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ACTIVE NOISE REDUCTION IN PASSENGER VEHICLES WITH PLASMACOUSTIC TRANSDUCERS

Stanislav Sergeev[1*] **Mark Donaldson**[1] **Hervé Lissek**[2]
[1] Sonexos SA, Route de la Grotte 6, CH-1003 Lausanne, Switzerland
[2] Laboratory of Wave Engineering, Ecole Polytechnique Fédérale de Lausanne, Switzerland

ABSTRACT

Low-frequency noise in commercial passenger vehicles is difficult to mitigate, as conventional methods often rely on heavy, bulky materials with limited effectiveness at these frequencies. This study investigates the application of plasmacoustic metalayer-enabled transducers for in-cabin noise control. The system employs ten 18x18 cm transducers, strategically distributed within the cabin, and evaluated under static conditions. The transducers, using the corona discharge mechanism, employ active impedance control to regulate the acoustics, enabling direct sound field management through interaction between ionized air and surrounding air particles. These transducers are lightweight and feature a slim form factor, achieving inertia-free operation and an extended bandwidth of sound control. Experimental results demonstrate broadband global noise reduction exceeding 3 dB across an operating frequency range of up to 700 Hz, effectively suppressing low-frequency resonant peaks and attenuating direct sound when transducers are placed along noise propagation paths. These findings highlight the potential for side panels and rear benches integrated with plasmacoustic technology to provide scalable and efficient global noise control solutions in passenger vehicles, reducing weight and eliminating the use of unsustainable materials.

Keywords: *plasmacoustic metalayer, sound absorption, vehicle interior noise.*

****Corresponding author***: stanislav.sergeev@sonexos.com.*

1. INTRODUCTION

Active noise reduction techniques have advanced significantly over recent decades and have been implemented in commercially mature products. Effective noise cancellation can be achieved across broad frequency ranges in acoustically controlled environments, such as ear canals or waveguides, such as exhaust and ventilation ducts [1–3]. However, active noise reduction remains challenging in generic three-dimensional spaces, where passive solutions, including porous and resonant absorbers, presently dominate. These passive materials often require substantial mass and volume to achieve the desired performance in the lower frequency range [4], limiting their applicability in vehicle cabins, where the added weight affects performance. Active methods, such as active noise cancellation (ANC) [5] and active sound absorption [6, 7], present promising alternatives by improving acoustics without compromising vehicle performance to the same degree.

ANC systems in vehicles typically employ multichannel adaptive feedforward techniques, predominantly using the filtered-x LMS algorithm [8]. These systems rely on multiple reference and error sensors, usually microphones and accelerometers, placed throughout the cabin, along with loudspeakers integrated into the vehicle's interior - typically as part of its audio entertainment system. ANC effectively reduces low frequency engine and exhaust noise, when good corelation of the noise at source and target locations can be measured. Reducing road and wind noise is more challenging due to difficulties in obtaining accurate reference signals, thus necessitating additional sensors and processing powers. Enhancements like remote microphone sensing and passenger head tracking [9] improve performance, but can increase complexity and costs while limiting the effective spatial noise control area. More research is required to expand the capabilities of the ANC and expand the noise reduction zone.

Active sound absorption modifies the acoustic properties by equipping small surface areas with active transducers designed for perfect or partial sound absorption. Recent research introduced plasmacoustic metalayers [10], which utilize ionized air layers controlled by alternating electric fields, enabling sound absorption without mechanical parts. The tests demonstrated perfect absorption at normal incidence over a bandwidth exceeding 1 kHz, achieved through a compact design adaptable to various shapes and sizes without affecting performance.

In the previous work [11], a respectable reduction in low-frequency broadband noise was achieved in a simplified rectangular volume using just a few plasmacoustic transducers if the volume presents a significant degree of reverberation. Further numerical simulations of more realistic spaces, such as a real vehicle cabin, have indicated that although a larger number of transducers may be needed to achieve similar noise reduction performance, the proportion of the so-called active absorbing area still remains low (below 3%) and can be practically realized. In this work, we attempt to achieve a significant noise reduction in a real vehicle cabin by deploying the prototype plasmacoustic active sound absorption (PASA) system in the vehicle cabin interior.

2. SETUP OF THE EXPERIMENT

2.1 Plasmacoustic transducer

The plasmacoustic transducer used in the experimental setup is illustrated in Figure 1. It consists of two electrodes that create a corona discharge. The corona electrode is a thin tungsten wire arranged in a parallel back-and-forth pattern and secured within a rigid plastic frame. The second electrode, called collector, is made from a perforated metallic plate with a high open-area ratio, ensuring minimal acoustic obstruction. The electrode system is enclosed with an acoustically transparent ozone filter. The gap between the electrode is approximately 5 mm and follows a patented geometry. The active area established between these electrodes measures 180×180 mm^2. The device operates within a voltage range of 5 to 8 kV. The ionized particles generated by the discharge interact with the surrounding air, transferring energy from the discharge zone. A detailed explanation of the operating principles is provided in previous work [10, 12]. Each transducer is powered with a compact electronic control unit (ECU),

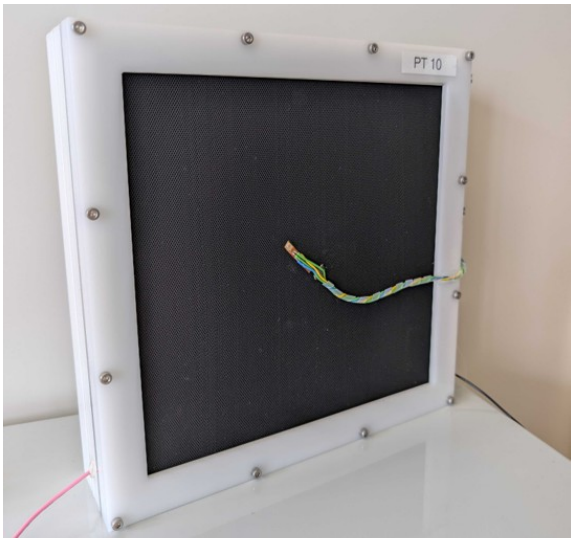

Figure 1. Assembled plasmacoustic transducer covered with the ozone filter. A control microphone is fixed in the middle of the transducer's surface.

which combines a high-voltage amplifier with an embedded electronic controller. The microphone measures the total sound pressure on the front surface of the transducer, providing input to the control algorithm. The closed-loop control aims to establish a target acoustic impedance condition over the active area of the plasmacoustic transducer. In this experiment, the controller was set to achieve an impedance close to the characteristic impedance of air:

$$Z_0 = \rho c, \tag{1}$$

where $\rho = 1.23\ kg/m^3$ is the density of the air and $c = 343\ m/s$ is the speed of sound in the air. The control transfer function is derived analytically [10], discretized and executed on the controller with a sampling frequency of 100 kHz. Thus, each of the plasmacoustic transducers is driven with an independent single-input single-output control system.

2.2 Test environment

The experiment was carried out in the Tesla Model 3 cabin of the model year 2022 as shown in Fig. 2. No changes were made to the original trim or other interior components. This vehicle model was chosen because it represents a midsize BEV deployed with a typical acoustic package. At the same time, its interior design, offering a number of flat surfaces, allows for a simpler installation of prototype plasma transducers.

Figure 2. Vehicle under test with 10 plasmacoustic transducers placed in the cabin above; schematic locations of the microphones (red dots) and plasmacoustic transducers (blue rectangles) below.

Measurements were performed under static conditions. The sound field in the cabin is excited by a loudspeaker placed in the corner of the trunk. In this configuration, when playing back a broadband noise signal, different low-frequency acoustic modes of the cabin can be excited. Additionally, noise is filtered by the car's trim while passing from the trunk into the cabin, which resembles a dynamic noise spectrum. Sound pressure spectra are captured by measurement microphones that are attached to the headrests of the four seats.

Ten 180×180 mm^2 plasmacoustic transducers are placed in the vehicle cabin (blue rectangles in Fig. 2). They provide a total active area of approximately 0.32 m^2 and 1.5% of the entire surface of the cabin. Four transducers are placed on the dashboard (see Fig. 2), four other are distributed on the back seat shelf, and two are attached to the left and right back doors. Those locations are chosen as reasonable candidates for an actual deployment of the system. The ECUs are connected to the transducers from the outside of the car.

3. EFFECTIVE NOISE REDUCTION

Noise reduction performance is evaluated by comparing the noise spectra at different microphone locations when the PASA system is off and on. These frequency responses with the PASA system in passive and active modes are presented in Fig. 3.

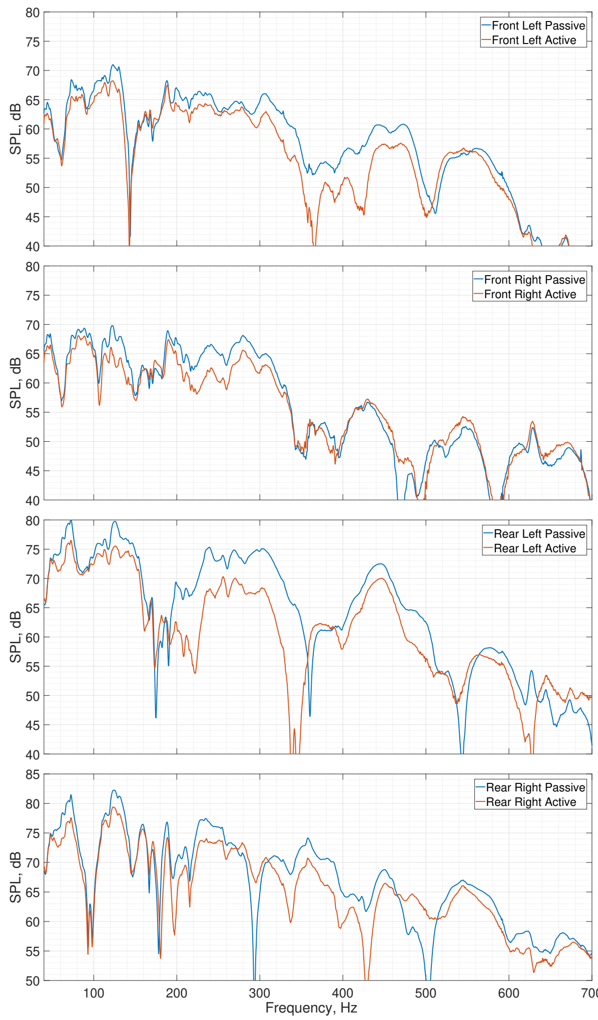

Figure 3. Measured frequency responses at different microphone locations in the vehicle cabin labeled by a seat position. Blue - PASA system is turned off; red - PASA system targets Z_0 impedance.

As discussed in the Introduction, realistic three-dimensional spaces rarely exhibit a high level of reverberation. Typically, they experience considerable acoustic losses as a result of the vibration of lightweight structural components and air leaks. As a result, only a few first low-frequency cabin modes with limited amplitudes can be identified in the 40 to 140 Hz range. It is also worth noting that the front seat microphones are positioned near the center of the cabin, which is close to a pressure node of the first resonance. Nevertheless, the active plasmacoustic transducers effectively dampen these low-frequency modes. This effect is observable at all measurement locations, though it is more pronounced at the rear seats, where the microphones are placed closer to the cabin boundaries.

At higher frequencies, the cabin also shows limited reverberation. In this range, the mechanism by which the PASA system reduces acoustic noise changes. In addition to dampening the resonances of the cabin, plasmacoustic transducers absorb the direct noise propagating past the panels. As a result, a broad level of noise reduction is observed rather than reduction at the resonant peaks. Overall, while performance varies across frequency bands and measurement positions, the dominant spectral components are attenuated throughout the entire measured frequency range, from 40 to 700 Hz. The global noise reduction achieved well exceeds that possible by traditional ANC techniques, whose effect is limited to specific control locations.

4. CONCLUSIONS

In this study, the PASA system has demonstrated its potential to reduce acoustic noise in compact three-dimensional environments such as vehicle cabins. The application of a plasmacoustic metalayer significantly extends the operational bandwidth of a single device for local acoustic impedance control. Although a realistic environment with considerable inherent damping requires a larger active surface area, effective control can still be achieved with a relatively small number of transducers. In this experiment, only 1.5% of the interior surface area of the cabin was covered by an actively controlled impedance surface provided by the PASA system. With transducers distributed throughout the cabin and tuned to achieve a target impedance close to Z_0, the PASA system successfully reduced noise levels in the 40 to 700 Hz frequency range. Different sound absorption mechanisms dominate in different frequency bands: at low frequencies, resonant peaks are suppressed, whereas at higher frequencies, noise is reduced through the absorption of direct sound. In the latter case, placing transducers in close proximity to potential noise sources enhances effectiveness. Therefore, the ability of plasmacoustic transducers to attenuate higher-frequency direct sound depends on their position relative to the excitation source. This is an important consideration in dynamic driving conditions due to the spatially distributed nature of the noise sources. In summary, the active sound absorption system based on plasmacoustic transducers offers a broadband, global, light-weight, and environmentally sustainable form of active noise reduction, potentially deployable at a significantly lower cost of ownership than conventional active road noise cancellation techniques, which require multiple drivetrain-mounted accelerometers and higher, networked computational demands.

5. CURRENT STATUS AND OUTLOOK

Figure 4. Exterior aesthetics of a commercial version of a plasmacoustic transducer.

Sonexos will be manufacturing a plasmacoustic transducer ”Plasmapanel®” featuring reduced operating voltages and enhanced long-term reliability. As illustrated in Fig. 4, the transducer comprises electrodes enclosed within a hermetically sealed plastic housing. The front face of the enclosure is acoustically transparent, enabling effective sound transmission, while maintaining the electrode assembly in a controlled gas environment. This configuration significantly reduces the required operating voltages and protects electrodes from corrosion. Multiple Plasmapanel® units can be assembled into arrays, providing flexible scaling of the active surface area to achieve specific noise reduction targets.

6. ACKNOWLEDGMENTS

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