Damage Sensitivity Study in 3D-Printed PLA of Different Infill Densities Using the Electromechanical Impedance Method

SHISHIR KUMAR SINGH, MOHAMMAD ALI FAKIH, SAMIR MUSTAPHA and PAWEL H. MALINOWSKI

ABSTRACT

In many industries, complicated parts have been produced using additive manufacturing (AM) technology. The values of such products can significantly increase if they have fault detection and load sensing features. Modern industries, especially those with crucial applications, like aerospace and civil construction, have recently begun incorporating AM components into their designs. This necessitates the creation of precise and trustworthy methods for assessing and tracking the structural integrity of such components. Based on the local structural reaction in the high-frequency region, the Electromechanical Impedance (EMI) approach is frequently used to assess the health condition of lightweight structures with minute damage. This study investigates the sensitivity of the EMI technique to potential damage in 3D-printed polylactic acid (PLA) plates with different infill densities. Five healthy and five damaged PLA plates were printed using fused deposition modeling (FDM) with infill densities ranging from 20% to 100% at a step of 20% for the experimental study. Piezoelectric wafers (PZTs) bonded to one side of the plates were used for the measurements. Damage was mimicked by placing two strong magnets on either side of the healthy plates, and several EMI measurements were taken for the healthy states while changing the distance of the magnets away from the PZT. The conductance (G) and resistance (R) EMI measurements were fused together before the root mean square deviation (RMSD) damage index was used for the damage-sensitivity study. It was found that damage-sensitivity distance decreases with the decrease in the infill density. Further, damage-detection thresholding was investigated when using multiple sensors from identical healthy and damaged plates with printed built-in damage. The damage was detected for all the examined infill densities by the PZT positioned at a center distance of 102.5 mm from the damage.

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INTRODUCTION

Additive manufacturing (AM) produces complex lightweight structures with several applications including aerospace, oil and gas, automotive etc. The lack of appropriate non-destructive evaluation (NDE) techniques to certify the high-quality end products of AM have seen as a major barrier to further industrialization [1, 2]. Electromechanical Impedance (EMI) is one of the promising NDE methods to detect structural abnormality in metals and composites. The EMI method employs high frequencies range in assessing the local structural response. In this method, the piezoelectric PZT (Lead Zirconate Titanate) transducers work as actuators, and sensors are used for diagnostic purposes [3, 4]. Scheyer et al. recently incorporated sensors within AM structures to monitor the structures' health. The polylactic acid specimen was printed with the Fused Deposition model to track health performance based on simulated mass and drilled holes [5]. The EMI method is a significant technique that allows damage localization of concrete structures, composite structures, etc. based on the comparative study of the spectrum for pristine healthy and damaged structures. The RMSD index is typically used to detect abnormalities in the structure under electromechanical impedance (EMI) method application [1, 2]. Shishir et al. performed comparative sensitivity of various actuators to the presence of damage in additively produced (AM) polymer structures. For the research, a horizontally laid-up acrylonitrile butadiene styrene (ABS) plate was used, and two PZTs and one MFC actuator were attached [6]. Zhu et al. coupled EMI theoretical model and presented a coupled signature extraction methodology for circular PZT [7]. Jin et al. used non-destructive ultrasonic imaging to determine the infill density of ABS. Using effective density pictures, different infill densities in 3D printed things were detected and validated using computed values [8]. Recently, Shishir et al. combined the information of the sensor's resistance (R) and conductance (G) in the frequency domain and data fusion-based fused signature (F) is realized by multiplication of G and R [9]. Additionally, deep learning utilizes the classification of the 3D-printed M3-X plate as healthy, damaged, and repaired damage using fused EMI data [10]. A combined C-index-based damage index was also developed fusing G and R in the selected frequency range [11].

This paper illustrates a comparative study of fused signature (F) of different infilled densities patterns of the 3D-printed PLA structure. The study investigates the region of sensitivity for the added magnetic mass simulated on the surface of the plate. This would establish the relationship between the damage sensitivity and the variation in the infill density. Subsequently, built-in damage identification in identical structures is investigated using several threshold baselines of the healthy structures. The paper's structural framework includes the design of the experimental setup, results, and discussion of the printed PLA plates.

EXPERIMENTAL SETUP

Additively manufactured plates of dimension $325 \times 235 \times 4\ mm^3$ were used in the current study. The first set is composed of five intact plates manufactured from poly (lactic acid) (PLA) with different infill densities. The plates were printed using fused deposition modeling (FDM) with 20%, 40%, 60%, 80%, and 100% infill densities,

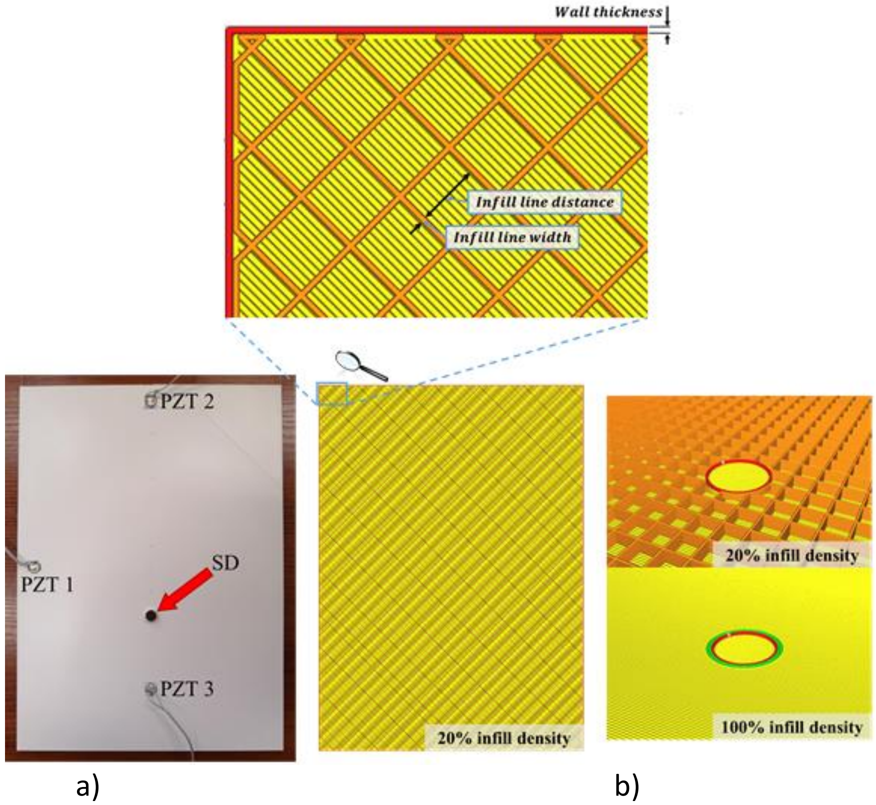


Figure 1. Example (a) One of the used 3D-printed PLA plates with simulated damage; and (b) a schematic of the plate's cross-sectional view showing its internal infill pattern.

respectively. The second set of built-in disc-shaped defects including a void of 10 mm diameter and 0.6-mm height was printed within the center of the damage plates for 20%, 40%, 60%, 80%, and 100% infill densities. Figure 1a shows one of the studied samples with a preview of its internal structure. Figure 1b shows detailed previews of the internal structure of the plates having an infill density lower than 100% (not fully solid) and also illustrates the internal structure of the printed defect's region of the 20%- and 100%-infill-density plates. Using cyanoacrylate glue, the piezo-actuators adhere to each PLA sample. One volt is the excitation voltage chosen for the EMI tests. An average of 50 measurements was taken during each test to improve the signal-to-noise ratio.

RESULTS AND DISCUSSIONS

Several healthy and damaged EMI measurements for the PZT3 were taken in the 1 kHz to 500 kHz frequency range for each of the five available PLA plates. A good deviation of the healthy and damaged conditions of the plate is found in the frequency range of 10 kHz to 250 kHz. The $F_{rescaled}$ plot with respect to the frequency for the healthy (hs) and damage conditions are given in Figure 2**.** The damage conditions were measured by adding magnets of dimension 20 mm in diameter and weight of 33.84 grams on both sides of the plate for the sensitivity study of various infilled PLA plates. The added mass was moved away from the transducer at the following distances: 10 mm, 40 mm, 70 mm, 100 mm, and 130 mm. Root mean square deviation

(RMSD) is used as a damage metric in the study of structural damages [3]. In the fusion of signatures, the data fusion technique uses parameter F that combines information of R and G for robust detection of low levels of damage. Variable-level data fusion (F=G×R) is done using the multiplication of the G and R. The RMSD damage index of $F_{rescaled}$ data was calculated to study the damage sensitivity. The acquired EMI F signals of the various health conditions were rescaled in the 20 kHz to 250 kHz interval, as expressed by equation1.

$$F_{rescaled} = F \times f_{max}/f \tag{1}$$

Where f is the frequency of the band and f_{max} is the maximum value in the frequency band.

The damage index of the 100%, 80%, 60%, 40%, and 20% infilled PLA plates for added mass moving away from the actuators are shown in Figure 3. From Figure 3, it can see that the infill density damage sensitivity for differentiating the distance-based damage severity towards the added mass is decreasing from solid to empty PLA plate. The highest sensitivity is shown by the 100% and 80 % infilled damaged plate and the lowest sensitivity is for the 20% infilled plate. The damage sensitivity for the 20% infilled plate is able to detect damage at a distance of 70 mm from the actuator. The PLA plate of 60% and 40% infilled plate has shown damage sensitivity at a distance of 130 mm. The 100% and 80% infilled plates also showed damage sensitivity for the distance of 130 mm. The solid plate shows a higher damage detection capability towards damage using $F_{rescaled}$ in the selected frequency range since having a higher value of the RMSD index of each damage case compare to the healthy state.

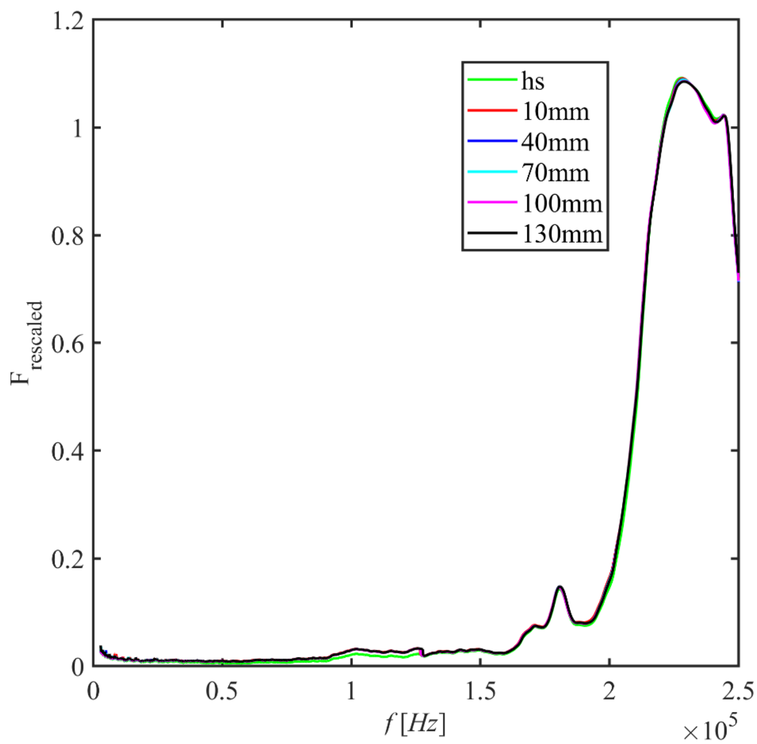
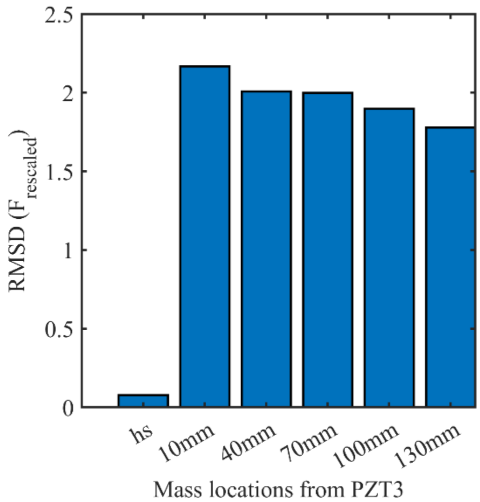
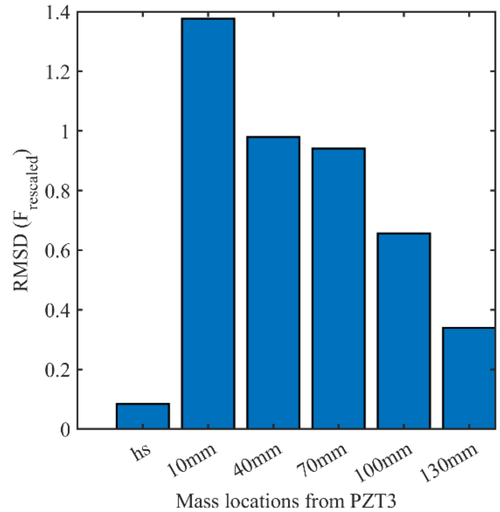


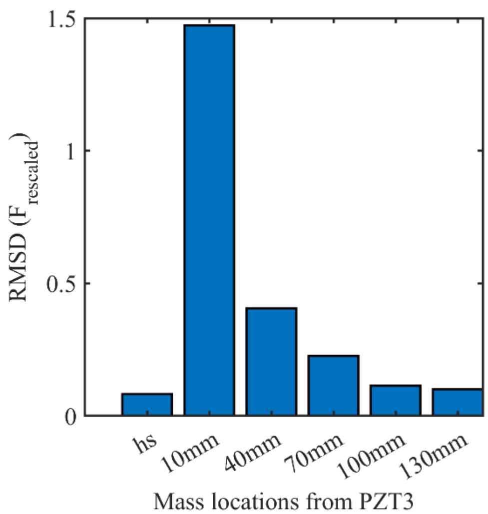
Figure 2. Fused data, $F_{rescaled}$ plot for 3D-printed 100% infill PLA plates with simulated damage.



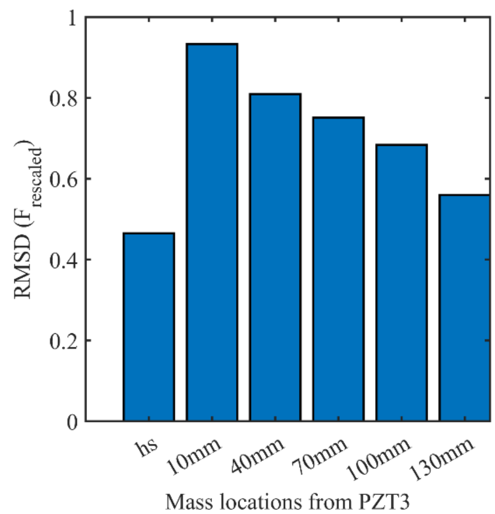
(a) 100%-infill plate.



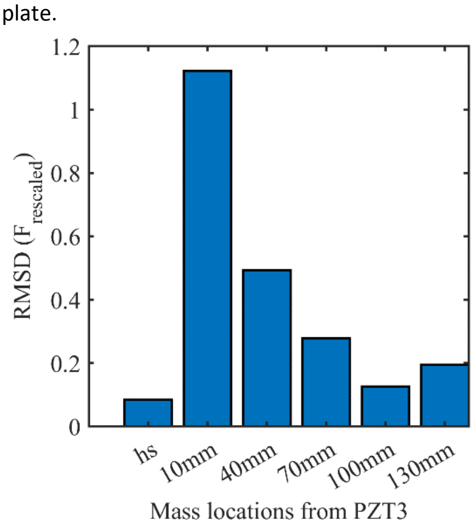
(b) 80%-infill plate.



(c) 60%-infill plate.

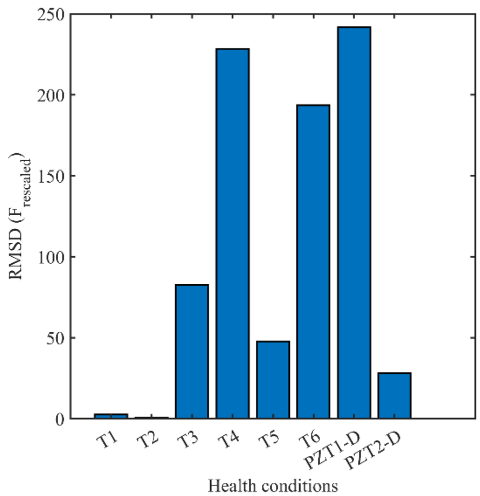


(d) 40%-infill plate.

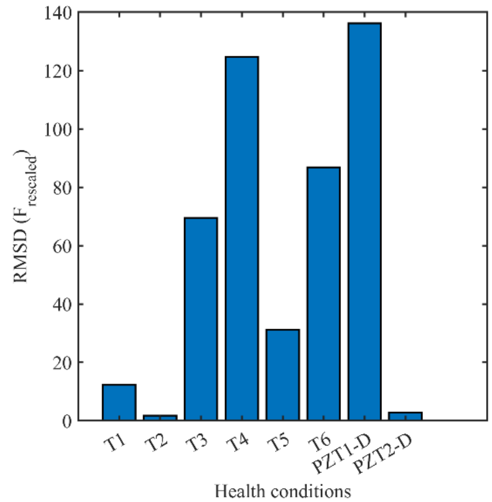


(e) 20%-infill plate.

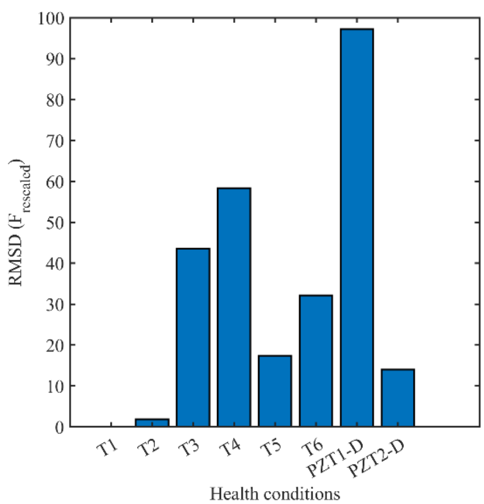
Figure 3. Damage sensitivity study of PZT3 using added mass with simulated damage.



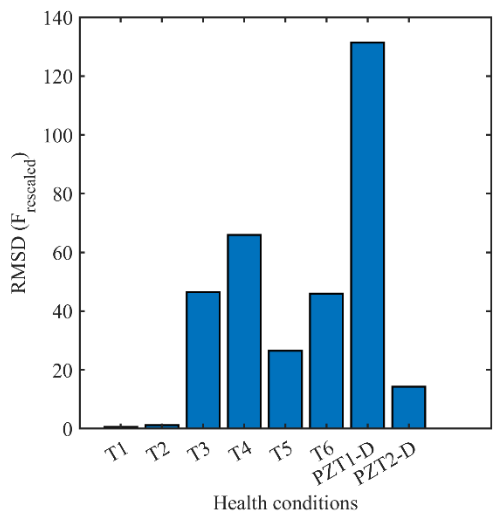
(a) 100%-infill plate.



(b) 80%-infill plate.



(c) 40%-infill plate.



(d) 20%-infill plate.

Figure 4. Damage study of built-in damage using PZT1 and PZT2 of the 3D-printed PLA plates.

TABLE I. SYMBOLS WITH THE EXPLANATIONS

Symbols	Descriptions
T1	RMSD of PZT1 for the repeated measurements
T2	RMSD of PZT2 for the repeated measurements
T3	RMSD of PZT1 w.r.t PZT2
T4	RMSD of PZT2 w.r.t PZT1
E1	|RMSD of PZT1 w.r.t PZT3 − RMSD of PZT2 w.r.t PZT3|
T5	T3-E1
T6	T4-E1
PZT1-D	RMSD of damage plate w.r.t healthy plate for PZT1 using $F_{rescaled}$ data
PZT2-D	RMSD of damage plate w.r.t healthy plate for PZT2 using $F_{rescaled}$ data

The preliminary findings show that the EMI approach can be used to examine the health of similar AM polymers and distinguish between their healthy and damaged states [10]. The healthy and damaged EMI measurements were taken in the frequency range of 10 kHz to 800 kHz for each of the ten available PLA plates due to large variations in the signature. The built-in damage detection was done using reference data of identically printed healthy plates for the 4 sets of damage cases. The T1 and T2 threshold are determined by considering the repeated measurements of respective PZT1 and PZT2. The T3 threshold was determined by using PZT2 as a reference for the PZT1. T4 is determined by taking PZT1 as a reference for the PZT2. In the calculation of the new threshold, PZT3 data were utilized to cancel out the effect of the asymmetrical distribution of PZT1 and PZT2 in healthy plates. So, when computing the threshold for detecting damage in similar AM damaged plates, the damage index-based error contributed by PZT placement is subtracted from the damage index of PZT2 with respect to (w.r.t) PZT1 or vice versa. The damage index-based error (E1) is calculated with the help of PZT3 using PZT1 and PZT2 in healthy conditions data of the plate as shown in Table I. All the threshold calculations in Table I (T1 to T6) are performed using the $F_{rescaled}$ data from the healthy plates. Figure 4 shows the identification of built-in damage by the PZT1 and PZT2 of a damaged AM plate. PZT1 depicts damage detection for all infilled densities. The damage index of PZT1-D is always higher than the threshold level of T1, T2, T3, T4, T5, and T6. The damage was detected in all the plates using all the proposed thresholds by PZT1, positioned at a center distance of 102.5 mm from the damage. However, PZT2 is not able to detect damage for 20%, 40%, 80%, and 100% infilled plates placed at 147.5 mm from the damage.

CONCLUSIONS

The fused signature F from the EMI measurements is used for the damage-sensitivity study using the RMSD. The sensitivity to added mass damage in 3D-printed polylactic acid (PLA) plates with different infill densities is decreasing with the increase in the distance from the PZT3. It was also found that damage-sensitivity distance decreases with the decrease in the printing infill density. Identical AM healthy and damaged plates were used for built-in damage identification in the varying infilled plate. The identical healthy plates were used as a reference for damage detection in the damaged plates using several proposed thresholding approaches. The built-in damage-detection capacity has been shown for 20%, 40%, 80%, and 100% infilled PLA plates. The damage was detected in all the examined infill densities and using all the proposed thresholds by PZT1, positioned at a center distance of 102.5 mm from the damage. However, the damage was not detected by PZT2 placed at 147.5 mm from the damage.

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