlight the need for a careful balance between mechanical properties and acoustic performance in selecting aerospace materials, with damping characteristics playing a pivotal role in reducing noise interactions with key aerodynamic surfaces.

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