Experimental Analysis to Enable Low-Latency Structural Health Monitoring for Electronics in High-Rate Dynamic Environments

Ryan Yount[1], Trotter Roberts[1], Jacob Dodson[3], Adriane Moura[4], and Austin R.J. Downey[1,2]

[1]Department of Mechanical Engineering, University of South Carolina, Columbia, SC 29208
[2]Department of Civil and Environmental Engineering, University of South Carolina, Columbia, SC 29208

[3]Air Force Research Laboratory, Eglin AFB, FL 32542

[4]Applied Research Associates Inc, Niceville, FL 32578

ABSTRACT
Electronic assemblies subjected to high-rate dynamic environments offer the potential of increased robustness and resilience to mechanical loading if integrated with active feedback mechanisms that respond when damage is present in the system or alter mission outcomes when appropriate. To enable active structural control of electronic assemblies, the rapid detection of mechanical damage is crucial. This study focuses on monitoring an electronic package under a shock and introduces a method for enhancing the durability of printed circuit boards through onboard frequency-based damage detection. The experimental setup is comprised of printed circuit boards equipped with representative electronic packages enhanced with embedded sensing capabilities, subjected to controlled shock tests using a drop tower system. This study details the data acquisition process, Fast Fourier Transform (FFT) implementation on the electronic assembly, and the algorithmic strategies for peak detection and response initiation. The frequency-based damage detection system has the capability to increase the robustness and resilience of systems experiencing shock when combined with a closed-loop control system. In future work, the electronic assembly will be re-designed to autonomously process the resulting vibration data using an FFT computed at the edge to identify a change in the critical frequency components associated with potential damage. This work not only extends the understanding of printed circuit board dynamics under stress but also showcases the practical applications of embedded signal processing to enable enhanced system durability and reliability.

Keywords: PCB, Fast Fourier Transform, shock mitigation, embedded signal processing

INTRODUCTION
The ability to rapidly detect structural damage in electronic assemblies exposed to high-rate dynamic events is crucial for ensuring reliability and longevity [1]. High-rate dynamic events occur frequently in various contexts, including automotive collisions, and aviation accidents. These high-rate dynamic events, or mechanical shock, are defined as abrupt modifications in force, position, velocity, or acceleration, which induce transient states in the system [2]. Such shocks can lead to rapid and unpredictable responses within the structural integrity of components, making it critical to ensure that systems can recover or adapt in real time. The integration of active feedback mechanisms capable of swiftly detecting and responding to structural damage plays a pivotal role in enhancing the robustness of such systems. These mechanisms employ a network of sensors that continuously monitor the system's state, detecting deviations from normal operation that may indicate damage or failure. Upon detecting an anomaly, the system can immediately implement corrective actions—such as adjusting loads, altering operational parameters, or rerouting energy flows—thereby preventing further damage. This capability not only mitigates potential failures but also optimizes mission outcomes by adding the possibility of adapting system behavior in response to detected damage [3]. By adapting the system's behavior in response to detected damage, these active feedback mechanisms ensure that mission-

critical tasks can continue with minimal interruption. Furthermore, this adaptability reduces the need for redundant system designs and manual intervention, thereby increasing operational efficiency and prolonging the system's lifespan [4]. Electronic packages subjected to shock and vibration must endure rigorous testing to validate their durability under real-world conditions. A useful approach to enhancing structural health is onboard frequency-based damage detection [5]. Traditional methods such as accelerometer-based monitoring for Structural Health Monitoring (SHM) have been extensively studied. Accelerometers are commonly used to capture vibration data and analyze modal characteristics of Printed Circuit Boards (PCBs) under varying mechanical loads [6]. Studies aimed at investigating how PCBs respond to mechanical stresses and dynamic forces contribute valuable insights into understanding how to build more robust electronics [7]. By embedding sensors within PCBs and employing signal processing techniques like Fast Fourier Transforms (FFTs) [8], it becomes feasible to monitor vibration signatures of electronic assemblies during and after shock events. The analysis of frequency components allows for the rapid identification of changes indicative of mechanical damage, enabling response mechanisms to mitigate potential failures.

In shock events, the impact can adversely affect the entire system, highlighting the importance of controlled and repeatable testing methodologies. To address this challenge, shock test systems such as drop towers are used, which simulate abrupt mechanical impacts to evaluate how electronic assemblies withstand sudden forces. These systems provide controlled, repeatable environments that replicate the dynamic stresses encountered during deployment. Dynamic analysis techniques have similarly been applied to investigate the behavior of electronic assemblies under mechanical shock loads. For instance, studies have focused on scenarios such as the dynamic analysis of fixed-fixed beams subjected to mechanical shock, revealing critical insights into the structural response and potential failure modes under high-rate loading conditions [9]. Furthermore, the fundamental principles of SHM have been clarified through comprehensive frameworks and theoretical studies. These include the axioms and foundational concepts that underpin effective SHM practices, guiding the development of robust monitoring strategies aimed at enhancing the reliability and longevity of electronic systems [10]. For electronic feedback, resistive circuits have been employed for continuity measurements in electronic assemblies, facilitating real-time assessment of circuit integrity under dynamic conditions [11]. This method is particularly effective in detecting and diagnosing potential faults promptly, thereby enhancing the reliability of electronic systems in high-stress environments.

Advancements in edge computing present promising avenues for real-time data processing in SHM applications. Edge computing architectures enable data analysis closer to the source, which reduces latency [12] and supports timely decision-making based on monitored parameters [13], particularly in smart electronics applications [14]. This capability is particularly advantageous in SHM, where rapid responses to dynamic events are critical for preemptive maintenance and operational efficiency in electronic assemblies.

This study focuses on the development and implementation of a frequency-based damage detection system for electronic assemblies undergoing shock tests using a drop tower setup. The experimental framework involves equipping PCBs with embedded sensors capable of acquiring the necessary vibration data. An FFT algorithm is employed to extract critical frequency components associated with structural integrity, facilitating rapid assessment of damage. Key aspects of this research include a detailed description of the data acquisition process, the implementation of FFTs on the acquired data, and the algorithmic strategies for peak detection and initiation of response actions. The contribution of this work is the advancement our understanding of PCB dynamics under shock-induced mechanical stresses and introducing the application of embedded signal processing for enhancing durability. This study also contributes to the broader field of structural health monitoring in electronic assemblies. While this study focuses on frequency-based damage detection, the next step will involve developing edge computing frameworks to implement these processes in real-time.

METHODOLOGY

To determine the expected modal frequencies of the PCBs under investigation, vibrational simulations were conducted using finite element analysis software. The geometry and boundary conditions used in the simulation are provided in Figure 1. For this experiment, a 5.5 inch PCB was clamped with a pseudo-fixity setup. Since the clamp extended 0.5 inches and was positioned 0.5 inches from the board's edge to provide space for data acquisition wiring, the effective length of the PCB measured from the edge of the clamp to the opposite edge of the board was determined to be 4.5 inches.

The simulations were performed with and without the additional mass attached to the board, aiming to understand the impact of the mass on the board's vibrational characteristics. A frequency analysis was performed to identify the natural frequencies and mode shapes of the PCB as shown in Figure 2. The material properties used in the simulations are shown in Table 1. This analysis was useful in determining expected outcomes for how the board will respond to mechanical shock and the resulting vibrations.

Table 1: Material properties used in the simulations of the PCB

Material	Density (lb/ft^3)	Young's Modulus (psi)	Poisson Ratio
FR4	118.64	2,697,707	0.2

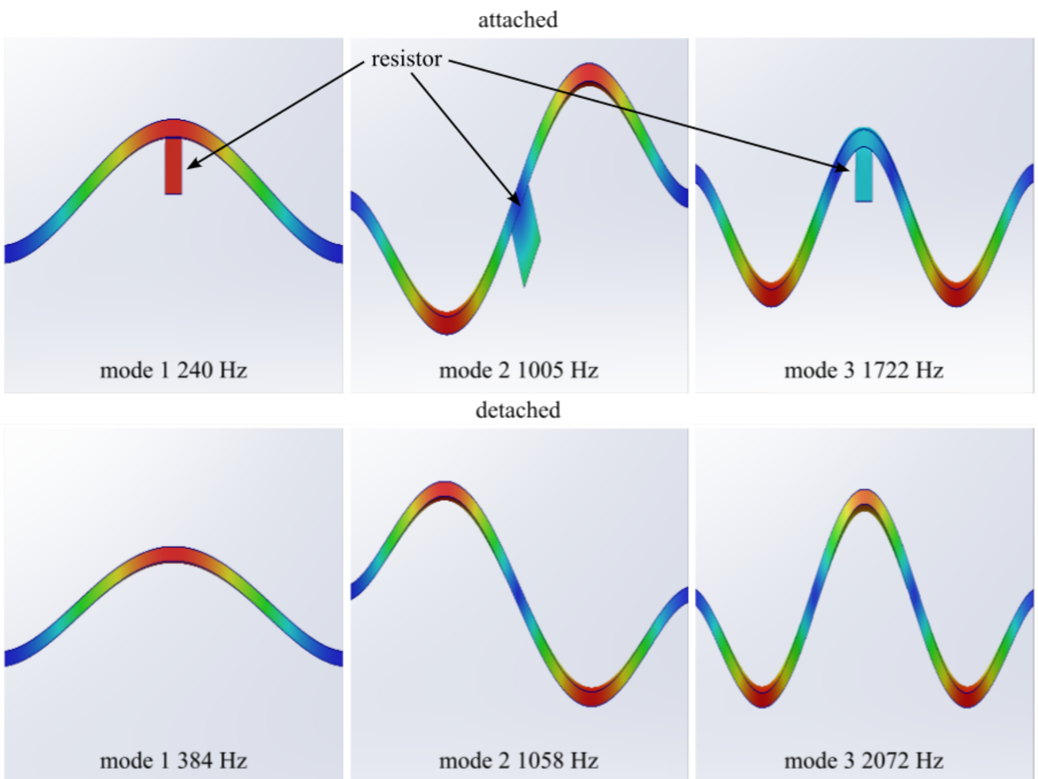

Figure 2: Simulation results showcasing the mode shapes and frequencies with and without the mass attached.

Notably, the first mode, which is of primary interest in this study, exhibited significant variation depending on the presence of additional mass. With the resistor connected to the board, mode 1 was found to have a frequency of 240 Hz. After the resistor was removed, the frequency of mode 1 increased to 384 Hz.

To enable the detection of mechanical damage in the PCBs, a frequency-based approach utilizing FFTs is employed [5]. This method leverages the inherent vibration signatures of the assemblies captured by the embedded sensors during shock. The FFT

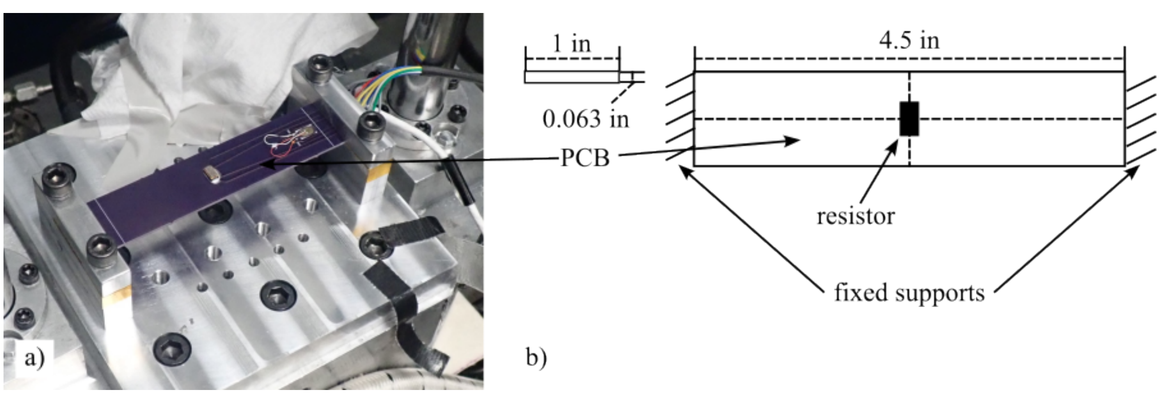

Figure 1: a. PCB configured in the test setup b. Geometry and boundary conditions created for simulation of the PCB.

algorithm converts the time-domain vibration signal $x(n)$ into the frequency domain $X(f)$, as shown in Equation 1, allowing for the identification of specific frequency components associated with structural integrity. The signal is decomposed into its frequency components using the FFT. Next, the resulting spectrum is normalized by dividing by the number of samples. Lastly, only the positive side of the frequency spectrum is retained, as the FFT output is symmetric for real-valued signals.

$$X(f) = \sum_{n=0}^{N-1} x(n) e^{-j2\pi fn/N} \tag{1}$$

where $x(n)$ represents the sampled time-domain signal, N is the number of samples, and f is the frequency.

Algorithmic strategies for peak detection can be implemented on edge computing devices to provide more rapid damage assessment. Such algorithms are designed to analyze FFT-transformed data and identify significant peaks or changes in critical frequency components. As damage occurs, a shift in the modal frequencies is expected. Some strategies include threshold-based peak detection, pattern recognition, and adaptive filtering.

To implement edge computing for rapid damage assessment on the PCBs, several important factors must be considered. A suitable microcontroller capable of handling real-time signal processing tasks should be chosen. This microcontroller must be able to connect to all of the sensors in the system and have a high enough sampling rate to capture the vibration signals of interest. An algorithm to perform and read an FFT on the captured data must be deployed on the microcontroller. Other traits of interest would be a program to trigger a control response such as damping the system when vibrations exceed a threshold and wirelessly transmitting data to an external monitoring system.

While not implemented in this study, the integration of an edge processing device with the damage detection approach enables the implementation of a closed-loop control system. This system would monitor real-time vibration data processed on the edge and could initiate control decisions to mitigate mechanical vibrations when deemed critical. This approach could enhance the resilience of electronic assemblies by actively managing mechanical loads and optimizing performance under dynamic environments. It showcases the potential of edge computing in enhancing system durability through responsive, autonomous control mechanisms.

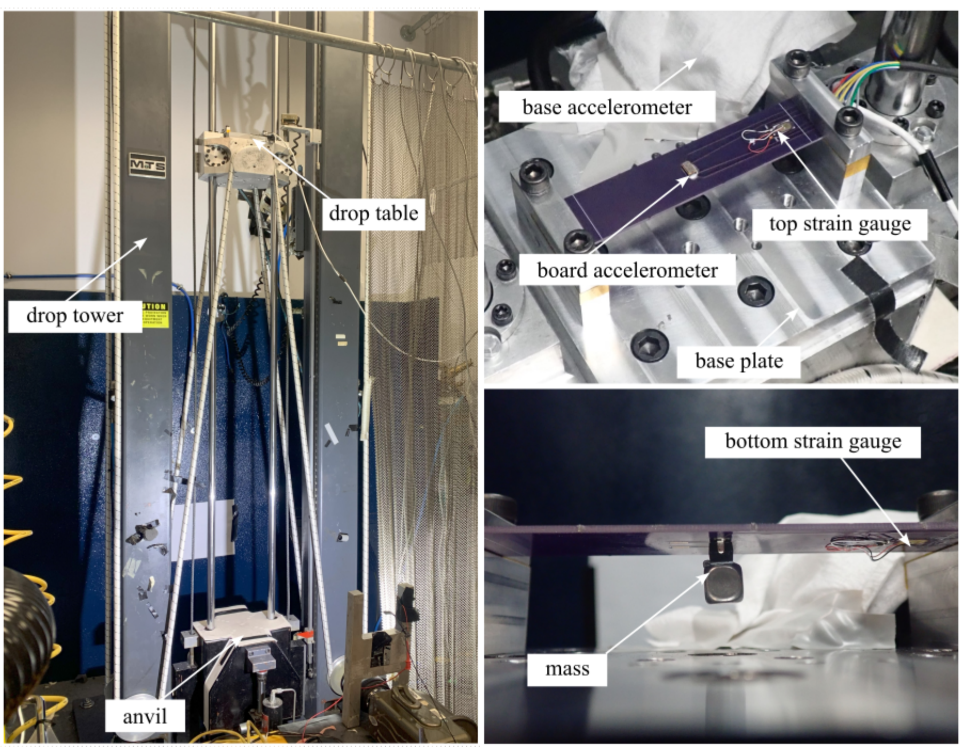

Figure 3: Drop tower test setup including the top and bottom of the fixed-fixed PCB.

EXPERIMENTAL PROCEDURE

The experimental setup utilizes a drop tower system to subject electronic packages to controlled shock events. This system, as shown in Figure 3, simulates abrupt mechanical impacts to assess the resilience of the assemblies under dynamic conditions. Controlled impacts allow for systematic evaluation of how electronic components respond to sudden forces, which is crucial for understanding their durability in high-rate dynamic environments.

The electronic packages under test were configured as 4.5-inch PCBs clamped as a fixed-fixed beam. Each PCB is equipped with a piezoresistive accelerometer, two strain gauges, and a resistor acting as a mass setup in a resistive circuit. This setup allows for the precise detection of impacts that cause the mass to fall, thereby indicating the onset of structural failure. A close-up example of the PCB before and after detachment is shown in Figure 4.

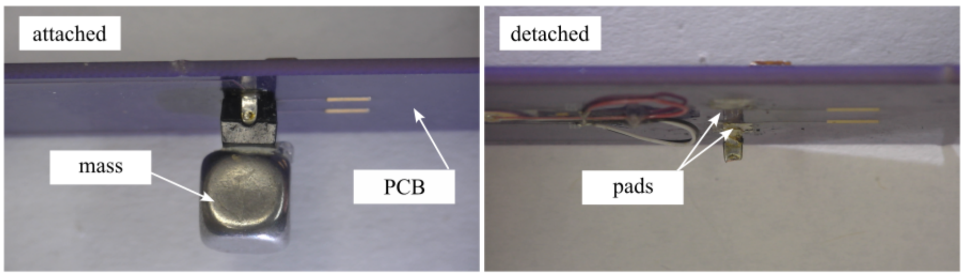

Figure 4: Close view of the PCB being tested before and after the mass was detached.

The integration of the shock test system and DAQ facilitated rapid data analysis during testing. The data acquisition process synchronized an accelerometer on the base of the hammer with the sensors on board the PCB for accurate correlation of input and output signals. Additionally, a voltage divider circuit, as shown in Figure 5, was used to monitor the integrity of the resistor. The DAQ recorded the output voltage from the circuit, which was 2.5 volts while the resistor was intact and dropped to 0 volts when the resistor detached, providing a reliable time reference for failure events.

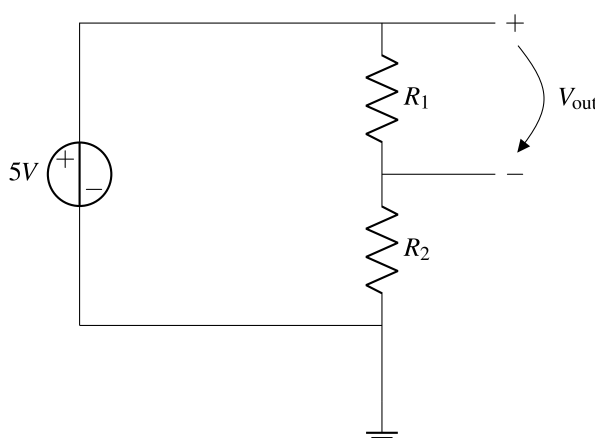

Figure 5: Voltage divider circuit used in the experiment to read from the PCB resistor.

The signals were sampled at a rate of 2 million samples per second. While this sampling rate is significantly higher than necessary, it ensured precise data capture and avoided aliasing. A high-speed camera was used in conjunction with the DAQ to visually capture the precise moment of damage initiation on the PCBs, as shown in Figure 6. This visual cue was a supplement of sensor data, enhancing the understanding of failure mechanisms under high-rate conditions.

After each test, the clamps holding the PCBs were torqued to 15 in lbs to standardize test conditions as each clamped end simulated a fixed support. Testing sequences ranged from lower to higher gravity (g) shocks, systematically increasing impact intensity to gather comprehensive data points before observing failure. An example of how the shock propagated throughout the PCB is shown in Figure 7.

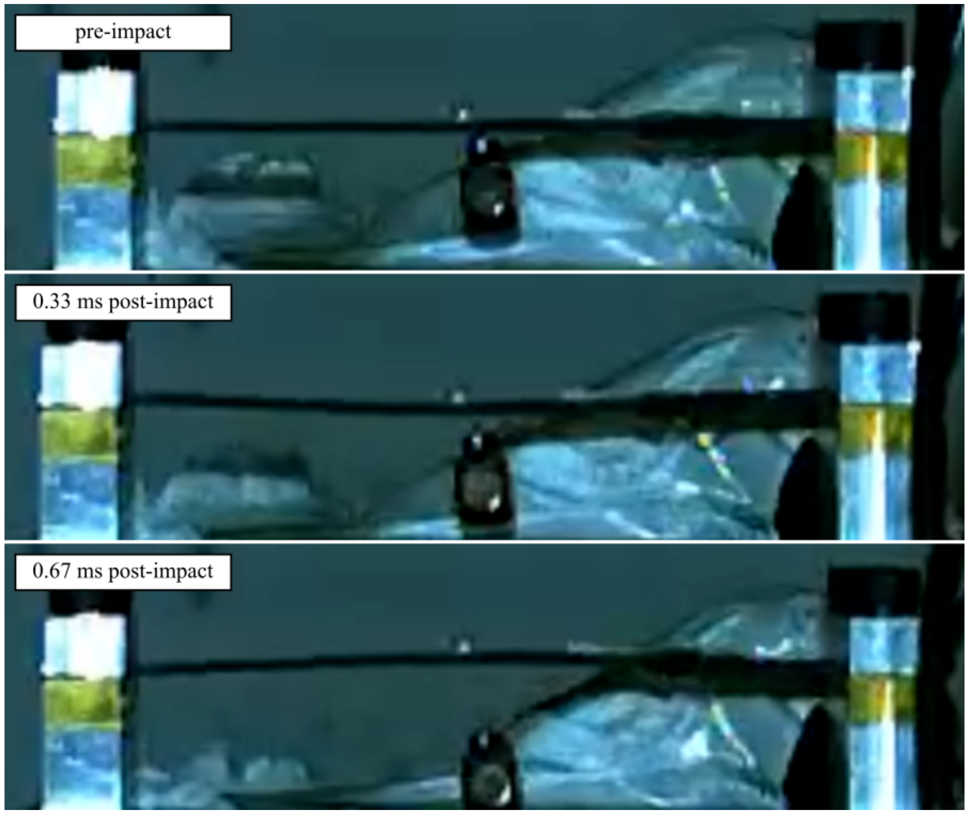

Figure 6: Frames from a high-speed camera showing the board during a resistor failure drop.

RESULTS AND DISCUSSION

The experimental data acquired from the shock tests, published in a public repository [15], revealed significant findings regarding the effect of the resistor circuit under stress conditions. Across multiple trials, the provided DC voltage to the resistor circuit stayed relatively constant until a shock occurred where the mass fell. A comparison of time domain signals to assess the

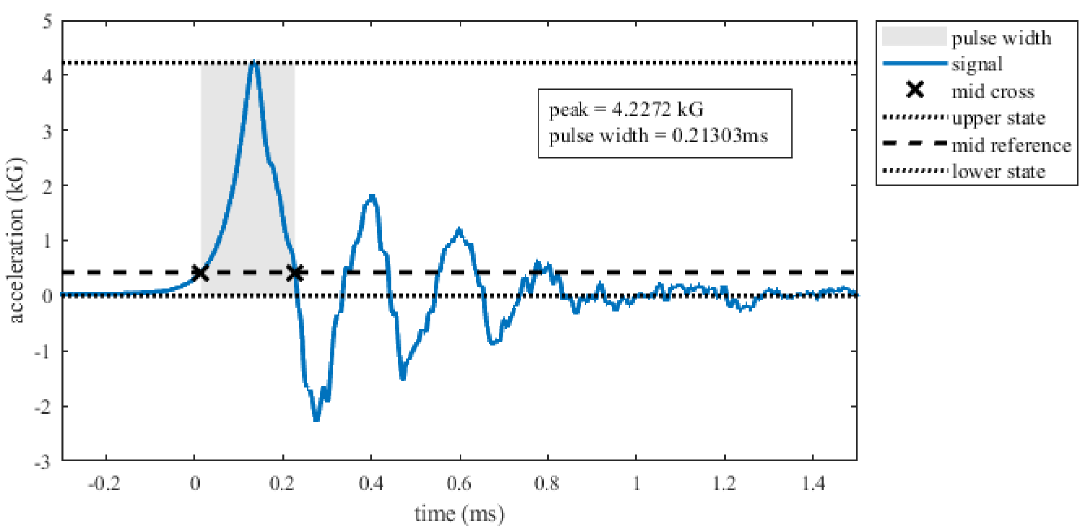

Figure 7: Analysis of a time domain signal from the accelerometer on the board during a shock test.

behavior of the PCB during the failure test was plotted in Figure 8. Some differences are shown during the response, which can be attributed to sequential excitations due to the detached component colliding with the board.

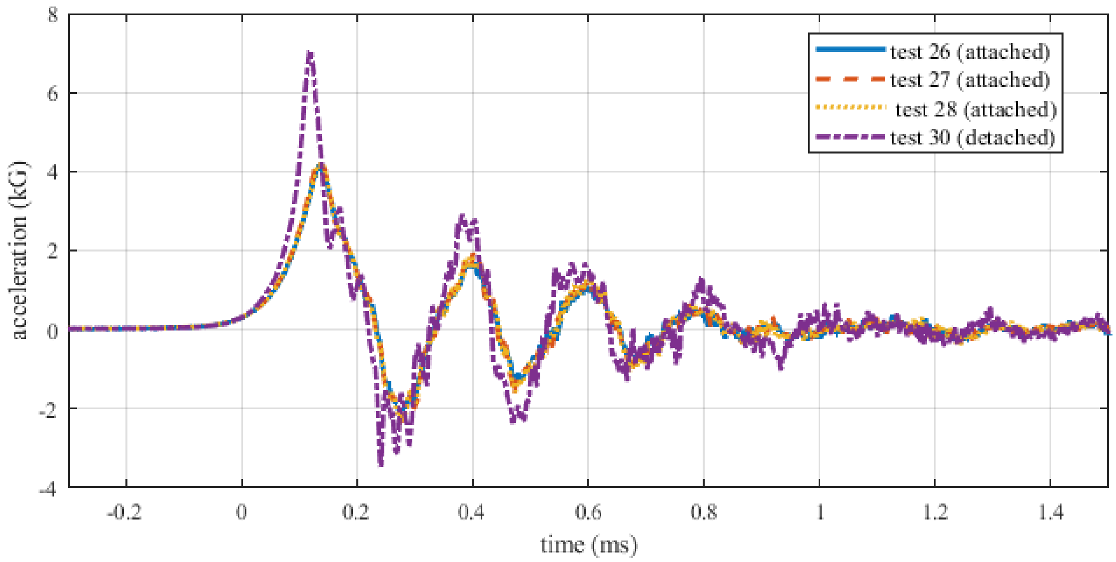

Figure 8: Time series representation of shock tests leading up to a final test where the resistor became detached.

The Fourier analysis conducted on each test indicated pronounced alterations in the frequency signatures of the boards following the mass detachment, as shown in Figure 9. Specifically, when observing the first modal frequency, there was a significant change in line with the change expected from simulations. In Table 2, an analysis of the difference between the frequencies seen in the tested data and the frequencies expected from the simulations is shown.

Condition	Simulated Frequency (Hz)	Tested Frequency (Hz)	Absolute Error (Hz)	Percentage Error (%)
With resistor	240	258	18	7.50
Without resistor	384	354	30	7.81

Table 2: Error analysis of the frequencies seen from the simulations and the tested data

This analysis highlights the impact of circuit failure on the electrical signal's spectral content, underscoring the feasibility of rapid damage detection using frequency analysis.

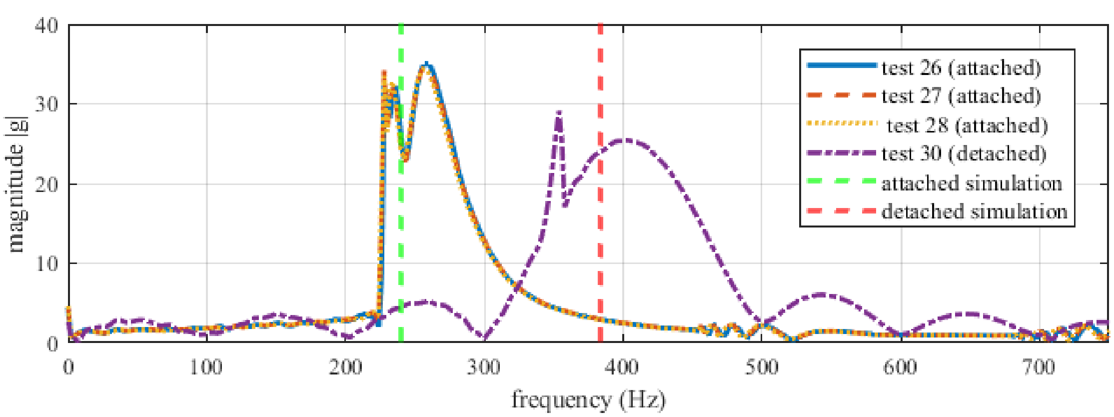

Figure 9: Sequential Fourier transforms from shock tests until the resistor becomes detached.

CONCLUSION

This study demonstrates the effectiveness of frequency-based damage detection using FFTs in identifying mechanical damage in electronic assemblies subjected to high-rate dynamic environments. The notable frequency changes observed upon the occurrence of damage highlight the viability of this method for enhancing SHM in such scenarios.

Integrating edge computing into the damage detection process offers several potential benefits. By processing FFT-transformed data locally on edge devices, the system can achieve rapid detection of damage events. This capability reduces latency in decision-making and lays a foundation for implementing responsive control strategies to mitigate mechanical vibrations before they lead to failures.

Future research on this project will include a multi-faceted approach including the implementation of an edge computing device, the optimization of sensor placements, the development of more advanced simulation models, and the integration of these processes with usual packing practices used to mitigate shock.

This paper establishes the foundation for the future development of edge computing architectures, which will enable the autonomous detection of structural changes in real-time. While this work successfully demonstrates frequency-based damage detection, the implementation of closed-loop control using edge devices will be pursued in subsequent studies.

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