Towards Active Structural Control Strategies for Electronic Assemblies in High-rate Dynamic Environments

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ABSTRACT

Electronic assemblies subjected to high impact and shock loadings could be integrated with transducers to actively mitigate their deflection during extreme dynamic events. Active structural control schemes have been proposed and explored for the mitigation of structural vibrations, however, their use for the active suppression of structural deflection in a system experiencing shock has received significantly less attention. Moreover, the investigation of active shock control in high-rate dynamic environments is an unstudied area. High-rate dynamic events are characterized by large uncertainties in external loads, high levels of non-stationarities and heavy disturbances, and unmodeled dynamics generated from changes in system configurations. This paper presents an experimental study aimed at enhancing the resilience and endurance of electronic assemblies through the incorporation of active control elements. In this study, a circular printed circuit board equipped with representative electronic components is subjected to controlled high-energy impacts. Finite element modeling complements the experimental tests, offering insights into the complex interactions between structural deflections and control mechanisms during shock. This research establishes a crucial foundation for developing sophisticated active control strategies. In particular, it gathers essential data on how electronic assemblies respond under high-impact conditions, which is vital for informing the layout, control methodologies, and the potential quantity of actuators needed for effective active shock mitigation. By closely analyzing the acceleration data and structural responses during these tests, this work suggests where actuators would be most beneficial in reducing deflections and absorbing shocks. This information is critical in determining the optimal configuration of actuators—where they should be placed, how they should be controlled, and in what numbers—to maximize their protective effects. Additionally, this work seeks to quantify the potential benefits of these active control systems, such as increased durability and extended operational life of electronic assemblies, setting a targeted path for future enhancements.

Keywords: active structural control, shock mitigation, high-rate dynamics, piezoelectric transducers, experimental dynamics, impact testing

INTRODUCTION

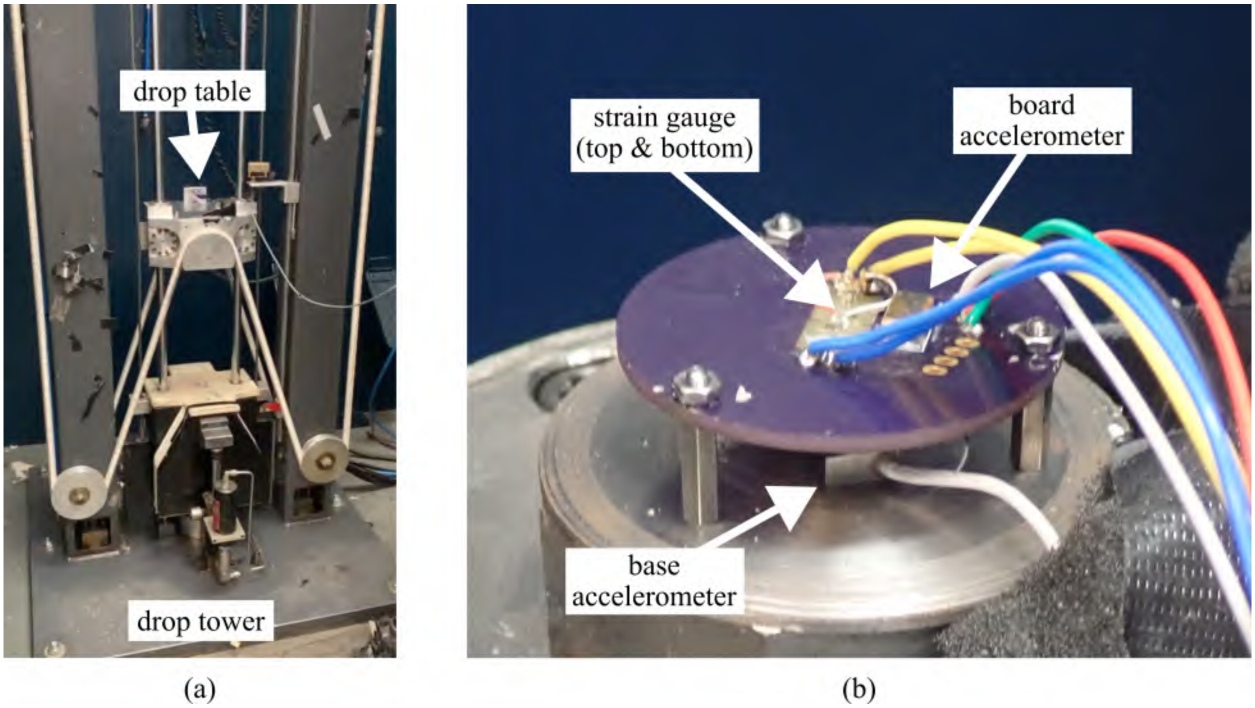
In the aerospace, defense, automotive, and industrial sectors, maintaining the reliability and durability of electronic assemblies is critical. These assemblies are routinely subjected to significant impact and shock loads, necessitating robust solutions to ensure their functionality and operational life. These short-impulse high-energy loads can be termed high-rate dynamics. Structures operating in high-rate dynamic environments present unique challenges, including uncertainties, non-stationarities, heavy disturbances, and unmodeled dynamics [1].

Active structural control for vibration suppression has been extensively studied. Fisco and Adeli demonstrated significant reductions in structural vibrations through various active control methods [2]. These studies have primarily focused on applications such as aerospace structures and industrial machinery, where vibration control is critical for performance and longevity. However, limitations of vibration control strategies when applied to high-impact scenarios have been noted. For example, a review by Ding et al., discussed the constraints and challenges of current vibration control methods, emphasizing the need for tailored approaches to address the unique demands of shock mitigation [3].

The integration of transducers to dynamically mitigate deflection, present a promising solution to the specific issue of active shock control. Recent research has explored the potential of transducers for active shock control in various applications. For instance, Jana and Kaushik reviewed shock wave/boundary layer interaction control in high-speed flows, highlighting effective methods such as porous cavities and vortex generators to mitigate shock effects [4]. Similarly, Phu et al. studied transducer-based shock mitigation in industrial equipment [5]. Despite these advances, comprehensive studies focusing on electronics are generally lacking, highlighting a critical gap in the literature. These strategies can protect electronic assemblies against damage, thereby increasing their durability and lifetime. However, the creation and optimization of such control approaches necessitate a thorough understanding of how the assemblies behave under high-impact conditions. Despite extensive research into active structural control for vibration suppression, the application of these approaches to reduce structural deflection in electronic assemblies under shock conditions, particularly for electronics, remains largely unexplored.

Piezoelectric actuators are particularly well-suited for this application due to their ability to convert electrical energy into mechanical strain, and vice versa. When an electric field is applied, piezoelectric materials deform, allowing for precise control of mechanical movements. This makes them ideal for dynamically mitigating deflection [6], absorbing shocks to protect sensitive components [7], and even utilizing ultrasound-powered methods for enhanced resilience in electronic assemblies [8]. Additionally, their small size and high response rate make them suitable for integration into compact electronic systems where space and weight are critical considerations.

In this paper, we describe the development and testing of a prototype electronic assembly for investigating active shock mitigation in electronic assemblies. The test article is a printed circuit board (PCB) that is subjected to a series of controlled shock tests using a drop tower, which enabled us to collect detailed acceleration and strain data. This data is further supplemented by Finite Element Modeling (FEM) to corroborate the experimental results and inform the strategic placement of sensors and actuators for future shock mitigation efforts. The primary contributions of this work are twofold. First, we have created a publicly accessible dataset derived from a series of controlled shock tests on PCB assemblies [9], providing a valuable resource for researchers investigating shock mitigation. Second, we developed Finite Element Models (FEM) that not only validate the experimental data but also offer guidance for sensor and actuator placement, supporting the design of more effective shock mitigation strategies in electronic assemblies and setting a foundation for future advancements in this area.



(a) (b)

Figure 1: The shock test system and specimen used in this work, showing: (a) the drop tower used for testing, and; (b) the printed circuit board with onboard components and sensors.

METHODOLOGY

The Experimental effort for this project used an accelerated drop tower to generate acceleration and strain data from a PCB at high levels of shock. All data is provided through a public repository [9]. These drop tests vary in height and acceleration, cycling primarily between approximately 5000, 10000, and 15000 g_n impacts. The printed circuit board undergoing these shocks, pictured in Figure 1, is made from a glass-reinforced epoxy laminate material (FR4) and measures 41.275 mm in diameter and 1.6002 mm. There are also three holes at 120º from each other at a diameter of 36.83 mm for standoffs to be placed. The board is equipped with two single linear strain gauges (Model C5K-06-S5145-350-33F by Micro-Measurements), at the center, on top and bottom, and an accelerometer (Model 72-20K by Endevco) on top just off to one side of the strain gauge.

The structure holding the board is equipped with an accelerometer (Model 7280A-60K by Endevco) as well, being placed under the board for minimum noise. Before each drop, the nuts for each standoff were tightened to 0.45 Nm to help keep the board from wiggling loose or changing the system's dynamics. The shock data is collected from the system first using a signal conditioner (Model 28000 by Precision Filters), which then feeds into a PXIe Chassis containing two multi-function data acquisition modules (Model NI PXIe-6124 by National Instruments). The chassis then outputs to a computer where the data is collected and recorded using a Virtual Instrument developed in LabVIEW. The data recorded from these experiments, shown in Figures 2 and 3 demonstrate the board's response to varying impact energies.

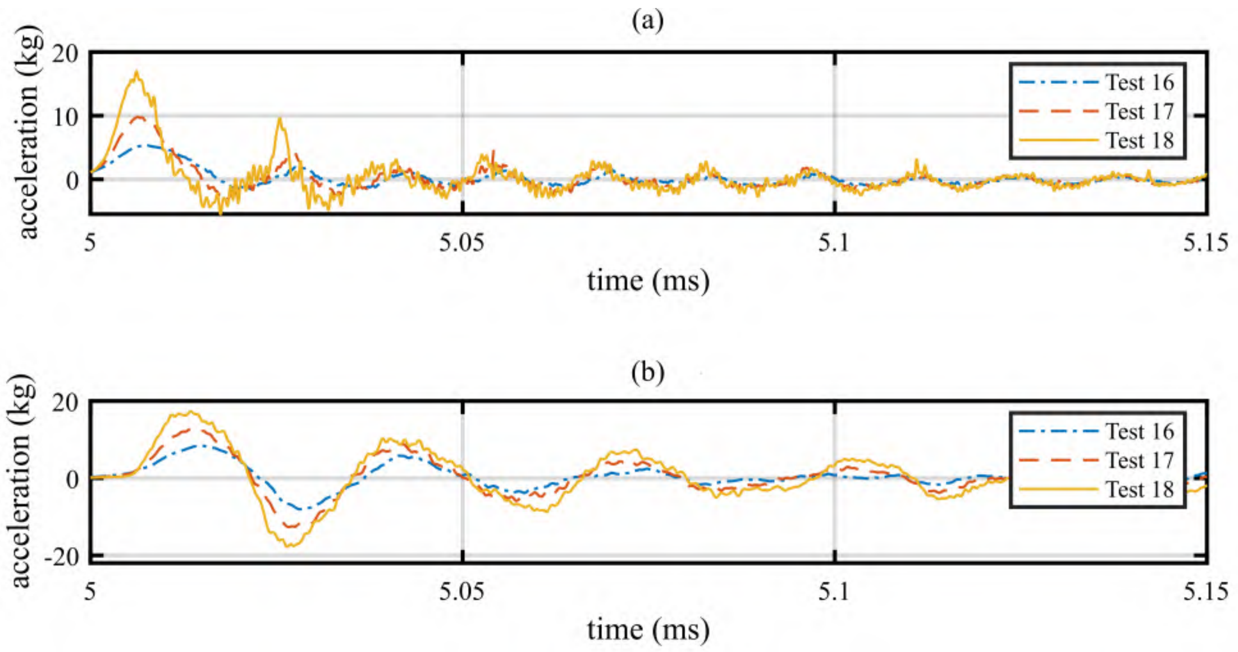


Figure 2: The acceleration data measured over time at varying drop heights, showing: (a) the acceleration of the base, and; (b) the acceleration of the board.

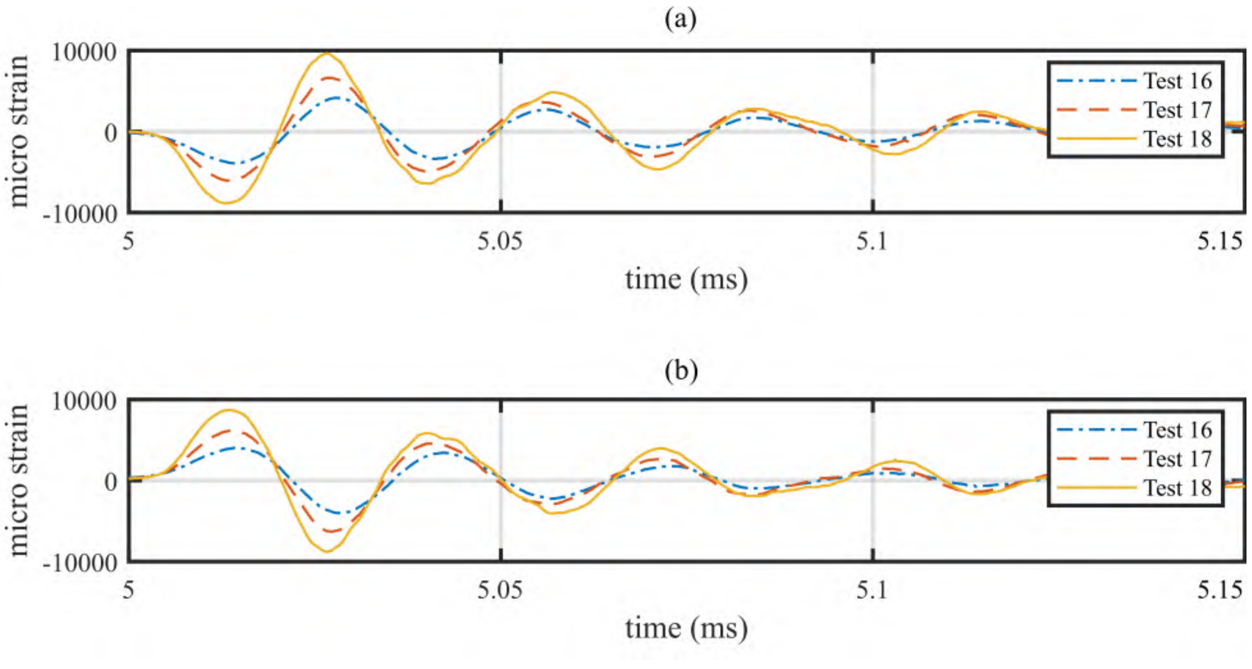


Figure 3: The strain data measured over time at varying drop heights, showing: (a) the strain at the top of the board, and; (b) the strain at the bottom of the board.

Table 1: The system specifications of the printed circuit board used in the simulations, covering key material and structural properties.

diameter	thickness	hole placement	density	Young's modulus	Poisson's ratio
41.275 mm	1.600 mm	36.830 mm	515.379 kg/m^3	18.602 GPa	0.2

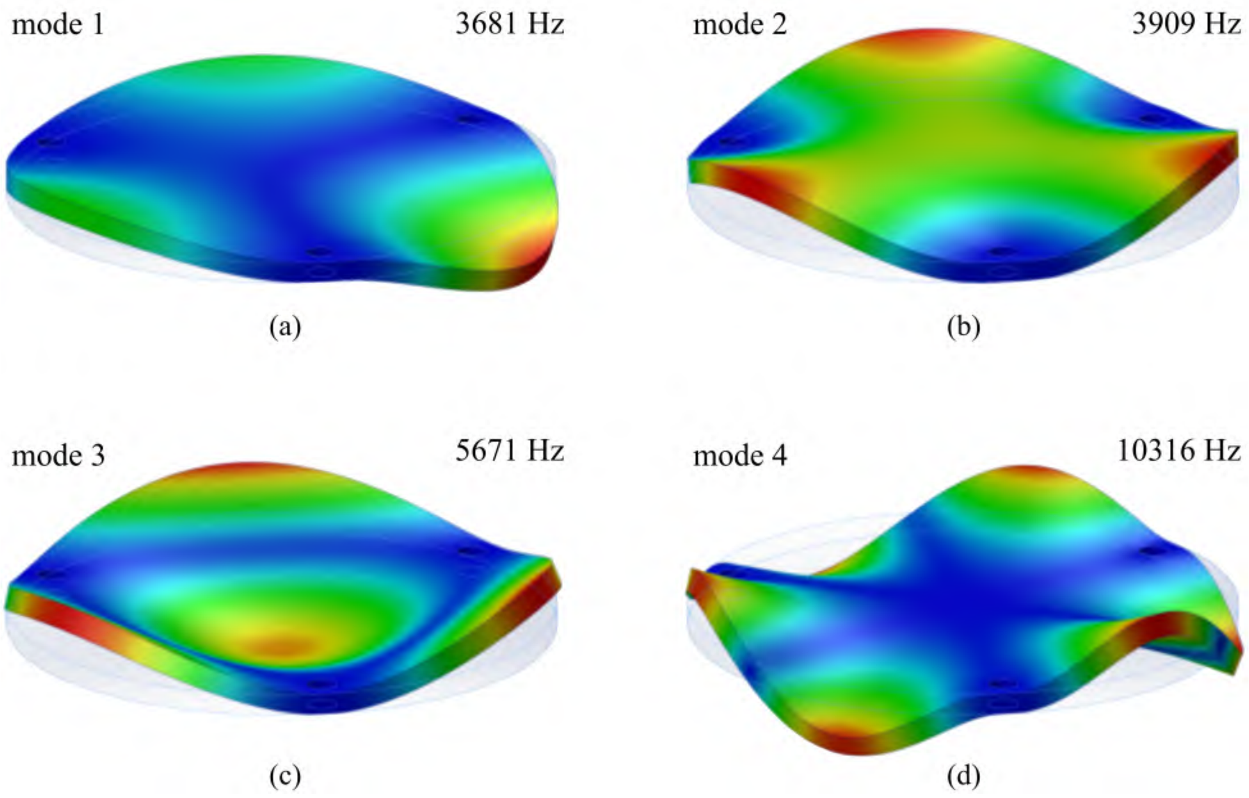


Figure 4: The simulated mode shapes and corresponding natural frequencies of the board, showing: (a) the first mode; (b) the second mode; (c) the third mode, and; (d) the fourth mode.

Finite Element Modeling was also done to supplement the drop-testing data. Frequency studies were performed to estimate the board's mode shapes and natural frequencies, shown in Figure 4, as well as dynamic studies, to estimate the system's strain, in Figure 5. The dimensions for the simulations are shown in Table 1, fixing the PCB on the inside of each standoff hole. These simulations ensure the accuracy of our experiments' natural frequencies and help us find the optimal place for actuation. Additionally, the simulations provide detailed insights into the dynamic response of the board under shock loads, allowing us to identify areas of maximum stress and strain. By validating the simulation results with the experimental data, we can refine our models to more accurately represent real-world conditions.

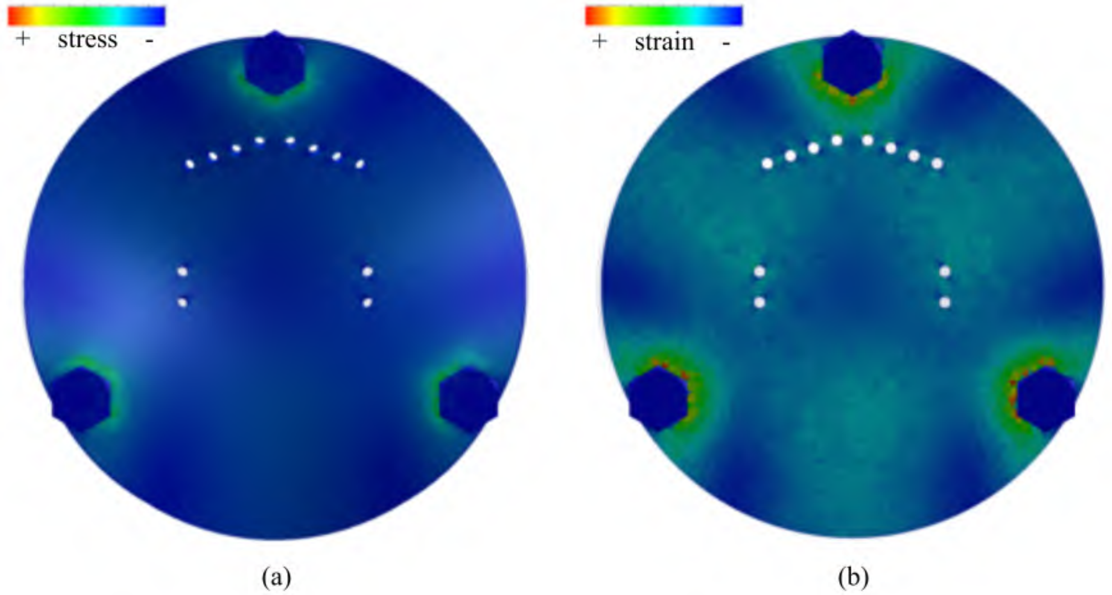


Figure 5: The simulated mechanical response, showing: (a) the stress distribution, and; (b) the strain distribution across the printed circuit board.

RESULTS AND DISCUSSION

This section analyzes the data collected during the drop tests as well as the conclusions drawn from the FEM simulations. The primary focus is on the board acceleration Fast Fourier Transform (FFT), the system Frequency Response Function (FRF), and the system coherence. These calculations are vital for understanding the dynamic behavior of electronic assemblies under shock loads, as well as approximating the optimal positioning of piezoelectric actuators. By pinpointing the optimal locations for these actuators, we aim to enhance the effectiveness of shock mitigation strategies, ensuring the durability and reliability of the electronic assemblies in harsh environments.

The FFT of the board acceleration data generates a frequency spectrum to help in determining the dominant frequencies at which the board vibrates. This information is critical for understanding the board's health state, as abnormal vibrations often indicate potential structural issues or degradation [10] and developing control strategies to reduce these vibrations [11]. Figure 6 shows the FFT of the board acceleration data, with peaks marked by red lines that correspond to the board's natural frequencies. While these frequencies do not exactly match the mode geometries identified in the FEM simulations, the discrepancy is limited to a maximum of 2.4 percent, as shown in Table 2. This small error may be attributed to system inconsistencies, such as variations in the simulation's fixtures or differences in the material properties of the circuit board.

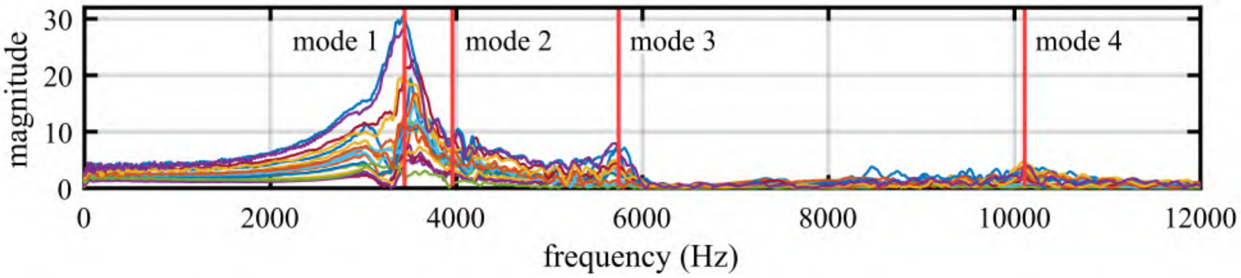


Figure 6: The system response in the frequency domain, shown as the Fast Fourier Transform of the board acceleration signal.

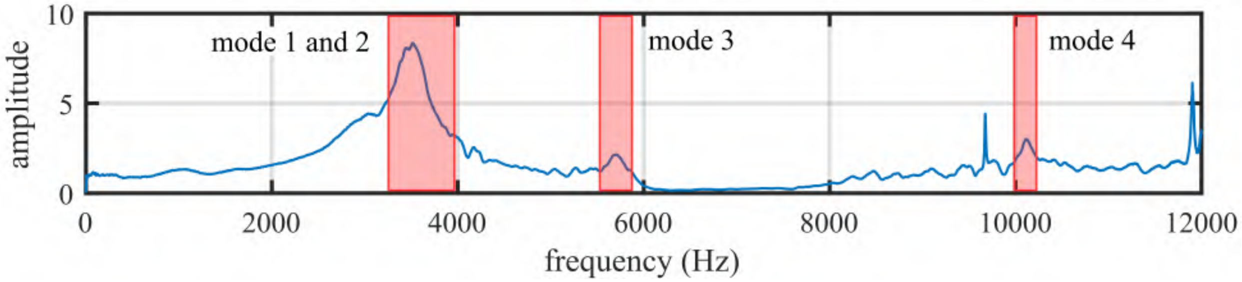


Figure 7: The system frequency response function (FRF), showing the relationship between input excitation and output response across a range of frequencies.

Table 2: Simulated and experimental natural frequencies, including the margin of error between the two.

	mode 1	mode 2	mode 3	mode 4
simulated frequency	3681 Hz	3909 Hz	5671 Hz	10316 Hz
experimental frequency	3600 Hz	4000 Hz	5800 Hz	10200 Hz
margin of error	2.20%	2.33%	2.27%	1.13%

The FRF describes the system's response to input excitation at various frequencies. Analyzing the FRF allows us to understand how the board and supporting structure behave dynamically. This function is derived from the ratio of the output acceleration to the input force in the frequency domain. The FRF aids in the confirmation of resonant frequencies and damping properties, both of which are necessary for the development of successful shock mitigation systems. The FRF results are presented in Figure 7, highlighting the system's resonant peaks.

The system coherence is investigated to ensure the reliability of FFT and FRF analyses. Coherence quantifies the frequency-domain correlation between input and output signals [12]. Typically, strong coherence values (with 1 being the highest) indicate a strong linear relationship between input force and output acceleration, implying that the system's behavior is predictable and well-understood, while poor coherence values (closer to 0) suggest nonlinearities or noise in the system [13]. In the case of this study, however, coherence must be interpreted differently, focusing on these nonlinearities. Initially, the system behaves as a rigid body, exhibiting a strong linear relationship between input force and output acceleration at lower frequencies. As the board reaches its resonant frequencies, the system begins to vibrate independently, leading to nonlinear behavior and a drop in coherence values. Here, values close to 1 indicate linear behavior and the absence of resonance, while values of 0.9 or lower suggest the presence of resonance or modes, where the output decouples from the input. Coherence, shown in Figure 8, highlights this transition, with natural frequencies marked in red and coherence dropping below 0.9, confirming the onset of resonance.

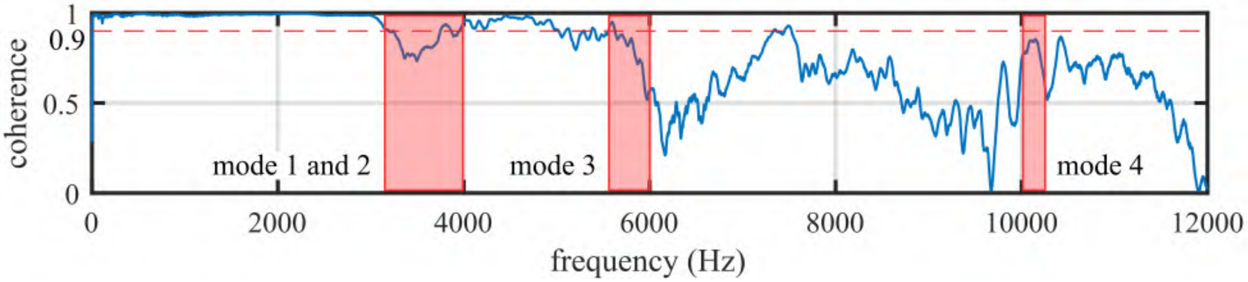


Figure 8: The system coherence, showing the degree of correlation between the input excitation and the output response across frequencies.

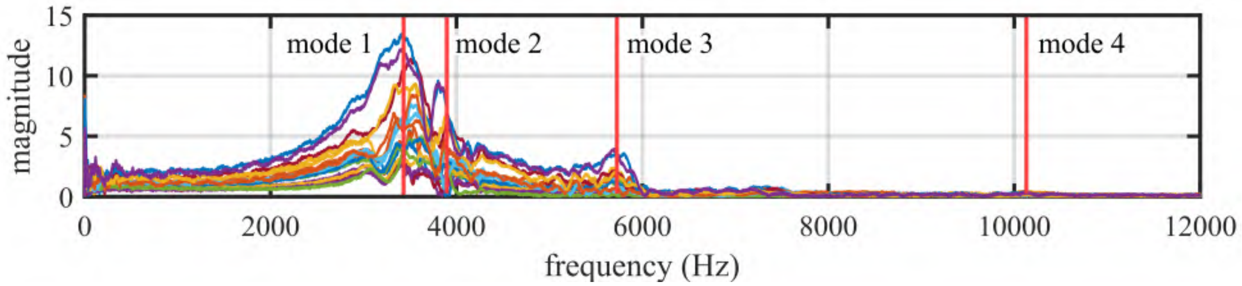


Figure 9: The system response in the frequency domain, shown as the Fast Fourier Transform of the board strain signal.

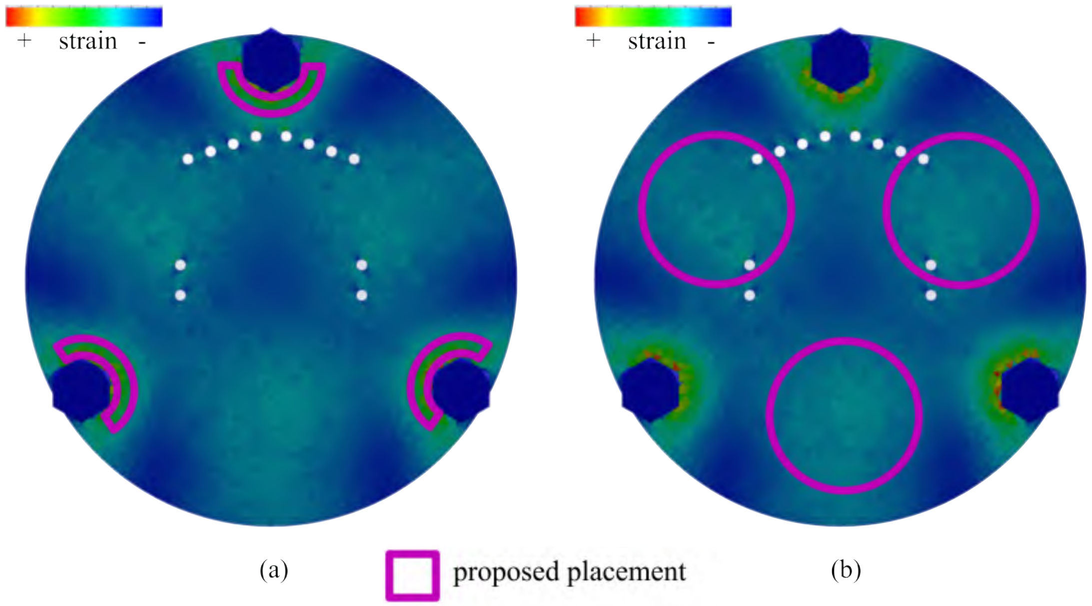


Figure 10: The actuator placement strategies for future investigation, showing: (a) the proposed placement, and; (b) a possible alternative placement.

This work is not limited to only using acceleration data for our experiment's analysis. As stated before, two strain gauges are equipped to the board's center on its top and bottom. Analyzing this data using FFTs and using it to equate our system's frequency response function can also help confirm the system's natural frequencies. Figure 9 shows the FFT of the board's strain data, with peaks marked by red lines that correspond to the board's natural frequencies. This FFT depicts mode 2 much clearer than either the acceleration FFT or FRF, demonstrating the importance of measuring the system's response in different contexts.

After verifying the experimental natural frequencies and comparing them to those found through simulation, we can confidently make use of the simulations to begin estimating where to place the piezoelectric actuators. In a study analyzing damage reduction using piezoelectric components, Baptiste Chomette, et al. confirm that the optimal placement for these components is in areas with higher curvature, i.e. locations with higher strain [14]. Logically, this makes sense. If stiffness is added to areas of any amount of strain, the strain will then be lessened. Therefore, the proposed area for most actuator effectiveness would be near the board's fixtures, or standoffs, as shown on the left in Figure 10. The area of most strain forms a sort of semicircle around the center-facing side of each fixture. Careful examination of the model shows that these areas measure at approximately 3.81 mm in radius. An experiment is currently being designed in order to test the effectiveness of this proposed placement, or if any effectual damping occurs. Alternatively, strain appears to be prominent in between fixtures, though less than those around the fixture. These are areas where modes create the most deformation and, therefore possibly the most damage. This alternate placement will be further studied along with the proposed placement in the future.

CONCLUSION

This paper presents a comprehensive framework for the active shock mitigation of electronic assemblies. By combining experimental data from drop testing with FEM simulations, we were able to get significant insights into the dynamic behavior of these assemblies under high impact. The key findings from the examination of the board's response FFT, system FRF, and system coherence have helped determine the best location for piezoelectric actuators.

Findings suggest that positioning actuators in high-strain places, notably around the board's fixtures, is most likely to reduce structural deflection and increase assembly durability. Both experimental and simulation data support this strategic placement since they demonstrate a high correlation in determining the board's inherent frequencies and mode shapes. The usage of piezoelectric actuators, which can convert electrical energy into mechanical strain, has been shown to be an effective way for dynamic deflection mitigation and shock absorption. Their small size, high responsiveness, and precision make them excellent for use in compact electronic systems where space and weight are important considerations. Future research will focus on improving these control techniques and experimentally validating the proposed actuator placements. Additional tests will be performed to assess the efficacy of the identified ideal placements as well as to investigate additional places that may benefit from shock attenuation.

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