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PLASMA-BASED ACOUSTIC METALAYER FOR SOUND CONTROL

Stanislav Sergeev[1*] **Hervé Lissek**[1]

[1] Acoustic Group - Signal Processing Laboratory LTS2, EPFL, Lausanne, Switzerland

ABSTRACT

Control of sound with active metamaterials presents several apparent advantages over passive approaches such as extended bandwidth of control, tunability of the technique, new acoustic properties not achievable with passive materials, and often a more compact form factor. However, the loudspeakers and other membrane-based electroacoustic transducers, which are typically used as the building blocks for active metamaterials, have limited authority on the control bandwidth due to their resonant nature. This work discusses a plasma-based acoustic metalayer that fundamentally differs from conventional transducers. The acoustic field is directly controlled through the interaction of the air particles with a layer of ionized air, which is produced in the metamaterial. This transduction principle allows reacting faster than membrane-based interfaces to an input acoustic signal and considerably increases the bandwidth of control. We demonstrate the broadband control of acoustic impedance, realizing a wide spectrum of acoustic properties, from a strongly reflecting interface to a perfect sound absorber. The plasma-based acoustic metalayer presents a promising concept for the research on acoustic metamaterials as the phase of the wave can be also controlled in a broadband manner.

Keywords: *corona discharge, active control, acoustic impedance*

**Corresponding author*: *stanislav.sergeev@epfl.ch.*

1. INTRODUCTION

Fundamentally, any passive causal acoustic structure is constrained by sum rules that translate into unavoidable bounds between the device size (in units of the acoustic wavelength) and the bandwidth of operation [1, 2]. As a result, passive sound control aiming at addressing wavelengths of several meters (below 200 Hz) requires materials of comparable size. On the other side, compact resonator-based materials being able to operate at low frequencies are narrowband [3].

Alternatively, active sound control techniques can provide better performance with relatively uncomplicated control methods of electroacoustic transducers. Being active allows extending the bandwidth of operation or realising acoustic properties not possible for passive materials [4, 5]. The majority of concepts employ membrane-based electrodynamic loudspeakers as controlled sources. Although such loudspeakers are inexpensive and their dynamics can be well captured with analytical models, the inertia of the driver limits the control over high frequencies. Moreover, their inherent permanent magnets increase the weight of such active acoustic treatment.

In this work, we propose a plasma-based actuator for broadband active sound control, which presents a relatively thin form factor and is therefore relatively lightweight.

2. ACTUATOR PRINCIPLE AND PROTOTYPE DESIGN

The plasma-based actuator operates on the principle of atmospheric corona discharge. Its construction includes two electrodes separated by an air gap. The first electrode (emitter) typically has a small characteristic dimension. The other electrode (collector) is significantly larger. If a positive constant high voltage (+HV) is applied to the emitter and the collector electrode is grounded, ionization process starts around the emitter due to the locally high magnitude of the electric field. Produced positive ions drift towards the collector electrode in the external electric field. They further transfer their momentum through elastic collisions to air neutral particles, which mostly fill the entire volume between the electrodes. As a result, such a process generates a volumetric force that acts on neutral air. A small amount of heat is also constantly released in the ionization region. If an alternating high voltage component is added to the constant high voltage, the electric field magnitude changes accordingly creating fluctuation in the force acting on the air and released heat. This process leads to the generation of sound waves. The actuator can also be used to control sound, for example, create an impedance-matched condition to leverage the reflection/absorption behaviour of the interface in a broadband manner.

The plasma-based actuator is illustrated in Fig. 1. The emitter electrode is made of a thin nichrome wire, which is arranged in a back-and-forth pattern of 5 parallel wire lengths spaced by 10 mm and fixed in the plastic frame. The collector electrode is fabricated from a perforated stainless steel plate. This electrode has a large open area ratio so its acoustic resistance is low. The actuator's active area is 50×50 mm^2, and the distance between the HV and collector electrodes is 6 mm. When the actuator is biased in the 6.5-10 kV voltage range a stable corona discharge is produced.

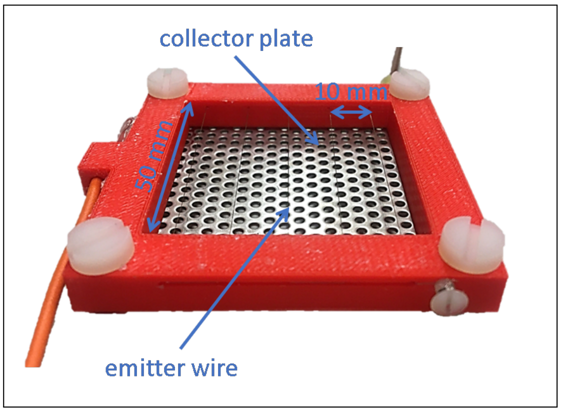

Figure 1. Plasma-based actuator prototype.

3. SOUND CONTROL

The active system that employs the plasma-based actuator targets to achieve a predefined acoustic impedance. With the impedance condition, various reflective or absorbing conditions with a controlled phase can be realized. The methodology is described in [6]. Here, we demonstrate that such a system can reflect sound with constant magnitude and different linearly varying phases if a correct target impedance is chosen.

The actuator is controlled with Speedgoat real-time controller. The sampling frequency of control is 50 kHz. The control microphone senses the total pressure in front of the transducer and feeds the controller input. The controller contains a control transfer function which is based on the analytical model of the plasma-based actuator and links the measured pressure to the voltage needed to be applied to the actuator in order to achieve a target impedance at the microphone position. The output signal from the controller is amplified with a high-voltage amplifier and powers the actuator. Measurements are performed in the Kundt tube where the actuator is placed at the termination and is enclosed at the back with a rigid wall.

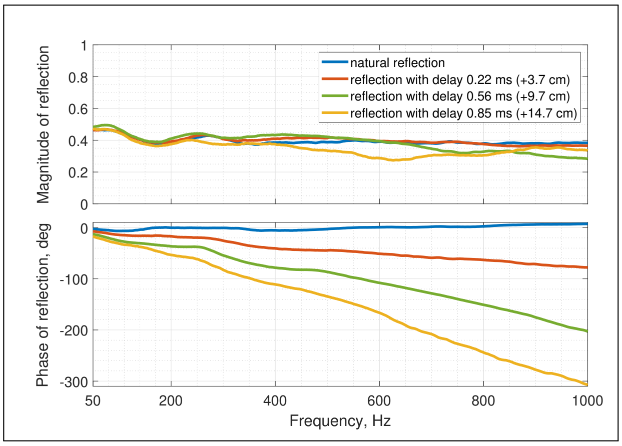

Figure 2. Magnitude and phase of reflection coefficient from the plasma-based actuator when targeting various linear phase roll-offs of sound reflection.

Fig. 2 illustrates one of the control cases, where the reflection magnitude of the plasma-based actuator remains the same but the phase changes linearly with different slopes. Note that the passive reflection of the plasma-based actuator enclosed by a rigid wall is close to unity. Various phases are achieved by changing the imaginary part of a target impedance. The magnitude of reflection is chosen arbitrarily at 40 % to demonstrate the versatility of the control. Note that the reflection coefficient of the passive actuator is defined by the enclosure and is close to unity in this case. The linear phase achieved in the experiment can be considered as a constant delay of 0.22, 0.56, 0.85 ms in the process of sound reflection (red, green and yellow curves in Fig. 2 respectively). It can also be seen as the rigid wall behind the actuator was virtually moved further back by 3.7, 9.7, and 14.7 centimetres. These values are consistent with the measured slopes of the linear reflection phases.

4. DISCUSSION

Plasma-based actuator prototype has proven its capability of controlling sound in a broadband manner employing an impedance control technique. In the presented example both the magnitude and the phase of the sound reflection coefficient are controlled from very low frequencies (50 Hz constrained by the measurement system of the Kundt tube) up to 1000 Hz. Such bandwidth of real-time control is not easily achievable with electrodynamic loudspeakers being controlled in a similar manner.

The present disadvantage of the plasma-based concept is a relatively low maximal level of incident sound that the device can control. It depends on the target impedance and typically lays in the range of 85-100 dB for the prototype shown. Higher sound pressure levels of noise require higher levels of driving voltage exceeding the dynamic range of corona discharge voltages.

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