Investigation of Thermo-formed Piezoelectret Accelerometer under Different Electrodynamic Vibration Conditions

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***Abstract*—Accelerometers are essential sensors utilized across various industry applications. They enable precise measurement of acceleration, tilt, and motion, facilitating advancements in fields, such as biomechanics, healthcare monitoring, automotive safety, and consumer electronics. With their versatile functionality, accelerometers play a crucial role in enhancing human safety, improving performance, and driving innovation in modern technology. The demand for new accelerometer technologies led to the use of piezoelectrets as the main sensing element. Piezoelectrets are advanced materials with unique structure and properties, similar to piezoelectric polymers but with enhanced performance due to their cellular microstructure. With promising applications in energy harvesting, sensing, biomedical devices, and acoustics, their remarkable efficiency and flexibility make them particularly appealing for compact and versatile transducers and actuators. Due to their abilities, piezoelectrets have been employed in the development of accelerometers for monitoring electrodynamic vibrations. Different designs have been proposed and, in this paper, the concept of an enclosed seismic mass superposing a sensing element is used together with an open tubular channel thermo-formed piezoelectret. The recently enhanced piezoelectret accelerometer, only analyzed in a custom-made workbench, is tested in this paper in a standard electrodynamic vibration setup at frequencies ranging from 50 Hz up to 1 kHz. The results from both custom-made and standard systems are presented for a much better understanding of this type of accelerometer.**

***Index Terms*—Accelerometers, piezoelectrets, functional materials, piezoelectricity, mechanical vibration.**

I. INTRODUCTION

In the realm of modern science and technology, the role of accelerometers has become increasingly significant across a diverse range of fields, owing to their exceptional capabilities in measuring and analyzing acceleration forces. Accelerometers, as electromechanical devices, are designed to detect and quantify changes in velocity, acceleration, and orientation in various contexts, thereby serving as pivotal instruments in scientific research, industrial applications, healthcare systems, consumer electronics, and beyond [1].

The relevance of accelerometers stems from their fundamental ability to capture and interpret motion dynamics with precision and accuracy. Originally developed for aerospace and military applications, accelerometers have undergone remarkable advancements, leading to their ubiquitous integration into everyday devices, such as smartphones, wearables, and automotive systems [2]. This widespread adoption underscores their indispensable role in enhancing human experiences and improving the efficiency and safety of numerous technologies [3].

One of the primary areas where accelerometers have revolutionized research and innovation is in the field of biomechanics and sports science. By capturing intricate movement patterns and biomechanical parameters during physical activities, accelerometers enable researchers and practitioners to gain profound insights into human performance, injury prevention, rehabilitation strategies, and sports equipment design. Moreover, accelerometers play a crucial role in the development of wearable health-monitoring devices, facilitating real-time tracking of physical activity levels, sleep patterns, and overall well-being, thereby empowering individuals to make informed decisions about their health and lifestyle choices [4].

Furthermore, accelerometers find extensive applications in automotive engineering and transportation systems, where they contribute to vehicle stability control, inertial navigation, crash detection, and driver assistance systems [2]. By precisely measuring acceleration and tilt angles, accelerometers enable the implementation of advanced safety features, such as airbag deployment algorithms, rollover detection mechanisms, and adaptive cruise control systems, thereby enhancing road safety and reducing the risk of accidents.

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In addition to their utility in conventional industries, accelerometers are also instrumental in emerging fields, such as robotics, Virtual Reality (VR), and Augmented Reality (AR). By providing real-time feedback on motion and orientation, accelerometers enable robots to navigate complex environments, manipulate objects with precision, and interact seamlessly with humans. Similarly, in VR and AR applications, accelerometers facilitate immersive user experiences by accurately tracking head movements and gestures, thereby enhancing the realism and interactivity of virtual environments [5].

In summary, accelerometers represent a cornerstone technology with profound implications for scientific research, industrial innovation, and consumer electronics. As the demand for enhanced motion sensing capabilities continues to grow across various domains, the ongoing advancements in accelerometer technology are poised to drive further progress and unlock new possibilities in the realms of science, engineering, and beyond. One of these technologies that pushes accelerometers to further possibilities is based on piezoelectrets.

Piezoelectrets are a class of advanced materials that have garnered significant attention in scientific research and technological innovation. These materials, akin to piezoelectric polymers, exhibit piezoelectric properties, yet are distinguished by their cellular microstructure and enhanced performance characteristics. Leveraging their unique structure-property relationships, piezoelectrets offer promising prospects for diverse applications ranging from energy harvesting and sensing to biomedical devices and acoustics [6]. The remarkable electromechanical coupling efficiency and flexibility inherent in piezoelectrets render them particularly appealing for developing compact, lightweight, and versatile transducers and actuators.

Because of these abilities, in this research, open-tubular channel thermo-formed piezoelectrets were employed as sensing elements for an accelerometer investigated in different electrodynamic vibration conditions, which range from 50 Hz up to 1 kHz. The accelerometer employed here is considered an improvement of a previous design and until now it has not been tested with standard equipment. In this paper, we demonstrate how the improvements can affect its performance and how it can be employed in further electrodynamic vibration experiments.

The rest of the paper is structured as follows. In Section II, we present a theoretical explanation of how accelerometers operate as well as their composition. In Section III, we present the state of the art related to the piezoelectret accelerometer. Section IV explains how the accelerometer presented in this work differs from previously presented open-tubular channel thermo-formed piezoelectrets and how the measurements were performed. In addition, a comparison between two electrodynamic vibration systems using this thermo-formed accelerometer is presented. In Section V, a comparison between two electrodynamic vibration systems using this thermo-formed accelerometer is presented. Further, a possible explanation for the observed effect is given. In Section VI, we conclude with a synthesis of this work, the major flaws, and the advantages of the proposed accelerometer, as well as how it performed in the two different systems.

II. ACCELEROMETERS

To comprehend the operational principles of the accelerometer made with a thermo-formed piezoelectret, it is essential to elucidate the construction process of accelerometers. Accelerometers operate based on the principles of inertial sensing, specifically by measuring changes in acceleration experienced by a mass within the device. The basic operation of an accelerometer involves the following components and processes:

Mass: At the core of an accelerometer is a mass, typically referred to as a proof mass, which is suspended within the device. This mass is designed to move in response to changes in acceleration.

Sensing Mechanism: Surrounding the proof mass, there are typically one or more sensing elements. These sensing elements can vary based on the type of accelerometer, but common types include piezoelectric, piezoresistive, capacitive, or electromagnetic sensors.

Reference Frame: Accelerometers are typically fixed within a reference frame, such as the Earth's gravitational field. When the accelerometer experiences acceleration in a different direction relative to this reference frame, the proof mass and sensing elements experience forces that cause them to move or deform.

Measurement of Displacement or Deformation: As the proof mass moves or deforms in response to acceleration, the sensing elements detect this motion. For example, in a capacitive accelerometer, the displacement of the proof mass alters the capacitance between electrodes, while in a piezoelectric accelerometer, the deformation generates an electric charge.

Conversion to Output Signal: The detected motion or deformation is converted into an electrical signal by the sensing elements. This signal typically corresponds to the magnitude and direction of the acceleration experienced by the accelerometer.

Signal Processing and Output: The electrical signal is processed by electronics within the accelerometer to filter noise, amplify the signal if necessary, and convert it into a usable output format. This output can be in the form of voltage, current, frequency, or digital data, depending on the specific design of the accelerometer.

By measuring the changes in acceleration, accelerometers can provide valuable information about the motion, orientation, and vibration of objects or systems in various applications, ranging from automotive safety systems and consumer electronics to industrial monitoring and aerospace engineering [3].

III. PIEZOELECTRET ACCELEROMETERS

Accelerometers made with piezoelectrets or ferroelectrets have been reported previously in the literature as a promising device for a growing demand [7], [8]. In the context of these investigations, seismic masses were positioned atop piezoelectret films and secured using springs affixed to the accelerometer frame. Nonetheless, according to [7], spring-based designs proved unwieldy, cumbersome, and lacking in hermetic sealing. An alternative methodology was introduced within this research, entailing the attachment of a seismic mass directly onto the piezoelectret surface, foregoing additional housing. This streamlined configuration was heralded as a more sophisticated solution; however, the authors underscored the utilization of supplementary static force to fortify the structural integrity of the accelerometer.

Drawing upon the aforementioned accelerometer concept, a hermetically sealed design, as depicted in Figure 1, was introduced in [9] using piezoelectrets with an open-tubular channel structure. The illustration additionally shows the frequency response of the device within the range of 1 Hz to 1 kHz. This accelerometer was fabricated with a freestanding mass above the sensor and the noise response observed in the frequency range is significant due to this design configuration.

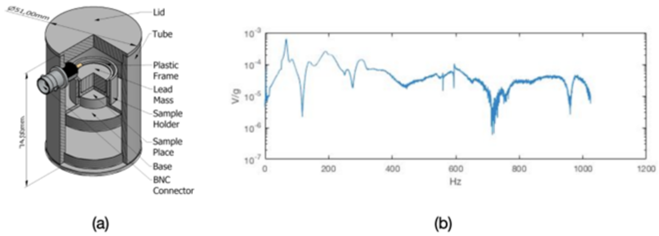

Fig. 1. (a) Schematic design of the piezoelectret accelerometer hermetically sealed. (b) Frequency response up to 1 kHz (as published [9]).

In pursuit of achieving a more consistent frequency response with this accelerometer configuration, enhancements have been implemented, based on a spring system [10]. The so-called evolution of the thermo-formed piezoelectret accelerometer, was tested in a custom-made electrodynamic vibration system, without any further standard characterization. Here, the performance of this accelerometer was verified on both systems, i.e. with a standard equipment setup and with the custom-made platform.

IV. EXPERIMENTAL DETAILS

This section outlines the thermo-formed piezoelectret accelerometer's construction, its difference from previous models, as well as the methodology and experimental setup employed to investigate and characterize it.

A. *Thermo-formed Piezoelectret Accelerometer (TFPA)*

The Thermo-Formed Piezoelectret Accelerometer (TFPA) presented in this study is shown in Figure 2, where (a) depicts a real photo of the device hermetic housing, (b) represents a schematic view of the accelerometer construction and (c) provides a front view of the thermo-formed piezoelectret prepared with open-tubular channels. The improved accelerometer design for a single detection axis 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 polytetrafluoroethylene (PTFE) sheath placed over a thermo-formed piezoelectret (sensor). An elastic component made of polyurethane foam with a density of 12 kg/m^3 is placed on top of the mass to provide mechanical support and restitution, while an aluminum guide vertically guides the mass. The employment of the foam on the top of the mass is considered a major advance, since it differs from the previously presented springs and should provide a noise reduction in the analyzed frequency range. To ensure mechanical resistance and electrical shielding, the transducer is connected to an Bayonet Neill-Concelman (BNC) connector and is enclosed in a cylindrical aluminum case measuring 74 mm in height and 51 mm in diameter.

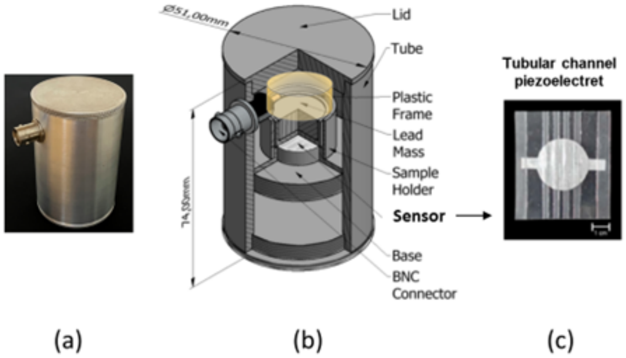

Fig. 2. (a) Photo of the TFPA prototype. (b) Exploded view of the TFPA internal structure. (c) Piezoelectret sensor, prepared with open tubular channels.

The thermo-formed piezoelectret was fabricated according to the lamination process described by Altafim et al. in [11], which provided a piezoelectret with four open-tubular channels with 1.5 mm width and an active area of 254.47 mm^2. The use of this particular piezoelectret was chosen due to the experience of the authors in fabricating such devices, the possibility to modulate its resonance frequencies with the variation of the geometric factors of the open-channels, the better temperature stability of the Teflon® fluoroethylenepropylene (FEP) in comparison with traditional employed polypropylene (PP), and previous understanding of the electromechanical behavior of this type of piezoelectret.

B. *Electrodynamic vibration setup*

The TFPA's frequency response, spanning from 50 Hz to 1 kHz, underwent meticulous characterization using the experimental setup delineated in Figure 3. This setup comprised an HP model 33120A function generator, calibrated to delineate the desired frequency spectrum. This generator interfaced with a robust Power Amplifier, from Brüel & Kjær (B&K) model 2707, tasked with a driving B&K shaker, model 4812, to induce controlled vibrations. Positioned atop this shaker, both a reference accelerometer (B&K model 8305) and the TFPA were affixed. The reference accelerometer's output was routed through a B&K conditioning amplifier Type 2635 while the TFPA was connected directly without further amplifications.

Simultaneously, the signals from both the accelerometer and the TFPA were captured using an oscilloscope (DSO-X 3024A model from Agilent Technologies), ensuring precise data synchronization and accuracy throughout the experimental procedure. It is important to mention that the shaker was calibrated with the reference accelerometer to drive a sinusoidal force of 9.81 N/mm^2.

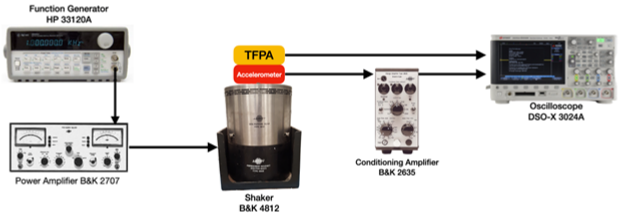

Fig. 3. Block diagram of the experimental setup set to monitor the frequency response of the TFPA.

The second electrodynamic vibration system consisted of a custom-made shaker 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. Calibration of this platform was performed with an ADXL327 accelerometer from Analog Devices, with an acceleration input range of ±2g, sensitivity of 420 mV/g and frequency response from 0.5 Hz to 1600 Hz, connected to an Arduino UNO® microcontroller board. A function generator from Tektronix (model AFG3022CA) was employed with driven signals and a Taramps TL-500 Class D Amplifier was used for the output signal amplification.

V. RESULTS AND DISCUSSIONS

The standard setup was previously calibrated with the reference accelerometer frequencies ranging from 50 Hz up to 3.2 kHz. The electrical signals captured by the oscilloscope are depicted in Figure 4, from which it is evident that the reference accelerometer exhibits a consistent linear sensitivity of approximately 314 mV/g across the entire frequency spectrum under evaluation. In contrast, the TFPA displays signals characterized by lower amplitudes and a distinct resonance peak at 100 Hz. Upon comparison with previously presented results from an accelerometer lacking polyurethane foam in Figure 1(b), it becomes apparent that the new configuration of the TFPA yields a significant reduction in the signal noise level. Additionally, the resonance phenomenon around 100 Hz is more pronounced. However, it is notable that the sensor's sensitivity experiences a strong decline at frequencies exceeding 300 Hz.

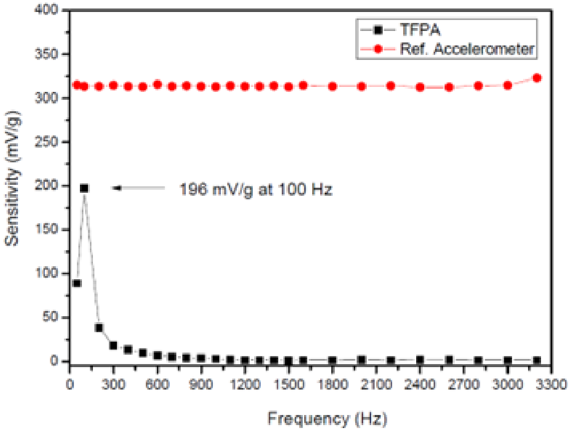

Fig. 4. Frequency response of the TFPA, with a resonance frequency at 100 Hz.

The output signal from the custom-made vibrating platform is presented in Figure 5 in comparison with the one obtained in the standard vibrating system. As can be seen, the clear resonance peak is also present in this setup, although a reduction in the accelerometer amplitude of approximately 44 mV/g is observed. It was also noticed that in this experiment, the sensitivity of the TFPA was kept reasonably constant around 30 mV/g, and the resonance peak was shifted to a higher frequency, i.e., 250 Hz.

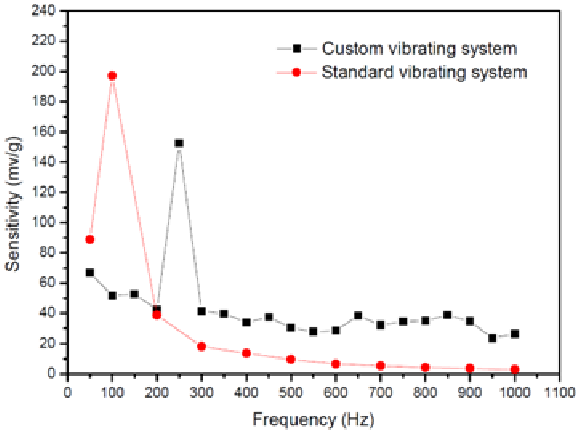

Fig. 5. Frequency response of the TFPA, investigated in the custom-made platform and with the standard setup, both results indicating a clear visible resonance.

Dynamic measurements performed on the same type of thermo-formed piezoelectrets for a frequency range from 2 Hz up to 60 Hz was reported in [12]. In such a study, a static force (16.9 kPa) was applied to the sensor superimposed with a sinusoidal stimulation of 5.6 kPa. From these, a linear response was observed over the entire frequency spectrum. The referenced work also investigated the sensor electrical response under different static forces, and it was demonstrated that with the increase of the static pressure, the piezoelectric response can be reduced by more than 80% (e.g. 30 kPa) compared to its value recorded at 10 kPa. In that work, this drastic reduction was attributed to the increase in the elastic modulus of the sample, therefore for higher effects a much lower static or dynamic force should be employed.

These reported experiments are similar in many ways to

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the TFPA characterization presented here. For instance, the previous static force was replaced here by a constant weight (lead mass) on the piezoelectret sensor while the previous superimposed sinusoidal force is pretty much the same regarding amplitude values. Now, considering that a 30 g weight was representing a static pressure of 1.157 kPa, it would be expected that the TFPA presented a high electrical response, however the superimposed dynamic pressure was calculated as being 38 kPa, which is higher than the 30 kPa, where the sensor loses more than 80% of it electromechanical response, thus explaining why the TFPA had such a low electrical response.

Nevertheless, in order to verify the relation between the inertial mass and the accelerometer sensitivity, masses with different weights, referenced here as M1, M2, were also employed in the electrodynamic vibration experiment. M1 with 6 g and M2 with 24 g, represented equivalent pressures of 0.231 kPa and 0.925 kPa, respectively. The results from this experiment, in the custom-made platform, are presented in Figure 6, where it can be noticed that the amplitude of the TFPA sensitivity varied according to inertial mass i.e. for M1, a sensitivity of approximately 11 mV/g was obtained, while with M2, this value was approximately 68 mV/g.

According to [13], depending on the piezoelectret design, an optimum sensitivity may be obtained when exposed to pressures below 1 kPa, meaning that the electromechanical response of these devices suffers an increasing effect with the increased pressure before it starts to drastically decrease. Thus, a similar behavior is observed here, where the accelerometer with M2 expected an optimum configuration.

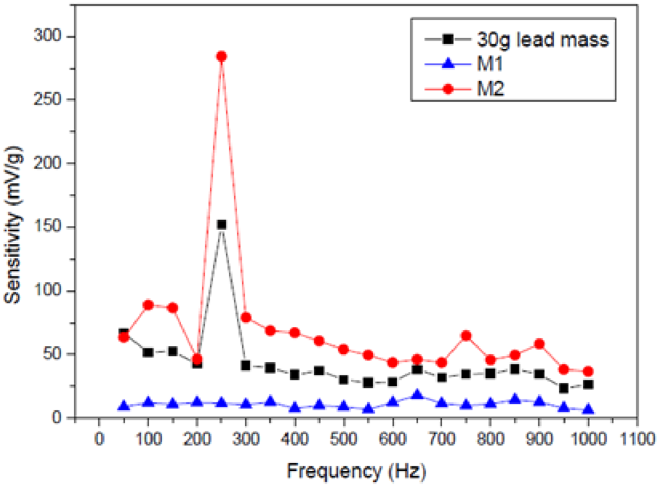

Fig. 6. Frequency response of the TFPA with different lead masses.

Regarding the resonance peaks, at 100 Hz and 250 Hz at the standard setup and the custom-made system, and the similarity of these experiments, one can understand that these resonances result from the electrodynamic vibration systems and not from the accelerometer. For reference, the resonance observed at 250 Hz was already reported during the characterization of the custom-made system in [10].

VI. CONCLUSION AND FUTURE WORK

In this study, an accelerometer utilizing thermo-formed piezoelectrets and implementing further enhancements was fabricated and subjected for testing under two different electrodynamic vibration conditions. The experimental setups, employed standard equipment, covered frequencies ranging from 50 Hz to 3.2 kHz and a custom-made system, which supported frequencies ranging from 50 Hz up to 1 kHz. Due to the last setup limitations, results were compared until 1 kHz. Our findings revealed a prominent resonance frequency at 100 Hz, with peak sensitivity reaching 196 mV/g, in the standard setup, and a resonance at 250 Hz with a peak sensitivity of 152 mV/g in the custom-made system. Beyond these resonances, the accelerometer maintained its signal response stable up to 1.0 kHz, albeit diminished amplitudes of 4.2 mV/g and 43 mV/g in the standard setup and the custom-made, respectively. The difference in sensitivity was attributed to a variation in the static load from both systems, which was further confirmed by changes in the lead mass of the accelerometer. The shift in the resonance peak was concluded to have originated from the mechanical vibrating systems. Further, the enhancements implemented in this accelerometer configuration mitigated the noise observed in prior iterations of similar piezoelectret accelerometers. This underscores the suitability of thermo-formed piezoelectret sensors for accelerometer applications, with the inclusion of a spring system proving advantageous in minimizing undesired mechanical vibrations. Building upon these results, a new design is currently being developed featuring reduced dimensions, addressing a concern echoed by other researchers in the field.

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