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Evaluating Temperature Influence on Low-Cost Microphone Response for 3D Printing Process Monitoring †

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Abstract: The 3D printing process deals with the manufacture of parts by adding layers of material onto a heated printing bed. Electret microphones are widely used, low-cost and precise measuring devices. However, its response is negatively affected by higher temperatures due to the Field Effect Transistor utilized in its construction. The Pencil Lead Break (PLB) method is a standardized artificial acoustic emission source utilized for the evaluation of sensors response. The present work aims to study the electret microphone response for 3D printing monitoring, and to evaluate the efficiency of a proposed housing to reduce the printing bed temperature's influence on the electret microphone's response. The microphone housing was 3D-printed utilizing ABS filament, and its geometry was designed with the purpose of separating the sensor from the heated bed and creating an acoustic shell. Then, PLB tests were performed, and the raw signal was collected from housed and non-housed microphones at 5MHz sampling frequency. The sensors were tested under three temperatures of the printer bed: at 25 °C (ambient), at 65 °C (operating temperature), and finally after the temperature of the table was naturally stabilized from 65 °C to 25 °C. The signals were investigated in the time and frequency domain. The results show that the housing impacts the microphone's response positively when operating at 25 °C, where the signals presented higher amplitudes in both domains. However, the response obtained by the housed sensor was considerably attenuated at 65 °C. Furthermore, the signals collected at 25 °C after exposing the housed microphone to heat demonstrate a "greenhouse effect", keeping the sensor at higher temperatures for an extended period. It can be concluded that the proposed housing did not succeed in reducing the temperature effects in the sensor's response. However, these effects were shown to be significant and the need for an alternative method to attenuate them is reinforced.

Keywords: 3D printing; process monitoring; signal processing; sensor's response evaluation; temperature; pencil lead break method

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1. Introduction

The Fused Deposition Modelling process, commonly referred as 3D printing process, deals with the manufacture of parts by adding layers of fused material onto a heated printing bed [1]. The material used for 3D printing is usually a type of thermoplastic filament [2]. Each type of filament requires different extruder and bed temperatures. For instance, the recommended bed temperature for the carbon fiber polylactic acid (CFPLA) filament ranges between 45–60 °C, as for the Acrylonitrile Butadiene Styrene (ABS) filament it ranges between 110–115 °C, and for the polylactic acid (PLA) filament is 65 °C [2,3].

The monitoring of the 3D printing process through digital processing of in-situ acquired acoustic signals has been a subject of many studies [4,5]. In the study developed by [4], the authors demonstrated that it was possible to diagnose different types of failures in parts manufactured by 3D printing through feature extraction and statistical analysis of signals acquired with an acoustic emission (AE) sensor placed on the 3D printer hot printing bed. On the other hand, in the study developed by [5], the authors demonstrated that it was possible to evaluate the first layer bond quality, a very important feature in the part adhesion and consequently final part quality, by means of digital processing of signals acquired by a piezoelectric polyvinylidene difluoride (PVDF) vibroacoustic sensor placed on the 3D printer hot printing bed.

On the other hand, electret microphones are widely used, low-cost and precise measuring devices [6]. There are some examples in literature of the electret microphone usage in the monitoring of manufacturing process studies [7,8]. However, the electret microphone response is negatively affected by higher temperatures due to the field effect transistor (FET) utilized in its construction [9].

Due to the importance of sensors in the *in-situ* monitoring of manufacturing processes, it is essential that their response is properly evaluated. Among the methods that verify the response of sensors found in literature, the Pencil Lead Break (PLB) method stands out [10]. The PLB is a standardized method settled as a replicable artificial source of acoustic emission [11]. Using a mechanical pencil, the graphite tip is firmly pressed against the surface of interest until breakage. At this moment, the stored stress is quickly released, generating microscopic movements on the surface of the structure, and releasing acoustic waves that propagate through the analyzed structure. The fast release of these waves acts like an impulse, enabling the frequency response of the sensor to be measured [10].

There are some studies found in literature that evaluates piezoelectric sensors response placed on a 3D printer heated printing bed when exposed to appropriate printing temperatures [10,12]. Among the studies, it was found that the elevated temperature in 3D printing has a negative effect on the piezoelectric sensor response.

The present work aims to study the electret microphone response for 3D printing monitoring, and to evaluate the efficiency of a proposed transducer housing to reduce the printing bed temperature's influence on the electret microphone's response.

2. Material and Methods

2.1. Experimental Setup

The present work is based on experimental procedures to investigate the influence of temperature variation on electret microphone response in 3D printing process monitoring. The tests were conducted in a 3D printer, manufacturer GTMax, model Graber i3. This model has a heated MK2B Dual Power PCB printing bed with NTC 100k thermistor type temperature sensor, which is in contact with a glass panel with the dimensions 200 × 200 × 3 mm.

Two 3 mm diameter electret microphones were used in this study. One of the microphones were fixed to the printing bed through multiple layers of a silicon-based adhesive, in the upper right part of the heated printed bed as seen in Figure 1a. The second microphone were housed in an ABS 3D-printed housing. The housing was fabricated with the geometry seen in Figure 1c, which was designed with the purpose of separating the sensor from the heated bed and creating an acoustic shell. The housed microphone, as seen in Figure 1b, was then fixed to the printing bed through multiple layers of a silicon-based adhesive, in the lower right part of the heated printed bed as seen in Figure 1a.

A ScopeCorder measuring instrument, model DL850, from Yokogawa, was used for data collection and storage. The graphite used in the PLB method had a 2H hardness and measured 0.5 mm in diameter. The temperature control of the glass printing bed was performed by the printer heating system and controlled through Repetier-Host® software. The ambient temperature of 25 °C was considered as baseline.

In the tests, three pencil lead breaks were performed for each selected temperature: 25° (baseline temperature), 65 °C (PLA recommended printing bed temperature), and, after turning off the bed's heating system and waiting for the bed to cool off, again at 25 °C. The PLB tests were performed maintaining a 45° angle between the graphite and the table. The graphite length and the mechanical pencil angle were established in accordance with ASTM E976. The ScopeCorder stored the acoustic signals, collected at a sampling rate of 5 MHz, and the data were later digitally processed with MATLAB® software.

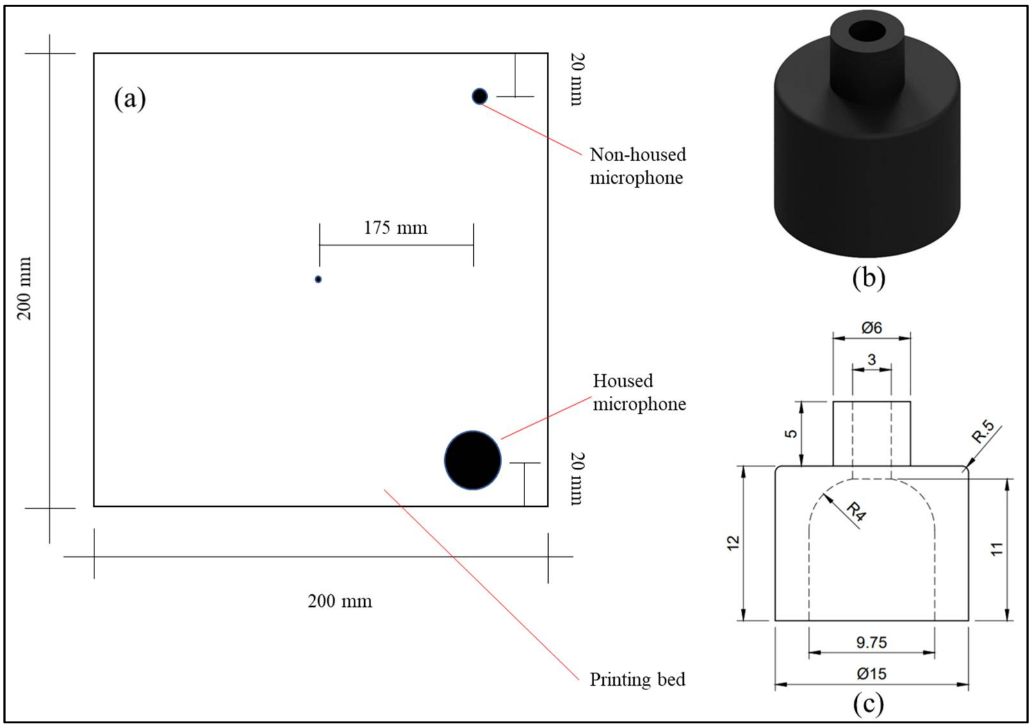

Figure 1. Setup Schematic. (**a**) Top view, (**b**) Housed microphone, (**c**) Housing diagram.

2.2. Signal Processing

The signals obtained from each microphone were investigated in the time and frequency domain. In each analysis, the temperature effects were compared between evaluated temperatures for each microphone, and between microphones.

In the time domain, an amplitude behavior analysis between the evaluated temperatures was conducted. For each evaluated temperature, only one of the obtained PLB repetitions was chosen to conduct the analysis. This is due to the fact that the three repetitions for each conducted test presented very close amplitude behaviors.

In the frequency domain, the average frequency spectrum was calculated from the three signals obtained for each temperature. From the averaged frequency spectrum signal, an amplitude variation study was conducted similarly to the one used by [10], between the evaluated temperatures.

3. Results and Discussion

3.1. Raw Signal Analysis

The signals collected from the PLB tests are shown in Figure 2. As shown in Figure 2a,d, at room temperature, it can be observed that the housing enhances the sensibility of the microphone. increasing its voltage output. This occurs due to the housing acting as an acoustic shell. It is also worth noting, however, that the signals share a similar, yet different, shape, where the main difference is a voltage peak in Figure 2d that occurs close to 25 ms, whereas the same cannot be seen in Figure 2a.

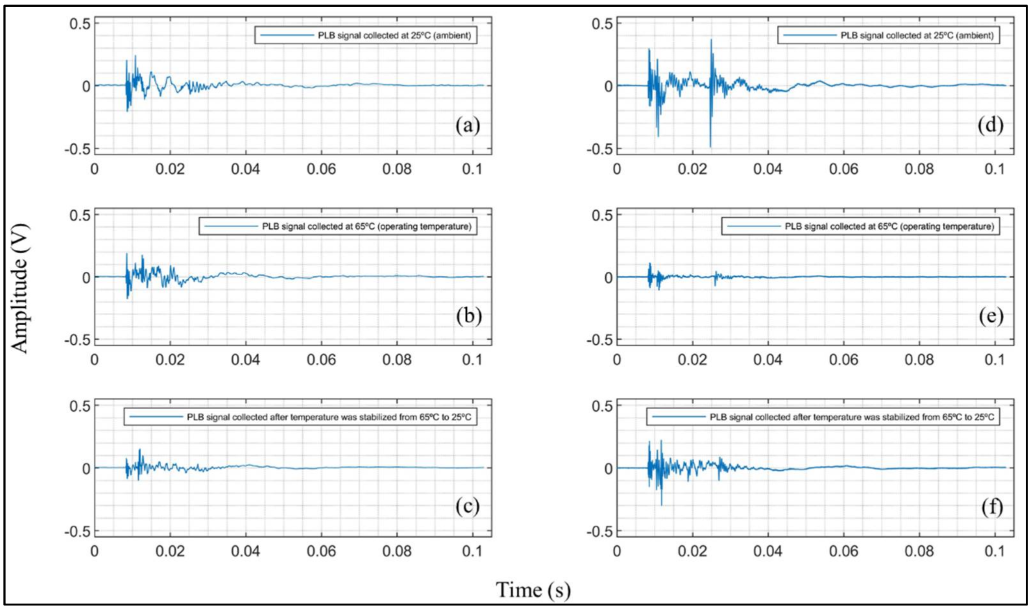

Figure 2. Raw PLB signal. (**a**) Non-housed microphone at 25 °C, (**b**) Non-housed microphone at 65 °C, (**c**) Non-housed microphone at 25 °C after process, (**d**) Housed microphone at 25 °C, (**e**) Housed microphone at 65 °C, (**f**) Housed microphone at 25 °C after process.

The effect of the operating temperature on the response of the sensors can observed in Figure 2b,e, where amplitudes for both where significantly attenuated in comparison to Figure 2a,d. Nevertheless, it can be pointed out that this effect is more prominent in the housed microphone. In Figure 2e features of the PLB test are almost indistinguishable from background noise, making it difficult to analyze, especially compared to its non-housed counterpart. This reveals that the housing had the opposite effect from what was expected. Lastly, contrasting Figure 2a,b it can be observed that higher temperature causes the signal of the non-housed microphone to become lower in amplitude. This result is closely related to those obtained by [9].

It is observed in Figure 2c,f that even when the temperature returns to 25 °C the performance of the sensors is not the same as previously seen. Looking at Figure 2c specifically, the amplitudes are even lower than the ones shown in Figure 2b. It can be inferred that the temperature effects linger for some time after exposure to heat and can even worsen with time. Figure 2f reveals that the housed microphone recovered better than the non-housed one in relation to amplitude, even if the signal is still more attenuated than the one in Figure 2d. Analyzing its shape, however, it shows there are significant differences in comparison to the other signals, particularly between 15 ms and 35 ms where there are barely some similarities between Figure 2d,f.

The effects on the housed microphone present in Figure 2e can be explained by the geometry of the housing creating a "greenhouse" type effect, which maintains the sensor at higher temperatures for an extended period. This defeats the purpose of the housing from keeping the sensor at a lower temperature and influences the results negatively instead. As the sensor will be most useful at the operating temperature of the 3D-printer, this effect is very significant and further analyzes should be considered. However, the housing was shown to be capable of attenuating the long-term effects of temperature, as seen in Figure 2f. This is due to the separation between the sensor and the heated bed found on the housed microphone, preserving certain integrity of the electret microphone.

3.2. Frequency Spectrum Analysis

The mean frequency spectra for both housed and non-housed microphones are presented in Figure 3 for each evaluated bed temperature. The frequency range presented in Figure 3 was adopted due to fact that the observed amplitude after 8 kHz presented very low values.

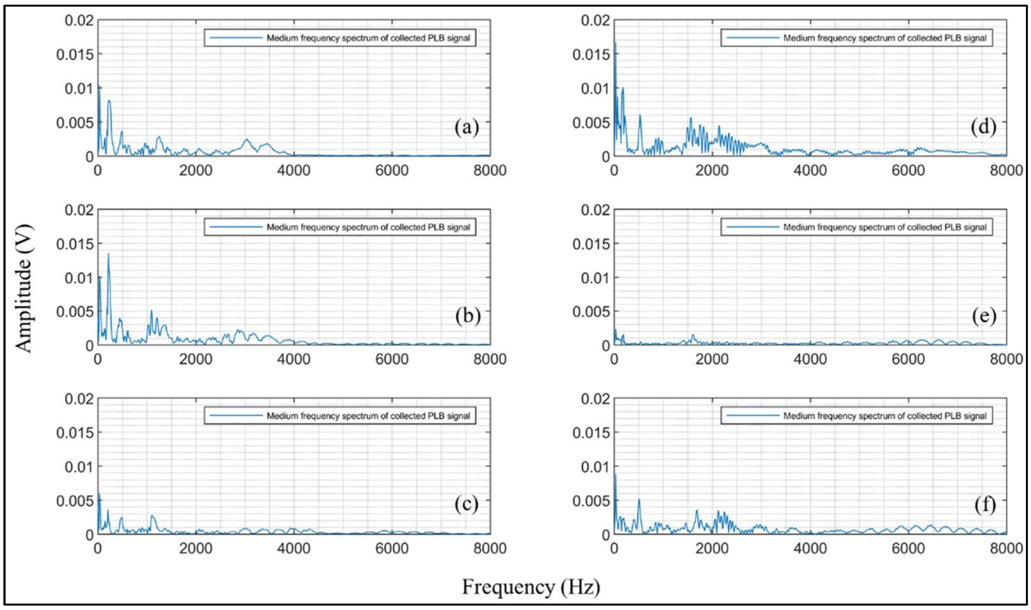

Figure 3. Mean Frequency Spectra. (**a**) Non-housed microphone at 25 °C, (**b**) Non-housed microphone at 65 °C, (**c**) Non-housed microphone at 25 °C after process, (**d**) Housed microphone at 25 °C, (**e**) Housed microphone at 65 °C, (**f**) Housed microphone at 25 °C after process.

Firstly, the mean spectra for the baseline temperature, presented in Figure 3d for the housed microphone, shows overall more amplitude sensibility than its non-housed counterpart, presented in Figure 3a. This behavior can be easily spotted when observing the amplitude values for the frequency ranges between 0 Hz to 500 Hz and 1.5 kHz to 3 kHz. This improvement seen in the amplitude sensibility on the housed microphone is attributed to the acoustic shell generated by the housing.

On the other hand, the mean spectra for the printing process temperature, presented in Figure 3e for the housed microphone, shows significantly lower amplitude sensibility than its non-housed counterpart, presented in Figure 3b. This behavior can be easily spotted through all the frequency spectra. The deterioration seen in the amplitude sensibility on the housed microphone is attributed to the greenhouse-type effect generated inside the acoustic shell. Due to the heating in the bed, the air inside the housing absorbs heats, which does not dissipate easily due to the heat transfer capabilities of the ABS housing.

Lastly, the mean spectra for the housed microphone, presented in Figure 3f shows higher amplitude sensibility than its non-housed counterpart, as presented in Figure 3c. This behavior can be spotted through all the frequency spectra. The deterioration seen in the non-housed microphone sensibility is attributed to the direct contact of the sensor with the hot printing bed, which damaged the electret microphone. In contrast, the sensibility deterioration seen in the housed microphone, which is easily spotted through all the frequency spectra when comparing the amplitude values to the baseline spectra, as presented in Figure 3d, is considerable lower than its non-housed counterpart, as seen in in Figure 3c. This difference is attributed to the fact that the housed microphone did not have direct contact with the hot printing bed, which alleviated the damages on the electret microphone.

4. Conclusions

In conclusion, the transducer housing failed in its main objective of reducing the temperature effects in the microphone's response, even having the opposite result in some cases, where it further attenuated the signal. This happened due to an unforeseen "greenhouse effect" happening inside the housing. Additionally, it was also shown that the change in the microphone's behavior due to the printing bed's operating temperature can last for some time after exposure to heat and even worsen in that period.

However, the housing was shown to be capable of reducing these long-term effects. Thus, considering the operating temperature of a 3D-printer greatly affects the electret microphone's response, the use of this transducer in 3D process monitoring is not possible without a method to reduce the negative temperature effects. Therefore, the need for improvement of the transducer housing design or other alternatives to attenuate the temperature effects is reinforced.

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