IN-NOVA
MSCA Doctoral Network

Active reduction of noise transmitted into and from enclosures through encapsulated structures.

Marie Skłodowska-Curie Actions

project no. 101073037

Milestone M7

Review and results validation on all cabin noise control system – decision on integration strategy

WP2 – Noise reduction in vehicle and aircraft cabins

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Introduction

The IN-NOVA project is dedicated to develop and provide knowledge and solutions in the field of noise reduction. Specifically, it aims to develop innovative and effective methods of noise control that mitigate noise, reduce negative impact on human health and enhance the acoustic comfort of people. This is accomplished by the education of a new generation of talented entrepreneurial young scientists at the cutting edge of these new noise-reducing technologies and transferring them to industry.

This document is the result of the collaboration of the doctoral candidates working on active and passive noise control methods. Their contributions are strongly related to their PhD topics and give an overview over the state-of-the-art and an insight into their individual results.

At the beginning, Andrey Hense introduces the reader into the objectives of noise control. In the following chapter Mahdi Ahi presents active and passive noise reduction techniques for cabin noise control. Examples from aircraft and car industries are given to demonstrate the practical use. Local control is the topic of Chung Kwan Lai. He shows how noise control works in bounded environments. Chao Liang extends the application of noise control to a global approach. Beside traditional adaptive filters he presents new controllers based on convolutional neural networks that can be integrated in active cabin noise control systems.

The beneficiary responsible for this report (DLR) would like to gratefully thank the doctoral candidates Andrey Hense, Mahdi Ahi, Chung Kwan Lai, Chao Ling, and Said El Kadmiri Pedraza for their support and their contribution to this report.

Objectives of Noise Control in Cabins – Andrey Hense (SISW)

The European Environment Agency warns that noise pollution is a significant environmental health issue in Europe. Over 125 million people are exposed to noise levels exceeding 55 dB. In Europe, noise pollution results in 43,000 hospital admissions and at least 10,000 premature deaths annually. The number of people indirectly affected by noise is substantial, making noise the second most common occupational disease. [1].

Common noise exposure is associated to transportation noise, that includes not only external noise radiation (environmental noise pollution) but also interior noise (inside vehicles and airplane cabins, for example). Interior noise is an important performance indicator for vehicles and aircraft design.

On the automotive industry the Noise, Vibration and Harshness (NVH) performance is well associated to the overall image of a vehicle and respective brand [4], [5]. Customer's commonly relate noise and vibration characteristics to the vehicle quality. The increasing competition between car manufacturer make the NVH performance a distinction factor to attract new customers. Noise control is usually related to eliminate rattles and squeaks and suppressing overall noise levels, but there is clear trend to analyse also sound quality and use active control to design the sound profile of a vehicle [5], [14].

Equivalent importance is given to the noise control in the aerospace sector. Flight vehicles are naturally noisy due to its powerful propulsion system, high-speed aerodynamics flow over aircraft surface, and onboard systems such as air conditioners [3]. These sources can produce high dynamics loads and generate unacceptable cabin noise for passengers, crew, and pilots.

The issue of excessive internal noise is worsened by the trend towards lightweight solutions, that comes to save resources and reduce energy consumption in manufacturing and operation phases.

The control of noise in cabins is crucial for enhancing passenger overall experience and reducing health implication, a non-extensive list of benefits of effective noise control in cabins is:

- Enhance passenger overall experience.
- Improve passenger comfort inside the vehicle and aircraft cabin for a more pleasant and relaxing experience.
- Improve sound quality by minimizing disturbance of unwanted sound and meet passenger sound quality expectations.
- Reduce annoyance due to specific unpleasant sound, such as tonal noise, low-frequency "booming", high frequency "hissing" [6], rattling noise and squeaks [5].
- Improve speech intelligibility ensuring that noise levels do not interfere with communication between passengers.
- Reduce fatigue and stress, prolonged exposure to high noise levels can lead to fatigue and stress.

- Hearing protection, protecting passengers and crew from potential hearing damage due to prolonged exposure to high noise levels.
- Increase safety, reducing noise ensures that announcements, alarms, surrounding noise are clearly heard. This helps in maintaining situational awareness and responding promptly to any emergencies.

This list can be seen as the final objectives for noise control solutions; however, it is of interest to translated them to specific parameters to quantify the subjective aspects of interior noise. Three common parameters are described by J. S. Mixson and J. F. Wilby [3]:

- Overall sound pressure levels (SPL [dB]): typically, the primary objective of cabin noise control is to reduce sound pressure inside the passenger compartment. The SPL adds audible frequency components equally.
- A-weighted sound level (SPL [dBA]): it reduces the contribution of low- and high-frequency components to correlate closer to human hearing perception.
- Speech interference level (SIL): this metric includes frequencies between 350 Hz and 5623 Hz and is related to communication quality.

To characterize psychoacoustic perception of the noise, also sound quality metrics can be used, such as loudness, sharpness, tonality, tone-to-noise ratio, etc. [13] The selection of which metric to use is case dependent, depending on the characteristics of the noise in analysis. For example, typically tonal noises are perceived as annoying type of noise, and it is well described by the tonality metric and/or tone-to-noise ratio. It can also depend on if it is a transient noise event or steady-state type of noise. Still the sound pressure level (often with A weighting when one-third octave bands are used in the analysis) is a straightforward approach and is commonly used in different noise control analysis.

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 [6]. 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 response (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 if the main goal is to preserve hearing, to enable easy conversation or provide comfort as previous discussion [6].

The sources characteristic required for interior noise analysis include frequency content and space distribution, so as the magnitude and phase of the sound pressure. The source can produce deterministic or random sound pressures [3]. The target and effective solution for each type of sound may be different.

The most prominent sources of an automobile are (i) powertrain noise (engine), (ii) road-tire noise, (iii) wind noise and (iv) auxiliaries' noise (cooling fans, HVAC, etc.). The main sources of an aircraft are (i) propulsion system (propeller noise, jet noise), also including engine noise, (ii) aerodynamic noise, loads coming from the turbulent boundary layer (TBL), and (iii) internal sources (e.g. ventilation system) [11]. The powertrain and propeller sources are characterized by a deterministic tonal harmonic frequency content while aeroacoustics and road noise are broadband random noise. The sources on automotive and aerospace applications are shown in Figure 1 and Figure 2, respectively.

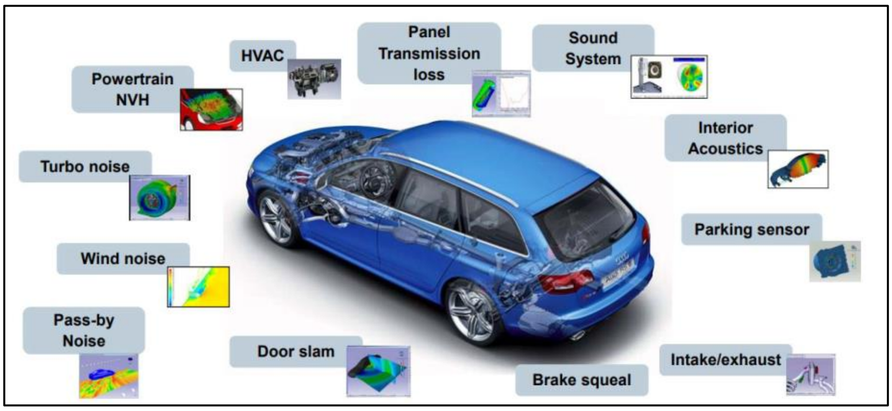
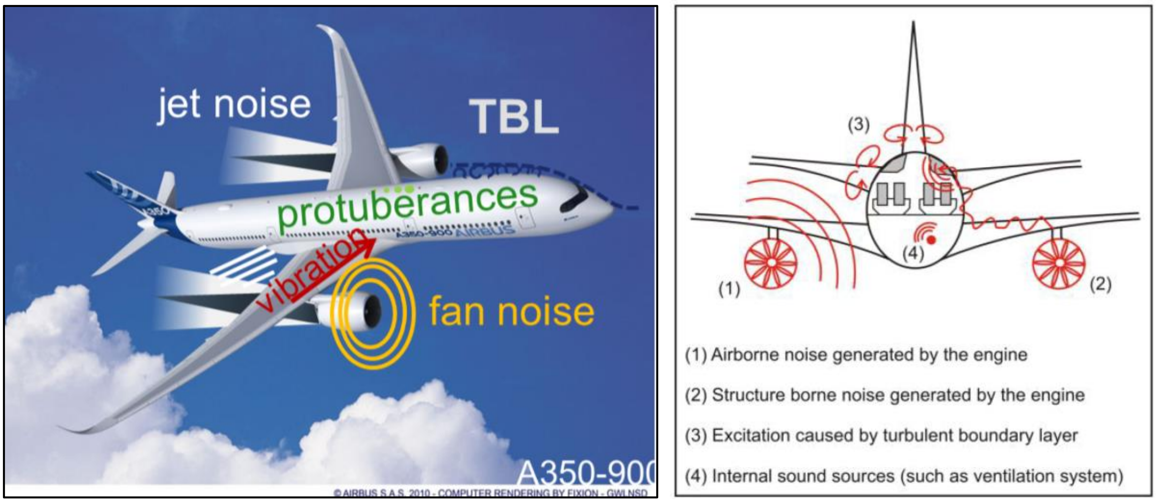


Figure 1: Automotive noise sources. [12]



(a) (b)

Figure 2: Aircraft interior cabin noise (a) sources [10] and (b) paths [11].

These sources propagate into the interior cabin through the structure of the vehicle or aircraft (termed structural-borne) and through the air by direct radiation of the source (termed airborne). Since the physic of the propagation through each type of path differ, also the control strategy can be focus in one path/source (e.g. engine mounts) or act globally (e.g. porous material to dissipate acoustic energy inside a cabin).

The approach to mitigate or eliminate unwanted sounds can primarily be divided in passive and active control methods. The passive method includes structural modification and inclusion of damping materials to dissipate structural and acoustic energy. The active control uses one or more secondary sources to generate an out-of-phase wave to cancel the original signal.

The active sound control can be distinguished depending on the control target and energy input for control [7]:

- Active Noise Control (ANC): the target is the sound pressure, acting with secondary sound sources.
- Active Vibration Control (AVC): the target is velocity (vibration minimization) by one or more structural actuators.
- Active Structural Acoustic Control (ASAC): the target is the minimization of radiated sound power by acting on the structural vibration. For cavities, the acoustic potential energy is used as performance metri, due to the presence of traveling and standing waves.

The target of active control can also be classified in two different approaches: local and global control. For three-dimensional sound fields, no global sound reduction is possible with ANC, on the other hand, "quite zones" can be achieved where the phase difference between primary and secondary waves is 180° [7]. In some situations, for vehicle cabins, for example, it is possible to target global cancellation by acting on the acoustic modes of the interior sound field. The effective global attenuation will depend on the frequency range and interior cavity modal density [8]. In free space, for example, a better global noise attenuation is reached by placing the secondary sources near the primary source [9]. On a local active control, the objective is to reduce noise near the receiver ears, the "quite zone" approach is particularly suited for applications like headphones and headrests [9].

Details of passive and active methods are discussed in the next section and local and global noise control approaches are described in the remaining two sections.

Active and Passive Methods for Noise Reduction – Mahdi Ahi (KUL)

Reducing the interior noise in passenger cabins of both cars and aircraft is one of the main design objectives of the Noise, Vibration, and Harshness (NVH) field. The interior cavity of a vehicle is usually surrounded by thin-plate parts, and its structural noises are caused by plate vibrations [15]. The transfer of these low-frequency vibrations through the vehicle's structure can be prevented using active noise reduction methods. The higher-frequency interior noise components can be addressed by passive noise reduction methods like sound packaging. In this section, both the methods are discussed along with examples from published works and compared in the end.

Passive Noise Reduction Approach

Reducing the intensity of sound sources, isolating the transmission path, and absorbing the sound energy, all fall into the category of Passive Noise Control (PNC) approaches [15]. PNC is based upon physical mechanisms such as the reflection of waves and the conversion of the wave energy into heat (commonly referred to as 'absorption' or 'damping'). As an example of PNC, structural dampening materials like asphalt pads and Liquid Applied Sprayable Damper (LASD) are placed on car's body-panels to mitigate their vibrations [16]. Also, dash, floor, and roof mats, muffler systems, door seals, and laminated windshields and window glasses can be specially designed to damp out incident sound waves before they enter the cabin. Some major sound packaging treatments inside a passenger vehicle are shown in figure 3 along with their volume percentage. Some of these barriers like dash insulator and underbody carpet are especially designed to block certain noise sources like engine noise and tire-road noise, respectively [17]. While designing sound packaging material for electric cars, several factors including durability, light weight, and thermal requirements should be considered. In any case, other features like water absorption, aerodynamics & stone impingement are also decisive for designing underbody panels.

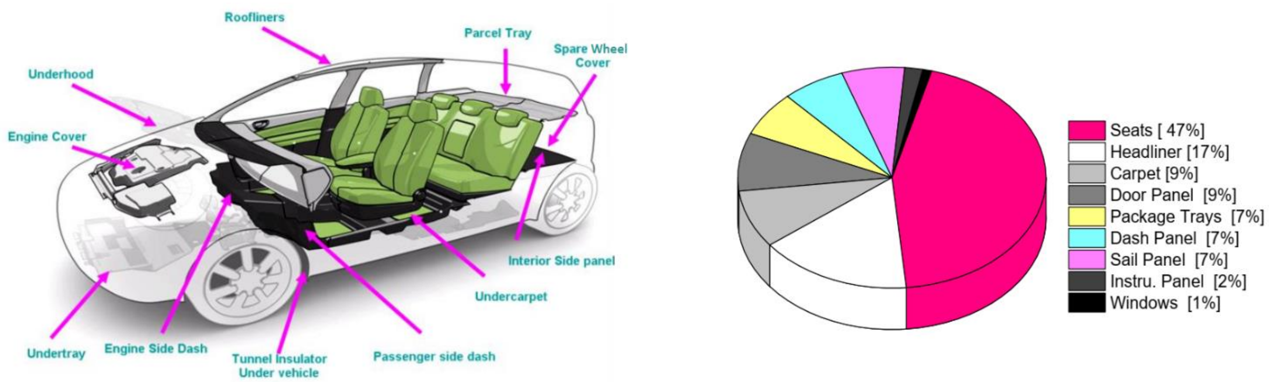


Figure 3: Typical sound packaging in a car; (left) locations, (right) volumetric percentages [17].

Passive methods for interior noise reduction are implemented differently for different means of transportation. For instance, the cabin of Hybrid Electric Vehicles (HEVs) can be protected against medium/high-frequency noise by fiber, foam, and polyurethane acoustic materials, as well as mineral wool and other cellular materials [18]. As a PNC approach in the case of aircrafts, acoustic insulating material and acoustic absorption material are put behind and on the side of the trim, respectively. Also, constrained layer damping can be applied on the inside of the aircraft skin. Finally, elastomeric mounts are used to reduce the noise transmitted through engine mounts, trim attachment points, luggage racks, and seats [19]. Therefore, further knowledge about different applications of passive treatment methods can help acousticians come up with better design ideas.

Different design features like thickness, areal density, and material of insulation layers can be carefully chosen to offer optimal sound absorption. Covering the cabin ceiling of a HEV (figure 4) as well as its floor with a combination of different layers has proved to be more effective than their separate use [18]. In this work, the underlying Isobutylene Isoprene Rubber (IIR) layer is used to restrain the steel plates' vibrations, reducing the interior noise levels at lower frequencies (below 400 Hz). The higher-frequency noises are subsequently absorbed by a secondary layer of polyester-polypropylene (PET-PP) fiber. This solution added an insignificant mass and cost to final production version of the car.

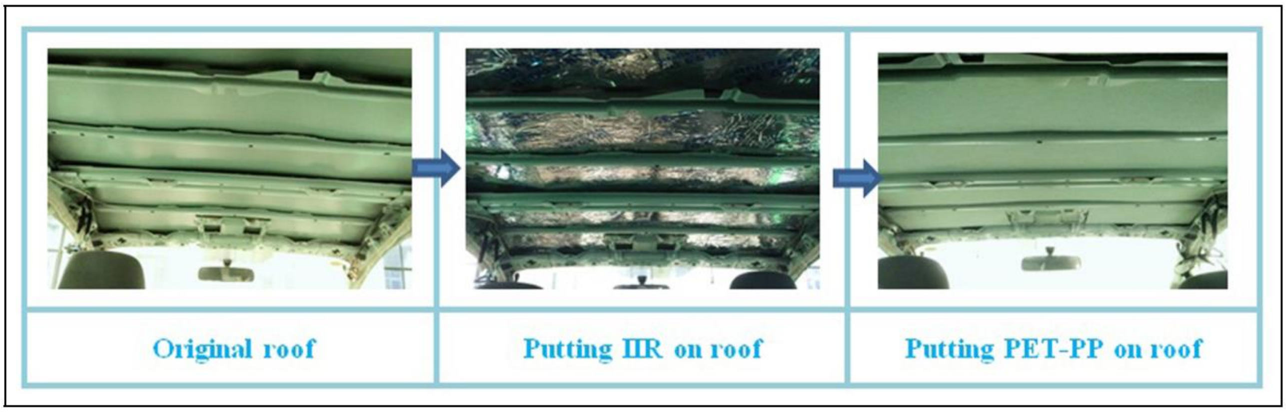


Figure 4: Multilayered sound-treatment of a HEV's ceiling [18].

A more creative and compound design of absorptive liners for passive insolation of interior of a Battery Electric Vehicle (BEV) against airborne road noise is proposed in [20]. Each of the liners covering the wheelhouse shown in left picture of figure 5 are made up of a Micro Perforated Panel (MPP) covering a series of identical cavities displayed on the same figure's right side. These cavities act as both Helmholtz resonators and quarter-wavelength resonators providing thermo-viscous losses in addition to the change of directivity. To be specific, once entering the twisted wave guide shown on right side of figure 5, the incident sound waves lose their energy with every reflection and change of direction. For further broadband absorption the cavities are also filled with porous material, ultimately offering an attenuation bandwidth from 800 to 4000Hz. The important design specifications considered for this work were maximum weight and cost per liner.

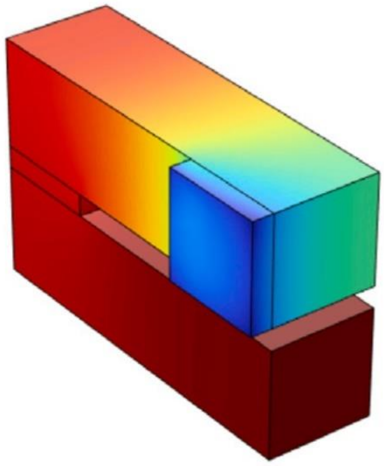


Figure 5: Wheelhouse liners; (left) Installation, (right) Periodically repeated cavities inside each liner [20].

Resonators as passive solutions

Tuned Vibration Absorbers (TVAs) are another form of passive noise reduction solution tuned for maximum attenuation at a specific frequency (e.g. rotation frequency of aircraft propeller at cruise condition). Using a tuned resonant mass and spring (elastomeric stiffness), TVAs increase the structural impedance locally [19], resulting in a reflection of the structural waves at the resonance condition. Broadening the absorption bandwidth around this frequency requires lowering the Q-value of the resonator which results in lower energy absorption [21]. A typical TVA solution targeting the structure-borne noise caused by the tire-road interaction and transmitted through the rear shock tower of a Sports Utility Vehicle (SUV) [22], is shown in figure 6.

Figure 6: TVA weighing 1.46 kg, installed on right-side rear shock tower of a car [22].

Metamaterial resonators

Compared to TVAs, vibro-acoustic Locally-Resonant Metamaterials (LRMs) are lighter and more compact passive solutions capable of also addressing the low frequency range [23].

Being producible through flexible methods like 3D-printing, these metamaterial resonators offer low-cost manufacturing and integration. Though perfectly tunable, the LRMs provide high Sound Transmission Loss (STL) for only a narrow frequency range called "stopband" or "band gap". Also, a dip in STL is often witnessed for LRM plates at frequencies just above this band due to the coincidence phenomena and the reduction of the effective dynamic mass [23]. While it also reduces the maximum STL at the broadened target narrowband, adding damping to the periodic mass-spring resonators is one of the methods to solve this issue [24].

The free propagation of bending waves throughout the host structure/panel is prevented by vibro-acoustic LRMs within the stopband. Among "Bragg scattering" and "local resonances", the two mechanisms through which these stopbands can be realized, the latter is more promising for lower (narrow-band) frequencies and stronger vibrational attenuations [25]. The resonance-based stopband behavior does not require periodicity of metamaterial resonators, and therefore allows designing more compact resonators elements like those shown in Figure 7. In this case, these dual-mode resonators were designed to feature natural frequencies close to the average frequencies of the first pair of vibration modes caused by the rear wheels, while being rotated at different speeds on a dynamometer [26]. For effective vibro-acoustic attenuation of bending waves, the resonator elements have to be placed within a subwavelength distance of half the structural wavelength propagating into the host structure at the target frequencies.

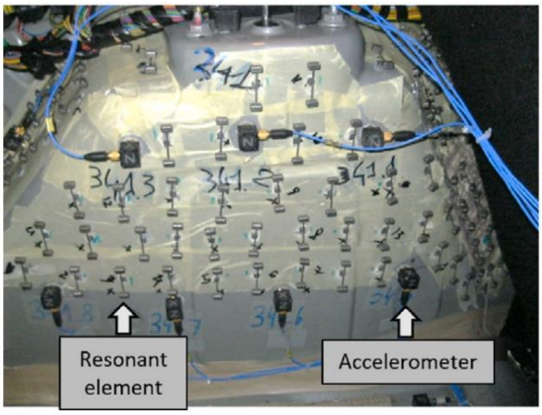


Figure 7: LRMs installed on rear wheel arches of a car; (left) Test setup of left-side rear wheel arch, (right) The resonator element [26].

Shortcomings of passive approaches

For a maximum absorption of the incident sound wave's energy, the layer of absorptive (e.g. porous) material sitting on a hard wall, should be as thick as at least a quarter of a wavelength at the target frequency. For most automotive applications, the required thickness for maximum absorption of noises at frequencies below 500 Hz would be too large and impractical in terms of available space. Similarly, sound barriers need to be heavy enough to reduce sound transmission between the spaces on either side. This would result in more transportation weight and consequently, higher fuel consumption and heat and pollutant emissions.

Using readily available passive solutions for noise reduction is not always the most convenient and practical choice. Using rubber mounts at connection points between the power-steering system and the subframe of an electric car is such a case. Less rigid mounts provide better isolation against vibrations. But, a too low rigidity deceases the stiffness of steering system, leading to the car's less agility while turning [27] or possibly instabilities. Instead, actively-controlled and smart solutions could be chosen for such cases, along with situations where stricter weight-requirements need to be fulfilled.

Active Noise Reduction Approach

The Active Noise Cancelation (ANC) method seeks to calculate and propagate an anti-noise with the same amplitude and opposite phase as those of the disturbance noise at certain locations. Of course, employing more actuators (loudspeaker) and sensors (microphones) increases the upper frequency limit of noises cancelable through global ANC. Practically speaking, in case of an enclosure with dimensions in the order of a few meters the method remains efficient only up to a few hundred hertz [21]. Globally-canceling the noise using only a few actuators, can be successful in the lower frequency range where the acoustic response is lightly-damped and the modal density is low enough [19]. The other sufficient requirement for global ANC is to be able to model the noise sources as point sources instead of distributed ones, and also the possibility to place speakers within a quarter wavelength distance from these noise sources [19].

ANC in automotive applications

In case of global ANC in cars, the loudspeakers' characteristics determine the lower frequency limit for the control bandwidth, and the upper limit depends on the vehicle's interior and component placement [28]. Some of these ANC components are indicated in Figure 8. In case reference sensors are also used to pick up the vibrations originating from suspension system, they should be placed far enough from the passengers. This way the ANC system would have enough time to compute the opposing sound wave needed, and emit it through speakers. This is one of the factors deciding the upper frequency limit of noises handleable in BEVs. An alternative solution to further reduce the turnaround time of ANC system, would be using near-field loudspeakers placed in the headrest, instead of using the car's own audio system. Nevertheless, the ANC system also needs other acoustics-related information about the interior sound field, including the occupancy of each seat, and how much open each window is.

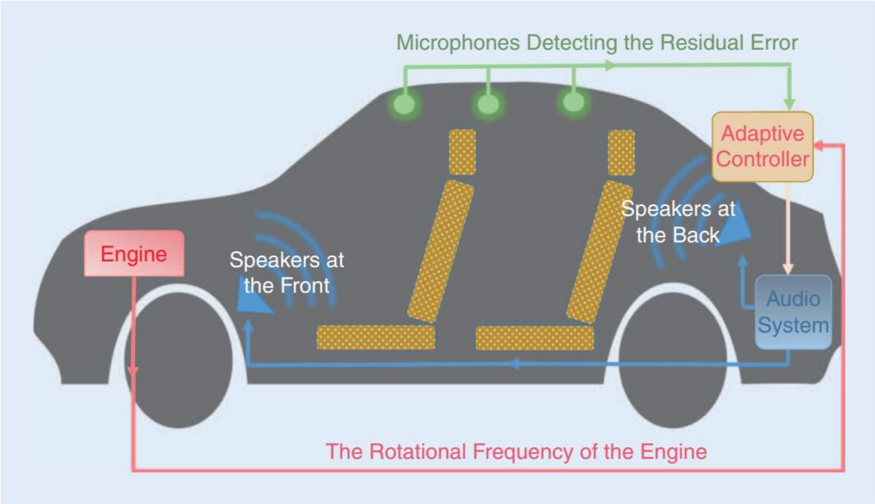


Figure 8: Schematic view of global ANC system in a car [28].

ANC in aircraft

The interior noise in a propeller aircraft's cabin include tonal harmonics of the propeller's Blade Passage Frequency (BPS). These low-frequency tonal noises are radiated inside the cabin due to the vibration of cabin walls. These vibrations are caused by the passing blades creating air pressure fluctuations that hit the fuselage structure. The produced interior noise level typically reaches 90 dB in the case of propeller aircrafts, and even 100 dB in the pilot's ear canal in the case of helicopters [21]. If used for this application, the ANC system can adapt itself to changes in the propeller's rotational speed during different flight maneuvers. It would also introduce much less weight to the airplane than the non-adaptive passive solutions require for treating low frequency noises [29].

To cancel such multi-component vibrations and noises exciting different acoustic modes of the sound field inside the aircraft cabin, the use of multi-channel adaptive controllers is unavoidable. As shown in Figure 9, multiple speakers and microphones would need to be installed around the cabin for global ANC. One advantage of reading the propellers' rotation speed as non-acoustic reference signals for the feed-forward adaptive controller, is that the common problem of the canceling loudspeakers' feedback effect on the reference microphone would be prevented. The other case requiring the use of multiple reference signals for feed-forward control is where the noise sources are uncorrelated [21].

The noise inside the cabin of passenger aircrafts propelled by turbofan jet engines is less intensive, but of higher frequencies than that heard inside propeller airplanes. Therefore, using global ANC systems for cabin enclosure of these airliners won't be as effective. In this case, the target zones of quiet for both the local and global ANC methods implemented for this application are moved closer to the major noise sources outside the cabin (i.e. intake and exhaust ducts of engine) [30].

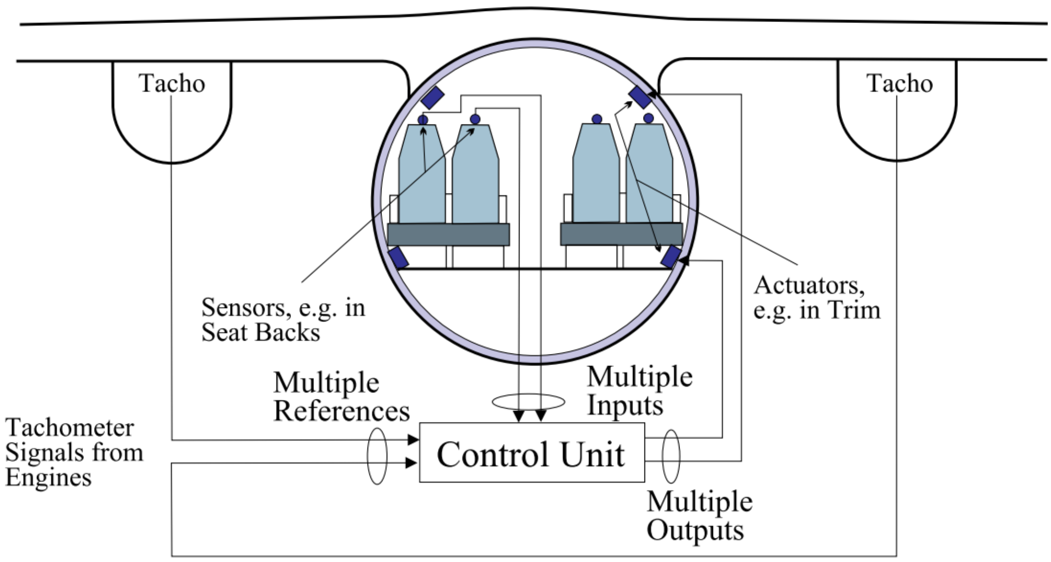


Figure 9: Schematic view of global ANC system in a propeller airplane [21].

Active Vibration Control (AVC) method

As another type of active methods for noise reduction, Active Vibration Control (AVC) aims at minimizing the sound energy radiated by structures through feedback forces [15]. For this method the reference and error signals can be picked up by accelerometers as well, and the non-acoustic actuator creates counteracting forces through charging a piezoelectric (PZT) material. As discussed in [27], the ANC method is incapable of canceling the interior noise (above 400Hz) in an electric vehicle due to the shimmy vibrations of the electric Motor-Driven Power Steering (MDPS) system caused by road excitation. After identifying the most dominant transfer path of the noise through subframe mounts, PZT stack actuators were used to adaptively control the transmitted vibrations through them. This AVC approach could effectively block the vibration transfers leading to a modulated noise caused by the MDPS motor's shaft rotation speed at around 460 Hz, and its second harmonic which happened to fall on a structural resonance at 920 Hz [21].

A similar effort to adaptively cancel the noise radiated into a simple academic model of car cavity made up of acrylic plate, is presented in [15]. As the plate is causing the most acoustic contribution to the interior noise, the cavity's top plate vibrations are both monitored (as reference signal) and controlled in order to minimize the sound measured at a point inside. This work may be considered as a very simple implementation of Active Structural Acoustic Control (ASAC).

Shortcomings of active approaches

Reducing the noise through adaptive control has also its own shortcomings. The feed-forward controller's effectiveness is proportional to the correlation between the reference signals and the disturbance. If insufficient correlation exists, the attenuation would happen only in case of periodic noises. If broadband ANC is targeted as well, care should be taken for the processing time not to be longer than the acoustical delay between the reference sensor and the secondary source [21]. Otherwise, the aforementioned correlation decreases and the performance is degraded. However, it's still more stable and robust than ANC through only feedback control. Since they work based on a minimum duration of only the error signal measured in the past, feed-back adaptive controllers need a longer time to respond. But a feed-forward controller senses the modified input disturbance sooner at the reference sensor's location, and has more time to provide the proper response.

Convenience of using ANC system in cars and its performance is normally questioned by its cost, stability and noncausality issues, complexity of the noise field inside the car, adaptive algorithm's convergence time, and poor spatial coverage [28].

The radius of the sphere of quiet around the error microphone obtainable through local ANC for any tonal noise, would be only one tenth of its wavelength [19]. Furthermore, using local control strategies may even increase noise levels at other positions within the enclosure (not measured by any control sensors), probably leading to even a higher total interior acoustic energy [21]. In other words, a local feed-forward control strategy is susceptible to unobservable modes that may cause enhancement of the acoustic potential energy [28].

Comparison between Passive and Active Approaches

PNC has the advantage over ANC solutions in that it does not require external electrical power. Moreover, some noise-isolation material can also provide thermal insulation and dampen vibrations. A disadvantage of ANC solutions is that the noise levels in the cavity can actually increase at locations not directly targeted by the ANC system. Furthermore, controllability and observability issues arise if the sources or the sensors are placed on the nodes of the sound field.

Unlike PNC which effectively reduces only high-frequency noises (e.g. honks & sirens), ANC techniques are more suitable for noise in the low-frequency range and for lightly-damped enclosures [21]. ANC provides superior background noise suppression at these lower frequencies (e.g. noises due to wind, road-tire interaction & air conditioning units).

Passive approaches (e.g. PNC) require significant increases in weight, size, and cost in order to target specific tonal noises. But active approaches (e.g. ANC) can provide targeted tonal and broadband noise reduction by using adaptive band-pass filters for the digital signal processing implementation.

For coping with new noise profiles and reduction requirements, the passive solutions would need to be redesigned. But in case of ANC, changing the controller's architecture without hardware modifications can be enough to continue noise cancelation within the new sound field (e.g. car cabin after rolling down the window). In case of ANC implementation in mass-produced vehicles, such system-tuning would involve the measurement of secondary path transfer functions and the determination of algorithm parameters such as the number of engine orders to cancel [28].

As pointed out throughout this section, there are interior noises of different nature and characteristics in cabin of transportation vehicles. On the other hand, the available passive and active noise reduction approaches each present advantages and drawbacks. Therefore, the acousticians and designers need to carefully weigh their options while facing each interior noise reduction challenge. In most cases, reduction efficiency is not the only criteria and other factors such as cost, weight, maintenance, durability, etc. also need to be taken into account.

Local Control of Noise – Chung Kwan Lai (UOS)

Local active control of sound aims to create a localised zone of quiet at a physical sensor location with secondary sound sources [31]. Contrary to global control strategies, which aim to reduce noise at all positions within an enclosure, the objective of local control is to attenuate sound within a region of space around the target location known as a 'zone of quiet'. This 'zone of quiet' is defined as the region where the original sound pressure level is reduced by at least 10 dB. This strategy, which is independent of the acoustical mode coupling between the primary and secondary source, offers a higher frequency control limit than the global control strategy.

However, this 'zone of quiet' tend to reduce in size with increasing frequency, and the sound pressure level outside this zone can exceed the original level. In a diffuse sound field, the zone of quiet, within which the original sound pressure level is attenuated by at least 10 dB is spherical and has a diameter of about 1/10-th of its wavelength [32]. When the secondary acoustic source is placed near to the error sensor, it is instead characterized by its nearfield characteristics of the secondary sound source. Joseph et al. [33] had analytically derived that the diameter of the nearfield zone of quiet, where sound is reduced by a general factor of ϵ, is bounded by a radial distance given by

$$\Delta r_\epsilon = \frac{2r_0\sqrt{\epsilon}}{\sqrt{1+(kr_0)^2}} \approx \begin{cases} 2r_0\sqrt{\epsilon}, & (kr_0)^2 \ll 1 \\ \frac{\sqrt{\epsilon}}{\pi}\lambda, & (kr_0)^2 \gg 1 \end{cases}$$

where Δr_ϵ is the diameter of the quiet zone, and r_0 is the distance between the secondary source and the error sensor. Further insights on the formation of the nearfield zone of quiet is shown in Figure 10, which shows the cross section through the corresponding acoustic zone of quiescence generated by cancelling the pressure at a point [34].

Active headrest as an application of local active control

Local active control of sound can be advantageous in specific scenarios where a reduction in sound within a particular region is desired. This strategy would be ideal if the system is employed to create a quiet zone surrounding the ears of a human head. This leads to the use of active headrest system proposed by Olson and May [35], as illustrated in Figure 11(a), where the zone of quiet is produced around the ears of a human head. However, there are various challenges in making this system practical, especially at mid frequencies. Since the zone of quiet decreases with frequency, it typically becomes necessary to position the error microphones close to the human ears, as illustrated in Figure 11(b), to guarantee noise cancellation at higher frequencies. Although the quiet zone might extend towards the surface of the human head due to the zero-pressure gradient boundary condition imposed by the head's surface [37], this extension is still dependent on frequency and will be limited up to a few centimeters away from the ear. Regardless, the placement of the microphone could limit head movement and potentially lead to discomfort for the listener.

We must note that this design constraint does not apply to some of the active headrest design such as by [38], [39], as their design involves of integrating the sensors as a form of wearables.

The concept of virtual acoustic sensors has been proposed to overcome this design constraint. This technique, also referred to as virtual sensing and illustrated in Figure 14, allows the quiet zone to be shifted from the physical sensor to the virtual error sensor. While there are various methods of virtual sensing thoroughly reviewed in [40], we shall discuss only a few virtual sensing techniques that are relevant in the active headrest application.

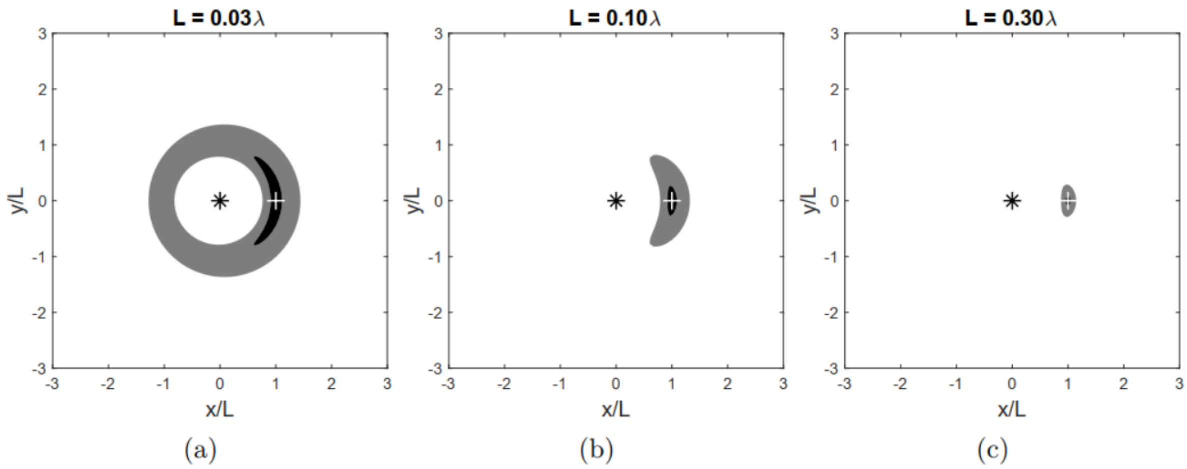


Figure 10: The cross section of the spatial extent of the zone of quiet generated at cancelling the pressure at x = L in a three-dimensional free field using a point monopole secondary source at the origin of the coordinate system of (a): 0.03λ, (b): 0.1λ and (c): 0.3λ, where λ is the acoustic wavelength. The grey shaded area within the solid line corresponds to at least 10 dB attenuation in the diffuse primary field, and the black shaded area correspond to at least 20 dB attenuation (Adapted and reproduced from [34])

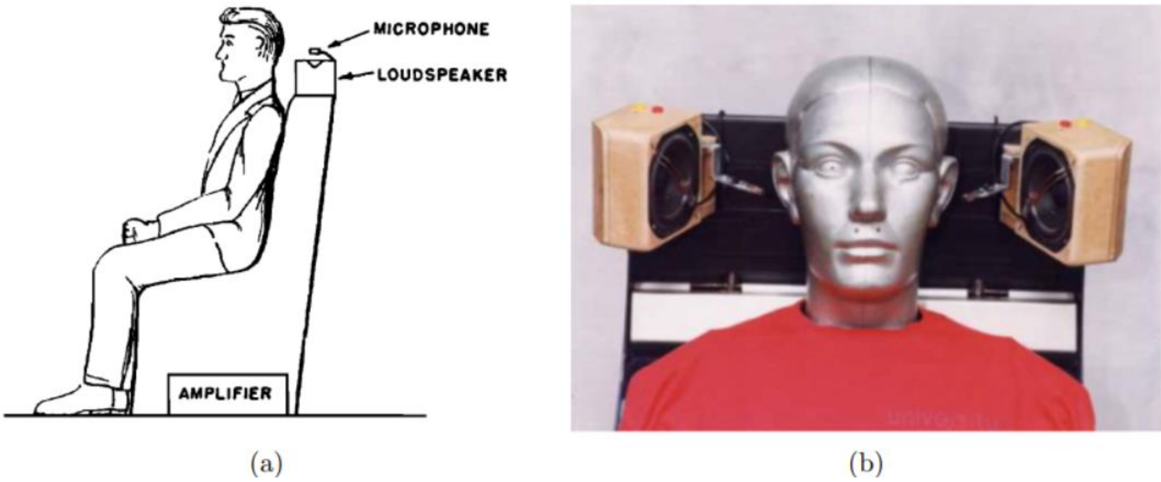


Figure 11: (a): The illustration of a local active control of sound near the head of a seated passenger [35], and (b): the recent development of active headrest [36].

Garcia-Bonito et al. [41] implemented a virtual microphone arrangement, a virtual sensing technique that estimates the error signal by correcting the secondary plant response, in an active headrest system. This method can shift the quiet zone towards the ear, but it has been found to be limited for low frequencies. This limitation was experimentally verified by [42], as the method assumes that the primary disturbance between the physical monitoring location and the virtual error location is identical. To overcome this issue, the remote microphone technique, as shown in Figure 12 [43], can be used. It employs an observation filter to predict the primary disturbance at the virtual error sensor location using the signals at the physical monitoring sensors. However, this estimation technique is highly sensitive to changes in the primary sound field [44]. Furthermore, the observation filter relies on the input from the physical monitoring microphones, which can lead to causality issues between the physical monitoring microphone and the virtual error microphones. [45] introduced the delayed remote microphone technique to improve the estimation accuracy for the remote microphone technique that experiences causality issues, although this requires the assumption that the primary disturbance is strongly ergodic.

Recently, the use of an additional filter, as shown in Figure 13 [46], has regained interest in local control headrest systems. This method, based on the strategy of model reference control, is found to be superior in robustness against uncertainties in the plant response compared to the remote microphone technique. Additionally, the additional filter method does not have the causality constraint in contrast on the remote microphone technique [47]. However, this method is highly sensitive to its reference characteristics [48]. but it can be overcome with the use of regularisation or classification techniques [49], [50].

Even when the virtual sensing method is implemented, the control performance at higher frequencies may still degrade when head movements occur, as the ears may move out of the quiet zone. As a result, past researchers have aimed to enlarge the quiet zone to improve the robustness of the control performance against head movement. García-Bonito and Elliott

[36] found that by implementing two secondary loudspeakers per ear to cancel the acoustic pressure at the ears and the particle velocity component at a position further from the head surface, the quiet zone significantly expands. This expansion is notably larger compared to when the position of the particle velocity component is at the same position as the pressure component. Lei et al. [51] and Chen et al. [52] obtained an optimised plant response by minimising the maximum residual noise level at different head positions and imposing the minimum required attenuation performance and stability constraint. However, this method significantly sacrifices the attenuation performance at the nominal head position that could be achieved.

Incorporating headtracking techniques to local active control

The constraints brought about by head movements in active headrest applications can be mitigated if the positions of the head and error sensors are identified during the control phase. This can be accomplished by integrating head tracking into the active headrest system [54], which facilitates real-time monitoring of the head's position. In the calibration phase, a set of measurements are performed with a dummy head placed at multiple, uniformly distributed grid positions. This process allows for the acquisition of various plant responses and the optimal observation filters corresponding to each head position. This data can then be employed to update the control filters and the modelled plant response in real time, as depicted in Figure 15. Consequently, this enables the achievement of optimal local control, even when head movements occur.

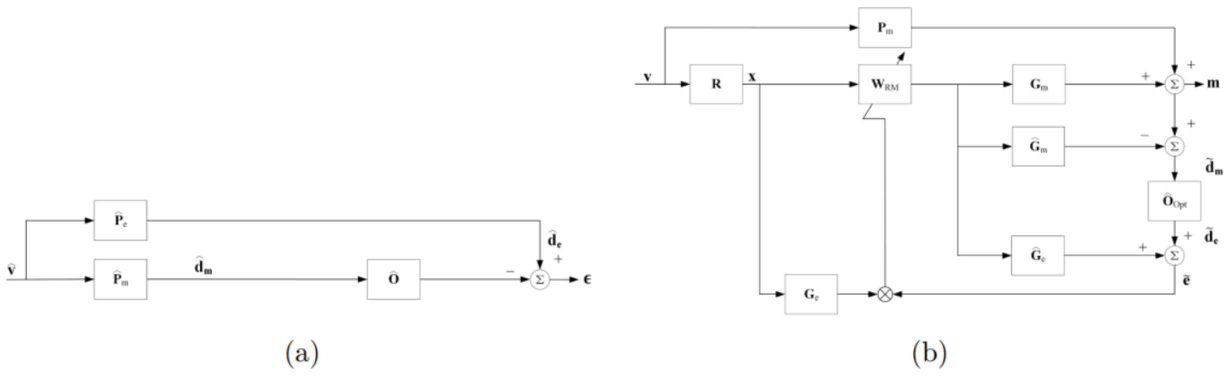


Figure 12: The block diagram of the remote microphone technique method during the (a): identification phase and (b): control phase. (Adapted from [48])

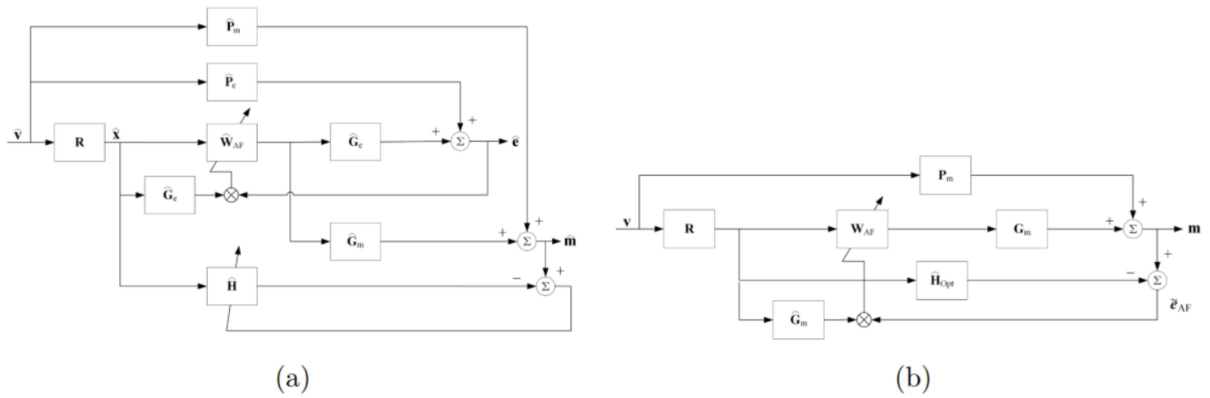


Figure 13: The block diagram of the additional filter method during the (a): identification phase and (b): control phase. (Adapted from [48])

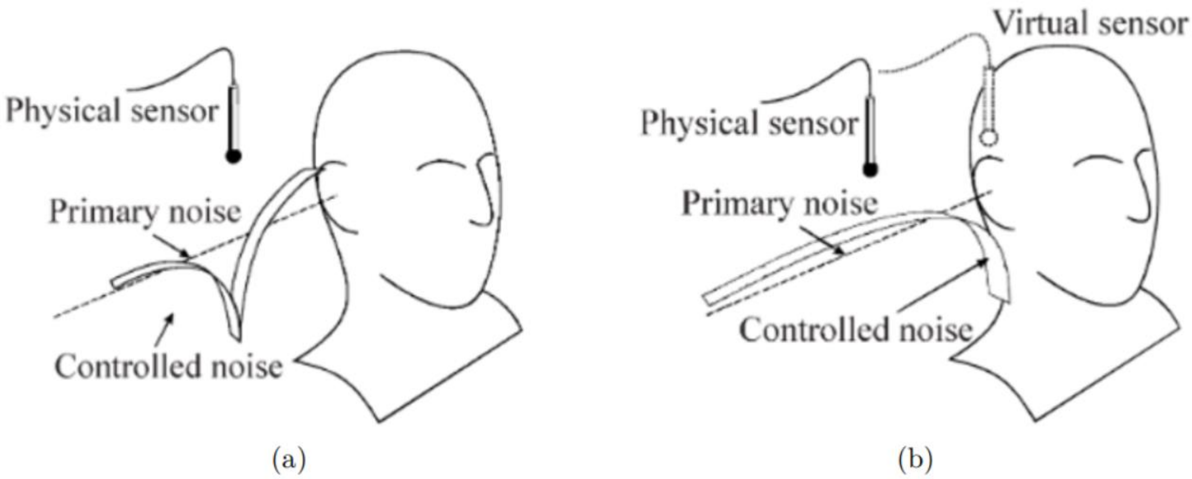


Figure 14: The comparison of local active noise control (a): at a physical sensor and (b): at the virtual sensor [53].

In the preliminary work of Jung [55], several assumptions are made in the active control system equipped with head tracking. For example, the nearest neighbour method is assumed, which updates the plant model and observation filter corresponding to the closest head location measured during the calibration phase. This essentially implies that while the discrepancy between the plant model and the physical plant can be diminished with head tracking, it cannot be completely eradicated. This is because the head could move to a location where the plant model for that specific head position was not measured during the calibration phase, thereby reducing the noise reduction performance. This issue can be addressed by implementing interpolation techniques to predict the plant response at positions where the plant model has not been obtained through direct measurements. Although it has recently been demonstrated that the plant model and its estimated observation filter can be reconstructed through various interpolation techniques using a set of plant models and observation filters previously measured from various head positions [56], [57], the physical limitations of interpolation techniques in active control systems have yet to be explored.

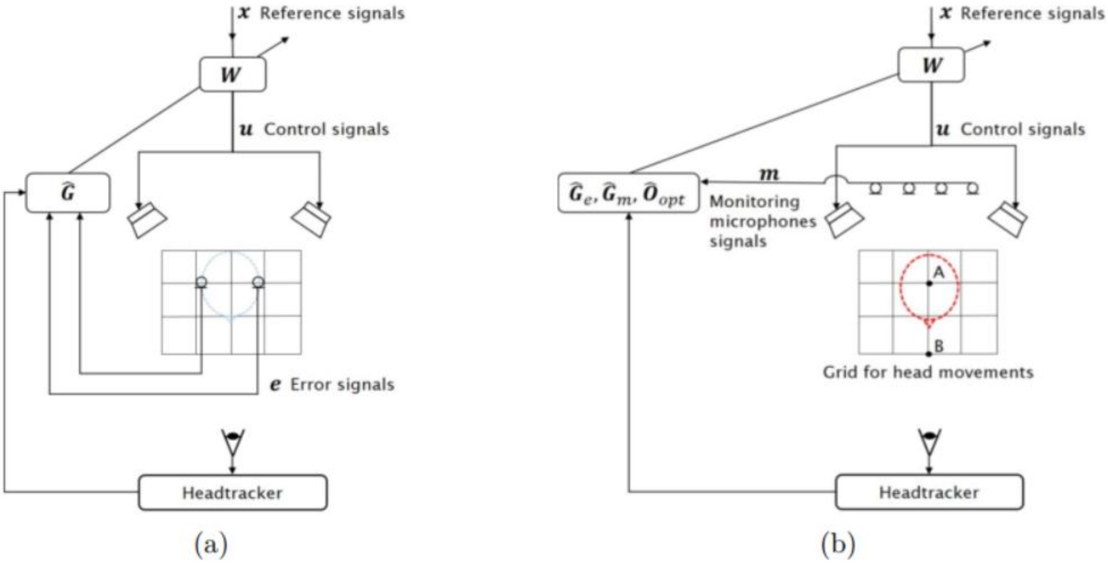


Figure 15: The schematic of the headtracker equipped local control system when (a): error signals at the ears were known and (b): remote microphone technique is used to estimate the error sensors at the ears (adapted from [55]).

While the head tracking technique can theoretically be utilized to monitor head rotations, it is not implemented in the initial work of Jung [55] due to the limitations of the tracking capability employed by the head tracker itself. One approach to overcome this is to enhance the head tracking capabilities to include head rotation [58]. An alternative method involves modifying the control system, such as increasing the number of secondary loudspeaker channels and error sensors corresponding to different head rotation angles, to create a large, overall quiet zone [59]. However, this method is constrained to lower frequencies, as the quiet zone will not maintain its overall large size at higher frequencies.

The enhancement in control performance based on the head tracking technique is also contingent on the control strategy employed. Buck et al. [60] conducted a comprehensive comparison between the head tracked and non-head tracked strategies. While the authors noted an improvement in the head tracked scenario, they also highlighted that the enhancement in broadband performance is dependent on the distance between the ears and the loudspeakers. This is attributed to the authors' implementation of a feedback control system, where the bandwidth for feedback control is limited by the delay in the plant response [61]. Chang et al. [62] and Han et al. [59] precomputed the optimal control filter directly at different head positions, thereby avoiding the use of virtual sensing and adaptive filtering during the control phase. However, this technique forfeits the ability to adapt to changes in the primary disturbance signal.

Global Control of Noise – Chao Liang (PDM)

Traditional control design typically involves two main steps: identifying model parameters and designing a control system based on the identified model. However, direct data-driven control algorithms as shown in Figure 16, particularly those used in the time domain, streamline these processes by directly utilizing input-output data to design controllers, reducing the system's dependence on a pre-identified model.

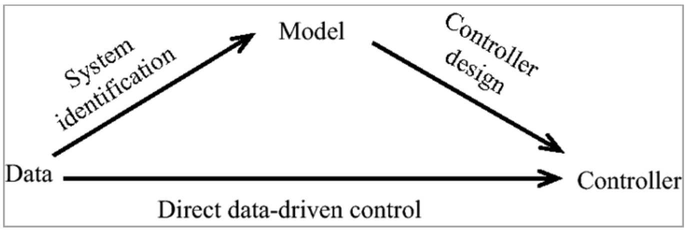
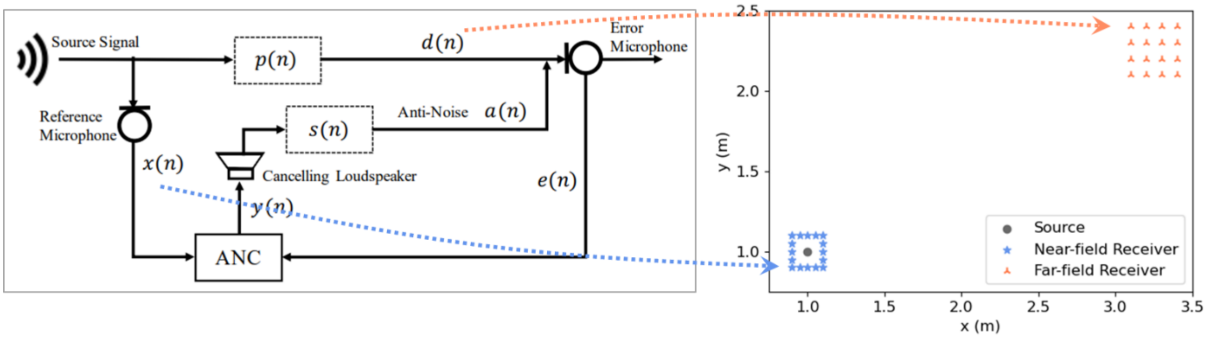


Figure 16. Direct data-driven control

In noise control systems as shown in Figure 17(a), the effectiveness of the control depends heavily on the accuracy of the primary path (noise propagation) and secondary path (compensation) models, which are critical for designing effective feedback control laws. Given the challenges in accurately modeling these paths, direct data-driven approaches offer an alternative by allowing for the computation of controllers suitable for active noise control (ANC) using near-field acoustic holography [63].

This method involves arranging microphones on the appliance's fuselage to study the acoustic emissions and the sound field generated by a loudspeaker array, without requiring detailed knowledge of the system model. In this setup, near-field acoustic holography predicts the overall sound field from near-field noise, and the direct data-driven method is then applied to develop practical algorithms for innovative noise canceller designs.

For sound estimation, we focus on a target zone where noise control is required. Within the global sound field, estimating noise in the far-field presents greater challenges compared to other areas. To address this, we deploy both near-field and far-field receivers: the near-field receivers capture reference noise, while the far-field receivers monitor primary noise. In Figure 17(b), receivers around the source receive near-field sound, while the far-field receivers are distant from the source. The size (width, length, height) of the room is (4, 3, 2) m along the x-y-z axis, respectively. The source is at (1, 1, 1) m. The receivers, all positioned at a height of z = 1 m, are organized into two distinct patterns. Firstly, 16 near-field receivers are arranged in a square configuration centered around the sound source, and each adjacent receiver is spaced at a distance of 0.05 m from one another. Secondly, 16 far-field receivers form a square array centered at coordinates (3.25, 2.25, 1) m. The spacing between them is set at 0.1 m.



(a) ANC system. (b) Positions of the source and receivers.
Figure 17. Far-field sound estimation for ANC using near-field measurements

Methodology

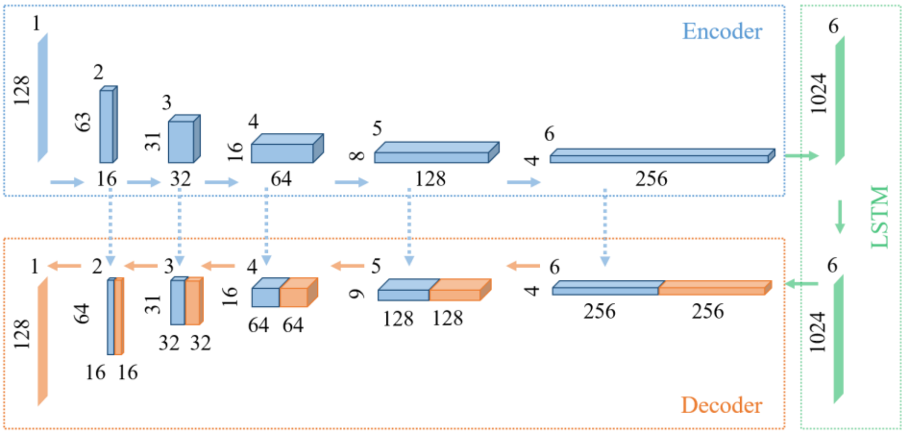
Sound estimation methods include physics-based and data-based approaches. For the former, wave-based methods, geometrical acoustic models and diffusion methods are developed [64]. However, they are still limited to prior knowledge. Recently, data-driven approaches are explored to overcome the limitation [65]-[72].

Hahmann et al. [65] proposed a method for reconstructing the spatial sound field by utilizing local basic functions and dictionary learning. Kristoffersen et al. [66] and Lluis et al. [67] utilized U-Net networks for reconstructing magnitude at low frequencies with a reduced number of microphones. Borrel et al. [68] and Chen et al. [69] investigated the application of physics-informed neural networks (PINN) in estimating one-dimensional and three-dimensional sound fields, respectively. Sanaguano et al. [72] applied variational auto-encoders and long short-term memory to generate a binaural room impulse response.

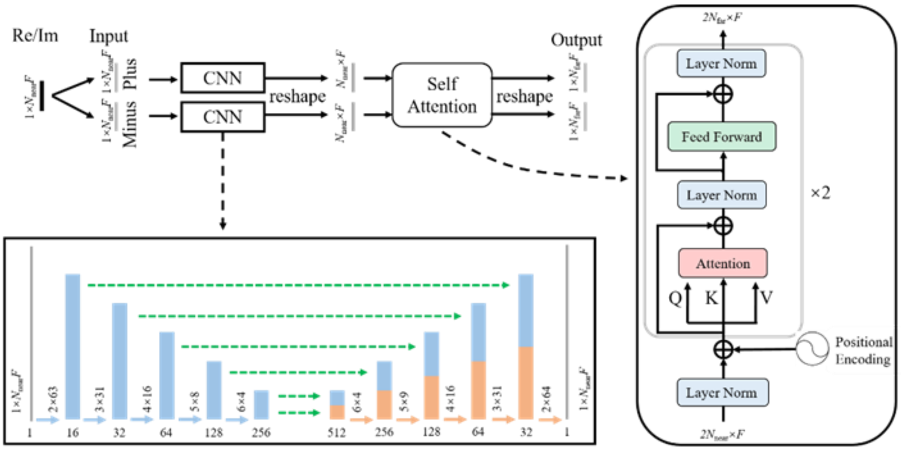
On the other hand, space-time reconstruction of sound field in real-time is important but rarely studied. Considering the convolutional neural network (CNN) is suitable for image domain [73], we apply it for spectrum reconstruction. For temporal prediction, long short-term memory (LSTM) is always preferred. Besides, signals of near-field measurements are normally centralized and processed to obtain far-field estimation. The attention mechanism [74] may be taken to approximate the procedure.

Figure 18 shows two novel network architectures for sound reconstruction. Figure 18(a) combines the advantages of CNN and LSTM. Figure 18(b) is an attentive convolutional network

(ACN). They can reconstruct and predict the far-field acoustic spectra in real-time, both temporally and spatially.



(a) Diagram of the CNN-LSTM Network



(b) Attentive Convolutional Network (ACN) architecture.

Figure 18. Network architectures for sound estimation

As shown in Figure 18(a), we propose a CNN-LSTM network to predict the spectrum amplitude of far-field sound at spatial and temporal domains. The role of the encoder-decoder structure is extracting features of the sound amplitude at different positions, while the LSTM structure is capable of predicting the amplitude along time series. Spired by [75], which eliminates noise for speech enhancement, the network in [75] delete features that are irrelevant to speech. Whereas in our study, predicting all the details of far-field sound, it is essential to preserve as much information as possible at every layer of the model.

The ACN network (see Figure 18(b) incorporates CNN and Self Attention mechanism to reconstruct the raw far-field signal in spatial and temporal domains. The CNN is used for preliminary feature extraction, and it consists of the encoder, decoder and skip connection. The Self Attention structure refers to the encoder layer in Transformer. It assigns different weights to different positions. Positional encoding enables the network aware of the original positions of receivers. According to the attention mechanism, the information from different receivers are evaluated, and dominant values would be noticed.

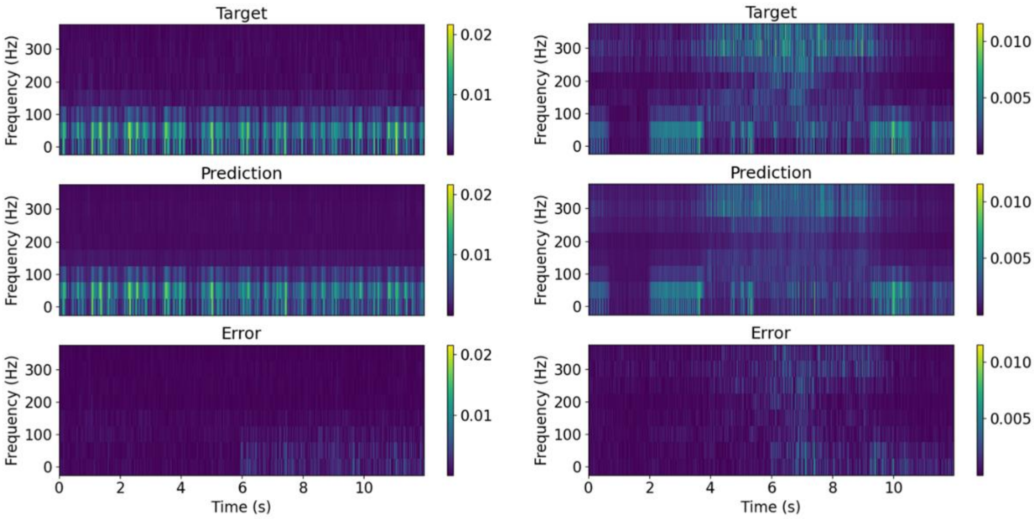
Dataset

To obtain room impulse responses (RIR) between the source and receivers in the room, we utilize the image method which is commonly used to simulate room acoustics. Thus, we can simulate the microphones by computing the sound of these receiver positions.

Subsequently, to simplify the temporal features of raw signals, short-time Fourier transform (STFT) is applied to process them into the time-frequency spectrum. The length of every signal is around 12 s. The sample rate of signals is 16 kHz. We set the window size to 320 samples and overlap to 160 samples. One signal is decomposed into 161 different frequencies. We choose engine noises as the sound source. The noise spectra show tiny amplitude at frequencies over 350 Hz. Therefore, we ignore those frequencies and focus on the first 8 low frequencies. For spatial features, we stack the 16 near-field (as well as far-field) spectra along the frequency domain, thus we obtain spectra of 128 (16×8) low frequencies. A single time frame (20 ms) in the near-field/far-field spectra is taken as an input/target of the network.

Results and discussion

For CNN-LSTM network, we test the model using stationary, piecewise stationary, and non-stationary sources. In the case of the stationary sound source, the spectra in Figure 19(a) exhibit a periodic and regular pattern along the time domain. The discrepancy between the predicted amplitude spectrum and the target is exceedingly small. For the non-stationary source in Figure 19(b), the spectrum looks quite irregular in the range (4, 10) s. The model can predict most features in this range, and the error is more conspicuous compared to the stationary case in Figure 19(a).



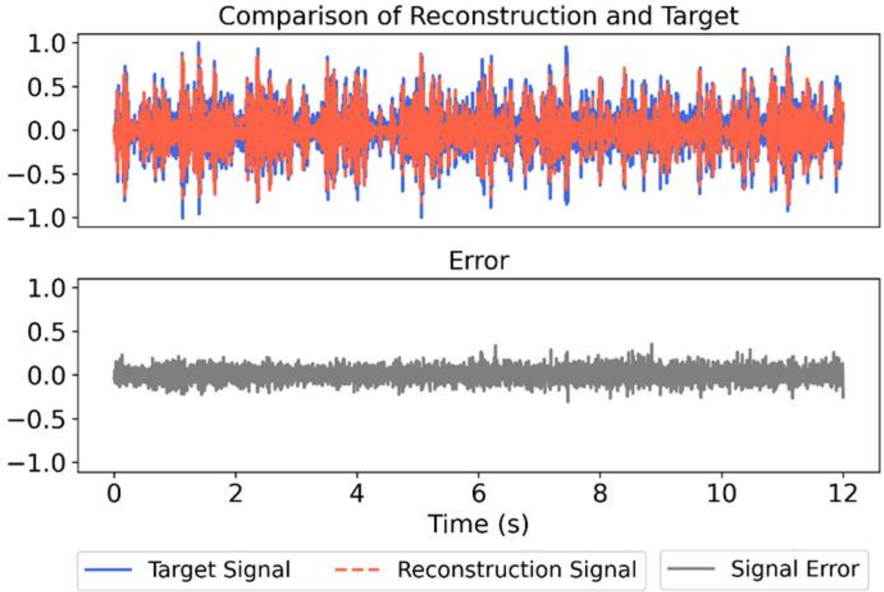
(a) The source sound is stationary. (b) The source sound is non-stationary.

Figure 19. Amplitude spectrum of the first far-field receiver.

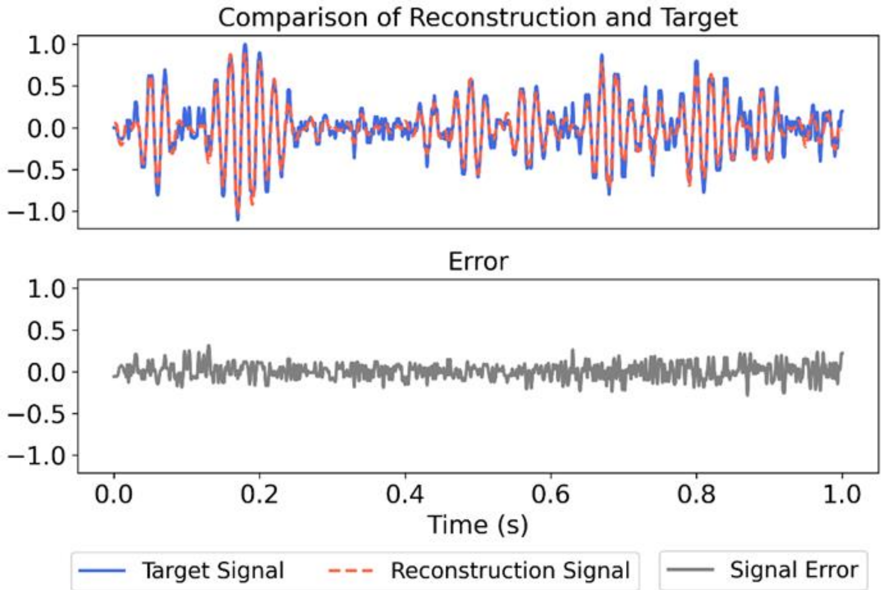
For CAN architecture, Figure 20(a) shows the normalized signal of the first far-field receiver. The signals from rest far-field receivers are similar and not shown here. The reconstructed signal aligns well with target signal.

The mean absolute error (MAE) of the normalized signal error is 0.052, which is considerably small. Figure 20(b) presents the zoomed signal of the first second in Figure 20(a). We can observe the shape of the constructed signal accurately matches the major fluctuations of the target signal.

The proposed two networks can independently estimate far-field sound in real-time, both temporally and spatially, without relying on prior knowledge. The results suggest that these networks have the potential to be effectively integrated into ANC system.



(a) the signal length is 12 seconds



(b) zoomed first second.

Figure 20. Normalized signals of the first far-field receiver.

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