Corona discharge actuator for active sound absorption

Stanislav Sergeev, Hervé Lissek

CORONA DISCHARGE ACTUATOR FOR ACTIVE SOUND ABSORPTION

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

[1] Laboratoire de Traitement des Signaux LTS2, Ecole Polytechnique Fédérale de Lausanne
1015 Lausanne, Switzerland

stanislav.sergeev@epfl.ch, herve.lissek@epfl.ch

ABSTRACT

This work focuses on the development of a plasma-based electroacoustic transducer for active noise control applications. The transducer is based on the atmospheric corona discharge in a wire-to-mesh geometry. The main motivation for plasma technology is its simple robust design and absence of moving parts in the actuator, which could be advantageous when used in harsh environments. We characterise the corona discharge as an electroacoustic source. Further, we describe the active impedance control strategy for sound absorption by means of this type of discharge. The system is implemented experimentally in an impedance tube under normal sound incidence. The achieved sound absorption demonstrates the potential of the corona discharge actuators for use in active noise control systems, as an alternative to conventional electrodynamic transducers.

1. INTRODUCTION

1.1 Active Noise Control

Active noise control techniques, employing electroacoustic transducers to reduce or absorb sounds in certain environments, present numerous advantages compared to passive solutions, especially at low frequencies where material thickness matters [1, 2]. A number of works demonstrate reasonable performance in active noise reduction by applying different techniques, such as acoustic pressure cancellation, impedance control, and hybrid passive-active absorption [3–7] methods. Although in the majority of works the conventional loudspeakers were used, for some applications alternative types of the actuators would be of high interest. For example, for the aircraft noise reduction the loudspeaker membrane may appear fragile and the whole actuator is heavy due to the presence of copper coil and permanent magnet in the construction.

Intensive work has been carried out in the field of airflow control with different types of plasma-based actuators, such as dielectric barrier discharge (DBD) and corona discharge (CD). By means of these actuators it is possible to locally influence the airflow, particularly reduce flow induced aerodynamic noise [8, 9] and control the instability waves in the turbulent jet [10, 11].

Previous research suggests that plasma-based actuators could potentially serve as electroacoustic transducers. The studies on application of plasma actuators for active noise control and thorough acoustic assessment are still limited. The corona actuator is lightweight and does not include any moving parts, which makes it robust. The previous work of the authors introduced the corona discharge actuator in the wire-to-mesh geometry and analyzed its physical principles of sound generation [12]. This work presents the actuator for use as an active sound absorber. The prototype is first characterized as an electroacoustic source, and then experimentally assessed as an active sound absorber.

2. ACOUSTIC CHARACTERIZATION

Some basic acoustic characteristics of the sound source such as frequency response, directivity pattern and harmonic distortion have been assessed for the CD actuator. For these measurements, we built a prototype with thickness of 7 mm in the wire-to-mesh geometry, as this configuration leads to the corona discharge operation in the range of DC voltages 6.5-10 kV [12]. The discharge is produced on the area of 50x50 mm^2 (Fig. 1 on the left). The emitter electrode is made of nichrome wire with diameter of 0.1 mm. For collector electrode a steel mesh is used. The emitter wire is strung on one side of the dielectric frame and passes five times through the sample hollow area. The wire lengths are separated with 10 mm intervals. The mesh is fixed on the other side of the dielectric frame. The operating area of the actuator corresponds to the cross section of the impedance tube where we further plan to investigate the sample with the control applied.

For most of the applications the actuator should be enclosed on one side. To simulate this situation and investigate the optimal distance to the hard wall, an enclosure with a sliding back-wall was used (Fig. 1 on the right). It covers the prototype hermetically from the emitter wire side.

2.1 Directivity

The measurements of the acoustic properties of the CD actuator were carried out in an anechoic chamber (cut-off frequency 80 Hz). An omnidirectional microphone was mounted 1 m away from the sample surface. The directivity curves of the CD actuator are shown in Fig. 2. The measurements were performed without the enclosure. The prototype was centred and mounted on a turntable. The sound pressure level was estimated with a 10 degrees step

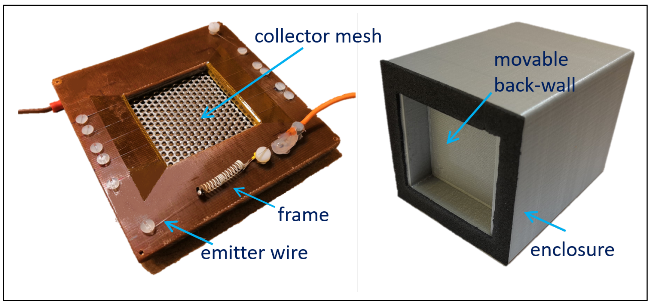

Figure 1. Corona actuator on the left and enclosure with a movable wall on the right.

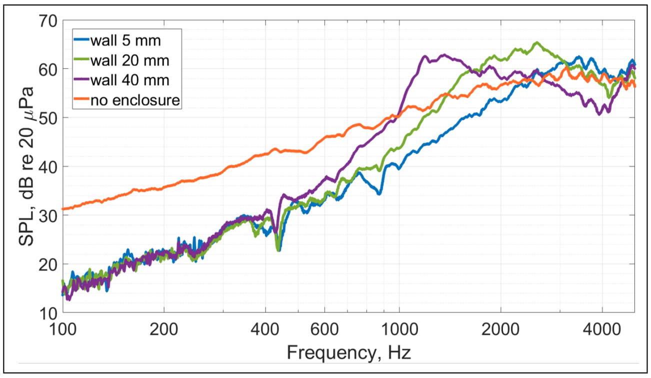

Figure 3. Sound pressure levels produced by the corona actuator with different enclosures.

at frequencies 0.5, 1, 2, 4, 8 kHz. The patterns resemble the directivity of a dipolar source. The shape of the patterns remains the same below 4 kHz. As the frequency increases, the sound source becomes more directive and at 8 kHz, secondary lobes appear. In this specific geometry, the back radiation (i.e. towards the thin wires side) is around 5 dB lower than on the opposite axis. Therefore, it is more practical to enclose the back side of the actuator, keeping the high voltage emitter isolated and having more radiated power.

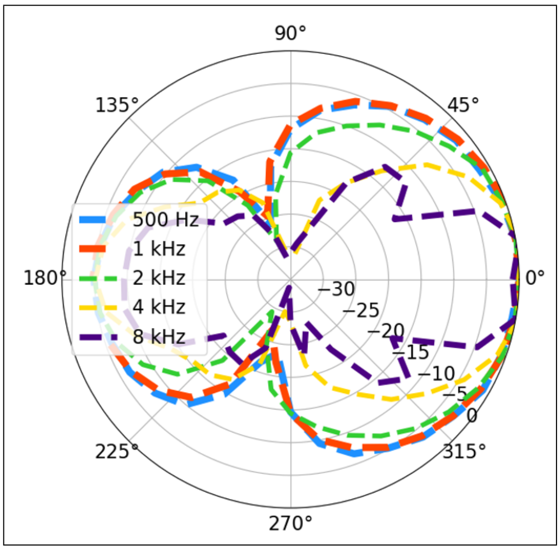

Figure 2. Directivity patterns of corona discharge without enclosure.

2.2 On-axis Sensitivity

The sensitivity curves, representing the sound pressure levels generated by the actuator at 1 m distance with an electrical excitation of U_{DC} = 8 kV, U_{AC} = 300 Vrms are shown in Fig. 3. The measurements are performed for different wall distances from the CD in the frequency range 100 Hz - 5 kHz. Without the hard wall at the back the actuator does not exhibit a prominent resonance frequency due to the absence of moving mass (orange curve in Fig. 3). Below 2 kHz, the response grows with a rate of approximately 20 dB per decade and remains rather flat (± 3 dB) at higher frequencies. When the prototype is covered with a rigid wall box, the response significantly diminishes at frequencies below 500 Hz. This can be explained because a corona discharge behaves as a bidirectional sound source. Reflection of the back radiation and subsequent addition with the front one results in a reduction of low frequency levels produced. Depending on the wall distance the acoustic radiation increases at higher frequencies. This graph can help to find a trade-off between a sample total size (with enclosure) and its capabilities to generate a sound.

2.3 Harmonic Distortion

The Total Harmonic Distortion (THD) shows the amount higher order harmonics the actuator brings to the generated acoustic pressure when a pure sinusoidal electrical signal is applied. For all control techniques distortion should be kept as low as possible since it might impair the active noise control performance. In this test the AC voltage responsible for sound generation varied from 300 to 750 V rms. The THD values obtained for different excitation signal amplitudes are shown on Fig. 4 (top), as well as the sound pressure level of the fundamental harmonic (Fig. 4, bottom). The combination of these two graphs can be used to choose the optimal signal amplitude in order to have satisfactory THD with maximal sound pressure output. Since the CD prototype presents an almost flat frequency response above 2 kHz, the sound pressure levels at 2, 4, 8 kHz stay close to each other at different values of the applied signal. It is interesting to note that the THD can fall from 10-15% to 5% if the signal amplitude is reduced from 750 to 450 V rms, however, the sound pressure level decreases by less than 3 dB.

The measurements carried out in this section provide information about the frequency range of CD actuator performance depending on the enclosure, directivity of the source and optimal signal output limits. These observations will be taken into account when applying the control to the CD actuator.

3. CONTROL STRATEGY PRINCIPLES

The idea of the noise reduction is to create a sound absorbing condition at the CD actuator interface by active means. In this study we make the first effort to implement

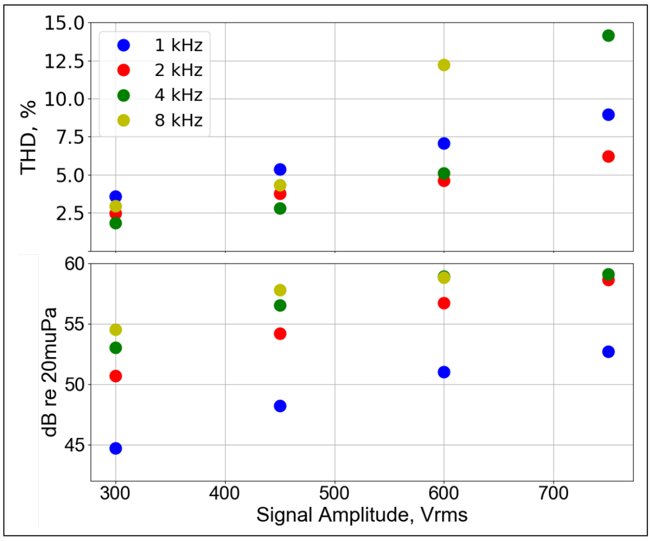

Figure 4. Total harmonic distortion and sound pressure level dependence on the applied voltage amplitude.

so-called "hybrid absorption" control technique [6, 7] for the corona discharge actuator. This method utilizes the absorbing properties of passive structures combined with an active control of the actuator. The approach is advantageous for the corona discharge since it relies on the pressure measurement close to the actuator. Only the relatively low distortion from the actuator for effective absorption is required and no knowledge of the actuator physical model is needed.

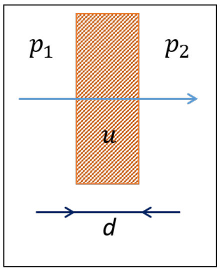

Figure 5. Flow resistance of porous medium.

When pressure difference is applied between the opposite sides of a porous material (fibrous wool, perforated plate) of thickness d, the viscous flow velocity v can be written as:

$$v = (p_1 - p_2)/rd, \tag{1}$$

where r is the resistivity of the material to the viscous flow (Figure 5). The same equation holds for acoustic pressure and velocity at low frequencies. If the pressure behind the porous layer p_2 is set to zero, the material flow resistance rd becomes equal to the acoustic impedance at the front surface of the layer

$$rd = Z_1 = p_1/v. \tag{2}$$

Under normal incidence with constant cross section area, an absorbing condition can be attained when Z_1 matches the characteristic air impedance value $Z_0 = \rho c$, where ρ is the air mass density, and c the speed of sound in air. Therefore, by choosing the proper thickness of porous material with a known resistivity it is possible to create an anechoic termination at the interface (front surface of the passive absorber). The aim of this strategy is to employ the CD actuator behind the porous layer in order to maintain pressure release condition $p_2 = 0$ at any frequency of the incident wave. Under grazing incidence, the optimal value of impedance for absorption is complex and should be identified by simulations or according to the analytical models [13, 14]. Although there is no possibility to control the reactive part of the impedance with this technique, the resistive part can be adjusted to bring the total impedance closer to the absorbing one.

4. IMPLEMENTATION AND RESULTS

The capability of the hybrid absorption method applied to the CD actuator was investigated in a rectangular duct with 50x50 mm^2 cross section. The noise source represented by a loudspeaker is mounted at the duct termination Fig. 6. The active absorbing system is located at the other end. It consists of porous material, CD actuator, and a back cavity with rigid termination. In the experiment we use a 12 mm layer of glasswool placed 10 mm in front of the corona sample. The hard wall distance is fixed at 20 mm.

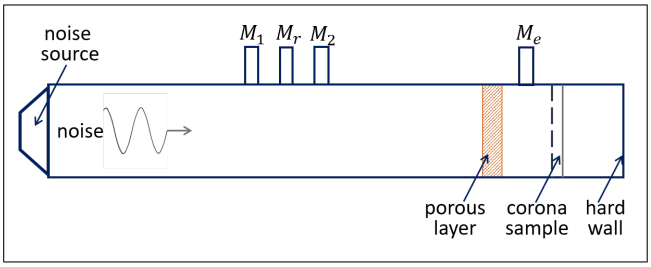

Figure 6. Setup scheme for hybrid absorption.

Microphones M_r (reference) and M_e (error) measure the reference noise from a source and pressure at the rear face of the porous layer respectively. We use two additional microphones M_1 and M_2 to estimate the absorption coefficient and acoustic impedance at the porous material front face with the two microphones transfer-function method.

The aim is to minimize a sound pressure at the back of a porous material i.e. at the microphone M_e location. The least mean square algorithm used in this study calculates only the AC part of the signal to apply to the CD actuator. The output is further offset with a DC voltage of 8 V and amplified by the factor of 1000 through the high voltage amplifier. The control system runs with a sampling frequency of 10 kHz, which limits the highest noise frequency that the CD can counteract without creating noticeable distortion due to the sampling. For that reason, the higher frequency limit is set to 1'300 Hz for the experiments. Since the CD actuator frequency response (Fig. 3) presents a high-pass behaviour, we set the lower frequency limit to 300 Hz (with cavity length of 20 mm).

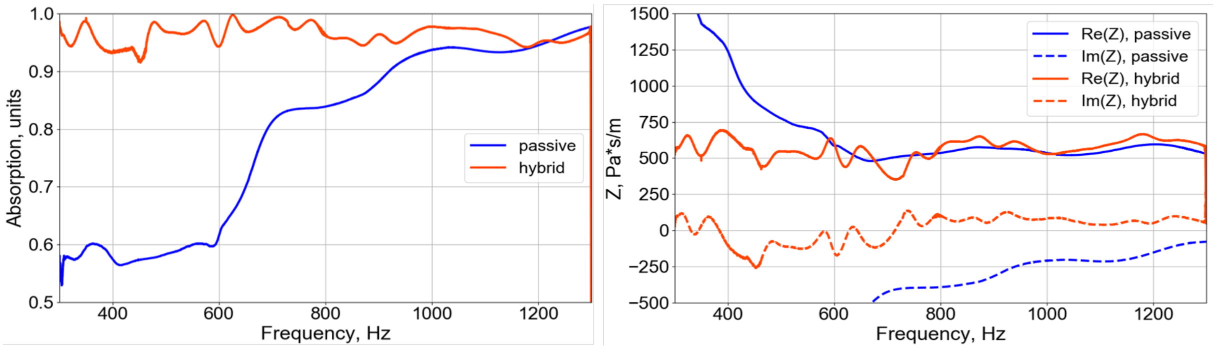

Figure 7. Sound absorption coefficient (left) and acoustic impedance (right) measured with the system composed of the porous layer and the CD actuator when the actuator is powered (hybrid, red curve) or not (passive, blue curve). 12 mm glasswool porous layer is installed.

The sound absorption performance when the corona actuator is active (hybrid system) and turned off (passive system) is presented in Fig. 7. The passive system consists of the porous layer and the back-cavity. The CD actuator without control is transparent for sound as it consists only of thin wires and a coarse grid. Therefore, such termination forms a quarter wavelength resonator/absorber. The absorption grows as the frequency increases (blue line in Fig. 7). When the control is on, absorption ranges between 0.92 and 1 in the whole range from 300 to 1300 Hz. These results were obtained after the algorithm was trained with a broadband noise. The corresponding acoustic impedances at the front surface of the porous layer are depicted in Fig. 7 on the right. In this frequency range, the reactance becomes negligibly small under control (red dashed line) compared to the passive case (blue dashed line). The real part imposed by the hybrid control fluctuates around 560 Pa·s/m, which corresponds to the flow resistance value of the glasswool layer. Such high values of absorption coefficient achieved prove the possibility to use corona discharge as a transducer for active control. Although an optimal resistance value $Z_0 = \rho c$ corresponds to a glasswool thickness of about 10 mm, the material is significantly inhomogeneous at such dimensions and difficult to manipulate with to achieve precise values.

5. DISCUSSION

Hybrid absorption technique was proposed and applied to an electroacoustic transducer based on the corona discharge. If the resistance of the porous layer is chosen close to the optimal impedance for sound absorption, the system can effectively absorb sound in a broadband manner. Therefore, the CD technology appears to be suitable for active noise control, and can offer some flexibility in design and application.

There are several aspects in the application of CD actuators which require further investigation. The disadvantage of all the methods based on pressure cancellation is that the actuator has to counteract the sound pressure from a noise source. The relatively low output acoustic power of CD actuators appeared to be a limiting factor for this method. In this study the CD actuator (with a surface of 50x50 mm^2, thickness of 7 mm) could only counteract sound pressure levels up to 80-85 dB in the impedance tube. However, according to [15], corona discharge with larger operating area, voltage and distance between electrodes can reach significantly higher sound pressure levels. Another aspect is the high-pass behavior of the CD at low frequencies if the actuator is enclosed. Since the CD is a bidirectional source, the back radiated wave reflects from the hard wall behind and affects the front radiation. More elaborate enclosures could be designed for CD actuators in order to tackle this problem.

6. ACKNOWLEDGEMENTS

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