# Investigation of Noise Mitigation in Urban Air Mobility: A Review of Acoustic Liner Concepts

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# 1 Abstract

The purpose of this study was to review a wide range of noise mitigation strategies for Urban Air Mobility (UAM) vehicles, with a focus on pre-existing acoustic liner technologies that were originally developed for aerospace propulsion systems. Following the exponential growth of electric vertical take-off and landing (eVTOL) concepts, noise pollution has emerged as the most significant challenge to gaining public acceptance and obtaining regulatory approval. This paper showcases the physical mechanisms and dynamics behind UAM noise generation, environmental and health impacts of urban noise exposure and offers analysis of the principles of acoustic liners based on Helmholtz resonance.

This study evaluates cutting edge noise control technologies such as active noise control (ANC), hybrid passive–active systems, and additively manufactured acoustic metamaterials for their potential adaptation to UAM application. Multiple liner configurations such as curved micro-perforated panels (MPP), multi degree-of-freedom (MDOF) honeycomb structures, bio-inspired or media augmented designs are compared for their manufacturability, mass, and ability to disrupt broadband. A 3D-printed hybrid liner design was proposed as it manages to combine MDOF cavities, lattice bio-inspired shells, and porous damping layers to achieve efficient broadband attenuation while maintaining low unit mass and high durability. The review concludes that additive manufacturing and metamaterial based liners offer the most promising solution for effective, lightweight, and scalable noise reduction solutions for the next-generation of UAM vehicles.

# 2 Introduction and Background

The following literature review investigates urban air mobility (UAM) devices and the issue of noise pollution surrounding them. UAM refers to a system of air transportation that utilises electric vertical take-off and landing (eVTOL) to transport goods and people within cities and urban areas. The concept has only recently begun to gain proper traction, but the development of technology up to now has played a pivotal role in enabling what could be the main mode of transportation in the future.

The first helicopter was invented by the French engineer, Paul Cornu. Fast forward to the early 1940's the first mass-produced helicopters were produced. Over the years, UAM technology has taken leaps and bounds to get to where it is today. In recent years, drones and other VTOL devices have become common in societies due to the technologies advancing greatly. With the population in urban centers across the globe growing year in and year out, the need for more efficient solutions has been a growing issue for city planners and commuters alike. As a result Urban Air Mobility (UAM) has emerged as a proposed solution and has seen large investment and interest from both the aviation industry and academic research. Specifically referring to emerging intra- and inter-city air transport services, with particular emphasis on new aircraft concepts capable of VTOL [1].

UAM aircraft are typically envisaged as electrically powered, distributed-propulsion systems capable of accurate point to point operation within congested cities. The goals associated with UAM include but are not limited to reduced road congestion, lower journey times and a transition towards a more sustainable transport through electrification. However, despite these, it has faced many challenges in relation to real-world deployment, particularly in relation to public acceptance and environmental impacts. Among these, noise pollution has been consistently challenged as one of the most pressing technical issues with the implementation of these vehicles [2].

## 2.1 UAM and Noise Emission

While traditional air transport passes over cities, it is largely restricted to airports located on their peripheries. UAM differs in that its vehicles are proposed to operate at low altitudes within densely populated urban areas. Unlike conventional rotorcraft that typically operate from nearby airports, UAM vehicles are expected to fly at low altitudes within densely populated urban areas, greatly increasing community exposure to noise. On top of this, their designs are significantly different from traditional helicopters and tiltrotors, as they often employ multiple rotors that operate at variable speeds, lower tip Mach numbers and specialised propulsions, for example, a pusher propellers for forward flight. These features alter the frequency content of the noise relative to conventional aircraft [3].

In addition, rotors operating in close proximity to one another create a wide range of complex aerodynamic interactions that cause unsteady aerodynamic loading, leading to increased noise pollution. Unsteady aerodynamic loading occurs when sudden changes in airflow around a blade alter the forces acting on it. Some of the best known examples include Blade Vortex Interaction (BVI), where a blade passes through the swirling wake of another blade causing rapid pressure fluctuations along its surface. Similar effects occur in Blade Airframe Interactions (BAI), where disturbed airflow from the rotors interacts with the aircraft body. Fuselage Wake Interactions (FWI) also contribute to unsteady loading, particularly in UAM vehicles where the varied and unique configuration and placement of multiple rotors around the fuselage needed to maintain the wide range of mobility required by these craft can lead to complex wake blade interactions. These effects collectively generate significant broadband noise as the wide variety of wakes and flow disturbances combine across a wide range of frequencies to create a distinct acoustic footprint that is more noticeable to urban communities than that of traditional rotorcraft. [3].

## 2.2 Environmental Concerns and Public Health Impacts of Noise

The implications of noise exposure extend well beyond annoyance and are closely linked to a range of both physical and mental health complications. Prolonged exposure to environmental noise has been strongly associated with sleep disturbance and cognitive impairment, both of which can contribute to cardiovascular disease. Evidence from 36 World Health Organization (WHO) studies, encompassing more than 173,000 responses, shows that when participants were asked directly about noise as the cause of poor sleep, the odds of being highly sleep-disturbed roughly doubled with every 10 dB increase in night-time noise, with aircraft noise proving the most disruptive. These findings demonstrate that traffic noise, particularly from aircraft, is a major contributor to night-time sleep disruption, with consistent patterns observed across both European and non-European populations. Sleep disruption is considered a central pathway through which noise exerts broader systemic effects, triggering physiological stress responses, elevated blood pressure and inflammatory mechanisms that lead to an increase in the risk of hypertension and ischaemic heart disease [4].

These findings highlight that for UAM to be socially and ethically acceptable, its noise emissions must be carefully regulated and controlled, not merely to prevent complaints, but to protect the long-term health and cognitive function of urban populations.

## 2.3 Acoustic Liner Concepts in Aerospace

Traditionally in aviation one of the most effective strategies for reducing engine noise has been the incorporation of acoustic liners in both the nacelles and ducts of the craft. By lining the inner walls of nacelles and ducts with acoustic structures, engineers can absorb and dissipate engine noise before it radiates into the environment. This has proven to be very effective in helping aircraft comply with noise emission regulation.

Liners traditionally consist of a hard-backed honeycomb and perforated face plate, with the perforated face enhancing sound absorption and maintaining aerodynamic flow as smooth as possible on the internal wall of the nacelle.

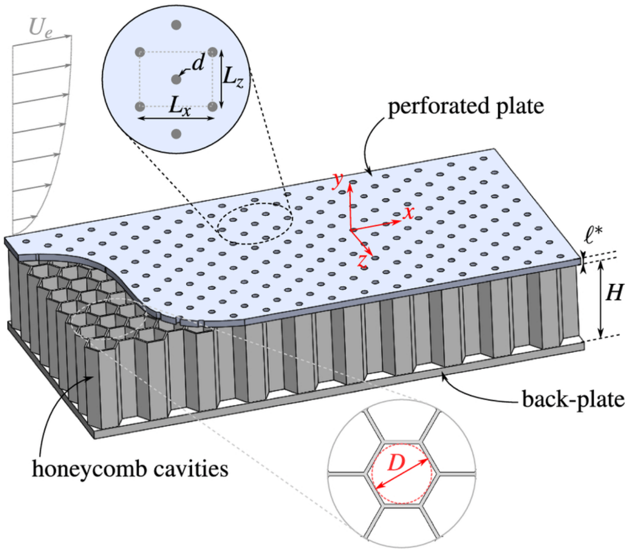



Figure 1: Diagram of the composition of a conventional acoustic liner [5].

The main principle behind how an acoustic liner works is through the Helmholtz resonance, a phenomenon that occurs when wind is forced in and out of a cavity known as a resonance chamber, causing the wind to vibrate a specific natural frequency. This principle is used in a variety of industries from designing musical instruments to reducing exhaust noise on cars. From an aerospace perspective, aeroacoustics has been a major topic of research since the dawn of the first turbojet engine in the 1950's. In order to investigate which type of acoustic liners would be suitable for use in UAM vehcles, it is worth investigating what different types of liners are currently being used in aerospace applications.

Noise control strategies are often broken into different strategies: active control approaches, geometric shape optimisation technologies, and passive control. Acoustic liners fall into the category of passive control, however there are various different forms of liners. Within the category of acoustic liners, there are conventional and unconventional methods for reducing aeroacoustics. The conventional method is the standard perforated liner approach, while unconventional designs are constantly being explored. A major challenge being faced by the aerospace industry is how the compact structure of aero engines often limits the space that is currently available for liners. Because of this, aerospace companies are now exploring unconventional approaches to designing acoustic liners [6].

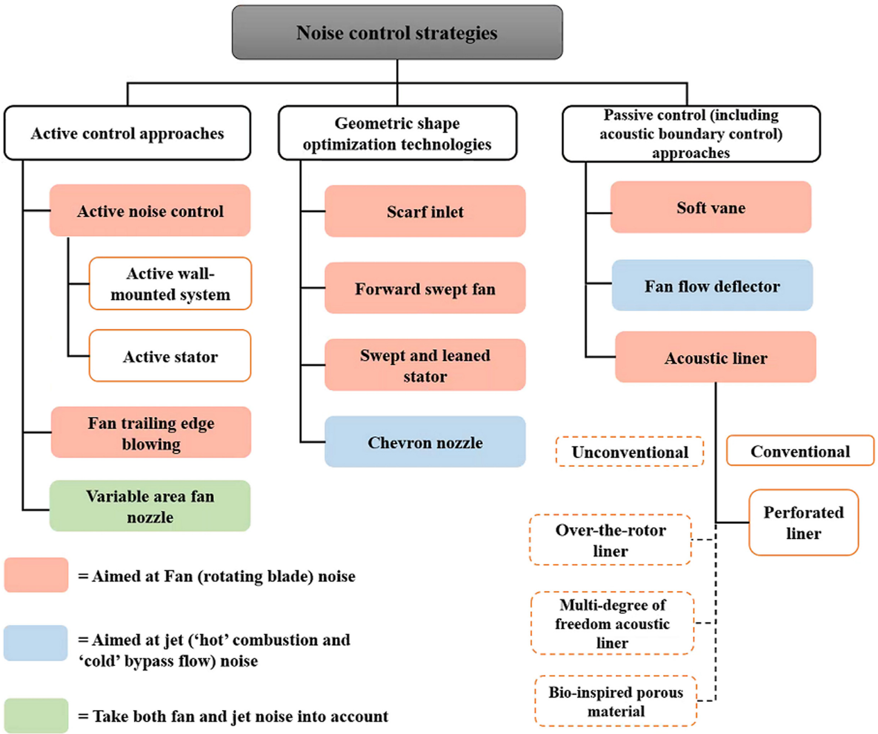
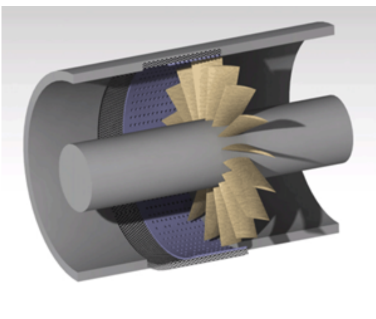



Figure 2: Different categories of noise control strategies for turbofan engines [6].

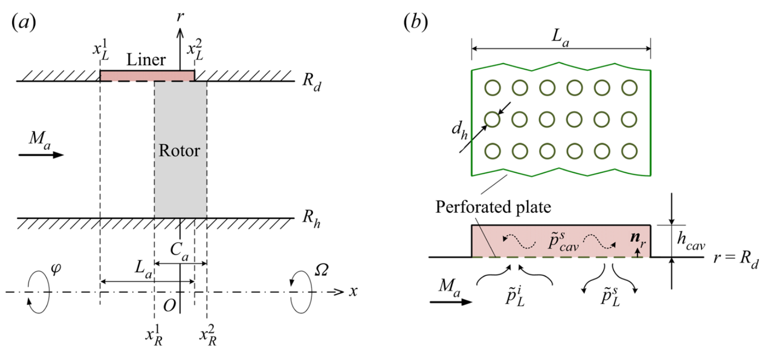
As seen in the above figure, there are many different types of unconventional acoustic liner designs that are being designed. For the sake of analysis, it is worth discussing each one and the functionality behind how the technology works. While these designs are used for turbofan engine noise control strategies, some could possibly be implemented in noise control strategies for drone blades.

### 2.3.1 Over-the-Rotor Liners:

One acoustic liner application of recent interest is the over-the-rotor (OTR) liner, which is mounted in the engine nacelle wall at or near the rotor tips. These liners provide a pressure release surface very near the source such that the source strength is reduced. They also absorb some of the remaining sound that is generated by the engine [7]. This configuration maximises the proximity to the primary noise sources (rotor-wake interaction and tip vortices), enabling direct coupling between the unsteady aerodynamic field and the acoustically treated wall. Conventional liners can only absorb propagating sound, whereas OTR liners can modify the source of the sound and the field through flow-acoustic coupling.



(a) Render of a turbofan over-the-rotor acoustic liner [8].




(b) Diagram illustrating the physics of an OTR liner. [8].

Figure 3: Illustrations of an over-the-rotor acoustic liner.

While over-the-rotor acoustic liners show great promise in reducing the aeroacoustics of turbofan engines, there is still a lot of research and development needed to make them commercially viable. The main researcher in this space is NASA, who hope to develop a version that can be adopted globally by the aerospace industry [8].

#### 2.3.2 Multi-Degree of Freedom Acoustic Liners:

Another type of acoustic liner being more widely adapted for aerospace applications are called multi-degree of freedom acoustic liners. A new emphasis on increased turbofan fuel efficiency means that higher engine bypass ratios and shorter nacelles will be required. These new designs mean a smaller area for liner installation and also a more broadband character. To adapt to these conditions, there must be an increase in acoustic absorption over a broader frequency range [9]. This led to the development of multi-degree of freedom acoustic liners. The development of these liners has also not yet been widely adapted by the aerospace industry, however the technology is being actively researched. Continue to Section 4.2 for a further, more detailed discussion on multi-DOF liner configurations and their application in to UAM device design.

#### 2.3.3 Bio-Inspired Acoustic Liners:

Another more niche, yet growing research area, is the development of bio-inspired acoustic liners. One of the only few papers on this research was published by NASA. The concept of bio-inspired broadband acoustic absorbers came from a motivation to reduce aircraft noise and pollution, and the natural ability for certain natural materials to dampen sound waves. Tests have shown that certain synthetic structures resembling natural bundles of reeds offer an increase in sound absorption at frequencies below 1000 Hz compared to state-of-the-art commercially available structures of similar thickness and weight [10]. While this concept has yet to be widely scaled or developed for commercial use, there may be certain applications for these liners if the technology improves.

## 3 The Physics of the Problem

### 3.1 Fundamentals of Aeroacoustics

Aeroacoustics is the study of how sound is generated from the motion of air, it explains how unsteady airflow produces noise. It combines the principles of fluid dynamics and acoustics to describe how turbulence, vortex shedding and flow separation produce pressure fluctuations which radiate noise. It is particularly useful when studying how solid surfaces, such as propellers or wings, generate noise.

Aeroacoustics was first established by Lighthill, who, in his analogy, reformulated the Navier-Stokes equations into an inhomogeneous wave equation which treated turbulent eddies as sources of sound [11].

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad \frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla p + \nabla \cdot \boldsymbol{\tau}, \tag{1}$$

where $\rho$ is the fluid density, $\mathbf{v}$ is the velocity vector, $p$ is the pressure, and $\boldsymbol{\tau}$ is the viscous stress tensor.

There are two crucial dimensionless parameters which describe aeroacoustics behaviour, the Mach number, $(M = \frac{U}{c})$, which indicates compressibility effects, and the Strouhal number, $(St = \frac{fL}{U})$, which relates dominant noise frequency to flow velocity and length. Despite operating at relatively low Mach numbers $(M < 0.3)$, UAM rotors can produce considerable tonal and broadband noise due to unsteady aerodynamic effects.

### 3.2 Flow Physics Around Aerofoils and Rotors

As air flows past an aerofoil, it separates into two streams, one below, and one above the surface. Air flowing over the surface flows faster than the air flowing underneath. This pressure differential is what generates lift needed for flight, however it also creates unsteady flow conditions that give rise to aerodynamic noise.

The thin layer of retarded flow, which we call the boundary layer, develops along the surface of the aerofoil due to the airs viscosity slowing down airflow nearer the aerofoil. When adverse pressure gradients become sufficiently strong, the boundary layer separates from the surface, creating flow separation. These separated layers create vortices that form a turbulent wake downstream from the aerofoil. This turbulence induce fluctuating aerodynamic forces on the foil which radiate as broadband noise [12].

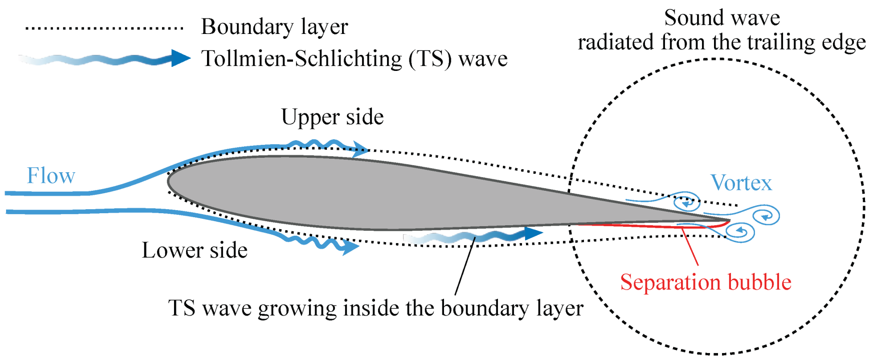



Figure 4: Schematic diagram of the generation of trailing-edge noise on a aerofoil [13].

### 3.3 Primary Noise Source Mechanisms in UAM

Noise generation in Urban Air Mobility (UAM) vehicles arises from several distinct physical mechanisms, each linked to unsteady aerodynamic loading and flow interactions around rotating blades. The combined effect of these sources produces a complex and often difficult-to-control acoustic signature.

- **Tonal Noise** occurs when there are periodic variations in aerodynamic force loading from the blades' rotation. It is most common during hover or low-speed flight, when the interaction between the blades and their turbulent wakes generate strong tones at the blade passing frequency and its harmonics [14].

- **Broadband Noise** is produced by random processes such as boundary layer turbulence, flow separation and wake instabilities. It has a large frequency range and tends to be the most prominent noise at higher flight speeds [15].

- **Blade-Vortex Interaction (BVI) Noise** arises when a rotary blade intersects the tip vortex created by another blade, generating pressure fluctuations an intense noise bursts [16].

- **Mechanical Noises** can also be prominent in UAM noise generation, arising from motors and other drive components. Although they are typically lower in amplitude, they do add to the total complexity of UAM noise emissions.

### 3.4 Near-field vs Far-field Propagation

The acoustic field around a source producing aerodynamic noise is typically divided into two distinct regions: the near-field region, affected mainly by hydrodynamic effects, and the far-field region, where pressure waves propagate independently through the air. In the near-field, acoustic energy – due to vortex shedding, blade-wake interactions, and turbulent eddies – oscillates with little uniformity [17]. Thus, in this region, the rate at which the energy of the wave dissipates, the amplitude decay, follows a steeper gradient than $1/r$, due to the pressure field being partially hydrodynamic, containing stored energy rather than radiating energy [17].

The span of the near-field depends on the source itself and on the frequency, Mach number, and wavelength of the sound waves, but it ends when the sound can be approximated as originating from a point source [18]. Surrounding this region immediately about the source are many cases of complex interference; this directly leads to the superposition of different sound waves and non-uniform pressure distributions. Propagation in the far-field follows uniform wave distribution, with energy radiating spherically over the volume of a sphere, because the acoustic pressure becomes decoupled from the flow [17].

In the far-field, sound-wave amplitude decreases approximately as $1/r$. The radiation patterns emerging in the far-field are governed by phase coherence of the waves, geometry, and rotational velocity of the propeller or rotor. Results from studies on propeller motion show that coherent sound waves, such as blade-passing frequencies, radiate effectively and therefore dominate what distant listeners experience, whereas incoherent frequencies such as broadband turbulence radiate poorly as they decay rapidly [18]. The region of transition from near to far is heavily dependent on acoustic wavelength; lower frequencies extend the near-field region. Both constructive and destructive interference can occur in the far field as sound waves in this region are phase coherent. This affects directivity and the level at which a listener perceives the sound [18]. Accurate UAM noise analysis and prediction require a bilateral approach: the study of near-field noise generation and far-field acoustic propagation to assess environmental exposure.

### 3.5 Psychoacoustics

Psychoacoustics involves studying the relationship between sensory perception and physical quantities—in this case, sound waves and their properties. The human hearing system does not respond uniformly to higher-pressure sound waves but is dependent on various factors, including frequency, duration, and pitch. Therefore, human perception of UAM noise is not related solely to the energy levels of the sound wave but also to different factors [19].

Specific to UAM's, noise from rotors or propellers arises in the form of complex acoustic signatures and is dominated by tonal components, occurring at both blade-passing frequencies and broadband turbulence from wake interactions. Simulation models have shown that these tonal properties have a disproportionate effect on perceived loudness, and consequently annoyance, when compared to similar energy steady-state or broadband sounds [20]. The conventional measure involving A-weighted decibels therefore underestimates the sensitivity of the human response to noise from UAM's, as it fails to capture the non-uniform perception of sharpness, fluctuation strength, and roughness. Measurement methods such as Aures tonality provide better insight into human perception and interpretation of these sounds [20].

Laboratory studies and simulations confirm that humans perceive UAM noise to be of greater annoyance than traditional transport methods such as cars or aeroplanes, even at equal intensity. The psychoacoustic response is shaped by the acoustic spectrum, temporal variability, and motion of the source, which, in the context of UAM vehicles, creates fluctuating audio that draws attention. The visual presence can further affect the sensitivity of the human response, amplifying perceived noise and thus further increasing annoyance [21].

Thorough understanding of the psychoacoustic effects of UAM vehicles is vital for the design and manufacture of low-impact products. Incorporating this knowledge allows engineers to target relevant aspects in terms of perception, such as reducing tonal peaks and optimising rotor speeds. By aligning initial design considerations with end-user experience and environmental impact, the integration of UAM vehicles into everyday life can be ensured .

### 3.6 Quantitative Analysis of Acoustic Liner Physics

An acoustic liner works by absorbing incident sound waves and dissipating their energy as heat and viscous loss within small cavities and pores. The liner system acts as a Helmholtz resonator array. Sound waves enter the perforations and cavities. Air in the holes vibrates in a similar way to that of a spring-mass system. The oscillating air dissipates energy through viscous friction and thermal energy transfer through the cavity walls. Through various experiments and research, engineers and physicists have been able to derive some governing equations to describe how acoustic liners work.

### 3.6.1 Acoustic Impedance:

The performance of a liner is described by its specific acoustic impedance, $Z_p(\omega)$, measured in rayls (Ry), which is equivalent to $kg/(m^2s)$ or $Ns/m^3$:

$$p' = \rho_0 c_0 Z_p(\omega) v_n' \tag{2}$$

where $p'$ is the unsteady pressure at the wall, $v_n'$ is the normal acoustic velocity, $\rho_0$ is the mean air density and $c_0$ is the speed of sound.

It can be defined in many different ways depending on what type of liner is used.

**a) Perforated Liner Impedance** is defined as:

$$Z_p = \frac{1}{\zeta}\left[0.006 + ik_0\left(t_p + 0.375d_h\left(1 + \frac{Z_e}{\rho_0 c_0}\frac{k_e}{k_0}\right)\right)\right] \tag{3}$$

where $\zeta$ is the porosity (open area ratio) of the liner surface, $k_0$ is the acoustic wave number in air, $t_p$ is the panel thickness, $d_h$ is the hole diameter, $Z_e$ is the impedance of the backing cavity, $\rho_0$ is the mean air density, $c_0$ is the speed of sound, and $k_e$ is the wave number within the cavity medium.

**b) Cavity Impedance** is when the backing cavity acts as a Helmholtz resonator, and is defined as:

$$Z_e = -i\rho_0 c_0 \cot(k_0 L_c) \tag{4}$$

where $L_c$ is the cavity depth.

At resonance, $Z_e$ becomes small due to pressure release, leading to maximum absorption.

### 3.6.2 Helmholtz Resonance Frequency:

The Helmholtz Frequency, $f_H$, is the frequency each cavity resonates at, defined as:

$$f_H = \frac{c_0}{2\pi}\sqrt{\frac{A}{VL_{\text{eff}}}} \tag{5}$$

where $c_0$ is the speed of sound, $A$ is the neck cross-sectional area, $V$ is the cavity volume, and $L_{\text{eff}}$ is the effective neck length.

### 3.6.3 Multi-Degree-of-Freedom (MDOF) Liners:

By stacking several perforated layers or cavities of different depths, where each layer has a unique resonance frequency, broadband attenuation can be achieved. This impedance can be calculated as:

$$Z_{\text{total}} = Z_{p1} + Z_{p2} + \cdots + Z_{pn} \tag{6}$$

### 3.6.4 Acoustic Absorption Coefficient:

The absorption coefficient, $\alpha$, quantifies how much sound energy is absorbed:

$$\alpha = 1 - \left|\frac{Z_p + \rho_0 c_0}{Z_p - \rho_0 c_0}\right|^2 \tag{7}$$

where $\alpha = 1$ means perfect absorption (no reflection), and $\alpha = 0$ means total reflection.

These equations were taken and adapted from the following scientific sources: [8], [9], [6].

# 4 State of the Art Noise Control Technologies

## 4.1 Emerging Noise Control Technologies in Aerospace

Urban Air Mobility (UAM) and next-generation rotorcraft demand noise reduction beyond conventional passive liners. Emerging approaches include active noise control (ANC), adaptive and hybrid liners, and acoustic metamaterials. These technologies exploit electronic control or engineered structures to extend attenuation to low frequencies and broad bands. Recent surveys note the importance of both passive design (e.g. blade shaping) and active strategies (e.g. on-blade actuators, zone control) for UAM vehicles [22]. Here we overview the principles and state-of-the-art of ANC systems, hybrid passive–active treatments, and 3D-printed metamaterial liners, highlighting their mechanisms, benefits, and challenges in rotorcraft/UAM applications.

### 4.1.1 Active Noise Control (ANC) and Adaptive Liners

Active noise control uses secondary sound sources (speakers or actuators) and sensors to generate anti-noise that destructively interferes with primary noise. By adaptively tuning the secondary source phase and amplitude, ANC can cancel broadband or tonal components, especially at low frequencies where passive absorption is bulky [23]. For example, Dimino et al. (2022) demonstrated an active headrest system in a turboprop cabin: two control speakers on either side of the passenger's head cancel propeller tones, yielding 2̃0 dB reduction in the ear region [23].

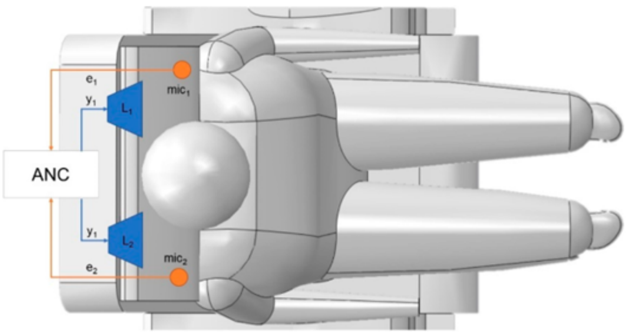



Figure 5: Diagram explaining how ANC works [24].

ANC algorithms typically use multi-channel filtered LMS control to adapt in real time, learning the system transfer functions and minimizing measured error signals. The advantage of ANC is weightless cancellation and effectiveness at low frequencies where passive liners would be impractically thick or heavy [23].

In practice, ANC systems have been implemented in aircraft cabins and cockpit seats and are under study for advanced rotorcraft. Experiments show that ANC can significantly reduce interior noise levels for targeted spectral components, improving passenger comfort [23]. However, ANC's limitations include limited spatial coverage, sensor/actuator density, algorithm convergence time, and sensitivity to changing conditions. Adaptive liners, which electronically or mechanically adjust their impedance (for example via tuneable Helmholtz elements), are an extension of ANC ideas at the wall. In effect, an adaptive liner can vary its boundary impedance to optimize absorption under changing flight conditions [25]. Such systems remain largely experimental but promise to maximize absorption bandwidth without adding physical thickness [25].

In laboratory tests, ANC headrest prototypes have been shown to cancel low-frequency tones to well below audible levels. In these setups, microphones placed near the ears and speakers embedded in the headrest seat complete the feedback loop. Real-time trials report 15–25 dB reductions of cabin noise for test tones and turbulence-induced loads [23]. These results illustrate ANC's potential for passenger-level noise control in eVTOL cabins but also highlight the challenge of scaling up: multi-rotor aircraft produce complex, multidirectional noise fields, and ANC would require large sensor/actuator arrays or on-rotor solutions (e.g. on-blade active flaps) [22].

### 4.1.2 Hybrid Passive–Active Acoustic Treatment

Hybrid liners combine conventional passive absorbers (e.g. wire-mesh or porous layers) with active control elements (secondary sources) to achieve broadband noise reduction. The passive layer provides high-frequency absorption and structural support, while active sources on the liner back face (often small loudspeakers) cancel low-frequency wave reflections or resonances [23]. describe a ducted hybrid absorber where a porous layer is backed by an adaptive control loop at low frequencies. The key idea is that the active system mimics an "infinite" backing impedance. by sensing pressure fluctuations behind the absorber and feeding back an inverted pressure wave, the active liner enforces a near-zero pressure boundary at the rear face. This yields full absorption at the control frequencies without requiring a physical quarter-wavelength depth [26].

NASA/Northrop Grumman developed advanced hybrid inlet liners for turbofan engines in the 1990's. The active section (arrays of Helmholtz resonator actuators) is placed upstream of a conventional multi-segmented passive liner [27]. In operation, the active elements scatter incoming modes to higher-order modes and then minimize transmitted noise by feedback control. Parente and Arcas (1999) report that their hybrid jet-engine liner was able to suppress certain fan tones by roughly 10 dB beyond what the passive liner alone could achieve [27]. In essence, the active subsystem preconditions the acoustic field, redistributing energy among modes so that the downstream passive sections absorb it more effectively [27].

Hybrid concepts offer advantages in turbomachinery and rotorcraft inlets by targeting tonal noise and expanding the effective bandwidth. Active control can compensate for flow effects or off-design conditions where passive liners alone underperform [27]. However, they bring drawbacks: added system complexity, power requirements, and potential stability issues. Moreover, hybrid liners have mostly been demonstrated in laboratory rigs [26]. Their implementation in real UAM/rotorcraft is still nascent. Mechanical integration and certification considerations (failure tolerance) pose challenges [22].

### 4.1.3 Acoustic Metamaterials and Additively Manufactured Liners

Acoustic metamaterials use engineered sub-wavelength structures to achieve unusual effective properties (e.g. negative bulk modulus or tailored dispersion) not possible with homogeneous media. Designs include arrays of coupled Helmholtz resonators, labyrinthine channels, slotted cavities, or periodic lattices that trap and dissipate sound [22]. Recent reviews categorize 3D-printed acoustic metamaterials into perforated, slotted, cellular lattice, and hybrid types [26]. By stacking multiple resonances or using coupled resonators, these metamaterials can produce multiple absorption peaks or a widened absorption band [26]. For instance, connecting two Helmholtz cavities in series yields a 2-DOF system with two resonant peaks and an intermediate anti-resonance, thus broadening attenuation beyond a single resonator [25]. In practice, such unit cells can be packed into a surface layer to form an effective acoustic barrier that is much thinner than conventional absorbers [22].

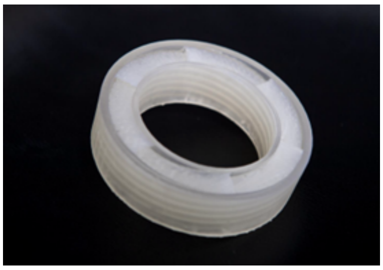


Figure 6: Photograph of a 3D-printed ring-shaped acoustic metamaterial (Boston University) that blocks sound while preserving airflow. Incoming sound waves entering the open central core are scattered by the helical channels visible inside the ring and reflected toward the source. Tests showed this metamaterial silenced over 90% of incident noise despite its open-channel design.

Despite their promise, metamaterials have disadvantages. Most designs rely on resonance and therefore offer narrowband attenuation unless many resonators are tuned across frequencies [26]. Also, losses (e.g. viscosity, thermal damping) and manufacturing tolerances can limit performance [28]. Recent research aims to overcome these limits: for instance, embedding active control inside metamaterial unit cells can achieve active acoustic metamaterials with bbbb or non-reciprocal behaviour [25]. Nevertheless, the maturity of metamaterials for aerospace noise is still emerging [22]. In UAM applications, metamaterial liners could provide lightweight, compact noise shields for ducts or fuselage panels, reducing low-frequency rumble without bulky foam. Their compatibility with additive manufacturing makes them attractive for custom engine nacelles or duct shapes typical of eVTOL designs [28].

## 4.2 Liner Technologies That Could be Used in UAM Applications:

Next-generation rotorcraft and Urban Air Mobility (UAM) demand liner solutions that provide wide-band attenuation in small, low-machine ducts. This section examines three cutting-edge, installable options: (i) traditional perforate-honeycomb liners (SDOF/2DOF, with mesh-cap localization and variable-depth variants) that have been validated under normal-incidence and grazing-flow conditions [29]; (ii) micro-perforated panels (MPPs), which achieve fibrous-free broadband absorption by using Maa-type tuning of sub-millimetre perforations and cavity depth, with rapid iteration made possible by additive manufacturing [30]; and (iii) media-augmented liners, where partial granular fill broadens bandwidth at low cost while maintaining resonance performance in duct tests with modest flow [31]. We highlight the test-rig evidence, manufacturing routes, governing mechanisms, and proven benefits that are most pertinent to UAM inlets and shrouds.

### 4.2.1 Conventional Perforate–Cavity Liners (SDOF/2DOF)

The perforate-over-honeycomb wall treatments used in conventional nacelle liners are either single-degree-of-freedom (SDOF), which consists of a perforated facesheet over a cavity, or two-degree-of-freedom (2DOF/DDOF), which includes a perforated or mesh septum to create a second resonant layer and expand the useful absorption band. In order to add effective degrees of freedom, NASA also documents a localised-tuning variant of this same architecture, where embedded mesh caps are positioned in each core chamber at varying heights and with prescribed DC resistances as seen in the below figure. In addition to these baselines, the same report's concept survey identifies metallic-foam cores and variable-depth liners, including bent-chamber versions to increase low-frequency reach as experimental broadband options [29].

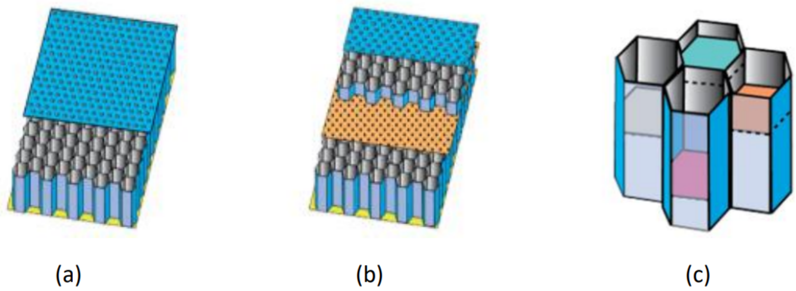



Figure 7: (a) Single (SDOF), (b) Double (DDOF) and (c) Four chambers of a linear core with embedded mesh caps [29].

Since their impedance (resistance and reactance) is well understood and consistently predicts measured absorption in representative test rigs, SDOF/2DOF perforate-honeycomb liners continue to be the baseline. NASA provides with- and without-flow datasets up to about Mach 0.6 from the Normal-Incidence Tube (NIT), Grazing-Flow Impedance Tube (GFIT), and Curved Duct Test Rig (CDTR), which together validate these designs under installed conditions. For UAM inlets and shrouds in compact ducts with subsonic or grazing flow and mixed tonal plus broadband noise, these liners offer a low-risk, lightweight, and manufacturing-ready starting point. They can be tailored with mesh-cap localization or variable-depth adjustments to enhance bandwidth [29].

| | NIT | GFIT | CDTR |
|---|---|---|---|
| Sample Dimensions | | | |
| Length, in (mm) | 2 (51) | 2 (51) | 30 (762) |
| Width, in (mm) | 2 (51) | 2 - 24 (51 - 610) | 15 (381) |
| Thickness, in (mm) | $\leq$ 24 (610) | $\leq$4 (102) | $\leq$3 (76) |
| Frequency, kHz | 0.4 - 3.0 | 0.4 - 3.0 | 0.4 - 3.0 |
| Centerline Mach # | 0.0 | 0.0 - 0.6 | 0.0 - 0.5 |
| Source Type (max level, dB) | | | |
| Stepped sine | $\leq$155 | $\leq$155 | $\leq$140 |
| Swept sine | $\leq$145 | $\leq$145 | n/a |
| Broadband | $\leq$140 | n/a | $\leq$130 |

Figure 8: NASA Langley Test Rigs Table – Key Features [29].

#### 4.2.2 Micro-Perforated Panel (MPP) Liners:

Thin, rigid sheets with sub-millimetre holes drilled into them and placed over an air cavity are known as micro-perforated panels, or MPPs. When sound strikes the panel, the backing cavity acts as a ”spring-mass” that determines which frequencies are most strongly absorbed, while the air in each micro-hole rubs against the walls (viscous/thermal losses), dissipating energy like an integrated ”resistor.” By using the classical Maa impedance model to co-tune the key knobs (hole diameter, open-area ratio, panel thickness, and cavity depth), MPPs can achieve broadband absorption without fibrous fill and their peak frequency/bandwidth can be positioned where you need it. The cited study’s impedance-tube measurements agree with the model’s predictions, demonstrating that straightforward geometric decisions consistently set performance [30].

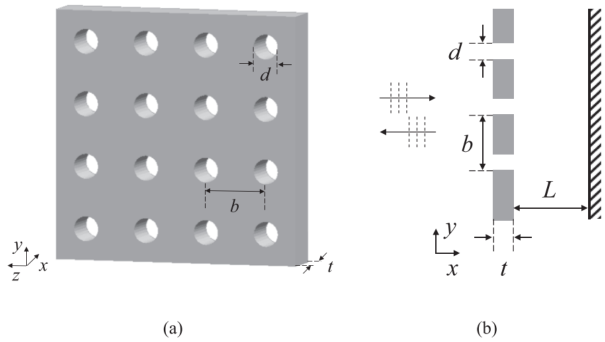



Figure 9: Schematic representation of a MPP: (a) Detailed view; and (b) backed by an air cavity to achieve an acoustic resonator [30].

Because nacelles and shrouds are small and sensitive to weight, this is important for UAM. According to the same study, Digital Light Processing (DLP) 3D printing can create precise sub-mm perforations (hole size controlled by exposure time), confirm geometry using microscopy, and create panels whose measured absorption closely resembles the Maa-based targets. This makes quick, inexpensive iteration feasible for constrained spaces and stringent mass budgets, which are common in UAM vehicles. In summary, MPPs are non-fibrous, thin, and lightweight liners that have a proven lab-to-print workflow and an equation-driven tuning method, making them a strong state-of-the-art option for UAM acoustic treatments [30].

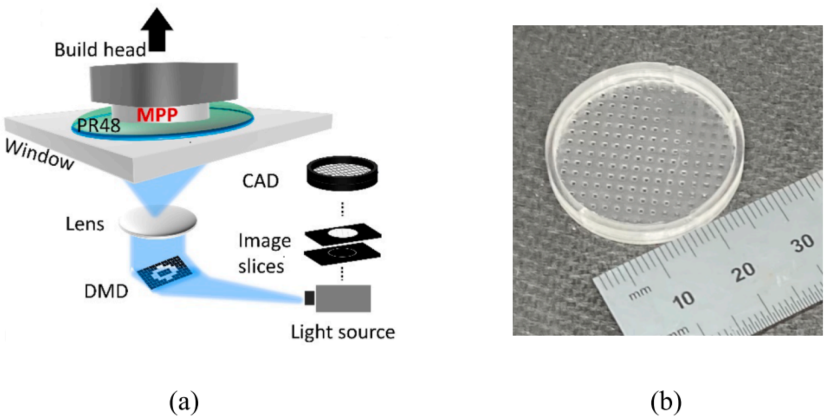



Figure 10: (a) Fabrication of the MPP samples using DLP 3D printing (3DP) technology, (b) detailed view of a printed MPP obtained from the MPP design image [30].

### 4.2.3 Media-Augmented Liners

A low-cost method of increasing the bandwidth of traditional SDOF/2DOF perforate-honeycomb liners without adding thickness is to partially fill honeycomb cells with light granular media (cork, balsa, or polymer granules). The effect lasted at approx. 140 dB and with moderate grazing flow (M = 0.13), with cork providing the largest broadening. In controlled tests, a fill of about 66 percent broadened the transmission-loss well while maintaining the resonance peak largely intact.The benefit remained with reduced cover porosity (Kevlar mesh) and improved with irregular, polydisperse grains over near-monodisperse spheres. The mechanism is consistent with inter-particle friction increasing effective resistance and slightly reducing reactance. In UAM prototypes and hardware, this pour-in, geometry-agnostic modification, is a useful method to ”dial in” additional bandwidth for compact inlet/shroud liners because it adds minimal mass, is adjustable by fill height and grain type, and retrofits into standard cells [31].

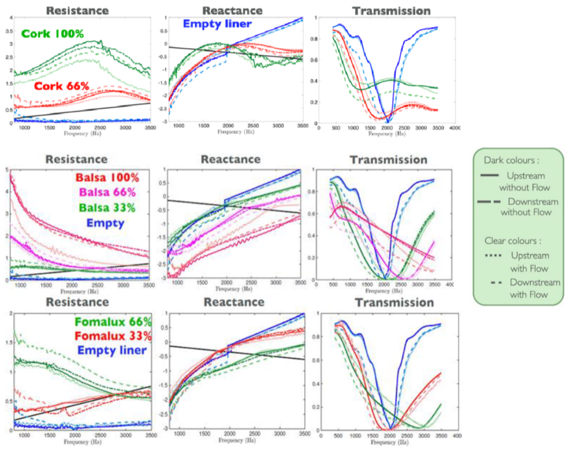



Figure 11: The effect of honeycomb filling with cork powder on resistance, reactance and transmission [31].

# 5 Potential Liner Designs for Additive Manufacturing

The following section explores possible acoustic liner designs that could be implemented for UAM, based on some of the state of the art noise control technologies currently being developed. The key criteria needed for liners in UAM applications are:

- **Lightweight:** Ensures agility and efficiency in flight.
- **Broadband performance:** Attenuates noise across rotor speeds.
- **3D printable:** Compatible with resin-based MSLA or FDM fabrication.
- **Durable:** Withstands operational stresses.
- **Low-Mach effectiveness:** Optimised for UAM flow conditions.

The liner of our choice needs to be able to be made for the test rig with low cost 3D printing (FDM and MSLA). An photograph of the rig is shown in the figure below.

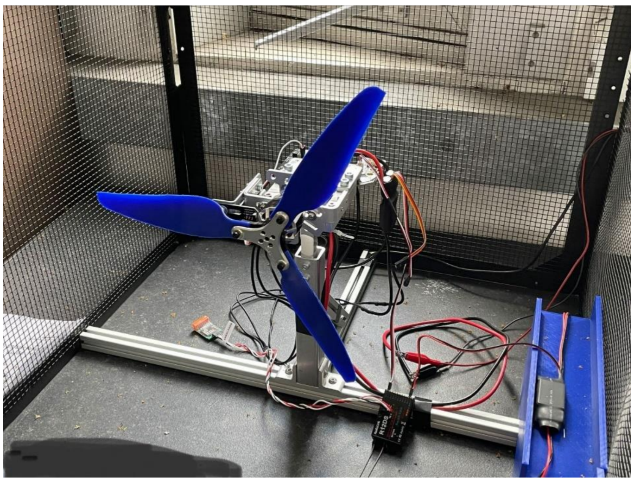


Figure 12: Photograph of the test rig being used to evaluate our choice of liner.

## 5.1 Potential Liner Designs for UAM Use

Based on the above analysis of the liner requirements, and following on from Section 4, we have analysed each different type of liner and tried to determine what type/combination of technologies would deliver the best performance in the rig.

### 5.1.1 Curved Micro-Perforated Panel (MPP) Liners

Curved micro-perforated panel (MPP) liners offer an effective and practical noise-control solution for ducted UAM propulsion systems. By introducing curvature to conventional MPP liners, the interaction path between incident sound waves and the liner surface is extended, resulting in broadband attenuation (100–3000 Hz) suited to the low-Mach, subsonic flow of UAM rotors. The design also enhances aerodynamic efficiency, improving thrust by approximately 30 g at 5000 rpm compared to a rigid duct. It also reduces overall sound pressure levels by up to 4.2 dB.

Because the liner relies on a thin micro-perforated structure, it remains lightweight and mechanically durable, and can be additively manufactured using resin-based 3D printing without compromising nacelle geometry. These combined attributes of low mass, broadband effectiveness, manufacturability, robustness, and efficiency under low-Mach operation make curved MPP liners highly suitable for integration into next-generation UAM acoustic treatments [32].

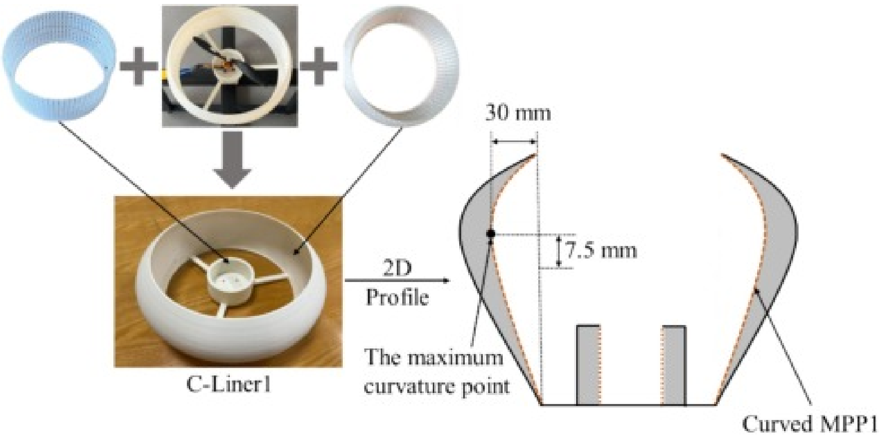



Figure 13: 3D printed liner and technical drawing of it [32].

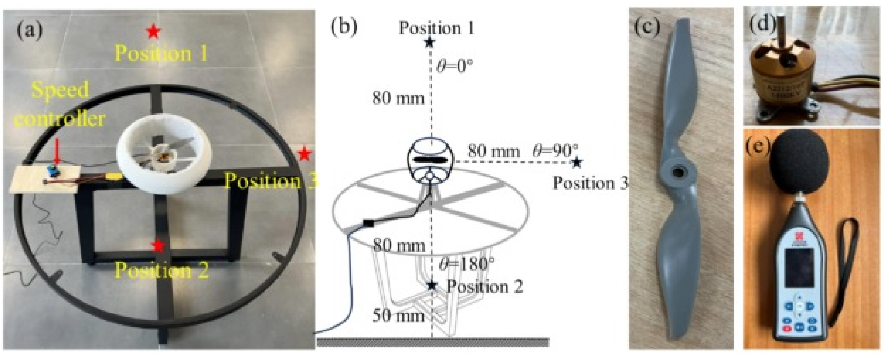
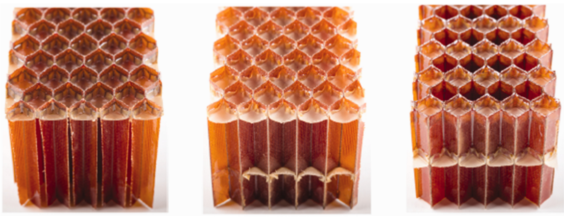


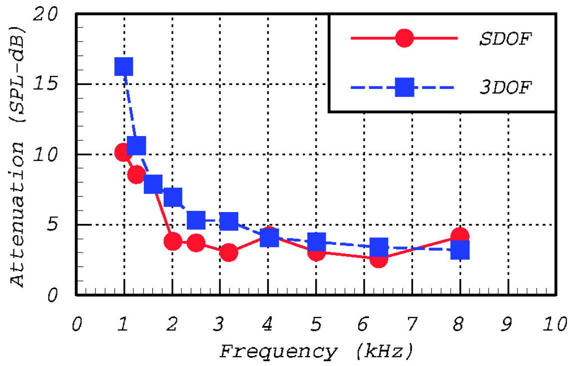

Figure 14: Photographs of the (a) Performance testing platform, (b) Sketch of the positions and angles for Position 1–3, (c) Propeller, (d) Motor, and (e) Multifunction sound level meter [32].

### 5.1.2 Variable-Depth/ Multi-DOF Graded Liners

The multi-degree-of-freedom (MDOF) liner configuration offers clear advantages for use in UAM devices. Its design, which is based on variable-depth resonant cavities within a single honeycomb structure, delivers broadband acoustic attenuation across tonal and broadband noise bands typical of drone rotors. The liner's lightweight composition combines thin perforated face sheets with polymer or composite honeycomb cores, minimising mass while maintaining structural integrity under cyclic aerodynamic loads. This satisfies durability requirements for continuous operation. The modular honeycomb and mesh-cap construction can be readily manufactured through additive or resin-based 3D printing, allowing custom altering of cavity depths and geometries for different designs. Its passive operation and low surface drag ensure effective performance under low-Mach, subsonic flow conditions. Together, these characteristics make the MDOF liner an efficient and easily manufacturable acoustic treatment option [9].



(a) Manufactured SDOF and MDOF liners for aerospace applications [9].




(b) Graph showing the performance of a SDOF vs 3DOF liner in attenuation over a large frequency spectrum. [9].

Figure 15: MDOF liners.

### 5.1.3 Bio-Inspired Liners

As explored previously in Section 2.3.3, bio-inspired liners have proven to have great sound wave attenuation properties. In fact they show improved low-frequency absorption compared to conventional design liners. The irregular pore distribution and interconnected flow channels of bio-materials enhance viscous and thermal damping. This enables a broadband performance similar to multi-layer liners - however in a much thinner and lightweight form. This makes them great candidates for UAM liners. Unfortunately, they lack the durability needed for UAM applications and so rules them out of contention. However, through replicating their designs using 3D printed polymer or composite lattices, a similar performance could be achieved while remaining lightweight and becoming more structurally robust. When designing a liner for UAM devices, it would be very effective to take inspiration from bio-materials and their compositions, however bio-materials themselves are not suited for use as UAM liners [10].

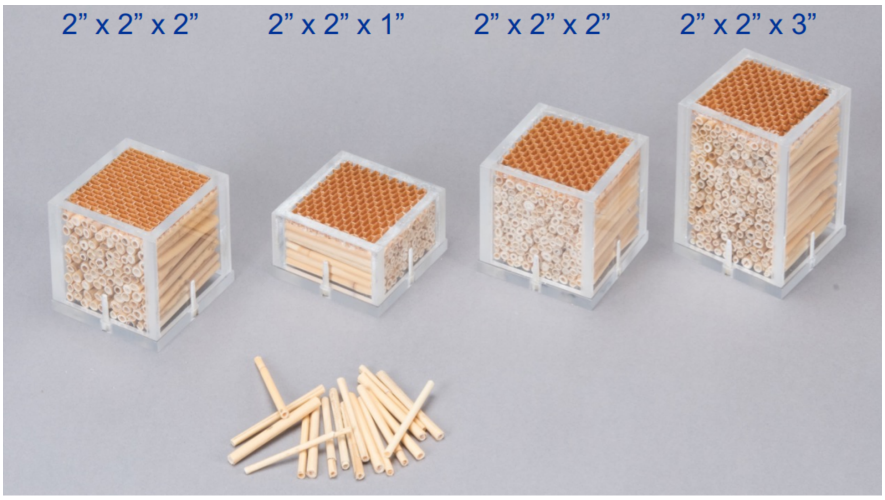



Figure 16: Bio-acoustic liner made using reeds [10].

#### 5.1.4 Media-Augmented Liners (Granular / Porous Fill)

As explored earlier, there could be a possible use for augmented filters, where cavities are partially filled with lightweight friction powders or granular media to enhance broadband absorption. By adding materials such as cork, balsa wood, or polymer granules to SDOF honeycomb cells, much there was better attenuation over a much larger broadband of frequencies. This effect arises from micro-scale friction between particles, which dissipates sound energy as heat. While this may seem like a good option for use in UAM applications the main concern is regarding durability. While this could be a lightweight, effective, and easily manufacturable solution, the augmented media would contain loose elements such as cork or polymer beads. This could lead to further vibration during flight which could lead to gradual wear [31].


Figure 17: Possible forms of media that could be used in the liners [31].

#### 5.1.5 3D-Printed Metamaterial Liners

When assessing some of the state of the art liner technologies, 3D printed metamaterial liners showed several key advantages. The lattice-style construction and sub-wavelength cell units enable broadband absorption, enabling them to attenuate varied frequency spectrum of a drone's blades during flight. As they are made from polymer or composite material, they are a good lightweight solution. These materials also offer a good stiffness-mass ratio, making them durable and suited to withstand in-flight vibrations. The liners are also very easily optimised. As they are designed using CAD, changes and improvements can be easily made and they can be very quickly manufactured by using 3D printing. This also means that they can be directly integrated into nacelle walls or ducts without further assembly. The designs can also be designed to function well in low-Mach environments making them suited for UAM.

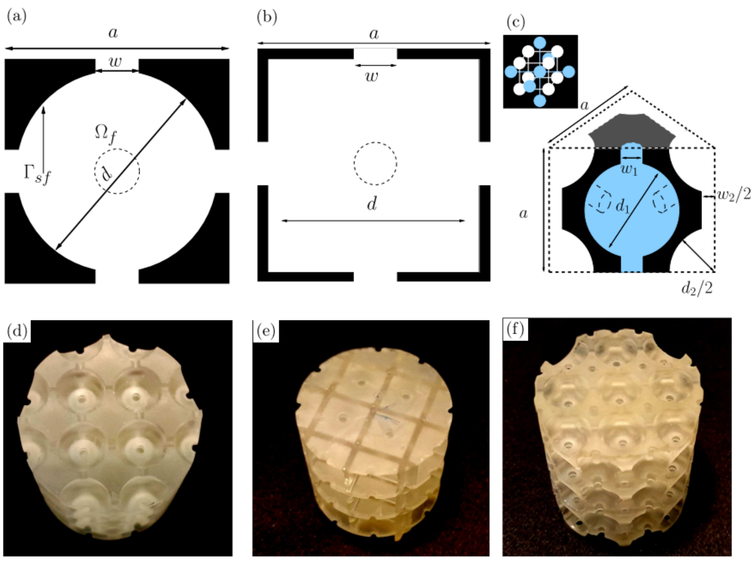



Figure 18: 3D printed liners [33].

## 5.2 Proposed Acoustic Liner Design for UAM

The optimal liner design for for UAM use would ideally incorporate all of the good qualities from the above mentioned liner types into a single hybrid design. To create a liner that could be tested in the rig, the liner should be a cylindrical or semi-ducted nacelle that can be placed around the propeller. The liner would be a 3D printed modular insert made using a resin-based MSLA or FDM technology. This would ensure that a rigid, lightweight, precise structure could be made. The design should also incorporate MDOF resonant cavities distributed around the duct. The outer surface should incorporate a lightweight lattice shell, inspired by the geometry of lightweight bio-materials such as reeds or honeycomb. Within each cavity there should be a porous sub-layer to act as frictional damping layer to broaden the frequency absorption.

The liner would be mounted one blade's length away from the rotor both downstream and upstream to capture both the inflow and outflow noise of the rotor. Microphones could be installed at each side to capture the sound intensity and pressure levels with and without the liners to document the liner performance.

# 6 Conclusion

UAM represents a monumental change in urban transit, but its success heavily depends on tackling noise pollution challenges. To summarise, this report highlights that while conventional acoustic liners are still critical in traditional aviation, the intricate geometries and low-Mach flow regimes of UAM vehicles require re-engineering to obtain efficient and lightweight solutions. Active noise control and hybrid passive active treatments offer suitable low-frequency performance but introduce a range of complex issues and power demands that are unsuitable for small eVTOL aircraft. In contrast, 3D-printed metamaterial and multi-degree-of-freedom liners, particularly when combined with biology inspired compositions and porous damping layers, provide an optimal balance of performance, manufacturability and weight efficiency. The proposed hybrid liner design integrates these principles to yield a modular, cost-effective acoustic treatment compatible with additive manufacturing. Ultimately, integrating advanced liner technologies will be essential to ensuring UAM systems achieve the environmental and social compatibility that is required for widespread roll out in urban environments.

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# 7 Minutes of Group Meetings

## Meeting 1 – Research Scope and Task Allocation

**Meeting Date:** 26/09/2025
**Meeting Attendees:** Finn, Brian, Billy, Karim, Emily

This meeting was organised to define the scope of the literature review and assign roles to each group member in accordance with their individual strengths and the project outline.

**Aims:**

- To review the assignment outline and understand the research challenge.
- To identify the strengths of each member and assign tasks accordingly.
- To agree on collaboration pairs and a preliminary timeline for the assignment.

**Discussion Points:**

| Ref | Discussion |
|---|---|
| Topic 1 | The group reviewed the assignment brief and marking criteria. Agreed that the report would focus on noise emission, acoustic liner design, and environmental considerations. |
| Topic 2 | Tasks were allocated based on member strengths: Finn – Sections 1 and 4; Brian and Billy – Section 2; Karim and Emily – Section 3. Referencing and formatting responsibilities were deferred to a later stage. Agreed that Google Scholar would be used for data collection, and a shared Zotero was established for document sharing. Next meeting scheduled for 06/10/2025. |

**Actions:**

| Action | Description | Responsible | Due date | Note |
|---|---|---|---|---|
| 1 | Begin individual research and collect minimum 3 key sources each | All Members | 02/10/2025 | Upload to shared drive |
| 2 | Draft outline of assigned section | Each Pair | 02/10/2025 | Collaborate in pairs |
| 3 | Prepare questions or gaps to address in next meeting | All Members | 02/10/2025 | Discuss with new member |

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## Meeting 2 – Integration of New Member and Task Reallocation

**Meeting Date:** 03/10/2025
**Meeting Attendees:** Finn, Brian, Billy, Karim, Emily, Michael

This meeting was held to integrate Michael (joined 01/10/2025), confirm adjusted responsibilities, and establish referencing and formatting management.

**Aims:**

- To welcome Michael and discuss how his addition affects section allocations.

- To confirm who will handle referencing and formatting for the final submission.
- To review initial progress on research and outline collaborative expectations.

**Discussion Points:**

| Ref | Discussion |
|---|---|
| Topic 1 | Michael was welcomed to the group. Since he and Finn are working together on Sections 1 and 4, they agreed to jointly manage referencing and formatting moving forward. |
| Topic 2 | Brian and Billy reported progress on the physics section. Karim and Emily continued reviewing literature on liner technologies. |
| Topic 3 | The group agreed to use Harvard referencing and set up a shared Zotero library for citation management. Formatting will follow the module template guidelines. Next meeting scheduled for 09/10/2025 to review section drafts. |

**Actions:**

| Action | Description | Responsible | Due date | Note |
|---|---|---|---|---|
| 1 | Begin drafting introduction and all sections | All Members | 05/10/2025 | Follow assignment marking criteria |
| 2 | Continue collecting liner technology papers | Karim, Emily | 06/10/2025 | Ensure minimum 3 sources per member |
| 3 | Establish Zotero library and manage citations moving forward | All Members | 09/10/2025 | Maintain Harvard style consistency |

After this meeting, pairs working collaboratively on sections met individually, and a final meeting date was set.

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## Meeting 3 – Final Document Review and Goal Checking

**Meeting Date:** 09/10/2025
**Meeting Attendees:** Finn, Brian, Billy, Karim, Emily, Michael

This meeting was held to confirm that all agreed targets were met and that the document format and bibliography conform to the assignment guidelines.

**Aims:**

- Ensure that all members had submitted their references.
- Confirm that all required topics are covered.

**Discussion Points**

| Ref | Discussion |
|---|---|
| Topic 1 | Each person had read the final document prior to the meeting; any outstanding formatting issues were brought to light and addressed during the meeting. |
| Topic 2 | Each section was reviewed; we ensured there was clarity between sections and that every topic was suitably addressed. |

**Actions**

| Action | Description | Responsible | Due date |
|---|---|---|---|
| 1 | Finalise LaTeX code and do one final read-through of each section. | Finn | End of Day |
| 2 | Ensure assignment submission. | All Members | 10/10/2025 |

# 8 CRediT Author Statement

- **K. Bakhet** – Sections 4.1 Ref 22, 23, 24, 25, 26, 27, 28
- **B. Gaffney** – Sections 3.4, 3.5. Ref 17, 18, 19, 20, 21. Meeting Minutes 3
- **B. Lee** – Sections 3.1, 3.2, & 3.3. Ref. 11, 12, 13, 14, 15, 16.
- **E. McAleese** – Sections 4.2, 4.2.1, 4.2.2, 4.2.3. Ref 29, 30, 31.
- **F. O'Connor** – Sections 2.3, 3.7 & 5. Ref. 5, 6, 7, 8, 9, 10, 31, 32. LaTeX formatting and Zotero file management.
- **M. Sadlier** – Sections 1 , 2.1 , 2.2 & 6. Ref. 1 , 2 , 3 , 4. Meeting Minutes 1 & 2. Assisting Finn with formatting

# 9 Group Grade Scaling Factor

K. Bakhet : 100%
B. Gaffney: 100%
B. Lee: 100%
E. McAleese: 100%
F. O'Connor: 100%
M. Sadlier: 100%