Acoustical Sensitivity and Linearity of an Air-Coupled 3D-Printed Ferroelectret Ultrasonic Receiver

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***Abstract*—3D-printed ferroelectret transducers, utilizing polylactic acid (PLA), present an eco-friendly alternative to ceramic-based transducers, which predominantly employ lead zirconate titanate (PZT). We demonstrate using 3D-printed ferroelectret ultrasonic transducers made from PLA featuring well-defined cavities as a sound receiver by developing a simple amplifier circuit and measure the resulting linearity and sensitivity. The quasi-permanently trapped surface charges inside the air cavities of the ferroelectret ultrasonic transducer serve as an electrical bias, resulting in a mechanical pre-stress due to the electrostatic force. The amplifier for the microphone does not need to provide a DC-Bias and is based on a charge amplifier with a flat amplification curve between 20 kHz and 80 kHz. We test the receiver in an anechoic chamber at a distance of 30 cm. We excite with a broadband electrostatic transducer over different frequencies and sound pressures. The receiver exhibits a linear relationship between output voltage and sound pressure, with a mean square error of 102.14 mV² at 50 kHz. The sensitivity varies with frequency, peaking at 29 kHz with -25 dB/VPa and has a 6 dB-bandwidth of 32 kHz. These results underscore the potential of easily manufacturable and adaptable ferroelectret transducers as viable, eco-friendly alternatives to traditional piezoelectric devices.**

***Index Terms*—Ferroelectret, ultrasonic receiver, 3D-printed, eco-friendly, transducer.**

I. INTRODUCTION

The development of eco-friendly technologies has gained significant momentum across various fields [1]–[3]. One such innovation is the introduction of 3D-printed air coupled ultrasonic ferroelectret transducers, which offer a sustainable alternative to traditional ceramic-based transducers [4], [5]. Conventional transducers predominantly utilize lead zirconate titanate (PZT), a material known for its piezoelectric properties but also associated with environmental and health concerns due to its lead content [6]. In contrast, 3D-printed ferroelectret transducers can be made of biocompatible polymers, thereby aligning with the growing emphasis on green technology [7].

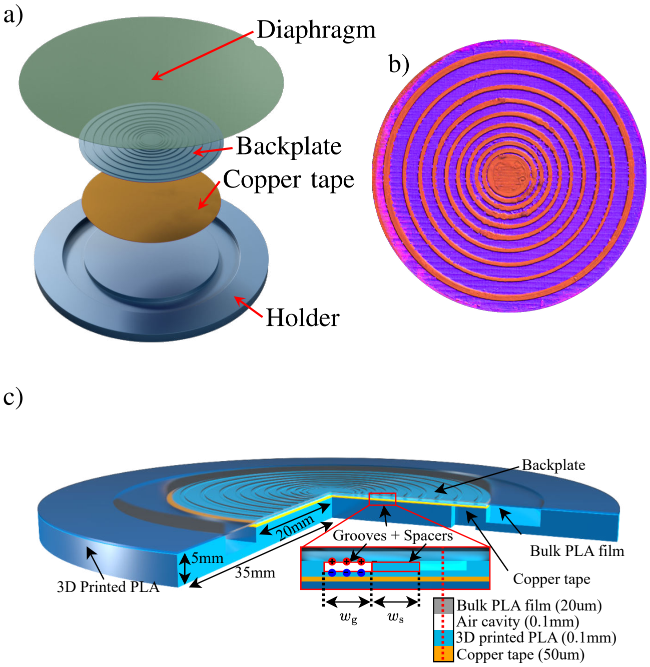

Fig. 1. Exploded 3D view of the 3D-printed ferroelectret ultrasonic transducers featuring well-defined cavities (a). The transducer consists of a backplate (b) featuring artificially created ridges spaced between 0.2 mm (inner) and 2 mm (outer), forming cavities. Once the transducer is assembled (c) and a conductive aluminum electrode is applied to the diaphragm (not shown), the transducer can be charged by trapping surface charges inside the cavities [1].

Ferroelectret transducers, characterized by their electret-like properties and the presence of permanent dipoles, have shown promise in various applications [4], [5], especially, as the acoustic impedance of porous polymers or structures from

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air-polymers-composites are close to air [8]. The advantage lies in the utilization of quasi-permanently trapped surface charges within the air cavities of the ferroelectret ultrasonic transducer [9], [10]. These charges act as an electrical bias, inducing mechanical pre-stress through electrostatic forces [11]. Ferroelectret transducers have been successfully employed as flexible ultrasonic transducers [12], loudspeakers in air [13], and even in water immersion applications [14], [15].

In previous work, we demonstrated a ferroelectret transducer made of polylactic acid (PLA) featuring well-defined cavities in its structure, fabricated by fused filament fabrication (FFF), along with a fixture that clamps the film and provides both mechanical and electrical bias through trapped charges [1], [5]. The resulting transducer exhibited large sound pressure levels (up to $106\,\mathrm{dB}$) and a wide bandwidth ($45\,\mathrm{kHz}$), making it effective for air-coupled ultrasound applications. However, these values were achieved shortly after charging, without the corresponding charge decay over extended periods [16].

In this study, we aim to extend the application of additively manufactured ferroelectret ultrasonic transducers featuring well-defined cavities by employing them as sound receivers without the need for a DC bias, using only the charges still present after a stabilization time of 19 days. This approach is advantageous for low-power applications. We develop a suitable amplifier and verify the performance of the resulting system in an anechoic chamber, focusing on its linearity, sensitivity, and applicability.

II. 3D-PRINTED FERROELECTRET TRANSDUCER

The ferroelectret transducer is made using an additive manufacturing process. The initial step involves fabricating the backplate, which has a diameter of $40\,\mathrm{mm}$. The backplate is made with a commercially available 3D printer (Prusa i3 MK3S+, Prusa Research a.s., Prague, CZ) from filament (PLA blue, REDLINE FILAMENT GmbH, Neuss, DE) and has a total height of $0.2\,\mathrm{mm}$.

Nine concentric ridges, each $0.45\,\mathrm{mm}$ wide, $0.1\,\mathrm{mm}$ high, and spaced between $0.2\,\mathrm{mm}$ and $2\,\mathrm{mm}$ apart, are 3D-printed onto the backplate, resulting in nine cavities with an inner circle with a diameter of $6\,\mathrm{mm}$ (Fig. 1). On the smooth backside of the backplate, adhesive copper tape is attached as an electrode for electrical contact, covering the cavities from the backside. Subsequently, the base of the transducer, which is $5\,\mathrm{mm}$ high and $70\,\mathrm{mm}$ in diameter, is 3D-printed, featuring a $6\,\mathrm{mm}$ gap to the inner circle of $40\,\mathrm{mm}$ to match the backplate diameter. The inner cylinder's height is designed so that the ridges are level with the top of the base.

Afterward, the contacted backplate is placed onto the base. A holder with an inner diameter of $80\,\mathrm{mm}$ is used to stretch a $20\,\mathrm{\mu m}$-thick bulk PLA film (PLA-Film, Yito Packaging Co. Ltd, Huizhou, China) over an embedded embossment, pre-stressing the PLA film. The holder is then placed over the base with the backplate and subjected to a heat press, creating the sandwich structure. Under a fixed force, the structure is thermally fused at $95\,^{\circ}\mathrm{C}$ for $1\,\mathrm{min}$, fully bonding the ridges with the bulk PLA film.

For symmetrical metallization, a $100\,\mathrm{nm}$-thick aluminum layer is deposited using a physical vapor deposition unit (BAL-300, Balzers Ltd., Oerlikon, CH) for the top electrode of the ferroelectret. A mask featuring a $40\,\mathrm{mm}$ hole, corresponding to the electrode diameter and the active part of the ferroelectret, is employed. Electrical charging is performed via contact charging at $1.28\,\mathrm{kV}$ for $3\,\mathrm{min}$ at room temperature, which initializes Paschen breakdown, polarizing the air-PLA interfaces [17].

The transmission behavior of this transducer was measured inside an anechoic chamber with a methodology, published separately, in which it featured a resonance frequency of $47\,\mathrm{kHz}$, with a bandwidth of $32\,\mathrm{kHz}$ [1].

III. AMPLIFICATION CIRCUIT FOR RECEIVING

When a pressure, or in this case, the excitation from sound waves, is exerted on the ferroelectret, the direct piezoelectric effect generates a proportional charge to the applied force [18]. However, when this charge is converted into a voltage, the resulting signal is proportional to the rate of change of the applied force rather than the force itself [19], [20]. Due to the typically low resulting charge, amplification is necessary, commonly achieved using a charge amplifier.

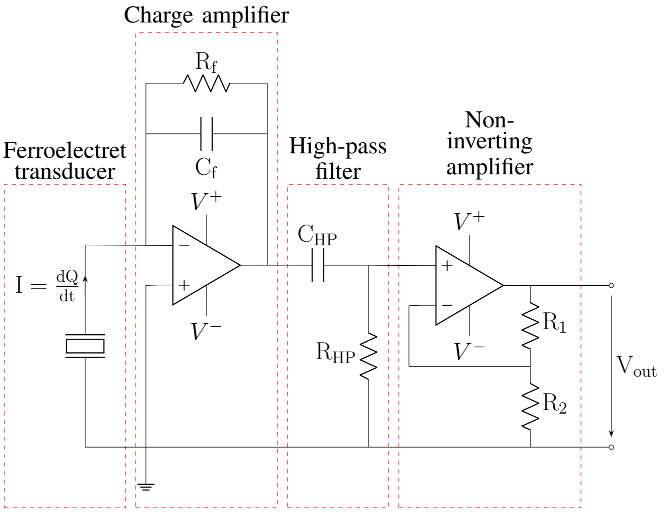

Fig. 2. Circuit diagram of our amplifier circuit, consisting of a piezoelectric model of our ferroelectret transducer with a charge amplifier, high-pass filter and non-inverting amplifier. The resulting amplifier circuit is able to amplify the low charge of a ferroelectret transducer, allowing for subsequent acoustic measurements.

In our setup, we employ a charge amplifier with a feedback capacitance $C_f = 10\,\mathrm{pF}$ and a feedback resistor $R_\mathrm{f} = 100\,\mathrm{k\Omega}$ (Fig. 2). To eliminate low-frequency noise, a first-order high-pass filter ($C_\mathrm{HP} = 100\,\mathrm{nF}$ and $R_\mathrm{HP} = 1\,\mathrm{k\Omega}$, $f_\mathrm{c} = 1592\,\mathrm{Hz}$) is connected after the charge amplifier. For additional amplification, we include a non-inverting amplifier stage with $R_1 = 1\,\mathrm{k\Omega}$ and $R_2 = 100\,\Omega$ (Fig. 2). The total gain of the system is given by

$$Gain = -\frac{1}{C_f} \cdot \left(1 + \frac{R_1}{R_2}\right) = -1.1 \cdot \frac{\mathrm{V}}{\mathrm{pC}}\ . \tag{1}$$

The operational amplifier used in our design (TLV3541, Texas Instruments, Texas, USA) features a high input resistance of $10\,\mathrm{T\Omega}$, a large gain-bandwidth product of $100\,\mathrm{MHz}$, a high slew rate of $150\,\mathrm{V}/\mu\mathrm{s}$, and a low input current of $3\,\mathrm{pA}$. Simulations (LTSpice, Linear Technology, Milpitas, USA) of the circuit, accounting for real component behaviors, indicate that our amplifier circuit maintains a flat amplification curve between $20\,\mathrm{kHz}$ to $80\,\mathrm{kHz}$, with an amplification reduction of $\sim 10\,\%$ at $80\,\mathrm{kHz}$ compared to $20\,\mathrm{kHz}$.

IV. EXPERIMENTS

The sensitivity of a microphone describes its responsiveness to changes in sound pressure and its ability to convert these changes into an electrical output voltage. By transmitting an ultrasonic signal from a known source over a frequency range to the receiver, its sensitivity can be calculated as the ratio of the output voltage (in volts) to the actual sound pressure (in pascals). We conducted two experiments to verify the functionality of the complete system, consisting of the amplifier board and the ferroelectret ultrasonic transducer. First, we determine the sensitivity over different frequencies, and second, we vary the sound pressure at individual frequencies to determine the linearity of the ferroelectret receiver.

For this, a transmission path in an anechoic chamber is established. This chamber, lined with mineral wool wedges on all walls, ceiling, and floor, absorbs sound, minimizing reflections. The measurement setup consists of a transmitter and a receiver placed $30\,\mathrm{cm}$ apart (Fig. 3). The ferroelectret transducer was charged at least 19 days prior to testing, allowing the trapped charge to stabilize [1]. The output voltage of the amplifier board is examined using an oscilloscope (DSO-X 2002A, Agilent Technologies, Santa Clara, CA). Measurements are taken within a frequency range of $20\,\mathrm{kHz}$ to $80\,\mathrm{kHz}$ and are compared against a calibrated reference microphone (Typ 4138, BRÜEL and KJÆR, Naerum, Denmark).

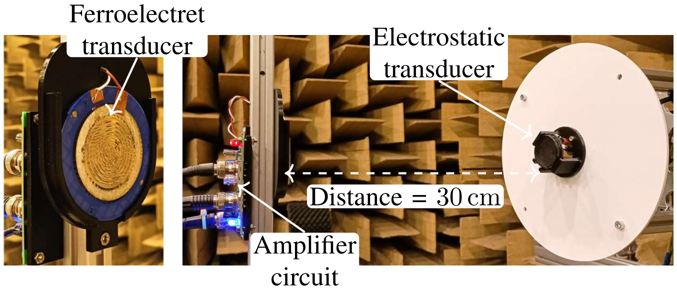

Fig. 3. Measurement setup for characterizing the microphone. The electrostatic ultrasonic transducer (500ES430, Pro-Wave Electronics) is placed $30\,\mathrm{cm}$ in front of the ferroelectret transducer, which serves as the sound receiver. By previously recording the frequency response of the electrostatic transducer with a calibrated microphone, the sensitivity of the ferroelectret receiver can be determined.

A broadband electrostatic ultrasonic transducer (500ES430, Pro-Wave Electronics Corporation, Taiwan) with high sound pressure is used as the transmitter. The necessary AC and DC voltage for the electrostatic transducer is generated by a function generator (33500B, Keysight Technologies Inc., Santa Rosa, CA) and amplified 50-times by a voltage amplifier (WMA-300, Falco Systems, Netherlands). A high-voltage DC power supply (6516A, Hewlett-Packard, Palo Alto, USA) provides the DC bias.

For measuring the sensitivity, an ultrasonic burst signal with a length of $0.5\,\mathrm{ms}$ is transmitted using the electrostatic ultrasonic transducer from $20\,\mathrm{kHz}$ to $80\,\mathrm{kHz}$ in $500\,\mathrm{Hz}$ steps with a constant V_{PP} of $150\,\mathrm{V}$ and a DC bias of $200\,\mathrm{V_{DC}}$. As the electrostatic transducer does not feature a flat sound pressure curve, we measure the resulting sound pressure with the measurement microphone at a distance of $30\,\mathrm{cm}$. Then, with the now known sound pressure curve, we replace the microphone with the ferroelectret receiver and measure the output voltages with the oscilloscope over the entire frequency range. By comparison of the reference curve to the measured curve of the FE transducer, we calculate the sensitivity.

In order for measuring the linearity, the same methodology is used. However, the step size is changed to $10\,\mathrm{kHz}$ and the AC voltage of the electrostatic transducer is swept over its input range. Using both data sets, the linearity over different frequencies is calculated.

V. RESULTS AND DISCUSSION

During the testing phase, an issue was encountered involving capacitive coupling between the ferroelectret transducer and the electrostatic transducer, which resulted in electrical interference. To address this, we cut the recorded signal and only used the data starting at the expected arrival time of the sound wave, approximately 875 µs after initiation. With this adjustment, the measurements were successfully conducted without further complications (Fig. 4).

The system developed exhibits a linear relationship between output voltage and sound pressure, with a mean square error of $102.14\,\mathrm{mV^2}$ at 50 kHz. The sensitivity varies with frequency, peaking at 29 kHz with -25 dB/VPa and has a 6 dB-bandwidth of 32 kHz. Using the measured linearity at 30 kHz, a sensitivity of 81.6 mV/Pa can be obtained, which translates to 74 pC/kPa after accounting for the amplifier characteristics.

Electret microphones are built with a field-effect transistor directly embedded, allowing for a direct comparison to our system. High-precision 1/2” electret microphones, commonly used for sound level measurements, typically exhibit a flat frequency responses and sensitivities ranging from 1 to 20 mV/Pa, while modern electret microphones designed for general use achieve sensitivities around 50 mV/Pa [18]. Compared to these, our receiver offers better sensitivity, though our effective area is approximately ten times larger. However, a significant drawback of our receiver is its linearity. While electret microphones usually maintain a very flat sensitivity curve, our system shows notable fluctuations.

VI. CONCLUSION AND OUTLOOK

In this work, we use a 3D-printed ferroelectret transducer featuring well-defined cavities as an acoustic receiver. The most significant benefit of 3D-printed ferroelectret transducers is their environmental friendliness due to the use of PLA,

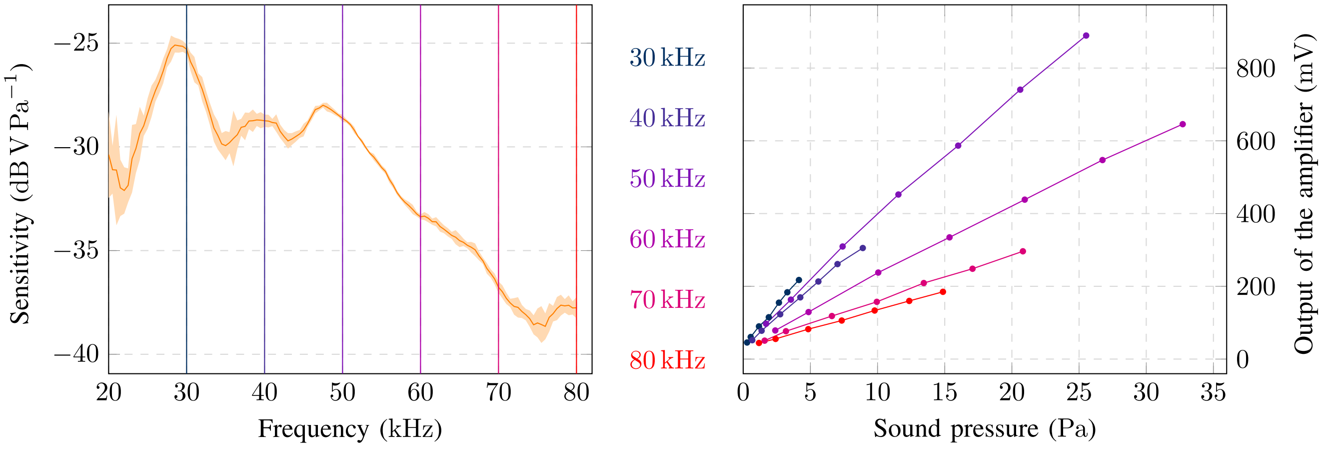

Fig. 4. Sensitivity (left) and linearity (right) of the ferroelectret transducer as a sound receiver. The sensitivity peaks at 29 kHz with -25 dB/VPa and has a bandwidth of 32 kHz. The ferroelectret also exhibits a linear response characteristic. The maximum sound pressure level of the reference transmitter varies over the measured frequency range, resulting in different sound pressure values at different frequencies, which explains the varying lengths of the displayed graphs.

a biocompatible material, and their ease of manufacturing. While this is promising, there is room for improvement, particularly in sensitivity and linearity.

Therefore, future work will focus on enhancing the receiver design to accumulate more charges within the ferroelectret receiver, on making the diaphragm thinner, and on improving the immunity against capacitive coupling. Additionally, we aim to refine the electronics to reduce susceptibility to electromagnetic interference. The potential of 3D-printed ferroelectret transducers is broad, and ongoing advancements in 3D printing technology and research in functional electric materials are expected to further enhance their capabilities.

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