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Review and results validation on comprehensive cabin noise control system

WP2 – Noise reduction in vehicle and aircraft cabins

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Abstract

This report presents a comprehensive review and validation of active and passive noise control strategies for reducing low-frequency cabin noise in aircraft and vehicle environments. The study integrates theoretical analysis, experimental validation, and multi-domain modeling to assess the performance and robustness of hybrid acoustic control systems across structural, acoustic, and environmental conditions. The first section, Contribution analysis for placing active and passive treatments in aircraft cabins, summarizes practical measures to reduce low-frequency noise and vibration in aircrafts, driven by Transfer Path Analysis (TPA) and Panel Contribution Analysis (PCA) results, by means of passive and active methods. The second section, Passive treatments for the reduction of noise transmission into aircraft, focuses on structural–acoustic interaction mechanisms and evaluates multiple low-frequency mitigation concepts. Constrained-layer damping (CLD) materials, tuned vibration absorbers (TVAs), acoustic metamaterials, and Helmholtz resonators are reviewed in the context of their transmission loss, added mass, and environmental robustness. The study further examines fuselage double-panel systems, vibration isolation mounts, and structural connection

modifications, showing that passive methods effectively reduce broadband and high-frequency noise but remain limited for tonal, low-frequency excitations. The third section, Perturbation analysis of cabin acoustics for robust active noise control, investigates active and hybrid control systems capable of adapting to geometric, structural, and thermal uncertainties. Theoretical modeling and simulation studies reveal that variations in temperature and boundary stiffness can significantly alter acoustic transfer functions and controller stability. Robust and adaptive control strategies including H∞ optimization, virtual sensing, and AI-assisted selective filtering are identified as promising approaches for maintaining consistent performance under dynamic cabin conditions.

Section 1: Contribution analysis for placing active and passive treatments in aircraft cabins – Author: Said El Kadmiri Pedraza

This section summarizes practical measures to reduce low-frequency noise and vibration in aircraft cabins after a Transfer Path Analysis (TPA) or Panel Contribution Analysis (PCA) has identified dominant paths. It distinguishes radiating panels, structural connections, and acoustic partitions, and adds a dedicated subsection on active noise control.

Passive solutions for low-frequency noise reduction of radiating panels

At low frequencies a few structural–acoustic modes dominate. Interior panels can radiate efficiently when excited near those modes. Increasing structural damping reduces the resonant response at natural frequencies. Stiffening and mass-addition shift the resonance peak from the original natural frequencies, and locally resonant devices can create noise stop-bands. The effectiveness depends on the panel properties (mass, geometry, stiffness) and its coupling to the structure of the aircraft and the different cavities, so the treatment should be placed and tuned where PCA shows the largest contribution.

An extended method to increase panel modal damping is the Constrained-layer damping (CLD). It consists of a soft viscoelastic layer constrained between the radiating surface and a stiff face layer, in a sandwich-type substructure. The damping performance is subject to material properties and geometric shape of the treatment [1].

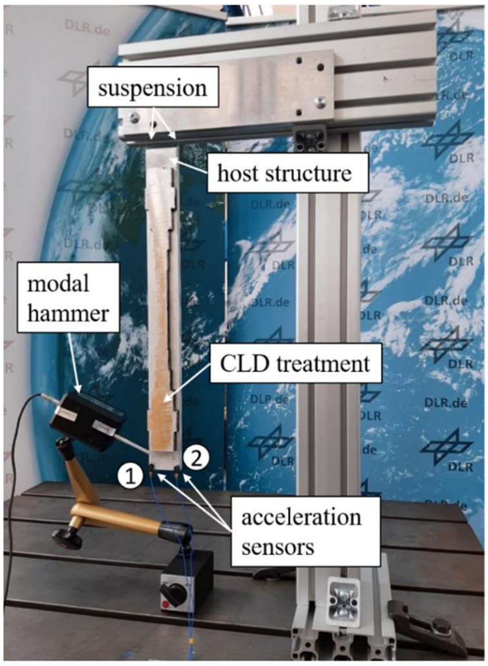

Figure 1. Constrained-layer Damping (CLD) treatment [1]

Another passive method is the use of locally resonant devices, like Tunable Vibration Absorbers (TVA) or Acoustic Metamaterials (AMM). They can target narrow low-frequency ranges when global damping or stiffening is impractical [2,3]. TVA or locally resonant metamaterials increase transmission loss around their stop-bands with modest added mass if they are placed at effective locations.

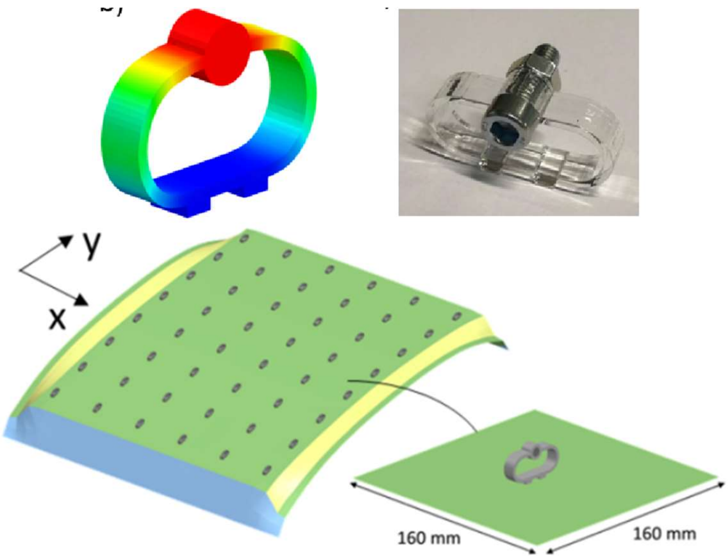

Figure 2. Metamaterial used in ceiling panel of the Acoustic Flight Lab [3].

The field of Acoustic Metamaterials and TVAs is wide and important research is going on to reduce the radiation of plate-like components. In this list, it is important to also mention Acoustic Black Holes (ABS) (Pelat et al. 2020) that combines a local stiffness reduction given by a modification of the structure thickness and a local increase in damping, leading to important attenuation properties [10]. Some advances have been done in the field of vibro-acoustic metamaterials, such as membrane-type (Dinçer et al.), that could in the future be embedded in aircraft interior panels [4].

Passive solutions for low-frequency noise reduction of structural connections

Dominant structure-borne paths at low frequency are often carried by rigid or lightly damped attachments and mount points. Reductions can come from dynamic decoupling, re-tuning mount stiffness to push the mount natural frequency far below the excitation tones, or adding active elements at the attachments when passive isolation is not feasible due to static or strength constraints.

A common approach to reduce vibration transmission is by decoupling active (sources of vibration) and passive components (receivers). This decoupling allows to isolate the vibration of active components, that could be for example the primary structure, and passive components like interior panels.
An extensive review in vibration isolators have been recently published in the field of space structures (Shi et al. 2024) [5]. In this paper, four different types of passive isolators are shown:

- Spring-damper isolations mounts. They are mechanisms that elastically recover the position but dissipate energy in the process through viscous/hysteretic damping. Among them we can find 1) viscoelastic (elastomeric dampers), 2) mechanical springs, 3) viscous fluid dampers (struts). An example can be found in Figure 3.
- Negative stiffness mechanism / quasi zero-stiffness.
- Adaptive / smart materials.
- Metamaterials.

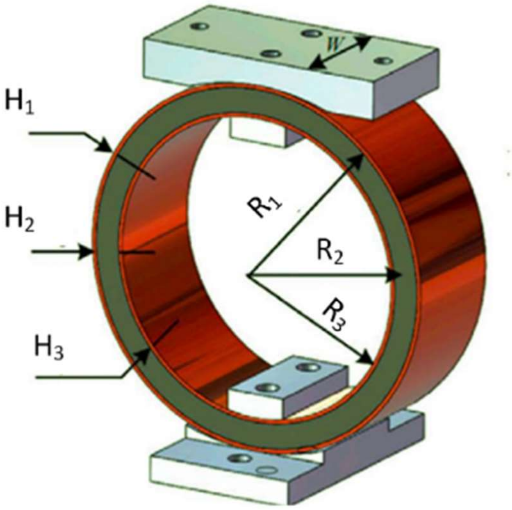

Figure 3. Vibration isolation ring [5].

Passive solutions for low-frequency noise reduction between acoustic cavities

Another mechanism of noise transmission is the acoustic excitation created by the fuselage that is transmitted airborne to the interior panels. This is a type of double-panel concept, and in many aircrafts this space is filled with porous blankets that attempt to absorb the transmitted noise.

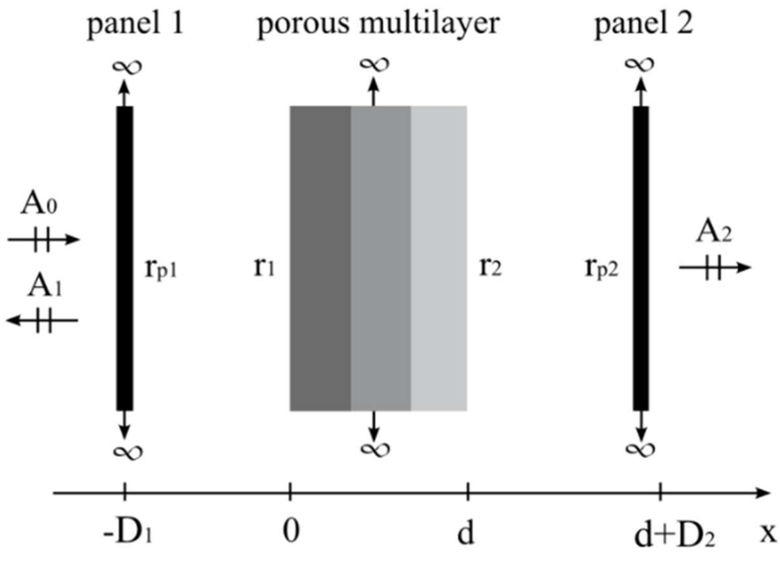

Figure 4. Example of double-panel noise transmission [6].

In this type of assemblies, sound can transfer through two different mechanisms: structure-borne transmission (through mountings) and airborne within the cavity. Attending only to the airborne transmission, in (Doutres O. and Atalla N. 2010) it is shown that at high frequencies

the blanket's transmission loss dominates, while near cavity resonances absorption governs the dissipation; poor blanket absorption at low/mid frequencies can even degrade total TL compared with an empty cavity [6].
In a NASA report (Mixon J., O'Neal R., Grosveld F. 1984), three sidewall configurations were compared: bare, a light "two-inch fiberglass" lining, and a heavier composite package [7]. At low frequencies where propeller tones dominate, all treatments showed limited sound reduction indicating the limitations of these passive treatments at low-frequencies. In the mid-frequency region, the paper demonstrates that absorption in the double-wall cavity is the principal driver of insertion loss: the authors explicitly note that in the important mid band the blanket-induced absorption works well. At high frequencies, the fiberglass-rich layers are the most efficient of the tested elements for high-frequency noise reduction.

However, it was shown in another NASA report (Kuntz H. 1991) that the tonal noise transmission can be suppressed with sidewall-mounted Helmholtz resonators tuned to the blade-passage frequency [8]. Low frequency noise reduction in secondary cavities is, though, a topic that might need deeper research in the future.

Active Noise Control solutions

Low-frequency turboprop noise is well suited for active control because the sound field is dominated by a few coherent components. Two complementary approaches are used: active sound control with loudspeakers to cancel acoustic tones locally or globally, and active structural–acoustic control (ASAC) using actuators on the structure or at attachments.
Classical in-flight feedforward ANC with cabin loudspeakers and reference signals showed robust reductions at several propeller harmonics, establishing feasibility for real cabins [9]. Active structural–acoustic control can target structure-borne transmission by driving the fuselage or mounts to reduce radiated sound power; NASA reports and later applications show this is effective for tonal fields when loudspeakers are impractical [11].
For personal zones, headrest ANC creates a local quiet region around the ears and avoids global energy injection. Recent work demonstrates practical multi-channel filtered-x LMS implementations tailored for turboprop cabins and virtual sensing to extend the quiet zone [12,13].
In terms of global noise reduction in aircraft cabins, late work has been done by attempting to reduce the tonal noise by performing ASAC using the ceiling panels working as loudspeakers [14]. A clear global reduction of the Sound Pressure Level was achieved at the ear-height positions at different target frequencies.

Figure 5. Disposition of microphones and actuators in an aircraft to perform global ASAC [14].

Section 2: Passive treatments for the reduction of noise transmission into aircraft – Author: Andrey Hense

As described in previous section and in [15], to control complex noise problems and efficiently act in the main contributor it is important to understand the system composed by three components: the source, the path and the receiver [16]. Mitigation strategies can target one or more of these components. Noise control at the source is often the most effective and least expensive and it usually requires a design change that reduces operational and transient loads, and lower dynamic excitations (structural or acoustic). Most corrective actions for noise control are implemented by changing the path between the source and the receiver. At the receiver side, it is important to understand what is considered acceptable for the listeners and what is the main goal: (1) preserve hearing, (ii) enable easy conversation or (iii) provide comfort [16].

Majority of aircrafts make exclusive use of passive methods to reduce cabin noise [17]. The passive approach involves making structural alterations to isolate, and integrating damping materials to dissipate, both structural and acoustic energy. The passive methods are characterized by not requiring an additional power supply to achieve noise reduction. The fundamental concept of cabin soundproofing has remained unchanged over time, although specific design details have been refined, especially to achieve greater treatment efficiency.

The underlying physics of sound propagation differ between structural-borne and airborne leading to different types of effective mitigation strategies. Another important consideration for noise control is the source characteristics frequency content and the spatial distribution of the excitation and propagation in the aircraft. In the following paragraphs, the most common passive methods will be shortly described.

Two examples of noise control treatment are shown in Figure 7 and 8. According to [17], a basic noise control treatment comprises one or more layers of porous material, an intervening sheet of heavy, limp material, and a covering impervious trim. The porous material layer is an essential solution for noise control on airplanes, a comparison of transmission loss (TL) with and without the porous material is shown in Figure 6. As a trade-off between weight and TL, a typical porous material used is fiber glass with density of approximately 10kg/m^3 [17]. Additionally, the trim panel is fixed to the fuselage structure at the frames—often using vibration isolation mounts.

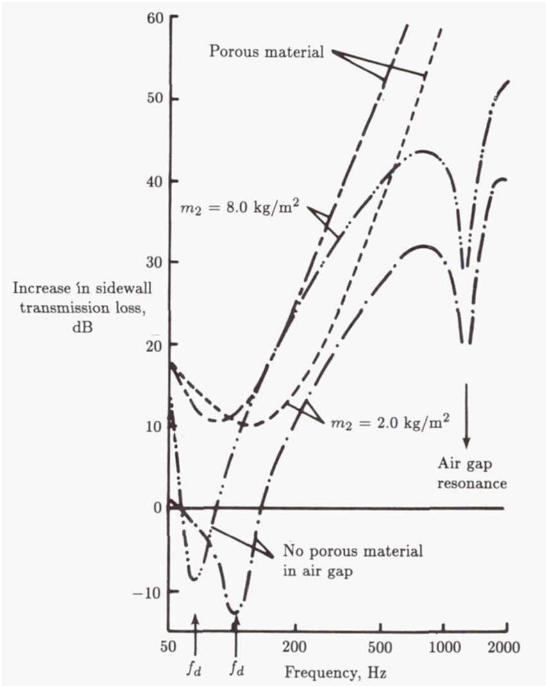

Figure 6: Increase in sidewall transmission loss (dB) with and without porous material [18].

In [19] it is argued that a single "limp trim panel" is actually not seen in aircrafts, instead two distinctive layers are used (figure 8), a first layer of glass-fiber blanket and a second trim decorative layer. However, the introduction of high stiffness composite for the trim panel increased the radiation to the interior cabin through the structural connections as a "flanking path" and the assumption of two independent layers is not valid anymore. A generic attenuation curve divided into 4 regions is presented by the author, see Figure 9. Each region is controlled by specific physical phenomena: a) double-wall resonance-controlled, b) mass law transmission-loss-controlled, c) attachment-point-forced transmission, and d) attachment point coincidence-controlled. Furthermore, some design guidelines are given.

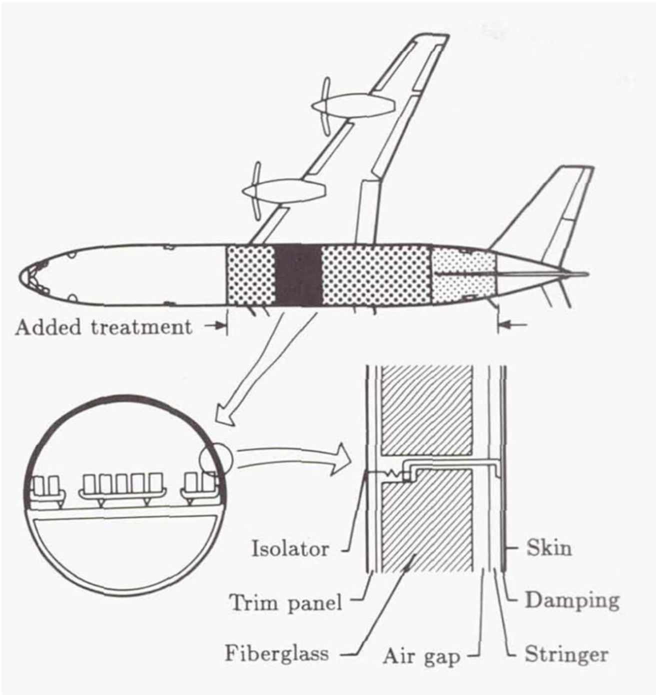

Figure 7: Cabin noise control treatment for a transport aircraft powered by propellers [18].

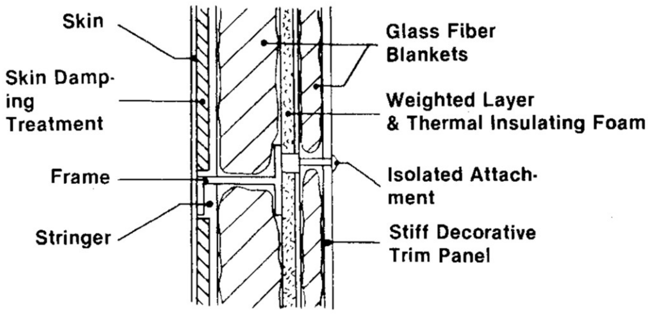

Figure 8: Cross section of representative technology interior treatment presented by [19].

The first region A (Figure 9) has a high dependency on the trim panel mass per unit area and on the airspace depth, doubling any of these parameters increases 6 dB on the attenuation. Typically concentrating masses as far from the fuselage as possible will benefit region A. At region C, the attachment points are dominant and fewer attachments per unit area are preferred. Region B is included for completeness and represents an upper limit to the double-wall resonance phenomenon associated with the direct transmission of sound from the cavity through the trim panel structure. At the region above the critical frequency, region D, current theory does not provide a closed-form estimation of the attenuation provided. However, we can make some observations from the case of sound radiation from point-excited beams.

Point attachments are rather used as line attachments. The trim should also have the highest critical frequency possible. On the region above the critical frequency, the system loss factor should be maximized.

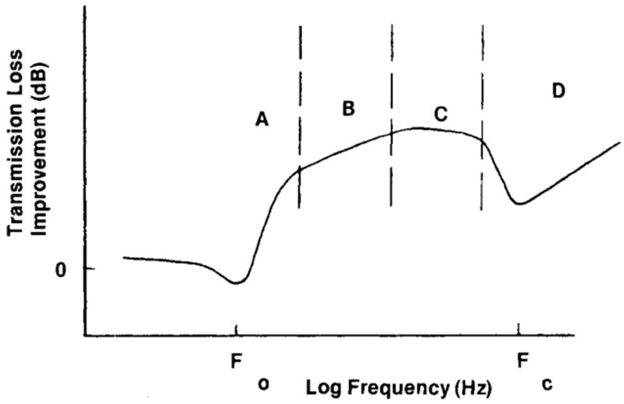

Figure 9: Generic attenuation curve for mounted trim panels [19].

Frequently aircraft structures and panels are designed for high-stiffness/low-weight and consequently presenting relatively low critical frequencies. The structural damping thus plays an important role to reduce the radiated energy on the trim panels. Not only in components with direct radiation into the interior cabin the dissipation of vibration energy is beneficial. Damping materials can be used to increase dissipation. They typically consist of a constrained damping layer because this configuration gives a higher damping peak for a given amount of material. It can be found as a tape of viscoelastic adhesive and an aluminum backing layer [18]. In addition to being applied in the trim panel, they can be placed in the fuselage skin, where they are effective over the panel fundamental frequency. To extend its effectiveness to lower frequencies they should be also applied on the frames and stringers. The operational temperature should be considered during design because the damping properties can vary significantly with temperature.

The addition of dissipative materials is typically effective on higher frequencies and some low frequencies sources, such as the tonal excitations of a propeller are harder to reduce. Some well-known noise control solutions to reduce specific frequencies are: (i) the Helmholtz resonators (or other types of acoustic resonators), (ii) tuned vibration absorbers and (iii) tuned dampers. The first one is the acoustic counter part of the second, that is a structural resonant device.

The use of Helmholtz resonators to increase the transmission loss (TL) of the sidewalls at propfan blade passage have been investigated in [8]. The resonators are placed between the fuselage and the trim panels and especially tunned to increase TL at propeller tones. Different configurations are studied and tested. During flight tests, 5 to 6 dB of noise reduction was achieved and a potential total improvement of 11 dB is pointed. The paper also mentions the possibility of adding resonators into the cabin.

The tuned vibration absorbers (TVAs) can be seen as a simple mass, spring, damping system designed to have its resonance on top or near the frequency to be attenuated. As the Helmholtz resonator, they are therefore suited to be applied on sources with tonal content. There is a tradeoff between bandwidth and maximum attenuation that is given by the damping. In aircraft application it is desired to have small masses, and in order to remain effective the damping should be low. Unfortunately, this reduces the frequency bandwidth of attenuation [20]. Variations on propeller speed may reduce drastically TVA's effect.

The TVAs can be attached to the fuselage near the attachment points so that the structure impedance increases and the vibration is not transmitted. With an increase of only 30 kg, a reduction of 10 dB is achieved on the blade passing frequency by [21]. A further 2 dB improvement is obtained by attaching 25 kg of TVAs in the trim panel of the aircraft. Other studies described on [20] corroborate on the impressive efficiency of TVAs for tonal noise reduction on aircrafts. In some cases, tuned dampers are chosen due to its better robustness to propeller speed variations and possible attenuation benefit also for the second harmonic [18].

Another way to reduce structural-borne transmission of a source is to use mounts to connect them to the main structure. In aircrafts, engine mounts are used. The mounts need to support the loads from the engine (static stiffness) with the lowest dynamic stiffness as possible to reduce transmissibility. They are typically constituted of viscoelastic material or metal [17]. Reduction in the order of 10 dB are reported in [22] by optimizing the mounts of the engine.

An aircraft can also be designed to have a self-supporting isolated interior shell mounted on vibration isolators strategically placed in low vibration areas of the fuselage frame. This approach can reduce the structural-borne noise transmission into the cabin. Further details are discussed in [23].

On propeller aircrafts, a noise control technique commonly used is to set and keep a phase angle between the engines. The purpose is to avoid acoustic beating caused by slightly different speeds (frequencies) and furthermore to use the difference in phase to cancel out part of the vibration and noise. This technic is called synchrophasing and is more effective in four-engine airplane than in two-engine airplanes due to the greater possibility of cancellation in the former case [17].

Section 3: Perturbation analysis of cabin acoustic for robust active noise control – Author: Praaveesh Raaj Sevaraj

Theoretical Foundations

The acoustic environment within an enclosure such as an aircraft or automobile cabin is dominated by a combination of structural vibrations and acoustic wave propagation, which interact through coupled boundary conditions. The governing physical model of cabin acoustics is often expressed via the Helmholtz equation for the acoustic pressure field and the Navier equation of linear elasticity for the structural domain. These equations are coupled at the fluid–structure interface, resulting in a complex vibro-acoustic system that exhibits significant sensitivity to geometric and material perturbations [24,25].

Understanding the effects of perturbations provides a valuable analytical tool to quantify how small deviations in boundary conditions, modal parameters, or excitation frequencies affect the eigenvalues and eigenfunctions of the system. By representing the cabin as a resonant enclosure, perturbation analysis allows an understanding of how mode shifting influences the effectiveness of active noise control (ANC). This is crucial since ANC performance is often optimized for specific modal patterns that can vary with passenger loading, temperature, or configuration changes [26,27].

The general control objective of ANC involves an electroacoustic or electromechanical system which cancels the primary noise or the disturbance using the principle of superposition. An anti-noise signal which is of equal but opposite in phase is generated via a secondary source which will combine with the primary noise resulting in the cancellation of both noises. This requires accurate modelling of the primary (source to error sensor) and the secondary (secondary source to error sensor) acoustic paths. Perturbations in either path can cause degraded performance or even instability. The basic single-channel ANC system described is shown in figure 10 [28].

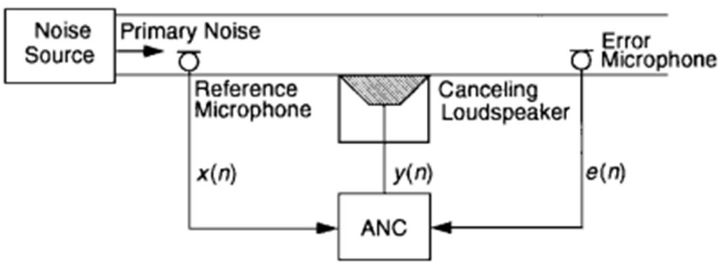

Figure 10. Single-channel feedforward ANC system in a duct [28]

Review of Perturbation Based Analysis in Cabin Acoustics

Modal Sensitivity and Structural Perturbations

The study of perturbation effects in cabin acoustics lies at the intersection of modal analysis, uncertainty quantification, and robust control theory. In the context of ANC systems, particularly those designed for semi-enclosed environments such as aircraft cabins understanding how small structural or environmental changes alter the acoustic modal landscape is essential for ensuring stability, performance, and predictability of the control process. Perturbation-based analysis provides the theoretical and computational tools for quantifying these variations without resorting to prohibitively expensive simulations. This section reviews the theoretical foundations, methodological frameworks, and key experimental observations related to perturbation analysis in cabin acoustics, emphasizing modal sensitivity and structural perturbations.

In acoustical modeling, the governing equations of motion, yield a set of eigenmodes and eigenfrequencies that describe the standing wave patterns within an enclosure. In an idealized cabin geometry, these modes are stationary and well defined. However, real aircraft cabins and similar enclosures exhibit parametric uncertainties arising from variations in geometry, boundary conditions, material properties, and internal objects such as passengers, equipment, and panels. These perturbations alter the system's transfer function matrices, leading to shifts in modal frequencies and mode shapes. This sensitivity is particularly pronounced in low-frequency tonal fields which is the operational range of most ANC systems where modal density is sparse, and each mode contributes significantly to the sound pressure distribution. This is caused by the dominant modal character of the sound field where small condition changes could lead to a perturbation of the dominant modes [29]. Experimental results from Kochan et al in 2009 shows that this primarily occurs at frequencies below 200Hz [29]. It was also noted that in worse-case scenarios, the uncertainties could cause noise amplification.

Conversely, at higher frequencies, the field transitions toward a diffuse regime, where multiple overlapping modes distribute acoustic energy more evenly. In this region, the same perturbations cause smaller fractional changes in the field structure, resulting in reduced uncertainty norms. This frequency-dependent modal sensitivity has been consistently reported in enclosure acoustics research, indicating a universal feature of coupled acoustic–structural systems [30].

Environmental Perturbations and Temperature Effects

The acoustic environment within an aircraft cabin is inherently variable. They could be subject to ambient temperature gradients, humidity changes, pressure fluctuations and structural thermal interaction that continually perturb the acoustic field. Thermal gradients can alter the speed of sound in the air, modify material stiffness, and thus shift both acoustic and structural secondary paths. The assumption is that under varying environmental conditions, the eigenfrequencies or modal characteristics could change. This would be detrimental for ANC systems such as the one implemented by Misol et al in 2020 where an active structural acoustic control (ASAC) approach was taken. A smart lining concept where the actuators, sensors and control were structurally integrated in the aircraft lining panel as seen in Figure 11 [31]. Hence a temperature variation would lead to a change in the structure dynamics of the lining and will affect the controller stability.

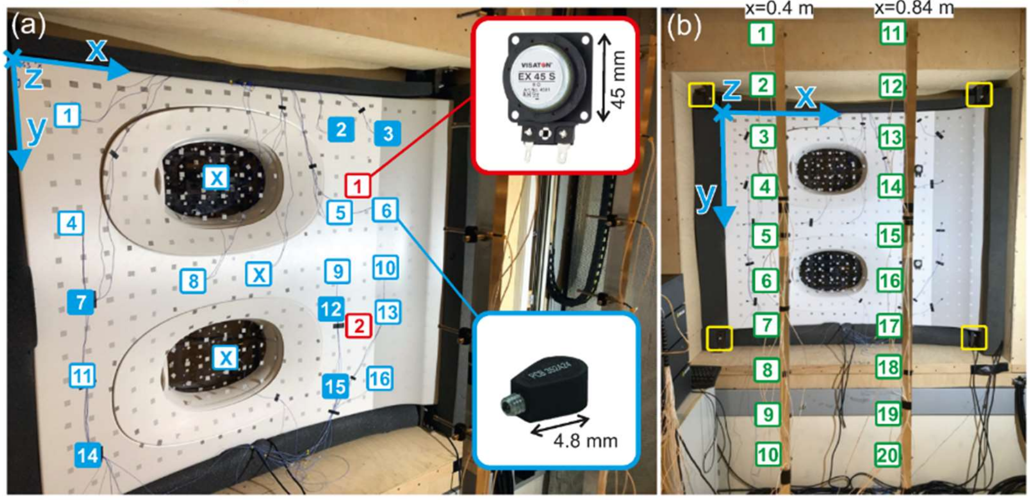

Figure 11. The locations of actuators and accelerometers are indicated in (a) and the microphone location are indicated in (b). Accelerometers are indicated as blue actuators are indicated as red and microphones are indicated as green [31].

Analytical and Simulation-Based Studies

Analytical and simulation-based studies serve as critical bridges between theory and implementation in cabin acoustic control. Recent research by Loiseau et al. in 2018 [32] has demonstrated how hybrid numerical-experimental methods can effectively predict ANC system stability, performance, and robustness before physical deployment. These studies mark a shift from simplified analytical modeling to data-driven MIMO (multi-input multi-output) control identification and real-time experimental validation.

Loiseau et al. introduced a rigorous multi-objective robust control methodology for broadband ANC in automotive cabins. The key contribution was a framework that jointly optimizes performance and robustness while respecting industrial constraints such as limited sensor count, feedback-only operation, and passenger comfort. Their approach centered on three analytical principles which were, Subspace-Based Identification of Acoustic Models and Multi-Model Robustness Analysis [32].

Subspace-Based Identification of Acoustic Models employed a frequency-domain subspace identification technique to obtain a high-fidelity state-space model of the cabin transfer functions within 20–1000 Hz. This approach bypassed parametric optimization and convergence issues common in time-domain LMS or ARMAX methods. The model captured modal coupling and damping, allowing robust control design even with high modal density and uncertainty. Multi-Model robustness framework captured environmental variability such as temperature, load and seating. This enabled performance evaluation under multiple operating conditions without the conservatism of unstructured uncertainty models [32]. This analytical-simulation synergy allowed accurate prediction of ANC performance without resorting to overly conservative bounds, demonstrating how robust optimization combined with multi-model simulation can replace trial-and-error controller tuning in industrial contexts.

Robust Active Noise Control Approaches

Robust ANC is essential for mitigating the sensitivity of adaptive control systems to modeling uncertainties, sensor and actuator placement, environmental perturbations, and signal variability. The goal of robust ANC is to maintain noise attenuation performance despite deviations in system dynamics, temperature, or acoustic boundary conditions. This section reviews key strategies for achieving robustness starting from traditional control theory formulations to advanced AI-based methods grounded in foundational works by Baek and Elliott in 2000, Zhang et al. in 2020, and modern deep-learning developments by Luo et al. in 2024.

The fundamental challenge of robustness was addressed by Baek and Elliott where they classified uncertainties in ANC systems into structured which covered correlated physical changes such as moving passengers or diffracting objects and unstructured which covered random modeling errors and measurement noise. Their analysis revealed that plant response uncertainty (ΔG) directly affects stability, whereas disturbance uncertainty (Δd) mainly affects attenuation level. As for the transducer placement they were found to strongly influences the system's sensitivity to ΔG, particularly actuator and sensor locations. Using singular value analysis of the plant response matrix, they also found that transducer sets minimizing control effort also yield higher robustness under structured perturbations. Baek and Elliott's findings established two key principles which are low-effort actuator configurations are inherently more robust and structured modeling of uncertainty for instance diffracting bodies or temperature shifts, enables predictive stability analysis. These findings remain the cornerstone of modern robust ANC design where plant modeling and sensor geometry optimization precede controller synthesis.

As cabin environments grow geometrically complex, virtual sensing techniques have been introduced to extend ANC performance beyond physically accessible points. Zhang et al. compared two dominant approaches in 2020 which were the Remote Microphone (RM) Method which estimates sound at virtual points such as near passengers' ears using observation filters and Additional Filter (AF) Method that employs model reference adaptive control to infer virtual microphone responses. Their study demonstrated that the RM method is robust to reference signal variability but sensitive to plant uncertainties and the AF method is robust to plant perturbations but more sensitive to reference drift. In automotive tests, both methods achieved good attenuation up to 1 kHz, but robustness degraded when secondary paths were misidentified or the virtual sensors drifted due to seat and headrest movement. To mitigate this, regularized observation filters were proposed, adding a regularization term, β as a trade-off between obtaining a good estimate signal at the error microphone and reducing the condition number of matrix being inverted, which determines the robustness of the virtual sensing method [33].

Recent years have seen the emergence of intelligent ANC systems leveraging deep learning for model-free robustness, particularly under dynamic or nonlinear perturbations. The study by Luo et al in 2024 introduced a Convolutional Neural Network (CNN) that autonomously selects the optimal pre-trained control filter for a given noise condition. Most deep learning-based ANC models utilize neural networks to substitute the control filter ANC system. However, the high computational complexity of these neural networks far exceeds the capabilities of real time processors, causing processing latencies. This is where CNNs can be utilized to select pre-trained control filters for incoming noises. Some of the key contributions from the study include modeling ANC as a Markov process, allowing the CNN to probabilistically infer the next best control state, using LayerCAM to visualize how CNN activations correspond to acoustic energy regions and achieving delay less real time control by coordinating a co-processor (CNN-based selector) and DSP controller [34].

Integrating machine learning interpretability with robust control theory represents the next frontier of ANC. Future systems will likely employ adaptive deep robust controllers using hybrid frameworks to anticipate and adjust to perturbations, achieving self-aware acoustic regulation within enclosures that vary dynamically due to temperature, occupancy, or mechanical vibrations.

Conclusion

The investigation into perturbation-based analysis for robust active noise control has underscored the role of uncertainty quantification in designing robust cabin acoustic systems. Aircraft enclosures are subject to continual perturbations arising from structural deformation, material variability, and environmental factors such as temperature and humidity. These variations modify acoustic transfer functions and modal coupling, directly influencing ANC stability and efficiency.

Theoretical modeling and experimental studies confirm that even modest perturbations can lead to modal frequency shifts and secondary-path mismatches, highlighting the importance of temperature-aware modeling and dual-path adaptive identification. Analytical-simulation frameworks bridge this challenge by integrating subspace identification, multi-model robustness analysis, and experimental feedback validation to maintain control fidelity under operational uncertainty.

Recent advances in deep-learning-enhanced ANC, such as the CNN-based delayless selective filter and Hybrid SFANC-FxNLMS, extend this robustness into the domain of real-time

adaptability. These systems combine neural inference with adaptive optimization to achieve self-compensating performance, enabling ANC to respond autonomously to evolving noise and environmental patterns.
In summary, perturbation-aware control design unites the strengths of classical robust control theory and modern data-driven intelligence. By incorporating environmental sensitivity modeling, uncertainty estimation, and adaptive learning, future ANC systems can deliver consistent, broadband noise attenuation with reduced energy cost and higher resilience.

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