New Design for a Thermo-formed Piezoelectret-based Accelerometer

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***Abstract*—The article discusses the development and analysis of a new design for piezoelectric accelerometers that are used to measure acceleration in various applications. The new design uses piezoelectret materials, which offer advantages over traditional piezoelectric ones, including improved resistance to humidity, greater stability in extreme temperatures, and increased flexibility in meeting design requirements. The piezoelectret used in this study is a thermo-formed piezoelectret based on open-tubular channel structures. The paper explains the manufacturing process of the piezoelectret, which involves thermal lamination of two fluoroethylene propylene (FEP) foils and a polytetrafluoroethylene (PTFE) template, resulting in four open-tubular channels separated by a distance of 1.4 mm. The polymer structure is coated with aluminum through evaporation to create electrodes. The piezoelectret sample is then used to create a new design of accelerometers with a single detection axis, consisting of a cylindrical lead seismic mass enclosed in a PTFE sheath placed over the piezoelectret. An elastic component made of polyurethane foam provides mechanical support and restitution. The authors conclude that this new design of piezoelectric accelerometers using piezoelectret materials has the potential to offer superior performance in various applications.**

Keywords*—*accelerometer, piezoelectret

I. INTRODUCTION

Accelerometers are widely used for measuring acceleration in various industrial, medical, and scientific applications. These accelerometers convert acceleration into an electrical signal, enabling the analysis and interpretation of the dynamic characteristics of a moving system. Since their invention in the 1950s, piezoelectric accelerometers have been fundamental tools for engineers and researchers in fields such as vibration analysis, process control, health monitoring, and structural testing [1].

In recent years, a new technology has emerged in the development of accelerometers: piezoelectret materials. These polymeric materials offer several advantages over traditional piezoelectric materials, including greater stability in extreme temperatures, improved resistance to humidity, and increased flexibility to meet different design requirements. Since 2004, Sessler and collaborators have provided an overview of this emerging technology, including the manufacture of piezoelectret accelerometers and methods for producing sensors with superior performance [2] [3]. In 2009, Altafim Pisani and collaborators [4] [5] developed a new piezoelectret material, named thermo-formed piezoelectrets, which presents a high piezoelectric coefficient with the same advantages of piezoelectrets. They also demonstrated that this material has a linear behavior with frequency until the frequency of 30 kHz, where a resonance peak occurs, which can be modified by the geometry of the channels [6]. In the following sections, we present and analyze a novel design of accelerometers utilizing this material. For instance, Section 2 describes the production of the piezoelectret and the accelerometer, including details on fabrication. In Section 3, significant results are presented and thoroughly discussed. Finally, in Section 4, we present our main conclusions.

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II. ACCELEROMETER DESIGN

A piezoelectret sample, as depicted in Figure 1, was fabricated using the thermal lamination technique described in [5]. In this process, two 50 μm-thick fluoroethylene propylene (FEP) foils were laminated at 300 °C with a 100 μm-thick polytetrafluoroethylene (PTFE) film placed between them. The PTFE was previously laser-cut with four rectangular openings through which the FEP films were bonded during lamination. After this process, the PTFE was removed, leaving an FEP structure with four open channels. The PTFE was designed to produce four channels that were 1.4 mm wide and 30 mm long, regularly spaced at intervals of 1.4 mm. The polymer film-like structure was later coated with aluminum through evaporation, creating electrodes with a final active area of 168 mm^2.

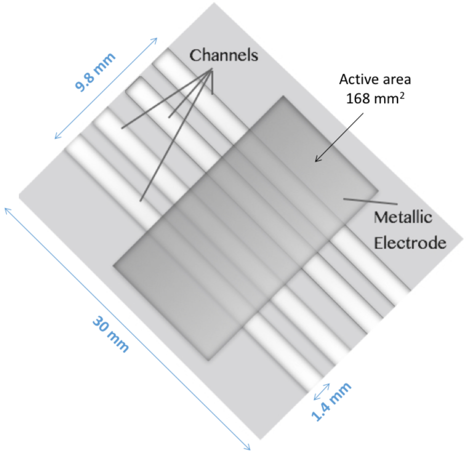


Fig. 1. Sample of Thermo-formed Piezoelectret with channels.

A. Description

Figure 2 depicts the schematic of the thermo-formed piezoelectret accelerometer (TFPA) with a single detection axis. The accelerometer is composed of a 30 g cylindrical lead seismic mass, with dimensions of 10 mm in height and 18 mm in diameter, enclosed within a PTFE sheath placed over a thermo-formed piezoelectret. An elastic component made of polyurethane foam with a density of 12 kg/m³ is placed on top of the mass to provide mechanical support and restitution, while an aluminum guide vertically guides the mass. To ensure mechanical resistance and electrical shielding, the transducer is connected to a BNC connector and is enclosed in an aluminum cylindrical case measuring 74 mm in height and 51 mm in diameter. This dimension is far larger than the standard accelerometer; however, it is expected that this design will be reduced by 10 times in the laboratory facilities.

For the tests conducted with the TFPA, a custom-made shaker was constructed using a 15.24 cm (6 inch) diameter mid-bass speaker from *Foxer Alto-falantes*®, equipped with a ferrite magnet and an aluminum single coil, with 4 Ω impedance, 80 W power, frequency response ranging from 30 Hz to 30 kHz, and sensitivity of 90 dB/W. An acrylic holder with a PTFE guide was fabricated to support the TFPA, as shown in Figure 3.

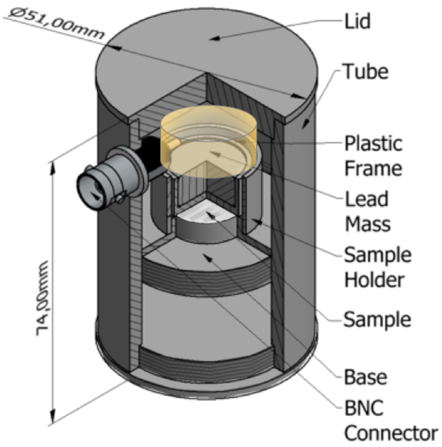
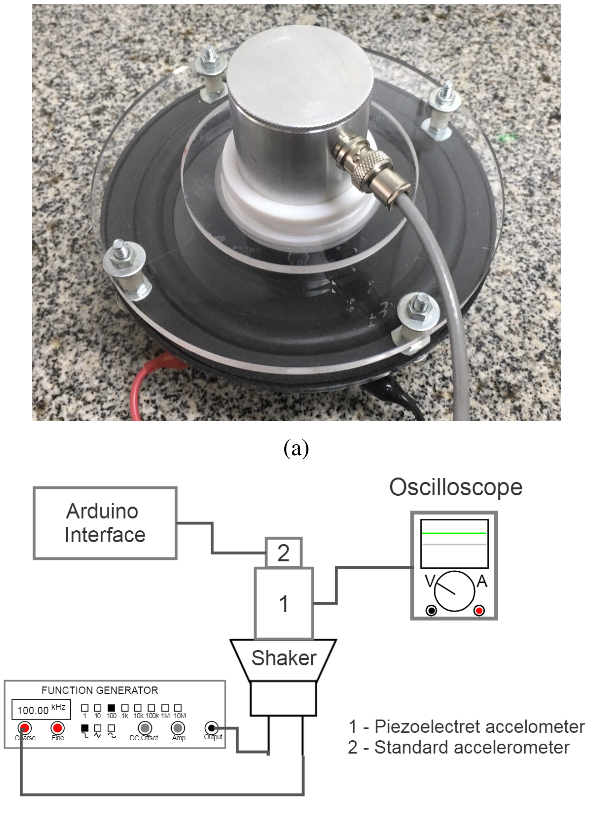


Fig. 2. New design of thermo-formed piezoelectret (TFPA) accelerometer, with polyurethane foam.



(a)

(b)

Fig. 3. (a) Custom-made shaker built for the TFPA tests. (b) Block diagram of the experimental setup.

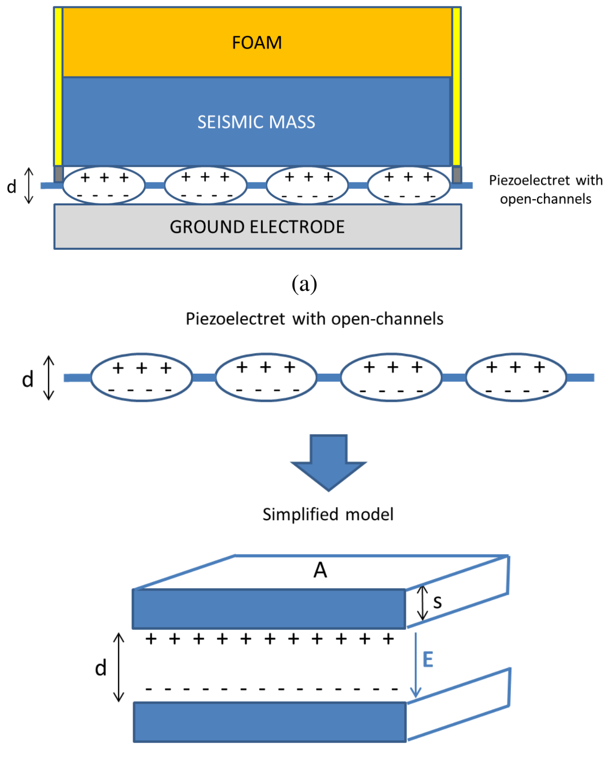
An ADXL327 accelerometer from Analog Devices connected to an *Arduino UNO*® microcontroller board was used as reference measure. It has an acceleration input range of $\pm 2g$, sensitivity of 420 mV/g and frequency response from

0.5 Hz to 1600 Hz.

The input signals for the shaker were generated using the Tektronix function generator model AFG3022CA. A Taramps TL-500 Class D Amplifier was used for signal amplification.

III. THEORETICAL CONSIDERATIONS

A simplified depiction of the thermo-formed piezoelectret accelerometer is presented in Figure 4 (a). As shown, the piezoelectret is placed under an enclosure seismic mass that compresses the piezoelectret channels when subjected to vibration.



(a)

(b)

Fig. 4. (a) Cross-sectional view representation of the thermo-formed piezoelectret accelerometer. (b) Representation of the simplified model for a piezoelectret.

The piezoelectret compression results in a change in thickness (Δd) and subsequently leads to a voltage variation (ΔV) at the sample electrodes [8]. According to Sessler et al. [7], if the piezoelectret cavities is modeled as rectangular cavities, as shown in Figure 4 (b), then the voltage variation ΔV due to a variation Δd can be mathematically determined by Equation 1:

$$\Delta V = E.\Delta d \tag{1}$$

where E is the electric field inside an air cavity (here represented by the open channels), and given by Equation 2:

$$E = \frac{\sigma s}{\epsilon_0(\epsilon d + s)} \tag{2}$$

where σ is the superficial electric charge density of the cavity walls, s is the thickness of the polymeric film, ϵ_0 is the vacuum permittivity, and ϵ is the relative permittivity of the polymeric layer.

The term Δd from Equation 1 can be determined from Young's modulus of the cavity plus foam (Y) when a force F is applied to it, as shown below in Equation 3:

$$Y = \frac{F/A}{\Delta d/d} \implies \Delta d = \frac{Fd}{Y.A} \tag{3}$$

As F can also be expressed as $m_s \Delta a$, where m_s is the seismic mass and Δa is the acceleration, ΔV can be determined by Equation 4:

$$\Delta V = \frac{\sigma s}{\varepsilon_0(\varepsilon.d + s)} \cdot \frac{d}{Y.A} \cdot m_s \Delta a \tag{4}$$

Thus, in the piezoelectret accelerometer, any variation in acceleration (Δa) generates a voltage variation (ΔV).

IV. RESULTS AND DISCUSSIONS

As previously described, the proposed accelerometer (TFPA) was tested over a shaker platform, which vibrated over frequencies ranging between 100 Hz to 1000 Hz. It´s output, recorded as peak-to-peak millivolts (mV) signals, provided the frequency response plot in Figure 5. The graph reveals a clear resonance peak at 200 Hz and a relatively linear response for frequencies above 400 Hz.

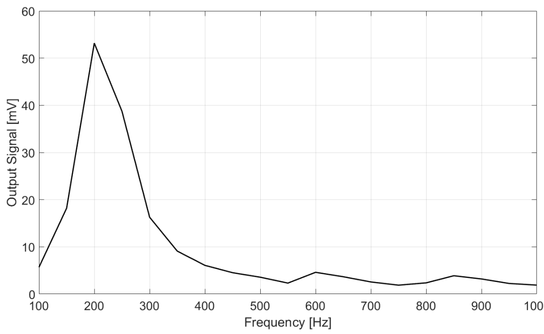


Fig. 5. Frequency response of TFPA output signal peak-to-peak voltage.

This result is analogous to the response obtained from a commercial accelerometer ADXL327 (depicted in Figure 6) under identical vibrating conditions. The comparison can be further elucidated by normalizing the values using their respective maximum peak-to-peak output voltage within the frequency range of the experiment, as shown in Figure 8, which have a correlation factor of 0,985.

Both the ADXL327 accelerometer and the TFPA exhibit a linear response within the same frequency range, suggesting that the 200Hz resonance may not be an inherent characteristic of the accelerometer but rather a consequence of the test system assembly used in the calibration procedure. Nevertheless, this system can still be utilized to determine the TFPA's

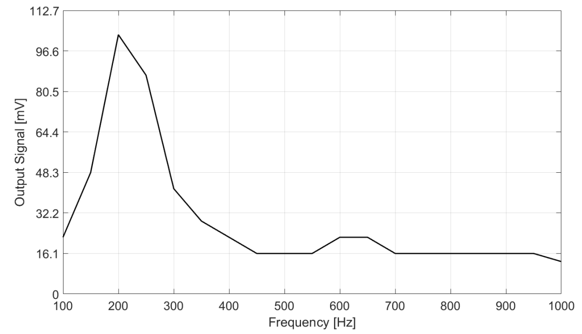


Fig. 6. Frequency response of ADXL327 reference accelerometer output signal peak-to-peak voltage.

sensitivity in mV/g, considering that the ADXL327 has a linear sensitivity of 420mV/g [9]. In such a case, dividing the data on the y-axis of Figure 6 by 420mV/g generates a graph of acceleration in m/s², shown in Figure 7. Furthermore, dividing the y-axis data of the graph in Figure 5 by the corresponding acceleration in m/s² for each frequency, Figure 7 allows us to determine an average sensitivity of 78mV/g for frequencies above 400Hz.

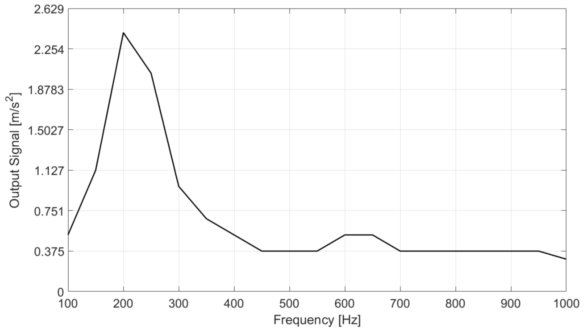


Fig. 7. Acceleration response of the system in $[m/s^2]$.

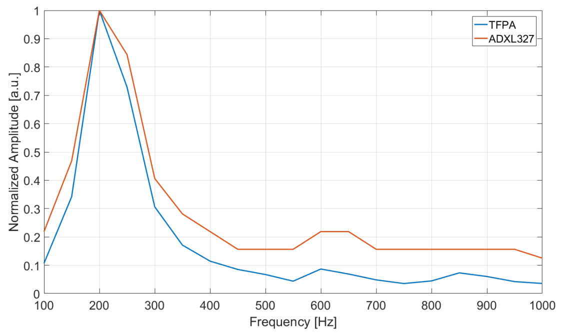


Fig. 8. Normalized frequency response of TFPA and ADXL327 reference accelerometer.

V. CONCLUSION

This article presents a novel approach for producing accelerometers using thermo-formed piezoelectrets. A brief description of the process for fabricating piezoelectrets with open channels is provided, followed by the construction of the accelerometer with a single detection axis. Some advantages of using FEP thermo-formed piezoelectrets over more traditional ones are emphasized, such as improved moisture resistance and thermal stability. Measurements in the frequency domain (up to 1 kHz) were performed and reported, allowing a comparison between the proposed accelerometer and a standard model (ADXL327). It was observed that both accelerometers presented a very similar response with a clear resonance peak at 200 Hz, which was attributed to the measuring setup. From this result, it was calculated that the TFPA presents a sensitivity of 78 mV/g while the commercial ADXL327 provides 420 mV/g. This discrepancy in sensitivity is related to the higher amplification gain and was not understood as a deficiency of the TFPA accelerometer. It was concluded that accelerometers with the proposed design, i.e., using piezoelectrets, can be explored in a variety of applications, especially in studies of motor and equipment vibrations. As for future developments, it is expected to reduce the physical dimensions of the accelerometer, extend the frequency range analysis to higher frequencies, and employ them in studies regarding motor mechanical vibrations.

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