Impedance-Based Structural Health Monitoring of Additive Manufactured Structures with Embedded Piezoelectric Transducers

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Objective

Experimentally investigate the feasibility of using embedded piezoelectric transducers to detect damage within an additive manufactured (AM) structures.

Motivation for Research

It is desired for additive manufactured structure to be used as end-use products. NASA is pushing to produce a rocket engine entirely from AM components (Figure 1) [1]. The AM technique can produce complex geometries through a variety of printing methods using a variety of materials. A few major drawbacks of AM methods are that structures have anisotropic material properties. Also, its difficult to validate the quality of the geometric and material properties of printed structures. Structural Health Monitoring (SHM) is a method that uses sensors to detect the development of damage in a structure. The goal is to investigate the feasibility of utilizing embedded piezoelectric transducers for impedance based structural health monitoring of additive manufactured structures.

(a) (b) (c) (d)

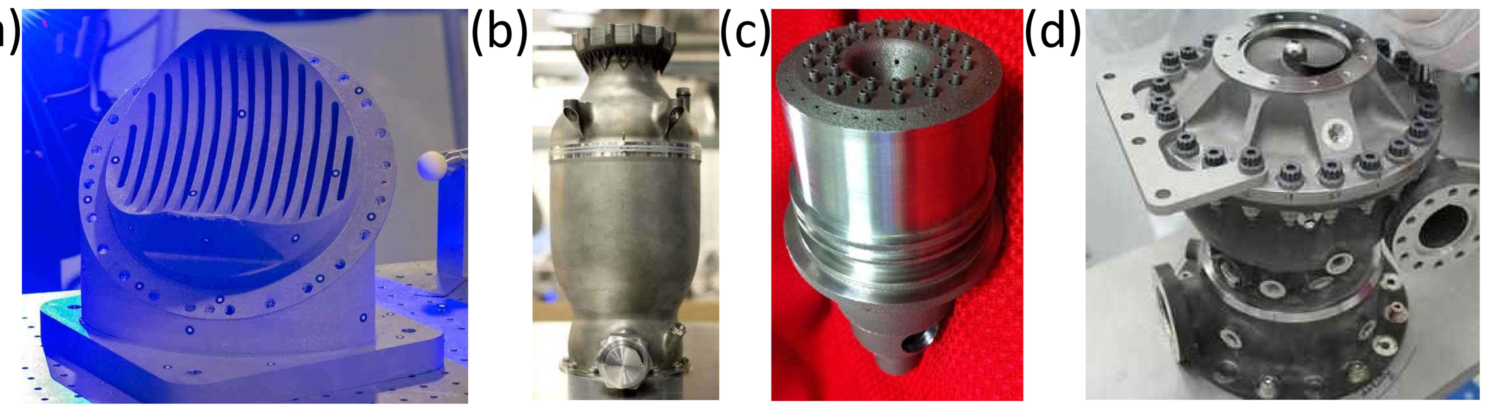

Figure 1. Additive manufactured aerospace components including (a) NASA Pogo-Z engine baffle, (b) SpaceX SuperDraco combustion chamber, (c) NASA's fuel injector, and (d) NASA's fuel pump.

Methods: Electromechanical Impedance

The electro-mechanical impedance (EMI) method is employed in order to investigate the health of an AM structure [2]. A piezoelectric transducer (PZT) is bonded to a structure (here embedded) and acts as both an actuator and a sensor to detect a change in the electrical response of the PZT. Utilizing the coupled electrical and mechanical properties of PZTs a change in the dynamic electrical impedance response of the PZT can be directly associated with a change to the mechanical condition of the structure [3]. An initial baseline reading is measured in a healthy state and used to compare with the various damaged states (Figure 2).

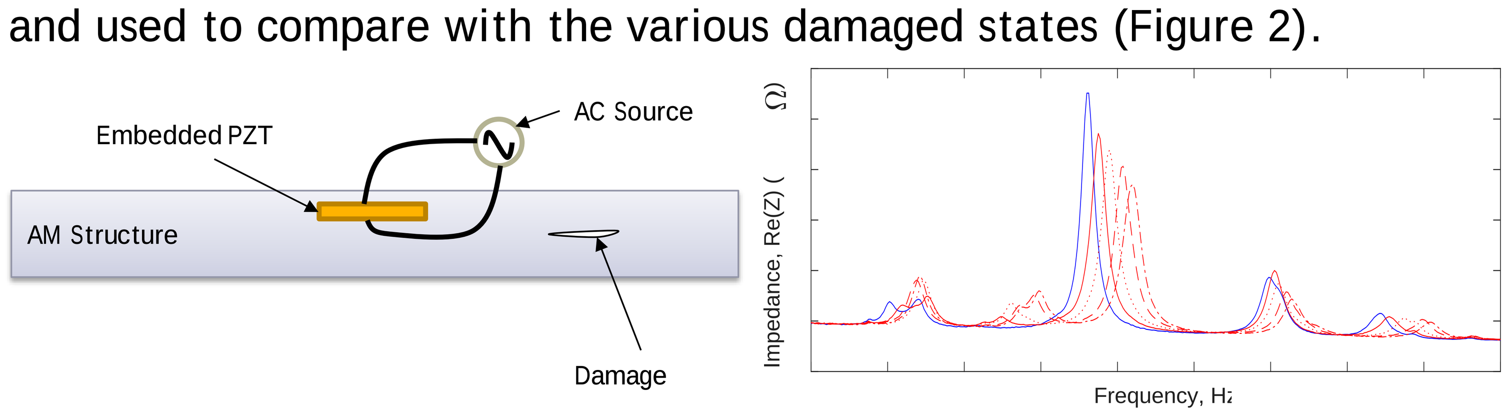

Figure 2: The EMI method being used on an embedded PZT to detect damage in an AM structure

Methods: Damage Quantification

Here damage is defined as any change to the systems mass, stiffness, damping, or boundary conditions that causes a significant changes to the dynamic response of the system. The Root Mean Squared Deviation (RMSD) method is utilized to detect changes in the dynamic impedance response of the system subjected to various conditions [4]. The RMSD function is defined as follows:

$$RMSD = \sqrt{\sum \frac{\left(\mathrm{Re}(Z_D) - \mathrm{Re}(Z_{BL})\right)^2}{\left(\mathrm{Re}(Z_{BL})\right)^2}}$$

Where $\mathrm{Re}(Z_{BL})$ is the impedance of the healthy state and $\mathrm{Re}(Z_D)$ is the impedance of the damaged state.

Methods: Specimen Design & Fabrication

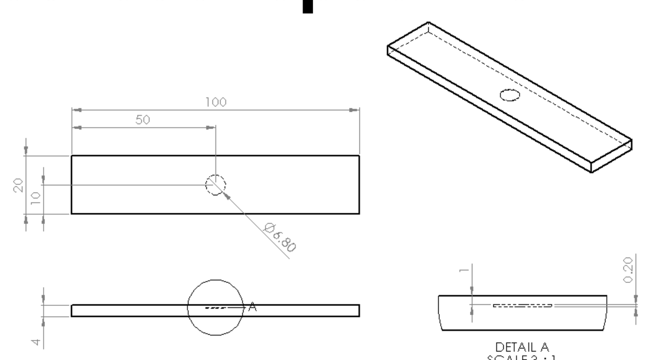

Figure 3: Specimen design and geometric dimensioning (all dimensions in mm)

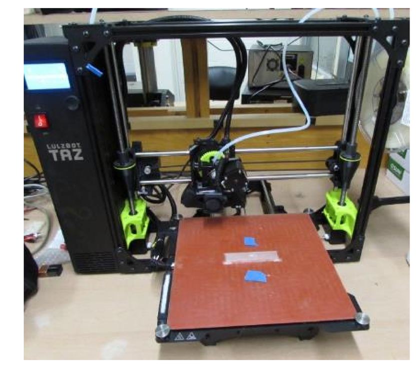

Figure 4: LulzBot TAZ 6 3D printer with printed specimen

The specimen design is given in Figure 3. The specimens are printed from natural PLA using a LulzBot TAZ 6 3D printer (Figure 4) using the printing parameters shown in Table 1. The material properties can vary dramatically due to changes to printing parameters. The print is paused after printing a pocket for the PZT. Using cyanoacrylate (super glue) the PZT is glued into the pocket and the print is resumed.

Table 1: Optimized printing parameters

Layer height (mm)	0.1
Shell Thickness (mm)	1
Bottom/Top Thickness (mm)	0.5
Initial Layer Thickness (mm)	0.3
Initial Layer Line Width (%)	120
Nozzle Diameter (mm)	0.5
Fill Density (%)	100
Infill Printing Speed (mm/s)	100
Shell Printing Speed (mm/s)	40
Bottom Layer Printing Speed (mm/s)	20
Nozzle Temperature (°C)	210
Bed Temperature (°C)	70

Methods: Experimental Setup

The impedance of the PZT is measured using a HP 4194A impedance analyzer. The frequency range investigated is from 10 to 100 kHz, measured in 10 kHz increments each containing 401 data points.

A fixture milled from aluminum is used to ensure consistent alignment of the specimen as a cantilever. A torque wrench is used to apply a consistent clamping force. Tip masses and drilled holes are used to simulate damage in the AM structure.

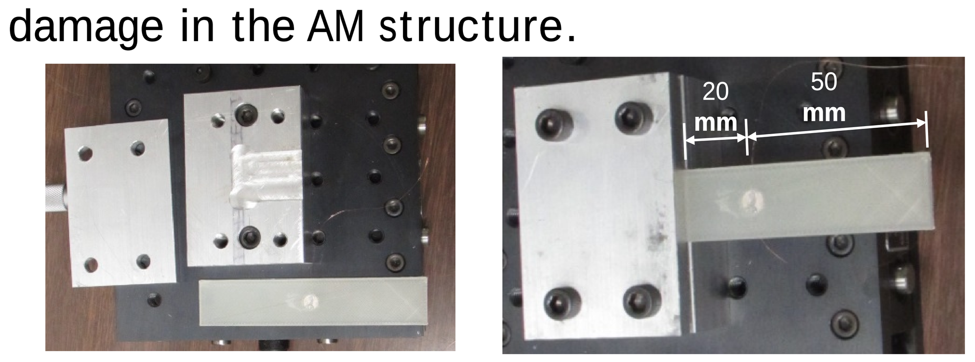

Figure 5: Specimen mounted as a cantilever beam in aluminum fixture

Figure 6: Experimental setup with HP 4194A and necessary tools

Results

In order to determine a threshold for an acceptable amount of RMSD, the RMSD associated with taking measurements and re-clamping a healthy structure are measured and determined to be 0.154 and 3.125, respectively. The system was tested with both nondestructive and destructive tests. The nondestructive tests are conducted by applying various masses to the tip of the cantilever beam (Figure 7). The impedance spectrum for the baseline, 50, 100, 200, and 400 gram masses from 10 to 100 kHz are displayed in Figure 8(a) and from 15 to 36 kHz displayed in Figure 8(b).

Figure 7: Cantilever beam with 200 g tip mass placed at the free end of the beam.

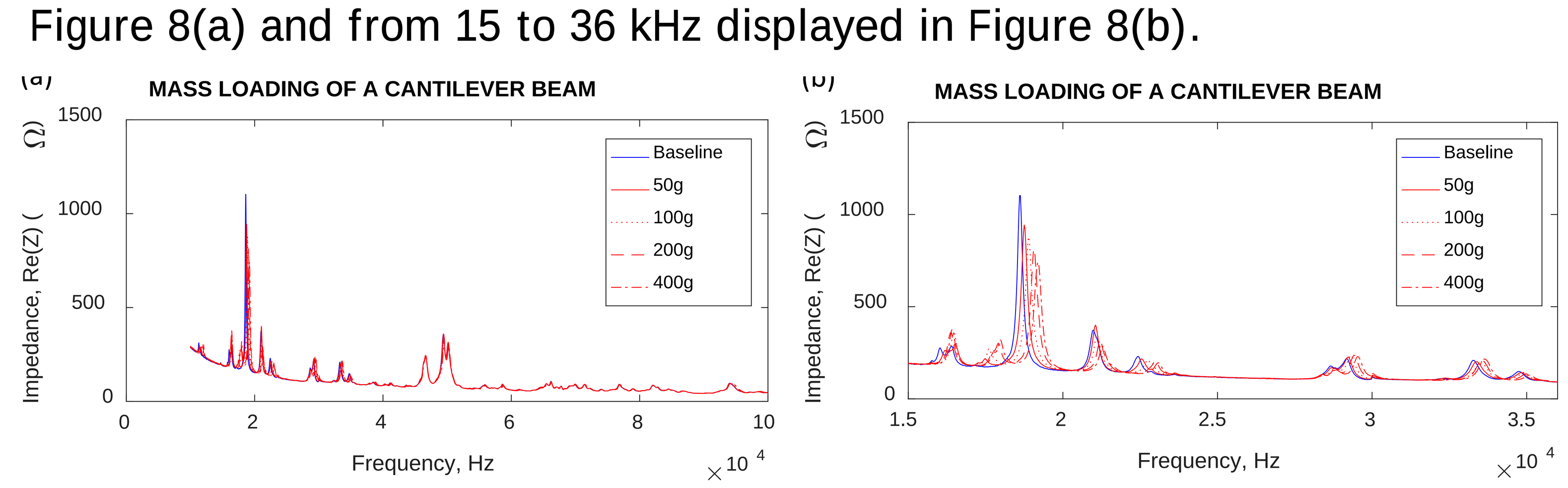

Figure 8: Mass loading of cantilever beam specimen with no mass (baseline), 50, 100, 200, and 400 g (a) broadband measurement from 10 to 100 kHz, measured in 10 kHz segments, (b) 15 to 36 kHz

The RMSD values for the mass loading condition are displayed in Table 2. The destructive tests are conducted by drilling holes of various sizes in near the tip of the cantilever beam, 1 cm from the tip and 4 cm from the PZT (Figure 9). The impedance spectrum for the baseline, 1, 2, 3, and 4 mm holes from 10 to 100 kHz are displayed in Figure 10(a) and from 43 to 51 kHz displayed in Figure 10(b). The RMSD values for the drilled hole condition are displayed in Table 3.

Table 2: RMSD of Mass Loading Conditions

End Mass (g)	RMSD (10-100 kHz)	RMSD (15 to 36 kHz)
50	4.09	3.99
100	7.89	7.56
200	10.42	10.03
400	11.39	10.71

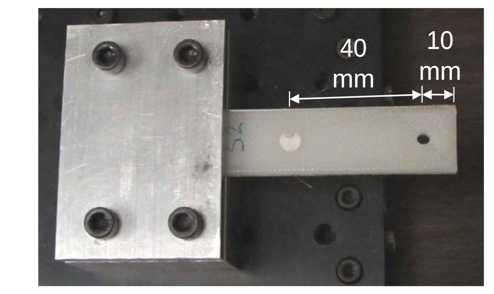

Figure 9: Cantilever beam with 3 mm hole drilled near the free end of the beam.

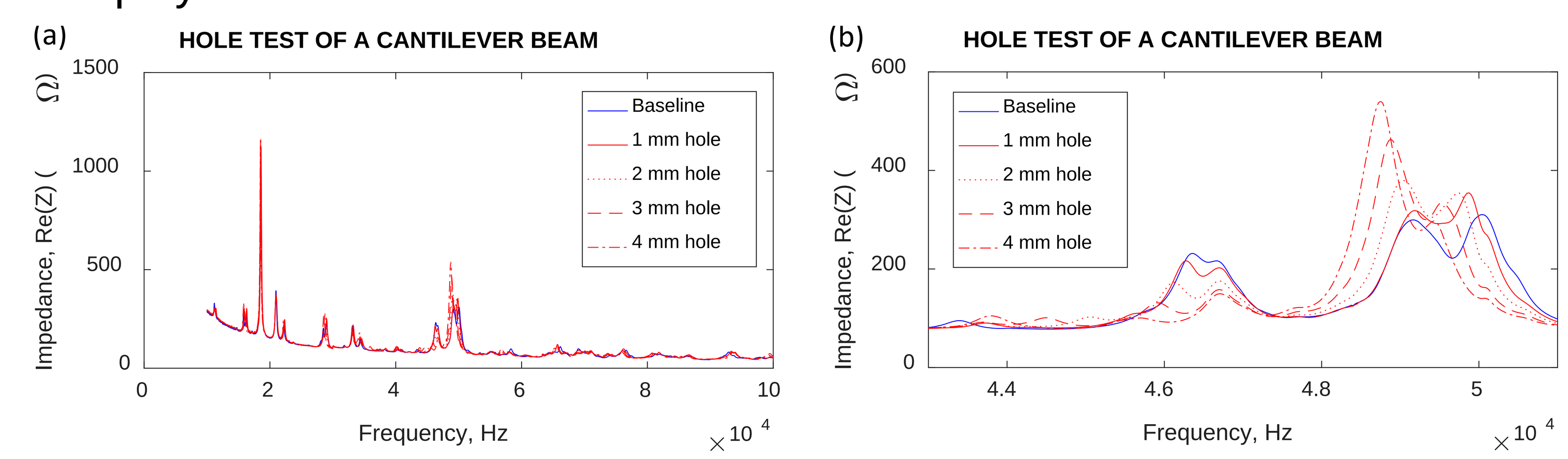

Figure 10: Hole test of cantilever beam specimen with no hole (baseline), 1, 2, 3, and 4 mm (a) broadband measurement from 10 to 100 kHz, measured in 10 kHz segments, (b) 43 to 51 kHz

Discussion

Table 3: RMSD of Drilled hole conditions

Hole Size (mm)	RMSD (10-100 kHz)	RMSD (43-51 kHz)
1	4.85	1.86
2	6.20	3.73
3	8.78	6.22
4	12.15	9.70

The specimen isn't re-clamed during the experiment and therefore a damage threshold RMSD value of 0.154 can be assumed. The regions with the most change are enlarged (Figure 8 (b) and Figure 10 (b)). From the data in Table 2 it can be seen that more than 95 percent of the RMSD value caused by mass loading is present in the 15 to 36 kHz frequency range. From the data in Table 3 it can be seen that the frequency range of 43 to 51 kHz contains nearly half to three fourths of the RMSD present in the destructive test. The minimum change to the boundary conditions causes a greater RMSD value than the re-clamping of a known healthy specimen. Due to these results it can be determined that embedded PZT's can effectively be use with the EMI method to detect damage within AM structures.

Conclusions & Future Work

It has been determined that impedance based structural health monitoring of additive manufactured structures can be accomplished with an embedded piezoelectric transducer. The ability to detect changes to a structures condition has been proven experimentally in this work. Future work for this research topic involves modelling the system using finite element modeling software (ANSYS).

References

[1] J. M. Waller, B. H. Parker, K. L. Hodges, E. R. Burke, J. L. Walker, and E. R. Generazio, 2014, *National Aeronautics and Space Administration*.

[2] M. Albakri, L. S., C. B. Williams, and P. Tarazaga, 2015, *International Solid Freeform Fabrication Symposium, Austin, TX*.

[3] C. Liang, F. Sun, and C. Rogers, 1994, *Journal of Intelligent Material Systems and Structures*, vol. 5, pp. 12-20.

[4] G. Park, H. Sohn, C. R. Farrar, and D. J. Inman, 2003, *Shock and Vibration Digest*, vol. 35, pp. 451-463.

Acknowledgements

It is the desire of the author to thank Mohsen Safaei and Ryan Kettle for their assistance with various aspects of this research topic.