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Study of the Temperature Influence on Electret Microphone in Monitoring the Fused Deposition Modeling †

Thiago Glissoi Lopes *, Paulo Roberto Aguiar, Cristiano Soares Junior, Reinaldo Götz de Oliveira Junior, Paulo Monteiro Carvalho Monson and Gabriel Augusto David *

Faculty of Engineering, Electrical Engineering Department, Sao Paulo State University—UNESP, Bauru 17033-360, Sao Paulo, Brazil; paulo.aguiar@unesp.br (P.R.A.); cristiano.soares@unesp.br (C.S.J.); reinaldo.gotz@unesp.br (R.G.d.O.J.); paulo.monson@unesp.br (P.M.C.M.)

* Correspondence: thiago.glissoi@unesp.br (T.G.L.); gabriel.david@unesp.br (G.A.D.)

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Abstract: The evaluation of the response of sensors fixed to the print bed in the Fused Filament Fabrication (FFF) process has been the subject of recent studies due to the increasing use of the FFF process. Many of these studies focus on topics related to monitoring the FFF process through the signals collected by sensors. Recently, some works employing piezoelectric diaphragm and electret microphone can be found in monitoring the FFF process, but the influence of the transducer response due to the variation of temperature has not been addressed. Thus, this work presents a study of the response of a low-cost electret microphone attached to the print bed under different temperature values. A 3D printer with Polylactic Acid (PLA) filament was used in the tests, which consisted in applying the Pencil Lead Break method (PLB on the heated print bed at temperature values ranging from 25 °C to 65 °C. The acoustic waves generated by the tests were captured by the electret microphone attached near the breakage point, and the signals were sampled using an oscilloscope at a frequency of 2 MHz. The signals were processed in the time and frequency domains, followed by comparative analyses between the signals obtained for different temperature values. The results showed that it was not possible to determine a single temperature value at which the response of the electret microphone starts to undergo significant changes, but rather there is inconsistent change in the transducer's response across all frequency bands, indicating that the influence of temperature takes place in a complex way as frequency varies. This complexity is further evidenced by the nonlinear behavior of RMSD values for the evaluated temperatures. Thus, the results can be helpful to those who use this type of transducer attached to the printing bed for monitoring purpose.

Keywords: electret microphone; temperature influence; Fused Filament Fabrication; monitoring; pencil lead breakage method

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1. Introduction

The Fused Filament Fabrication (FFF) manufacturing process, also known as 3D printing, consists of adding successive layers of melted filament on a heated bed [1]. The filaments used in the FFF process can be made of different types of materials such as Acrylonitrile Butadiene Styrene (ABS), Polyethylene Terephthalate Glycol (PETG), Polylactic Acid (PLA), Copoliester TRITAN, among others [2]. However, certain printer models are not capable of manufacturing parts with all types of materials, as these printers do not have the necessary heated print chambers for certain material types.

The temperature at which the print bed should be heated varies depending on the material used in the FFF process and is usually defined in a range of values. One of the reasons for defining a range of temperature values is the relationship with the characteristics of the material itself, which allows, in some cases, manufacturing under different print bed temperature values. The temperature range based on the material can be quite broad, as is the case with PLA, which can be manufactured at print bed temperatures ranging from 0 °C to 60 °C [3]. This allows even printers without heated print chambers to manufacture parts with PLA filament, since the print bed temperature range for this material includes ambient temperature values.

Currently, there are several studies aimed at monitoring the FFF process using sensors located on the print bed. Notably, the use of acoustic emission sensors can be observed in the works developed by [4] and [5]. Additionally, a literature review reveals works proposing the use of low-cost piezoelectric transducers for monitoring the FFF process as seen in the works of [6], and the use of low-cost electret microphone presented by the authors of [7] and [8]. However, it is known that elevated temperature values, such as those that can be reached on the print bed, have various effects on sensor's responses [9]. In the study referenced in [10], the impact of temperature on the mechanical-acoustic properties of condenser microphones was analyzed. The results reveal that temperature significantly influences the resonance of the microphone's membrane. It was discovered that certain microphones and preamplifiers function at temperatures below 100 K, a previously unobserved phenomenon.

One of the methods used to evaluate sensor responses under controlled conditions is the Hsu-Nielsen method, also known as the Pencil Lead Break (PLB) method [11]. In the PLB method, an artificial source of acoustic emission is generated by breaking a graphite pencil lead with specific hardness, dimensions, and angle defined by the ASTM E976-10 standard [12]. The obtained signal can then be processed and analyzed for its frequency components, as conducted in the study by [9].

Literature review reveals studies aimed at evaluating the influence of print bed temperature on sensor responses used for monitoring the FFF process through the PLB method [13,14]. However, no study was found that covered multiple temperature values within a specific range to determine the temperature value at which the sensor response would undergo significant changes.

Thus, the primary objective of this study is to investigate the influence of print bed temperature on the response of a low-cost electret microphone affixed to the print bed for FFF process monitoring purposes. The PLB method was employed, conducting pencil lead break tests at 5 °C intervals within the temperature range suitable for PLA filament printing, ranging from 25 °C (ambient temperature) to 65 °C. The aim is to determine at which temperature value the response of the low-cost sensor starts to undergo significant changes, following the frequency band analysis method used by [9] to determine if such influence on the response is limited to a specific frequency band of the sensor's response.

2. Materials and Methods

The following section will present the test bench and the digital signal processing methodology employed to achieve the objectives of this study.

2.1. Test Bench

To accomplish the proposed objectives in this study, tests were conducted using a Cartesian 3D printer model Graber i3, as shown in Figure 1a. The print bed of the Graber i3 has dimensions of 200 × 200 mm and a heating system that can reach up to 70 °C, but it does not have a heated chamber for printing. To accommodate this restriction, the present study evaluated temperatures ranging from 25 °C to 65 °C, the recommended range for PLA filament printing, using the PLB method. It worth mentioning that the acoustic emission sensor with a white color base showed in Figure 1 was not used in this work.

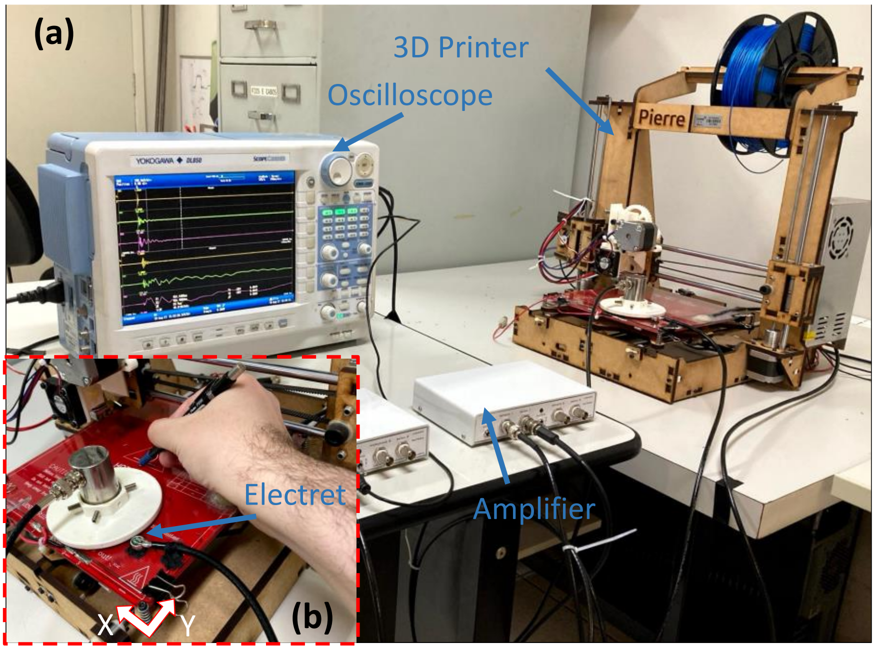

Figure 1. Test bench. (**a**) Complete test bench, (**b**) PLB method representation.

The pencil lead break tests were conducted at the print bed's center, adjusting the temperature in 5 °C steps and allowing a minute for stabilization. A mechanical pencil with a rubber hose at the tip ensured a 45-degree angle with the print bed, and therefore avoided contact of the metal cone cap and led sleeve of the pencil with the surface under test. The 2H-hardness, 0.5 mm diameter graphite is shown in Figure 1b. The print bed's temperature was computer-controlled via USB using Repetier-host® software. To ensure accuracy, three test repetitions were carried out for each temperature.

An electret microphone with dimensions of 9.7 × 4.5 mm was affixed at 37 × 50 mm coordinates on the print bed using silicone adhesive. It was directly attached without heat isolation and connected to a transimpedance amplifier, shown in Figure 1a. The microphone's signals were captured using a Yokogawa® DL 850 oscilloscope at 2 MHz sampling frequency, chosen for comprehensive signal analysis. Data was stored in the oscilloscope's hard drive right after data acquisition, and then downloaded for processing in MATLAB®.

2.2. Signal Processing

Initially, the data downloaded from the oscilloscope were converted from binary format into MATLAB® format to be digitally processed in the software. In order to evaluate the temperature's influence on the electret microphone's response, analysis focused on the frequency spectra were conducted. Firstly, Welch's power spectral density estimates for each PLB signal were computed through the MATLAB's pwelch function, using a Hamming window of 4096 data points. Subsequently, the spectral averages for each temperature condition were calculated from the three repetitions.

From the spectra results, the absolute values of the differences between each temperature's average spectra in relation to the average spectrum baseline of 25 °C for each frequency value were computed. Subsequently, the Root Mean Square Deviation (RMSD) was obtained with the purpose of scrutinizing the amplitude variations between each temperature's average spectrum in relation to the 25 °C average spectrum baseline. The RMSD values were computed in frequency steps of 1 kHz, spanning a frequency range of 20 Hz to 20 kHz, in alignment with the methodology proposed in the study of [9].

3. Results and Discussion

The absolute value of spectral differences at each temperature compared to the 25 °C baseline is presented in Figure 2. A preliminary analysis reveals significant differences between the spectra of all evaluated temperatures compared to the 25 °C spectrum across the entire frequency range analyzed. However, greater differences in absolute values are noted for certain temperatures within specific frequency bands, notably 2 kHz to 3 kHz and 4 kHz to 5 kHz. These observations corroborate the findings of [14]. Additionally, our analysis further demonstrates that the effect of bed temperature on the electret microphone's response is not merely prevalent across most of the device's response spectra, but it can rather show an increasing trend in signal amplitude within a specific frequency band, such as that observed from 2 kHz to 3 kHz.

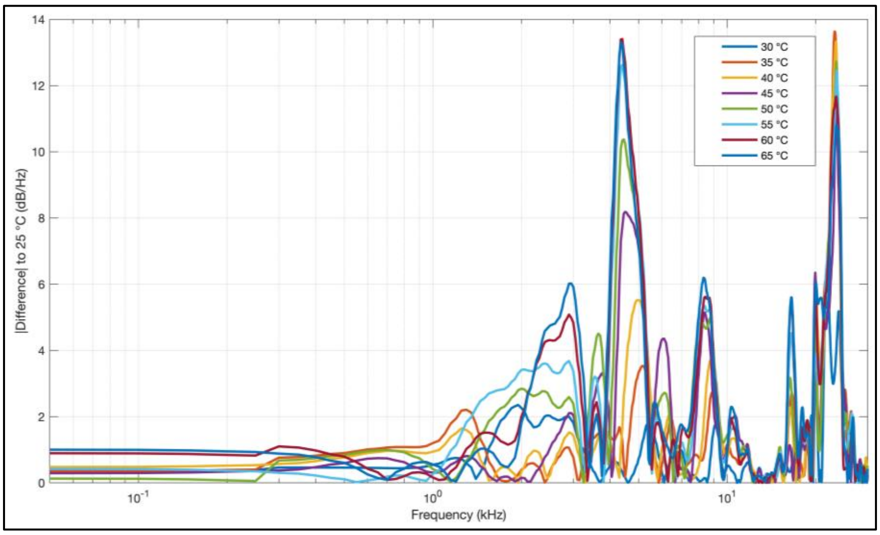

Figure 2. Absolute value of spectral differences at each temperature compared to the 25 °C baseline for each frequency.

The RMSD results of spectral differences at each temperature, compared to the 25 °C baseline, are shown in Figure 3. An initial analysis, focused on assessing the RMSD values for each temperature separately, reveals noticeable differences within each 1-kHz frequency band. For instance, RMSD values at 35 °C generally increase compared to those at 30 °C, particularly in the frequency bands of 4.02 kHz to 5.02 kHz and 17.02 kHz to 18.02 kHz. However, this upward trend is not consistent across all frequency bands at 35 °C, as seen in the bands from 2.02 kHz to 3.02 kHz and 19.02 kHz to 20.02 kHz.

A follow-up analysis, looking at the RMSD values for each frequency band individually, also shows significant variations in how temperature affects the electret microphone's response. Specifically, the frequency bands from 2.02 kHz to 3.02 kHz and 4.02 kHz to 5.02 kHz display an increasing, yet non-linear, effect of temperature on RMSD values. This behavior is not uniform and diverges in some frequency bands, such as from 9.02 kHz to 10.02 kHz.

These findings suggest that temperature variations influence the electret microphone's response in a complex way, differing across various frequency bands.

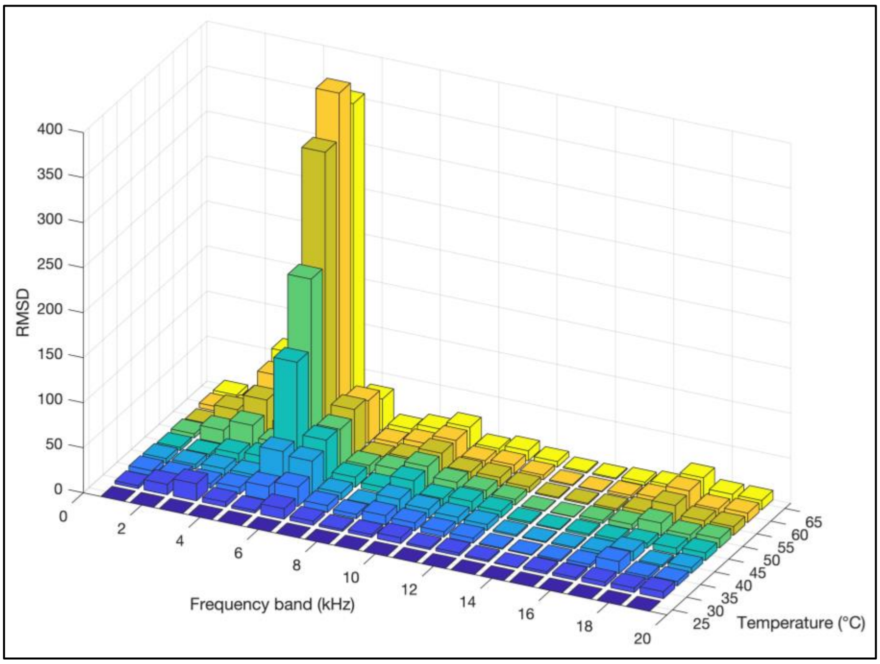

Figure 3. RMSD Values for Each Temperature Relative to the 25 °C Baseline, Evaluated Across Incremental 1 kHz Frequency Bands from 20 Hz to 20 kHz.

4. Conclusions

This study was designed with the primary objective of investigating how the print bed temperature influences the response of a low-cost electret microphone that is affixed to the print bed for monitoring the FFF process. Utilizing the PLB method, we conducted tests at 5 °C intervals in the temperature range suitable for PLA filament printing, from 25 °C to 65 °C. The goal was to pinpoint the temperature at which the sensor's response begins to manifest significant changes and to evaluate whether these changes are confined to specific frequency bands.

The data generated from our experiments provide mixed results. The absolute differences between each spectrum and baseline and RMSD values, presented in Figure 2 and Figure 3, respectively, do not yield a singular frequency range at which the sensor's response undergoes a general change due to temperature variation. Instead, our analysis reveals that the impact of temperature on the microphone's response varies across different frequency bands. Notably, distinct patterns of change are observed in the bands from 2 kHz to 3 kHz and 4 kHz to 5 kHz.

In addition, it was noted there is not a consistent change in the transducer's response across all frequency bands, indicating that the influence of temperature is complex and depends on the specific frequency band under consideration. This complexity is further evidenced by the non-linear behavior of RMSD values for the evaluated temperatures, as it can be seen, for instance, in the bands from 2.02 kHz to 3.02 kHz and 8.02 kHz to 9.02 kHz.

Finally, the study clearly shows the change in the transducer's response according to the temperature variation and frequency, and the results can be useful when utilizing this type of transducer attached to the printing bed for monitoring purpose. Future research may explore alternative signal processing techniques, delve deeper into the intricacies of how specific frequencies are affected by temperature, and broaden the scope to temperature ranges.

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