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Damage detection of 3D printed mold using the surface response to excitation method

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Abstract. The life of conventional steel plastic injection molds is long but manufacturing cost and time are prohibitive for using these molds for producing prototypes of products in limited numbers. Commonly used 3D printers and rapid prototyping methods are capable of directly converting the digital models of three-dimensional solid objects into solid physical parts. Depending on the 3D printer, the final product can be made from different material, such as polymer or metal. Rapid prototyping of parts with the polymeric material is typically cheaper, faster and convenient. However, the life of a polymer mold can be less than a hundred parts. Failure of a polymeric mold during the injection molding process can result in serious safety issues considering very large forces and temperatures are involved. In this study, the feasibility of the inspection of 3D printed molds with the surface response to excitation (SuRE) method was investigated. The SuRE method was originally developed for structural health monitoring and load monitoring in thin-walled plate-like structures. In this study, first, the SuRE method was used to evaluate if the variation of the strain could be monitored when loads were applied to the center of the 3D printed molds. After the successful results were obtained, the SuRE method was used to monitor the artifact (artificial damage) created at the 3D printed mold. The results showed that the SuRE method is a cost effective and robust approach for monitoring the condition of the 3D printed molds.

Keywords: 3D printed mold; structural health monitoring; damage detection; composites; inspection, SuRE

1. Introduction

Molded composite structures are increasingly used in aerospace, medical, automotive and many other applications due to the low weight, superior fracture behavior, long service life and longevity (Taheri *et al*. 2017). Early studies have been conducted for structural health monitoring (SHM) methods to detect the structural defects before failures takes place (Farhangdoust *et al*. 2019, Joyce *et al.* 2018, Farhangdoust *et al* 2018, Lee *et al*. 2019, Farhangdoust and Mehrabi 2019, Burdzik *et al*. 2018, Yazdi 2019). More recently, additive manufacturing methods are being used for rapid manufacturing of molded composite structures due to the significant ability of creating the very complex parts of molded composite structures, which cannot be easily manufactured by the conventional methods (Wohlers 2004, Shan *et al*. 2003). In additive manufacturing systems, parts are built layer by layer in their cabinet by following the Computer Aided Design (CAD) drawings with no material waste and common tooling requirements. Although the significance of the health monitoring of various type of composite molds is accepted and warmly embraced by engineering companies in general and related experts in particular, the load monitoring and defect detection for the rapid prototyping composite molds is a controversial issue and a matter of discussion. These days, 3D printers have an increasing role in producing various types of composite components. Various types of the molded composite components have been developed by 3D printer's technologies (Lin and Chen 2017, Li *et al*. 2016). Lower price and higher efficiency of 3D printing compared to other rapid prototyping technologies can be considered as one of the significant merits of it (Silva *et al*. 2008). Oftentimes, the composite mold segments may face with different types of defect either during manufacturing process or in the course of their service life. Howsoever, the latter stage covers the majority of likelihood for the wearing caused by the service loads (Chillara *et al*. 2015, He *et al*. 2006). On a closer scrutiny, most of the publications are dealing with the severity of negative influence of wearing on rapid prototyping molded composites. Indeed, mechanical wearing should be taken into consideration as the most effective factors for structural health monitoring of the rapid prototype molded composite structures, particularly in the long-term cycling cases study. Consequently, in order to tackle wearing caused by dynamic load, various teams and researchers have put their concentrations on understanding load monitoring and defect detection in the rapid prototype molded composite (Ding *et al*. 2003, Terrien and Colas 2018). Damage detection based

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on the passive and active SHM methods has been extensively addressed in previous studies (Sohn *et al*. 2002, Tamijani *et al*. 2018, Park *et al*. 2003, Giurgiutiu 2008). Passive methods monitor physical characteristics by using sensors only, without using any actuator. Active ones monitor the response of a target structure to a known excitation imposed by an actuator(s). In this study, the surface response to excitation (SuRE) method, which is a cheaper alternative for Electro Mechanical Impedance Spectroscopy (EMIS) method, was used to monitor the surface response characteristics of the mold. The SuRE method is a broad frequency range technique, which has been developed to eliminate the need for the EMIS analyzers (Tashakori *et al* 2018, Tashakori *et al* 2019). This method excites the surface and monitors the response by only using two, or more, piezoelectric elements.

2. Theoretical background

The SuRE method was developed as a low-cost alternative to the electromechanical impedance method, which uses the related instrument to evaluate the characteristics of a single piezoelectric element attached to the structure. SuRE method excites the surface at one point and monitors the propagated and reflected surface waves at another point (Tashakori *et al* 2016, Tashakori *et al* 2019). Any sensor and exciter pair may be used but piezoelectric elements or PZTs are widely used since they are cheap and available in different sizes and shapes. One of the PZTs is used to excite the surface in a wide range of frequencies and the dynamic response of the surface on the other side is recorded using another PZT. Frequency domain data is obtained with the help of the Fast Fourier Transformation (FFT). The change of the frequency domain characteristics is compared with the baseline to understand if there are any changes to the structure. The sum of the squared differences (SSD) of the amplitudes of the spectrums is calculated according to the following equation. Generally, the SSD values increase when the defect gets bigger. The SSD is the quantitative description of the difference between the collected data and the baseline obtained when the structure was in the pristine condition:

$$SSD = \sum_{i=1}^{m} \left| B_{m\times 1} - R_{m\times 1} \right|^2 \qquad (1)$$

In this equation, B and R are the amplitudes of the baseline data and responses of the structure.

3. Experimental setup

Acrylonitrile butadiene styrene (ABS) is one of the widely used materials in additive manufacturing. In this study, one of the parts of a mold with the 5” × 6” × 0.75” inch dimensions were printed by using QIDI TECH dual extruder 3-D printer. The shape of the part is presented in Fig.1. The mold was prepared for injection molding of a dog bone shaped part and two rectangular prism-shaped samples. The Fused Deposition Modeling (FDM) method was used to manufacture the part by using the ABS material with 50% fill ratio.

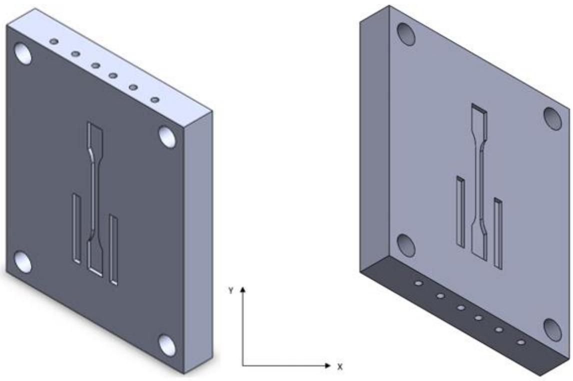


Fig. 1 3D Printed Mold

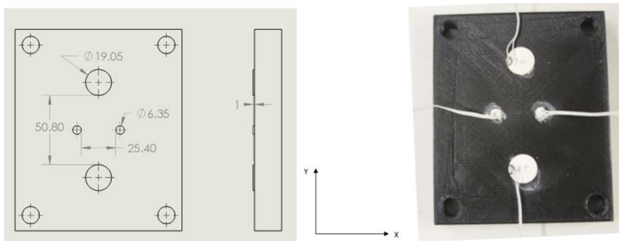


Fig. 2 Drawing (left) and actual part with PZTs (right) of attached PZTs on the back of the 3D printed mold (The unit dimension is millimeter)

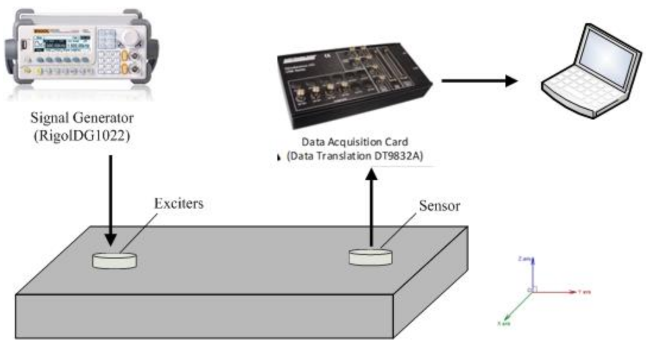


Fig. 3 Experimental setup

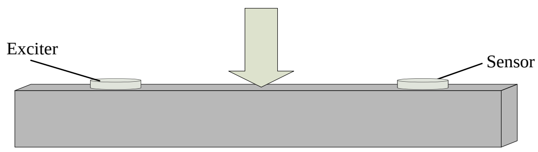
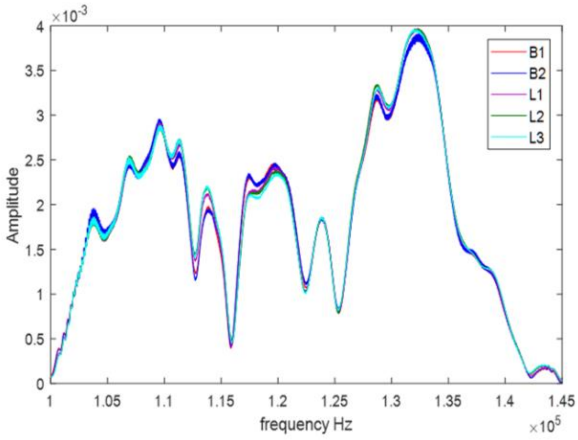


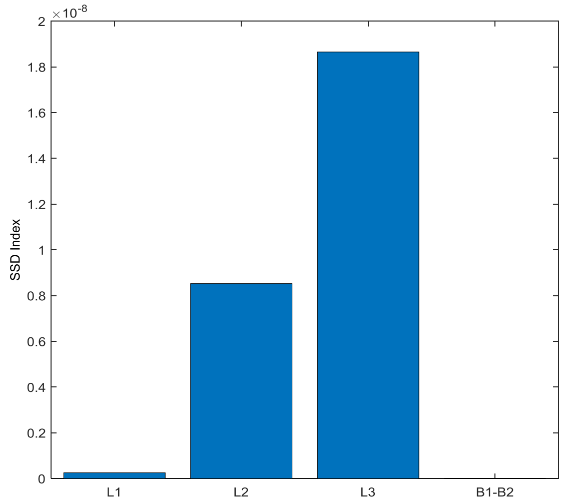
Fig. 4 Schematic of the setup

Two sets of piezoelectric transducers with different sizes (0.75” and 0.25” diameters) were attached on the backside of the mold. For each set, one PZT worked as exciter while the other one was used as the sensor (Fig. 2).

The experiments were repeated twice. First, the structure was excited in a wide frequency range (20 kHz-600 kHz) in order to find the optimum excitation frequency range. The spectrum of the surface response was studied. Based on the height of the amplitude of the FFT response, the frequency ranges between 100 kHz and 1145 kHz was chosen for the PZTs with 0.75” diameter. Using the same procedure, the excitation frequency ranges between 20 kHz and 420 kHz



(a) FFD



(b) SSD

Fig. 5 Frequency response and SSD values for load monitoring when 0.75 diameter PZTs were utilized

was selected for the PZTs with 0.25” diameter. The experimental setup is shown in Fig 3.

3. Results and discussion

Initially, it was decided to simulate the effect of damage by applying loads. Since, in this way, different loads representing different levels of damage can be easily studied without damaging the part. After we observed that the frequency response changed at different loading conditions, various damages were created on the 3D printed molds and the performance of the SuRE method was evaluated.

3.1 Evaluation of SuRE method by detection of the force applied in the center of the mold

For evaluating the performance of the SuRE method different loads were put at the middle of the mold (Fig. 4). The structure was excited between 100 kHz and 145 kHz by using one 0.75” diameter PZT. The surface response was monitored with the same size PZT that was attached to the other side of the mold.

The baseline data (B1, B2) was collected and FFT spectrums were calculated (Table 1). Then, 1 lb., 2 lbs. and 3 lbs. load (L1, L2 and L3) were applied. The surface response was collected at each loading level. Finally, all the loads were removed and data was collected at the same conditions the baseline data was recorded. The spectral characteristics of the response were collected for all the cases by using the FFT method and presented in Fig.5. The SSD values were calculated to represent the difference between the baseline and each test case with and without the load (Fig. 5).

The same process was repeated when two 0.25” diameter PZTs were utilized as sensor and exciter to study the effect of different size transducers. The PZTs was excited between 20 kHz and 420 kHz. The results for small PZTs are shown in figures 6, 7.

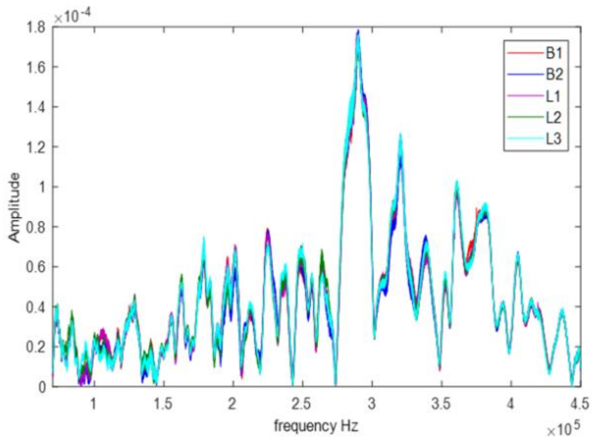
Table 1 Force detection results

PZT Diameter	Range of frequency	Applied Loads	SSD Values
0.75”	100-145 Hz	L1	0.03
		L2	0.85
		L3	1.85
0.25”	100-145 Hz	L1	0.5
		L2	1.25
		L3	2.8
	20-420 Hz	L1	0.02
		L2	0.1
		L3	1.6

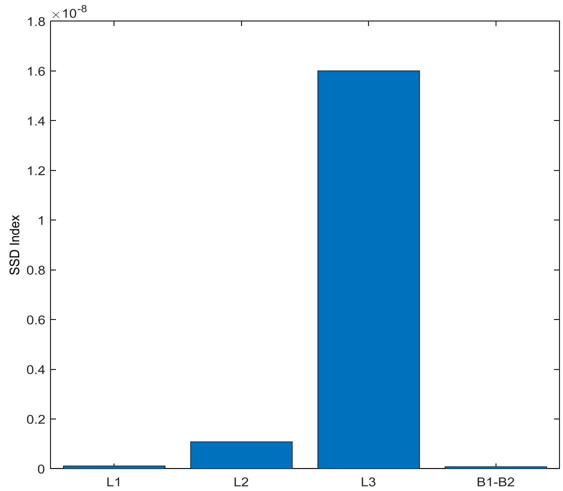
3.2 Subtitle: Damage detection

Dremel rotary tool kit with a grinding head was used to create damage at one of the cavity with 0.2” width and 1.6” length (Fig.8.a). The damage was created at the left side of the cavity with the hand tool to simulate the damage or wear of the mold artificially. Little slots were created with 0.5” length (Y direction). The widths of the slots were (X direction) 0.05”, 0.01” and 0.015” for three simulated wear cases. The artifact (artificial damage) or wear was also created on the right side of the cavity. The length of the slot was 1.6” this time in the Y direction. The width of the slot was also 0.05”, 0.01” and 0.015” in the X direction for the three additional simulated wear cases. The tested wear cases are presented in Table 2.

The experimental data were collected with the PZTs with 0.75” diameter first. The mold was excited in 100 kHz to 145 kHz frequency range with a sweep sine wave. The baseline data were collected twice without any damage for comparing the baseline responses SSD. The experimental data was also collected with the PZTs with 0.25” diameter. The baseline data was also collected twice with these smaller PZTs. The excitation frequency range of the sweep sine wave was 20 kHz to 420 kHz. These experiments were also repeated when the excitation frequency range of the

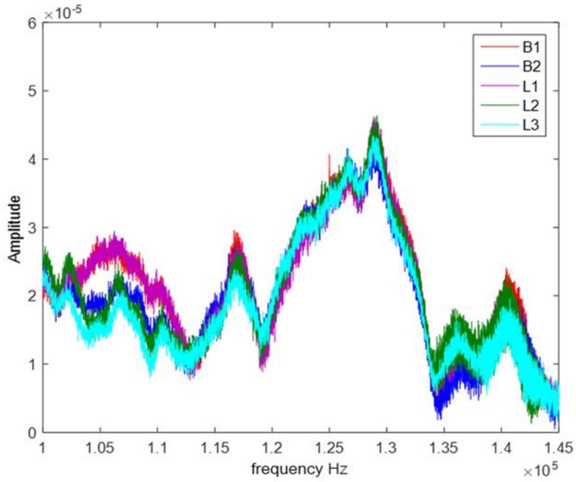


(a) FFD

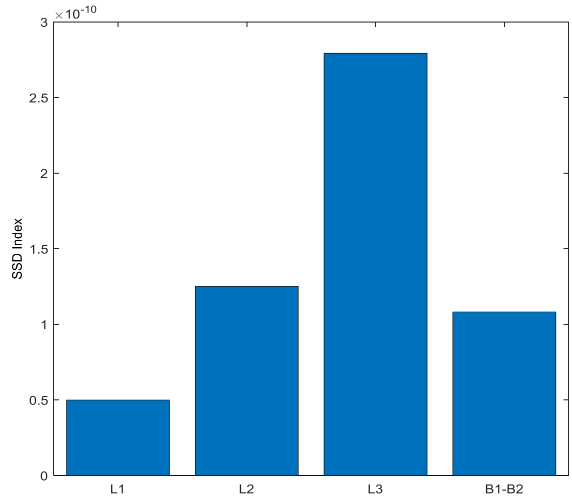


(b) SSD

Fig. 6 Frequency response and SSD values for load monitoring when 0.25 diameter PZTs and 20 kHz - 420 kHz frequency range were utilized



(a) FFD



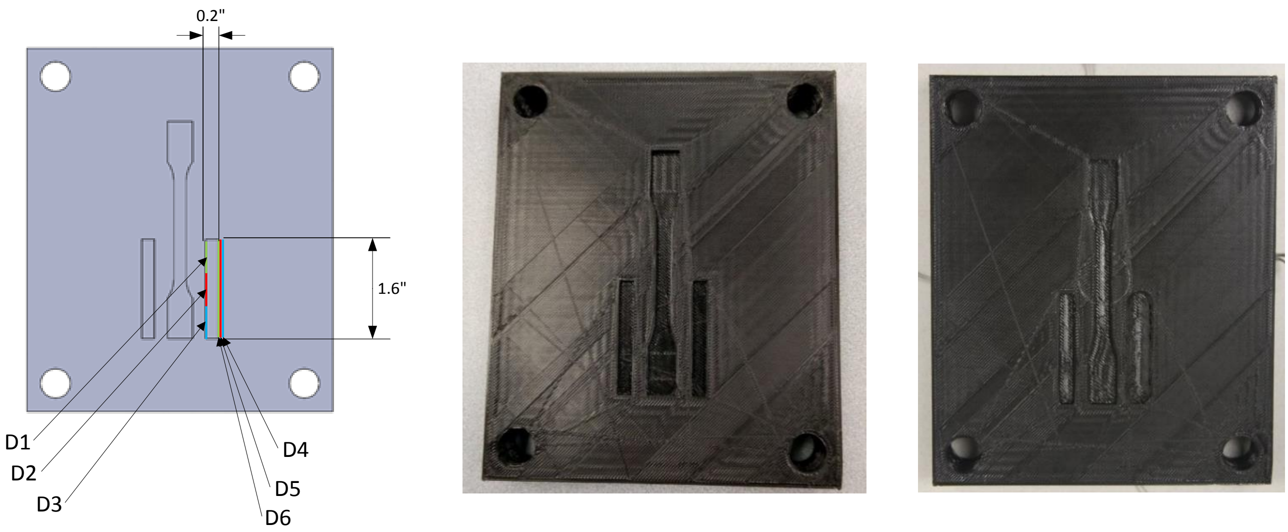
(b) SSD

Fig. 7 Frequency response and SSD values for load monitoring when 0.25 diameter PZTs and 100 kHz - 145 kHz frequency range were utilized

Table 2 Experimental test cases

Experiments at different wear or damage levels		Damage at the left side		Damage at the right side	
		Length	Width	Length	Width
Dataset	Baseline 1 (B1)	None	None	None	None
	Baseline 2 (B2)	None	None	None	None
	Damage 1 (D1)	0.5”	0.05”	None	None
	Damage 2 (D2)	1”	0.05”	None	None
	Damage 3 (D3)	1.6”	0.05”	None	None
	Damage 4 (D4)	1.6”	0.05”	1.6”	0.05”
	Damage 5 (D5)	1.6”	0.05”	1.6”	0.1”
	Damage 6 (D6)	1.6”	0.05”	1.6”	0.15”

sweep sine wave was reduced to 100 kHz to 145 kHz range. The right cavity of the mold was damaged as described in the first paragraph and Table 2 at six different levels. Experimental data was collected with the PZTs with 0.75” and 0.25” diameters in the indicated frequency ranges. The FFT of the data were calculated for each case and the SSD values were calculated.



(a) Drawing of the mold (b) Perfect Mold (b) Damaged cavity

Fig. 8 Created damage shown in three colors

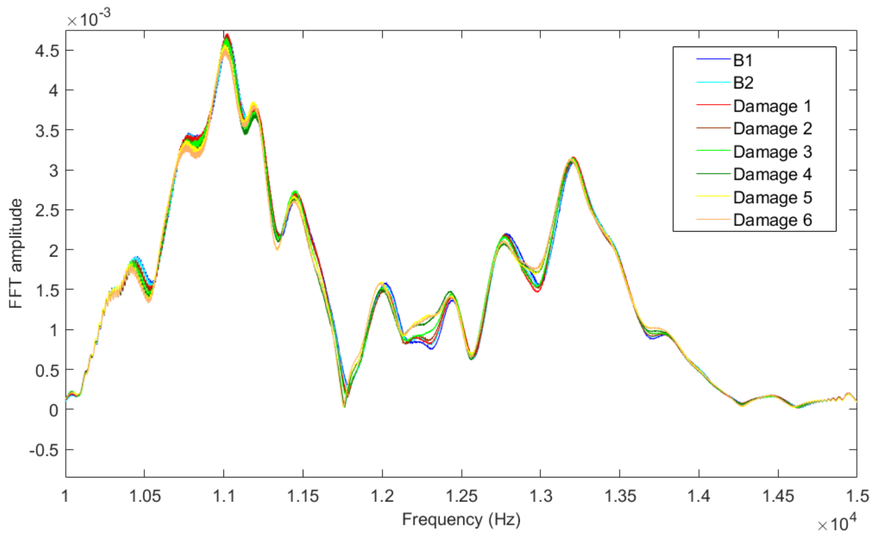
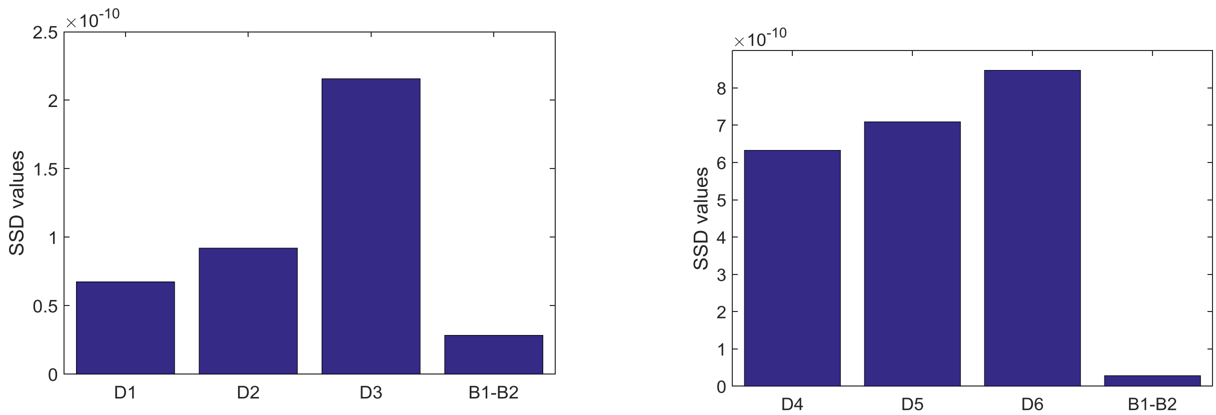


Fig. 9 The spectrums calculated by the FFT when the PZTs with 0.75" diameter were used at different artificial damage or wear levels. The excitation signal was a sweep sine wave between 100 kHz and 145 kHz



(a) Damages 1 - 3 (b) Damages 4 - 6

Fig. 10 SSD values for damage detection when 0.75 diameter PZTs were used. The excitation signal was a sweep sine wave between 100 kHz and 145 kHz. See the Table 1 for the artificially created damage or wear information

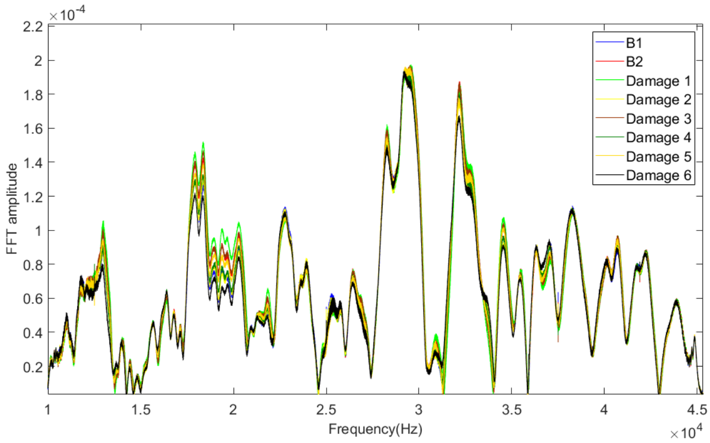
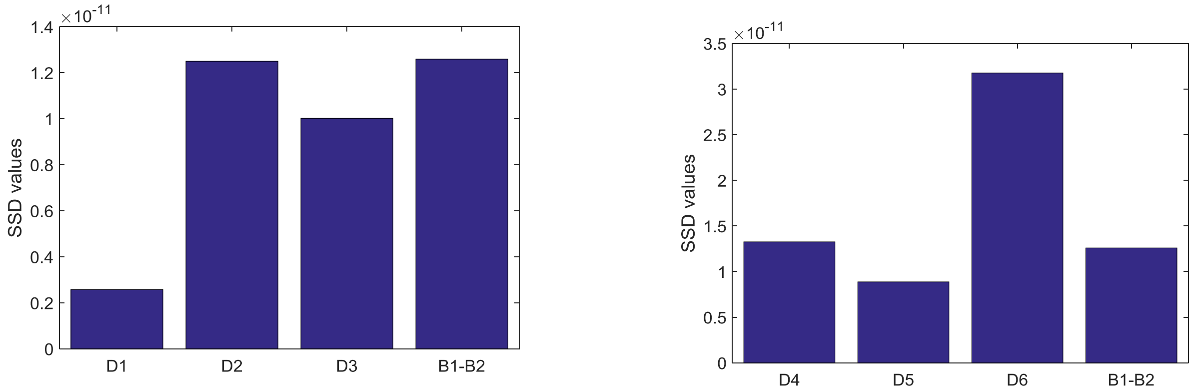


Fig. 11 The spectrums calculated by the FFT when the PZTs with 0.25” diameter were used at different artificial damage or wear levels (20 kHz and 420 kHz excitation)



(a) Damages 1 - 3

(b) Damages 4 - 6

Fig. 12 SSD values for damage detection when 0.25 diameter PZTs were used. The excitation signal was a sweep sine wave between 20 kHz and 420 kHz. See the Table 1 for the artificially created damage or wear information

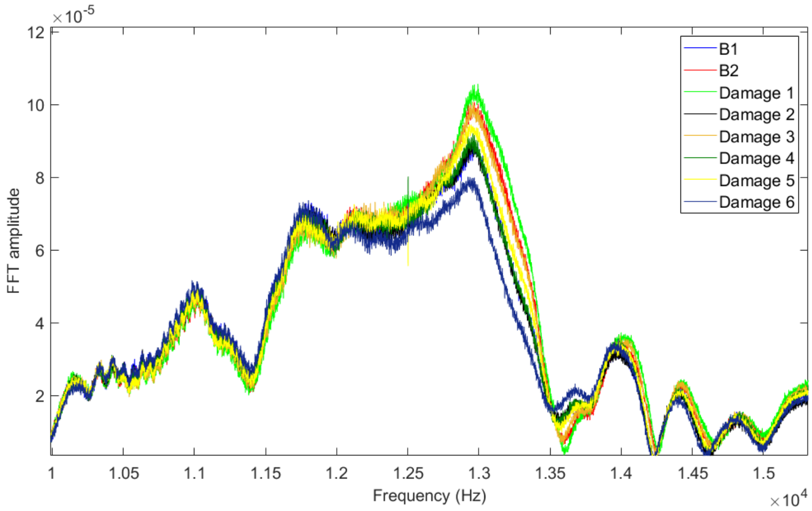
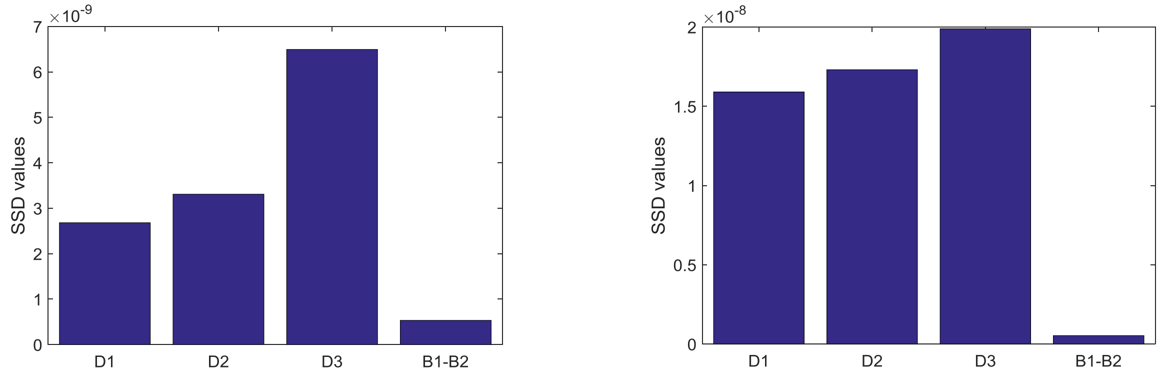


Fig. 13 The spectrums calculated by the FFT when the PZTs with 0.25” diameter were used at different artificial damage or wear levels. The excitation signal was a sweep sine wave between 100 kHz and 145 kHz

The FFT amplitude and SSD values for the PZTs with 0.75” diameter is presented in Fig.9 and Fig.10 respectively. The FFT amplitude and SSD values for the PZTs with 0.25” diameter are presented in Fig.11 and Fig.12 respectively (20 kHz to 420 kHz excitation). The FFT amplitude and SSD values for the PZTs with 0.25” diameter are presented in Fig.13 and Fig.14 respectively when the frequency of the sweep sine wave changed between 100 kHz to 145 kHz.



(a) Damages 1 - 3 (b) Damages 4 - 6

Fig. 14 SSD values for damage detection when 0.25 diameter PZTs were used. The excitation signal was sweep sine wave between 100 kHz and 145 kHz. See the Table 1 for the artificially created damage or wear information

5. Conclusions

In this study, the cavity wear of a 3D printed ABS mold was monitored by using the surface response to excitation (SuRE) method. The damage was created artificially and performances of two different size piezoelectric elements were evaluated. The challenges were if the created excitation would reach to the other surface of a 3D printed ABS part with 50% infill and if the meaningful signal would come to the sensor. The experimental results indicated that the piezoelectric elements with 0.25 and 0.75-inch diameters have different effective frequency intervals. This interval was 20-420 kHz for the piezoelectric elements with a 0.25-inch diameter. The interval was narrower 100-145 kHz for the larger piezoelectric element with 0.75-inch diameter. However, the smaller piezoelectric element worked more reliably at the 100-145 kHz range. The sensor received a strong signal when the test frequency range stayed at the listed values. The sum of the squares of the differences (SSD) increased with the load when the test was performed at the 20-420 kHz range with the piezoelectric element with 0.25-inch diameter. Similar results were obtained with the piezoelectric elements with a 0.75-inch diameter. The SSD values increased when the artificially created damage was increased as long as the experiments were performed at 100-145 kHz range with the piezoelectric elements with 0.25 and 0.75-inch diameters. The SuRE method properly identified the artificially created damages in all the test cases. The results showed that the SuRE method can be used to evaluate the condition of the 3D printed molds. As it was demonstrated in SSD results, the sensitivity of the SuRE method is contingent upon the excitation frequency range, PZT diameter, level of the applied force and sizes of the damage. Besides, the sensitivity of the SuRE method will vary for different materials.

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