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CORONA-DISCHARGE ACOUSTIC TRANSDUCER AS A PERFECT MATCHED ACOUSTIC SOURCE

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ABSTRACT

A reliable sound source is essential in acoustic facilities, such as impedance tubes. However, conventional loudspeakers, regardless of their design, are prone to sound reflections, contrarily to theoretical matched sources. This can severely compromise the accuracy of the measurements, especially for nonlinear devices under test, where the unavoidably reflected harmonic components are likely to pollute the measurements. To be able to experimentally assess the performance of nonlinear systems, an ideal matched sound source capable of generating, without reflecting, a prescribed incident pressure is still missing. The corona discharge transducer consists of a membrane-less flow velocity source which is inherently transparent to sound. When backed with an anechoic termination (e.g. melamine foam wedge), one can generate sound while avoiding any reflection from the back, resulting in an actual matched source. An experimental prototype of such matched source has been designed and assessed in an impedance tube, focusing on linear frequency response and harmonic distortion analysis. Finally, the matched source is employed for assessing non-linear systems in impedance tube, and compared to conventional loudspeaker, to provide a practical demonstration of its capabilities under realistic conditions.

Keywords: *perfectly matched acoustic source, corona discharge acoustic transducer, total harmonic distortion, transparent acoustic source, nonlinear acoustics*

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1. INTRODUCTION

While the development of a perfectly matched sound source remains a challenge, numerous theoretical studies have been conducted assuming that there are no reflections from the source [1-4]. This assumption, however, is not always realistic when studying objects with nonlinear dynamics, especially when they are positioned in close proximity to the source. In such scenarios, e.g., in an impedance tube setup, higher harmonic components radiated from the nonlinear study object can propagate towards the source and inevitably reflect back from it, which can adversely impact measurement accuracy. Therefore, the significance of employing a perfectly matched source in acoustic research is evident, especially in the presence of nonlinearity. Achieving a perfectly matched source using conventional electrodynamic loudspeakers is hindered by unavoidable reflections from their moving diaphragm [5-6]. As an alternative, corona discharge (CD) transducers with relatively higher acoustic transparency could be utilized to attain a near-perfect match.

The sound generation mechanism using a CD actuator is introduced in [7] and earlier for example in [8], where one can refer for detailed explanations. Here, only a brief description is provided for the sake of comprehensibility. The transducer is composed of two principal elements, sharp-edged emitters, and rather coarse electrically conductive collectors. While the collectors are grounded, a positive high DC voltage is applied to the emitter electrode, which induces a locally intense electric field around the wires with relatively high curvature. This strong electric field allows for the electrical breakdown in the vicinity of the emitter, triggering electron avalanches in a small surrounding gas volume. The initiated positive ions in the ionization region, on the other hand, are propelled away by the electric field towards the collector. These ions collide with neutral air particles on their path and exchange a part of their kinetic energy with them. A chain of such collisions induces a homogenous airflow in the drift zone between the electrodes. Such plasma-based air ionization can be used for example flow control [9]. The electric field in the ionization region can be modulated by combining the applied DC voltage with a sinusoidal AC component, which consequently leads to fluctuations in the driving force acting on the ions. Accordingly, the AC component can be tuned for desired local pressure field perturbation and sound generation at a favorable frequency. CD transducers can be employed for sound generation [8, 10-11], as well as sound absorption [12].

The theoretical concept of such a perfectly matched sound source has already been introduced and widely utilized in many analytical studies, however, it still remains a physically unattainable ideal. The current study pioneers an innovative solution to fill the gap and introduce a physical model of the concept using a CD acoustic transducer. An experimental prototype of such a matched source has been designed and assessed in an impedance tube. Frequency response and distortion analyses are taken into consideration as key metrics evaluating the performance. Lastly, an illustrative test study is conducted to showcase the enhanced performance and efficiency of the designed perfectly matched source for further investigations on acoustically excited study objects with nonlinear dynamics.

2. IMPLEMENTATION

Fig. 1 shows the prototype of the plasma-based acoustic transducer used for experimental analysis. The emitter electrode is made of a 0.1 mm diameter nichrome wire arranged in a back-and-forth pattern on a 3D-printed plastic frame, creating five parallel wires spaced 8.2 mm apart from each other. The grounded electrode is composed of six aluminum rods of 4 mm diameter, mounted on the frame with the same spacing between each pair. The two parallel planes, on which the electrodes are positioned, are interspaced with a 6 mm air gap, and the cross-sectional area of the actuator is 50×50 mm^2. The actuator is supplied with a constant DC voltage of 8.5 kV to provide a stable corona discharge.

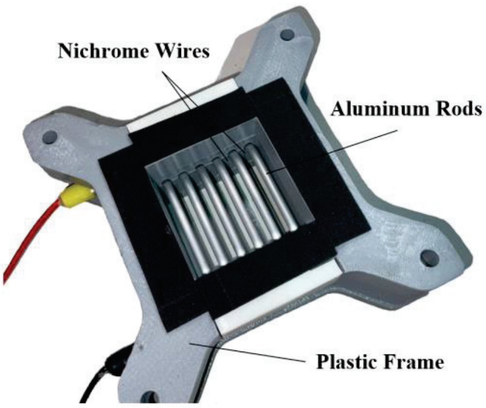

Figure 1. Prototype of the CD acoustic transducer.

Fig. 2 demonstrates the schematic of the experimental setup, where the performance of the CD transducer is evaluated in an impedance tube of the same cross-section. The sound waves generated in the actuator propagate in both directions as illustrated in Fig. 2. Those which travel in direction 1 may reflect back once they encounter the boundary element embedded in the setup. However, owing to the acoustic permeability of the transducer, the reflected waves can pass through it and accompany those heading in direction 2 until they are both trapped by the melamine foam anechoic termination at the other end of the duct. The proposed configuration of a perfectly matched acoustic source allows for producing desired incident sound waves in direction 1 without the interference of reflections from the transducer.

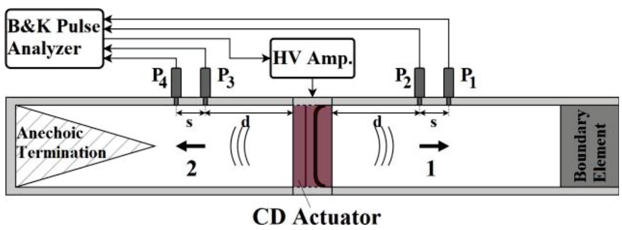

Figure 2. Schematic experimental configuration of the perfectly matched acoustic source.

As depicted in Fig. 2, four microphones are mounted on the impedance tube for standard transmission measurements [13]. A B&K Pulse Analyzer is utilized for frequency analysis of the obtained acoustic signals. To amplify the AC/DC components before applying them to the transducer, a custom-designed high-voltage amplifier is employed, increasing the magnitude by a factor of approximately 1000. The boundary element located at the right end of the impedance tube can be substituted with various alternatives, including a hard wall, an anechoic termination, an electroacoustic transducer, or left open, enabling the examination of different boundary conditions and their effects.

3. RESULTS AND DISCUSSIONS

The CD actuator is inherently transparent to sound waves. The assertion is assessed experimentally in the impedance tube. Accordingly, the boundary element in the experimental setup in Fig. 2 is replaced with an electroacoustic loudspeaker. Considering the planar propagation of sound waves, the transmission coefficient is measured across the CD actuator following the standard measurement protocol as [13]:

$$\tau = \frac{W_t}{W_i}, \quad TL = 10\log_{10}\left(\frac{1}{\tau}\right), \tag{1}$$

where W_t and W_i are the transmitted and incident sound power, and TL indicates the transmission loss.

Fig. 3 depicts sound transmission loss across the CD actuator, when it is supplied with no DC voltage. It should be taken into consideration that the total transmission loss across the transducer is partially related to the transmission loss of the impedance tube. Hence, it can be concluded that the designed CD transducer exhibits a high level of acoustic transparency, allowing the sound waves to pass through with minimal attenuation. As shown in Fig. 3, TL reduces from 0.68 dB at low frequencies to approximately 0.5 dB at higher frequency ranges. Relatively higher transmission loss at lower frequencies is mainly attributed to anechoic termination inefficiency in this frequency range.

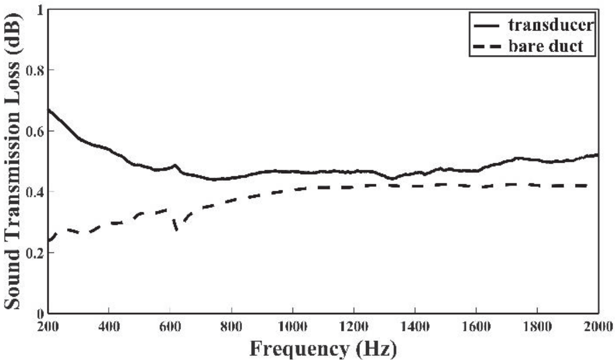

Figure 3. Sound transmission loss across the CD actuator.

Subsequently, the performance of the designed matched source is evaluated to ascertain its capability to maintain a desired incident pressure level in an impedance tube, regardless of the boundary element employed at the tube's end. Assuming planar wave propagation in Fig. 2, the incident and reflected sound waves between the CD actuator as the source and boundary element could be obtained through the standard procedure outlined in Ref. [14] as:

$$P_{\text{inc}} = \frac{P_2 e^{jks} - P_1}{e^{jks} - e^{-jks}} e^{jkd}, \quad P_{\text{ref}} = \frac{P_1 - P_2 e^{-jks}}{e^{jks} - e^{-jks}} e^{-jkd}, \tag{2}$$

where P_{inc} and P_{ref} are the incident and reflected waves, and $P_{1,2}$ indicate the corresponding acoustic pressure sensed by the microphones. Also d, s and k show the distance between microphone 2 and the CD transducer, distance between 2 microphones and the wave number, respectively. Accordingly, three distinct boundary conditions, namely a hard wall, an anechoic termination, and an open end are investigated. As anticipated, the reflected wave patterns exhibit significant variations among these three cases, as demonstrated in Fig. 4.

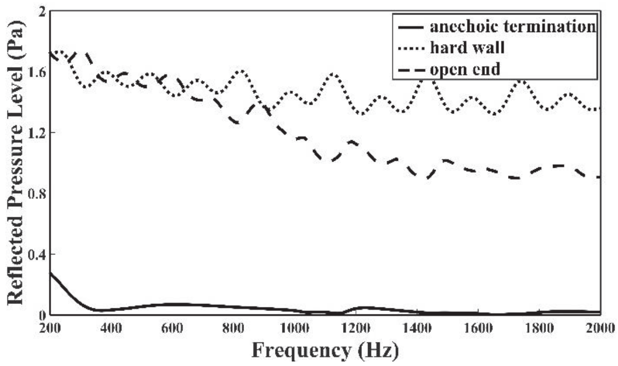

Figure 4. Reflected pressure level for different boundary elements.

On the other hand, as illustrated in Fig. 5, the incident pressure level remains nearly identical for different boundary conditions, affirming the effectiveness of the developed perfectly matched source to sustain a predefined incident pressure level regardless of the study object. While applying a constant level of AC voltage, the incident pressure level demonstrates remarkable stability across a broad frequency range owing to the absence of any moving mechanical component. This characteristic of the CD transducer offers a distinct advantage, as it mitigates the limitations imposed by the resonance in conventional loudspeakers and enhances the overall performance of the sound source.

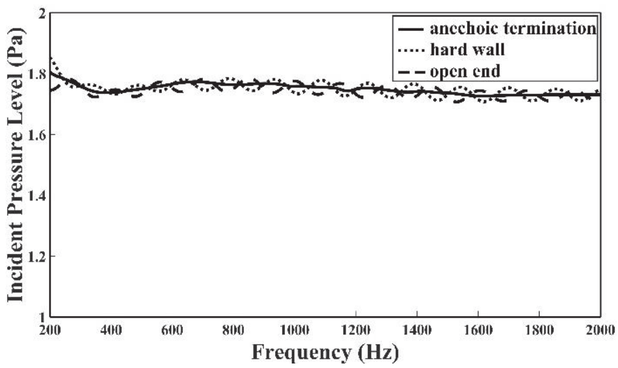

Figure 5. Incident pressure level for different boundary elements.

Harmonic distortion plays a pivotal role in the evaluation of a sound source's ability to reproduce a desired tone accurately. In this context, total harmonic distortion (THD) serves as a crucial metric for quantifying the nonlinearity of the signal. With an anechoic boundary element in experimental setup, this can be determined by summing the relative power of higher harmonic components present in the generated sound signal as [15]:

$$\mathrm{TDH} = 100\sqrt{\frac{f_2^2 + f_3^2 + f_4^2 + \ldots}{f_1^2 + f_2^2 + f_3^2 + \ldots}}, \tag{3}$$

where f_1 is the fundamental component, and $f_n, (n>1)$ are the higher harmonics of the signal. Fig. 6 presents the THD of the prototyped matched source at a constant incident pressure level of $|P_{\mathrm{inc}}| = 1.0\,\mathrm{Pa}$, where the remarkably low THD witnesses the high linearity of the output signal.

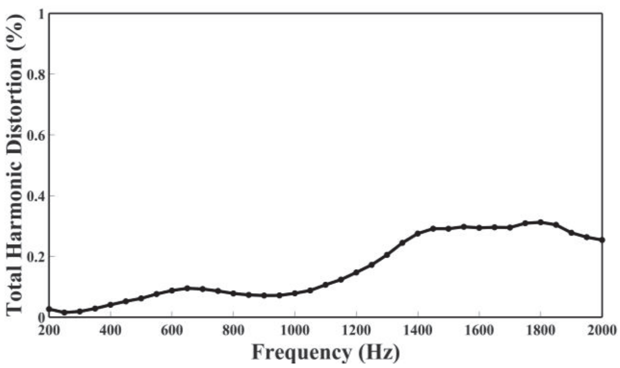

Figure 6. Total harmonic distortion of the prototyped perfectly matched acoustic source.

Lastly, the boundary element in Fig. 2 is substituted by a nonlinear ER to assess the reliability of the designed perfectly matched source for future studies on nonlinear objects under realistic conditions. Here, the performance of the developed matched acoustic source is assessed to examine if it can provide a single-tone incident pressure at a predefined level of $|P_{\mathrm{inc}}| = 1\,\mathrm{Pa}$ for an acoustically excited nonlinear ER in an impedance tube. The governing dynamic equation of a nonlinear ER with cubic stiffness can be represented as:

$$\ddot{x}(t) + c_1\dot{x}(t) + k_1 x(t) + k_2 x^3(t) = c_2 P_{\mathrm{inc}}(t), \tag{4}$$

where x denotes the displacement of ER diaphragm, while $c_1 = 840\,\mathrm{s}^{-1}$, $k_1 = 7.44\mathrm{e}6\,\mathrm{s}^{-2}$, $k_2 = 1.13\mathrm{e}20\,\mathrm{m}^{-2}\mathrm{s}^{-2}$ and $c_2 = 3.88\,\mathrm{m}^2\mathrm{kg}^{-1}$ are constant values. It is worthwhile to note that the nonlinearity of the system can be easily maintained through a feedback control signal as explained in [16]. Having noticed the system nonlinearity, a discernible presence of higher harmonics is anticipated in the reflected wave from the study object. Thus, the ideal sound source for this showcase study should not reflect the higher harmonics sound waves while generating the desired signal. The developed matched source is then substituted by a conventional electrodynamic loudspeaker (Visaton FRWS 5 SC), and the performance of the two sound sources are compared at excitation frequencies of 300 and 400 Hz in Figs. 7 and 8, respectively. Accordingly, the incident pressure, obtained from Eqn. (2), is decomposed into its frequency components through a fast Fourier transform to extract the spectral content of the signal.

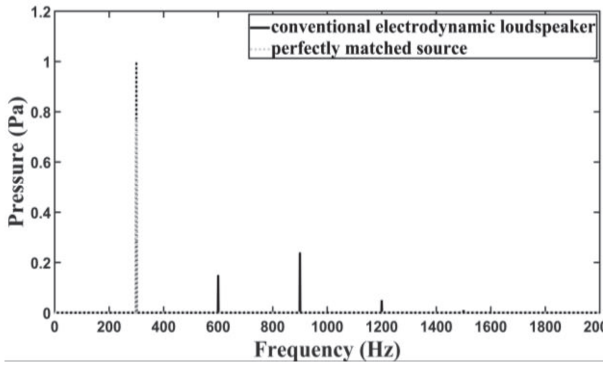

Figure 7. Frequency spectrum of the incident pressure at 300 Hz.

As depicted, the superior performance of the designed matched source is evident, as it overcomes the inherent limitations of conventional loudspeakers, which are unable to provide a desired incident tone in proximity of nonlinear oscillators due to unavoidable reflections from their moving diaphragm.

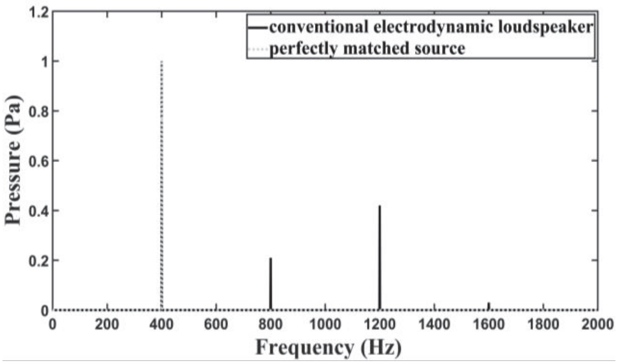

Figure 8. Frequency spectrum of the incident pressure at 400 Hz.

4. CONCLUSION

The current study leverages the inherent acoustic transparency of a wire-to-rod geometry of a CD transducer to design a non-reflecting sound generator. Accordingly, a proof of concept for such a perfectly matched acoustic source is prototyped and assessed in an impedance tube. With only a few tenths of dB STL, the acoustic transparency of the CD transducer is demonstrated through a standard transmission loss test. Different boundary conditions are taken into consideration to evaluate the non-reflecting characteristic of the source. The comparison of the results demonstrates consistency in incident pressure level despite totally different reflected wave behavior, which shows the capability of the matched source to maintain a predefined incident wave regardless of applied boundary conditions in an impedance tube. Using a CD transducer, non-inertial dynamics of an ultrathin layer of air plasma can be controlled by the applied electric voltage, which enables direct manipulation of the acoustic field without relying on any mechanically moving components. This advantageous characteristic provides independence of the emitted sound pressure level from the excitation frequency and mitigates the limitations imposed by the resonance in conventional loudspeakers. Moreover, the harmonic distortion analysis promises the linearity of the generated output sound signal as a key metric to evaluate the performance of the transducer. Finally, superior performance of the designed matched source is highlighted in comparison to conventional loudspeakers under realistic conditions, which overcomes the limitations attributed to the inevitable sound reflections and provides enhanced control for acoustic excitation of study objects with nonlinear dynamics. efficiency of the designed perfectly matched source for further investigations on acoustically excited study objects with nonlinear dynamics. This work contributes to the field by providing a transformative solution for precise and controlled sound generation. The unique characteristics of the designed perfectly matched acoustic source offers significant advantages for a high-quality and reliable sound source, paving the way for further advanced research, particularly in nonlinear acoustics.

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