Acoustic Metamaterials for electric Vertical Take-Off and Landing aircraft

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Introduction

The emergence of fully electric Vertical Take-Off and Landing (eVTOL) aircraft marks a significant transformation in urban aviation. These innovative aerial systems provide a cleaner and more sustainable alternative to traditional aircraft by reducing reliance on fossil fuels, enhancing energy efficiency, and utilizing carbon-neutral propulsion technologies [1]. While eVTOLs have the potential to revolutionize urban air mobility, they also come with challenges, such as noise pollution, safety concerns, and public acceptance, especially in densely populated areas [2]. Therefore, addressing these issues is crucial for the successful integration of eVTOLs into urban aviation. Unlike conventional aircraft, eVTOLs experience several flight phases, including vertical takeoff, hovering, and forward flight. The different operational modes lead to varying excitation frequencies, complicating the implementation of effective noise reduction strategies. While traditional aircraft mainly produce broadband noise due to pressure fluctuations from combustion, the noise generated by eVTOLs is primarily caused by factors such as unsteady turbulence loading, inflow turbulence ingestion, and boundary layer turbulence [3, 4]. Fan noise in both types of aircraft is primarily caused by the interactions between fan wakes and exit guide vanes. This interaction creates a combination of tonal and broadband noise. Traditional noise control solutions, such as Helmholtz-based composite sandwich acoustic liners for the ducted engine area, are designed to target specific operational frequencies, making them effective only within a narrow frequency range. However, because eVTOL propulsion systems have a high bypass ratio and varying acoustic needs, these conventional solutions are often limited in their effectiveness.

A more advanced approach involves the use of acoustic metamaterial liners, which leverage subwavelength structural designs to manipulate sound waves in unconventional ways. These metamaterials are composed of periodic unit cell structures that enable unique acoustic behaviors, such as wave redirection, cloaking, and enhanced absorption, achieved through properties like negative effective mass density and negative bulk modulus [5]. Significant progress has been made in metamaterial development, with designs tailored to various physical phenomena for noise control [6-9]. In traditional aircraft propulsion systems, these materials are already being employed for noise mitigation through mechanisms such as absorption, metasurface-based reflection control, noise trapping, and scattering reduction [10]. In contrast, metamaterials used within an aircraft cabin interior primarily focus on sound absorption to improve passenger comfort. The application of metamaterials generally falls into two categories: active and passive noise control systems. Both can be optimized to achieve specific acoustic objectives, making them highly effective for addressing the distinct noise challenges associated with eVTOL operations. Despite the remarkable development of acoustic metamaterials and the wide variety of systems that have been developed, it can be seen that practical application still presents challenges.

In this paper, the challenges related to the selection of acoustic metamaterials are mentioned, and it is discussed that not every design meets the requirements in real-world applications. We focus on eVTOLs that are based on ducted fan drives. We aim to identify metamaterials with potential applications based on a filtering concept, which is presented here. Based on the filtering concept, it is recognized that membrane-type metamaterials, which represent a special group of metamaterials, have high application potential in the area of ducted fans of eVTOLs. In the interior cabin wall areas of eVTOL, usually more space is provided, where alternative structures could be considered.

Challenges using Metamaterials

At the start of this work, we discuss the challenges of implementing new metamaterial designs for sound absorption in the ducted fan area of an eVTOL vehicle.

The literature showcases these innovative structures as a viable alternative to traditional honeycomb-based liner designs, which depend on the Helmholtz principle, as illustrated in Fig. 1. Integrating conventional liners into

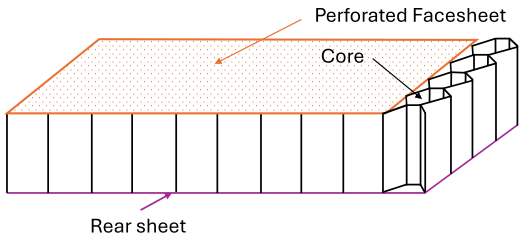

Figure 1: A three dimensional representation of an conventional acoustic liner.

eVTOL systems that use ducted fans poses significant challenges, primarily due to the limited space within the nacelle inlet. Typically, effective low-frequency sound absorption requires sizable volumes of metamaterials for installation, which makes their use in such confined spaces difficult. Furthermore, structures based on Helmholtz resonance depend on micro-perforated panels (MPPs), which work well in conventional aircraft but present issues for eVTOL propulsion systems that transition between vertical and horizontal flight. During this

transition, dust and rainwater can enter the Helmholtz cores through the MPPs, which necessitates specialized drainage systems for effective control of that issue. In terms of acoustic absorption properties, Helmholtz structures provide narrowband absorption at specific operational frequencies. This narrowband characteristic complicates their use in eVTOLs, as excitation frequencies can fluctuate with changes in flight modes. To address these challenges and explore alternative metamaterial structures and their potential applications, we propose a filtering concept that allows us to evaluate metamaterials based on their design and absorption characteristics. Specifically, we focus on the ducted fan area and the interior cabin walls of the eVTOL.

Filtering Concept

To test our filtering matrix, we need various metamaterial samples for data acquisition. We differentiate the metamaterials existing in the literature into structures based on Helmholtz resonator design, coiled-up space structures, membrane-type structures, and miscellaneous combined structures, as represented in Fig. 2 [11]. The

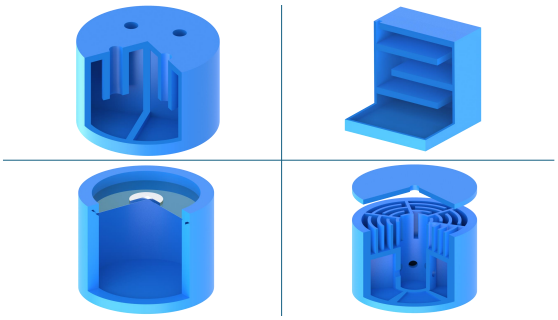

Figure 2: Representation of a structure based on Helmholtz resonator design (top left), a coiled-up space structure (top right), a membrane-type structure with an attached body (bottom left), and a miscellaneous combined structure integrating Helmholtz resonators with a coiled-up space structure (bottom right).

miscellaneous structures group refers to metamaterials with novel designs based on resonance phenomena or combinations of various subgroups. We focus on individual metamaterial unit cells because local resonance phenomena enable sound absorption, while Bragg scattering offers additional opportunities for enhanced absorption by coupling unit cells. We designed four metamaterial samples for each individual group and manufactured them using 3D additive manufacturing technology. To verify the acoustic properties, we carried out numerical simulations with COMSOL Multiphysics and validated them with a two-microphone impedance tube. The numerical simulations were performed with a finite element digital twin model of the impedance tube including accounting for thermo-viscous losses.

Our filtering concept consists of four sub-stages. In the first stage, we establish criteria for further evaluation. The second stage involves introducing specific evaluation measures for these criteria, focusing on the performance of each metamaterial unit cell in terms of design and absorption within the impedance tube. In the third stage, we assess the importance of each criterion by weighing them according to their relevance for the intended applications. Finally, we calculate a total score for each metamaterial based on the findings from the previous stages.

List of Criteria

To evaluate a metamaterial based on its unit cell design and acoustic absorption properties, we focus on key criteria such as subwavelength thickness, mounting volume, mass, and acoustic efficiency for both narrowband and broadband absorption. We also consider grazing and bias flow effects on the liner resistance, the potential for whistling noise, and tunability, specifically, how many resonances can be absorbed per unit cell. We exclude mechanical properties, environmental durability, cost, and manufacturability due to the complexity of evaluating these factors without specific manufacturing and further process details.

Scoring Criteria

To evaluate the individual criteria, we analyze each metamaterial unit cell in detail using a min-max normalization approach to standardize our assessment on a scale from zero to one [12]. Depending on the criterion, a value of zero may indicate better performance, while for others, a value of one is preferred. We normalize subwavelength thickness, mounting volume, and mass based on operational frequency behavior, factoring in wavelength. To assess absorption properties, we examine the quality factor and acoustic energy absorbed. For broadband absorption, we conduct an integral analysis and normalize it within a defined frequency range, focusing on off-resonance areas. We evaluate the effects of flow by examining design, porosity, and open perforation area, considering their impact on liner resistance for both bias and grazing flow [13]. Additionally, we introduce two criteria to assess the potential for whistling noise in these flow scenarios. Finally, we measure tunability by the number of absorption peaks per unit cell.

Criteria Weight

Once we have established the evaluation criteria, we systematically prioritize them to determine their relative importance for the intended application. The significance of each criterion may vary depending on the specific application and can be adjusted as necessary to meet different requirements.

Total Score

To assess the filtering concept as a whole, we consider the solution scores for each sample along with the assigned weights for each criterion. Although a criterion may receive a high score for a specific metamaterial, its significance in the overall score could be limited if it is not particularly relevant to the intended application. This comprehensive score reflects how suitable each metamaterial is for the specified application.

Application

We apply the filtering concept to evaluate the compatibility of metamaterials in eVTOLs for two applications: (1) cabin walls and (2) ducted fan areas. Each area has its

own specific requirements for metamaterials. In eVTOL applications, mass is a critical factor due to its direct impact on battery range. The cabin walls typically offer more available space for metamaterials than the ducted fan regions, given the mounting volume constraints. For both applications, the acoustic absorption properties are crucial, with both narrowband and broadband criteria being significant. Flow effects are not expected in the cabin wall area. In contrast, for ducted fans, mass is the most significant consideration, followed by the effects of grazing flow, which notably influence metamaterial performance. Generally, as flow effects increase, the acoustic performance of a metamaterial decreases [14]. Metamaterials used in ducted fans must be much thinner compared to those in cabin walls. The potential whistling noise caused by grazing flow is of secondary importance in our assessment, while the bias flow effects were ignored.

Results and Discussion

After applying the filtering concept to ducted fans and cabin interior walls, the results from various metamaterial samples and subgroups indicate that membrane-type metamaterials have significant potential for application in ducted fans. This is due to their acoustic properties that resist airflow (no perforations) as well as their subwavelength resonance behavior in very thin structures. However, it should be noted that the mechanical properties, which were not taken into account in the filtration concept, could strongly influence the results, as the membrane life expectancy under strong external loads is expected to be shorter compared to other concepts [15]. In the area of the interior cabin wall, the miscellaneous structures, despite their increased mass, show a good application potentiality, followed by the membrane-type structures as well as coiled-up space structures.

Conclusions

Our study presents a filtering framework for evaluating metamaterials based on their acoustic properties and design, with a focus on electric Vertical Take-Off and Landing (eVTOL) applications. We classify existing metamaterials, analyze representative designs, and assess their performance through experiments and simulations. The results are compiled into a filtering matrix to determine suitability for cabin walls and ducted fans. Membrane-type metamaterials show strong potential in flow environments while combining Helmholtz resonators with coiled-up spaces is optimal for cabin walls. Future work will explore membrane-based designs, considering mechanical properties and boundary layer effects.

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