SHM in Space: On-Orbit Impact Monitoring for Satellite Structures

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ABSTRACT

The rapid proliferation of satellites, scientific equipment, and debris orbiting the Earth necessitates advanced solutions to enhance the safety and efficiency of future space missions. As low Earth orbit becomes increasingly congested, the risk of unforeseen impacts grows, threatening the stability of orbital assets and jeopardizing mission success. Hence, systems to monitor the condition and integrity of satellites and other space vehicles are critical. An integrated Structural Health Monitoring (SHM) system can provide both real-time impact detection and ongoing damage assessment for orbiting vehicles, making it a key element of On-orbit Servicing, Assembly, and Manufacturing (OSAM). In this work, the authors explore the application of Acellent's SHM system for impact detection and quantification. The system incorporates both "passive" and "active" operational modes. The first set of experiments focused on low-velocity impacts mimicking docking operations. A drop-tower test using aluminum- and composite-tipped projectiles simulated interactions between dissimilar vehicles. In the second set of experiments, each structure was impacted with projectiles at ballistic velocities of 1000–2000 km/s to simulate collisions with meteorites and other space debris.

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The results demonstrated the potential of an integrated SHM system to successfully detect impacts and assess damage to structures deployed in the vacuum of space. This study suggests a critical role for SHM in monitoring space vehicles as a part of a broader OSAM strategy.

1. INTRODUCTION

Satellites and other space-based systems form the backbone of modern communication, navigation, and defense infrastructure. Despite their strategic importance, these platforms operate in highly challenging environments and are subjected extreme temperature fluctuations, intense radiation exposure, mechanical vibrations, and the ongoing threat of high-velocity collisions with micrometeoroids, orbital debris, or low-velocity impact by other spacecraft during docking or other process. Ensuring structural integrity under such conditions demands continuous monitoring solutions. Structural Health Monitoring (SHM) has become a critical technology in this context, offering real-time assessment of structural condition through lightweight, integrated sensor networks. SHM systems facilitate the detection and evaluation of anomalies, including impact events, and have applications ranging from routine condition monitoring to On-orbit Servicing, Assembly, and Manufacturing (OSAM), where autonomous inspection capabilities are essential.

Among SHM technologies, systems based on PZT transducers are particularly versatile, offering both active and passive monitoring capabilities. Impact detection can be approached through model-based techniques [1]-[5] or data-driven methods, including artificial neural networks [6]-[8]. In addition to impact detection, PZT-based SHM systems are capable of monitoring vibration levels and conducting ultrasonic guided-wave inspections, a feature especially valuable for satellite operations [9], [10]. Acellent Technologies' SMART Layer® system is a well-established example of a PZT-based SHM solution, featuring dynamic sensing capabilities that allow for both real-time impact monitoring and detailed structural interrogation. Depending on the hardware used, the system operates in passive mode to detect and localize impacts or in active mode to perform acousto-ultrasonic inspections, thereby supporting comprehensive structural diagnostics [11]. This dual-mode functionality positions PZT-based SHM systems as a critical asset for next-generation spacecraft, enabling detection, localization, quantification, and prognosis of structural damage across a wide range of mission profiles.

This study focuses on evaluating the performance of Acellent Technologies' PZT-based SHM system for detecting and localizing impact events under simulated space conditions, such as vacuum environment. The research explores the feasibility of using the SMART Layer® sensor network and its associated hardware and software solutions for in-situ impact detection on spacecraft structures. The SHM system employs surface-bonded PZT transducers that function as both actuators and sensors, enabling both passive and active monitoring modes. Experiments were designed to simulate a range of impact scenarios, from low-velocity events representative of on-orbit servicing activities to high-velocity collisions resembling micrometeoroid and debris strikes.

Tests included impacts at various angles, velocities, and projectile materials, with a focus on evaluating sensor performance and impact localization accuracy. This outcome is to confirm the operational acceptance of PZT-based SHM technology for future space applications and contribute to improved safety, situational awareness, and durability of spacecraft.

2. LOW VELOCITY IMPACT TESTS

2.1 Specimens

A 6U satellite was selected as the representative structure, offering an optimal balance between complexity and scale, making it suitable for experiments in a vacuum chamber. The typical dimensions of a 6U satellite are $200 \times 340.5 \times 100$ mm^3. The satellite frame is generally constructed with one of two main panel designs: flat panels or orthogrid and isogrid panels. In this study, three types of specimens, representative of 6U satellite panels, were considered: aluminum panels of uniform thickness; aluminum panels with orthogrid ribs; carbon-fiber composite panel and aluminum honeycomb specimen.

3. IMPACT DETECTION USING SHM SYSTEM UNDER VARYING CONTACT CONDITIONS

Low-velocity impact tests were conducted to evaluate the SHM system's capability to detect mechanical contact with another spacecraft or structural element. In this work, the performance of a SHM system was examined under various low-

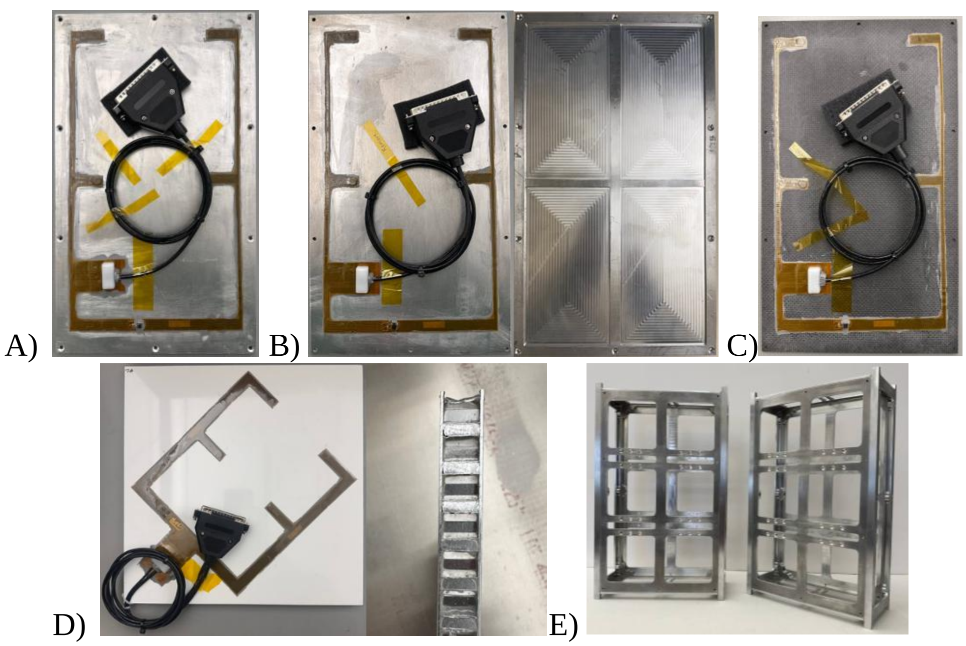


Figure 1Test articles with installed SMART Layer sensor layout: (A) Aluminum panel of uniform thickness; (B) Aluminum panel with orthogrid ribs (top and bottom views); (C) Carbon fiber composite panel (D) Aluminum honeycomb panel (top and side views); (E) 6U satellite frame.

velocity impact conditions. The effects of impact height, angle of incidence, and projectile material on the system's ability to detect and localize impacts were investigated. Tests were carried out on aluminum panels of uniform thickness and carbon fiber composite panels using a custom-designed drop tower setup. Impacts were produced with projectiles made of different materials, e.g. aluminum and composite, representing contact with structures of varied composition, and were applied at multiple locations and incidence angles to evaluate the system's sensitivity across a wide range of impact scenarios.

3.1 Experimental Setup

The impact experiments were performed on a custom designed drop tower. The panel specimen was fixed in the rigid frame and placed beneath the drop tower guide. SMART Layer sensor layout was connected to AIM hardware. Data processing was performed by AIM software. Experimental setup is shown in Figure 2, A**Error! Reference source not found.**. Two types of projectiles used in the low-velocity study—steel bodies equipped with tips made of aluminum 6061 and carbon-fiber composite are shown in Figure 2, B. This was done to investigate the effect of projectile's material on the impact signal.

3.2 Effect of Impact Parameters on SHM Response

To investigate the influence of impact height on the response of the SHM system, a series of low-velocity impact tests were performed. For the aluminum panel, projectiles were released from heights of 40 cm and 60 cm. Tests were conducted using both aluminum and composite projectiles to assess the influence of projectile material on the system's response.

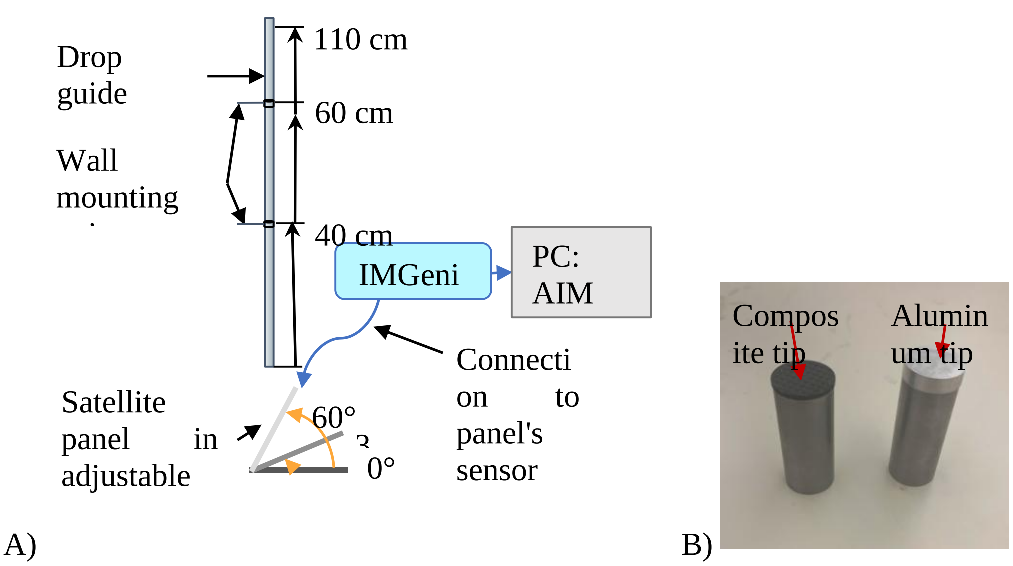


Figure 2. (A) Schematic of the drop tower test; (B) Projectiles with aluminum and composite tips.

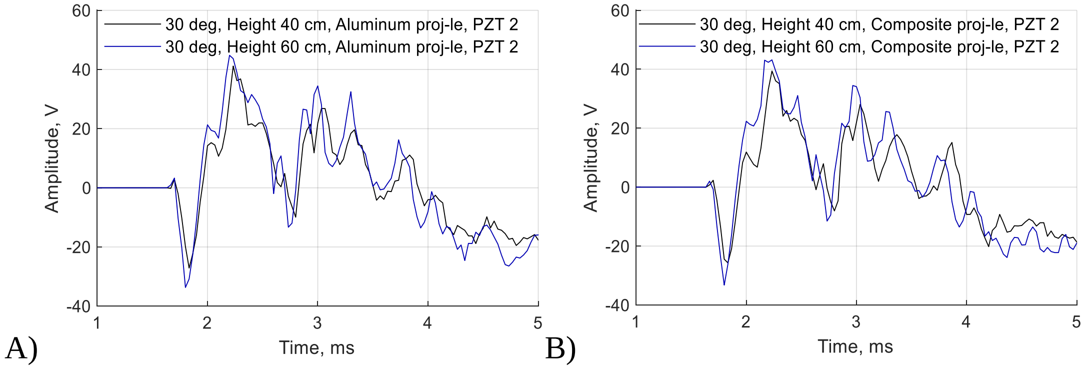


Figure 3. (A) Zoom-in portion of the signals for an aluminum panel; PZT #2, angle 30 degree; for 40- and 60-cm height, aluminum projectile; (B) Zoom-in portion of the signals for an aluminum panel; PZT #2, angle 30 degree, for 40- and 60-cm height, composite projectile

The effect of impact angle on the response of the SHM system was evaluated to understand how variations in the angle of incidence influence signal characteristics. Tests were conducted with the panel inclined at 0-, 30-, and 60-degrees relative to the projectile's direction to replicate different mechanical contact scenarios that may occur in real-life.

The experimental results demonstrated that increasing the drop height led to higher signal amplitudes, confirming a direct correlation between impact energy and the SHM system's response. Tests with inclined panels showed that as the impact angle increased, the amplitude of the recorded signals decreased, indicating reduced energy transfer to the structure at oblique angles. Additionally, while the projectile material had only a minor effect on the overall signal characteristics, subtle differences in amplitude and arrival time suggest the potential for distinguishing between different materials under controlled conditions.

3.3 Impact Localization for Aluminum Panel of Uniform Thickness and Composite Panel

Impact detection experiments were conducted on both aluminum panel of uniform thickness and composite using AIM hardware and software. Impacts were applied at various locations, and the system's ability to localize the point of contact was

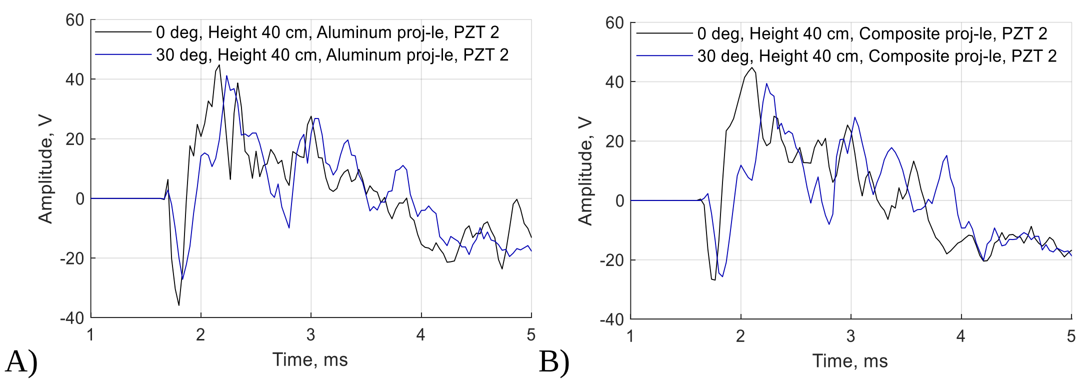
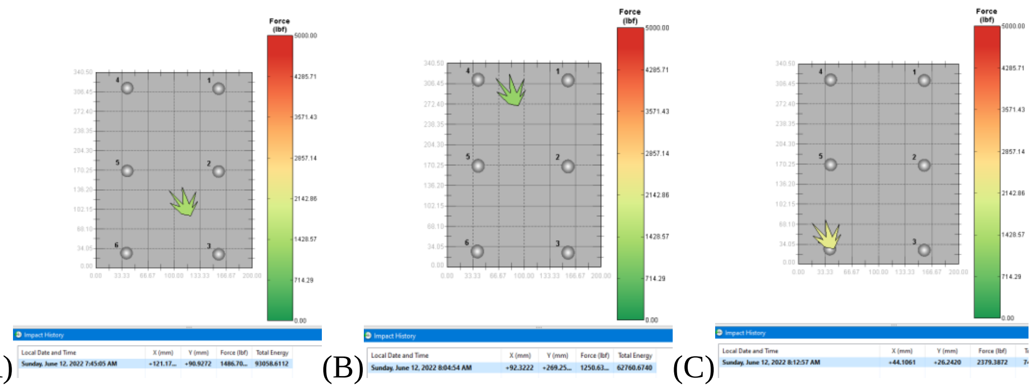


Figure 4. (A) Zoom-in portion of the signals for an aluminum panel; PZT #2, height 40 cm; for 0- and 30-degree inclination, aluminum projectile; (B) Zoom-in portion of the signals for an aluminum panel; PZT #2, height 40 cm, for 0- and 30-degree inclination, composite projectile.

assessed. The predicted impact coordinates obtained from the SHM system were compared with actual measured locations, and localization errors were quantified in both X and Y directions. The examples of impact detection obtained by AIM software for aluminum panel of uniform thickness for Location 1, 2 and 3 are shown in Figure 5 a-c.



(A) (B) (C)

Figure 5. Impact location map obtained with AIM Software for aluminum panel of uniform thickness for (A) Location 1; (B) Location 2; (C) Location 3.

For the aluminum panel, root mean square errors vary between approximately 16 mm and 27 mm, depending on the impact location, while the composite panel showed slightly larger deviations in certain tests. These results demonstrated reliable detection performance across different test scenarios.

4. HIGH VELOCITY PROJECTILE TESTING OF SATELLITE PANELS

4.1 Impact Tests

To characterize the response and evaluate the survivability of a PZT sensor-based SHM system under extreme conditions, a series of high-velocity projectile impact tests were conducted. High velocity impact testing was conducted using a rifled-bore powder gun with a 7.62 mm diameter bore. This gun was integrated into a vacuum stainless-steel chamber with data access ports and optical windows. Vacuum pumps attached to the test chamber allowed testing in atmospheres ranging from ambient (~86 kPa) down to a typical test vacuum of less than 10 torr. Test projectiles were CNC machined from copper and had a weight of 8.4 g and diameter of 7.11 mm. After the projectiles are fired, they impact a thin trigger plate with embedded wires. High speed cameras are triggered from the falling edge signal associated with the breaking of embedded trigger wires.

In this work, schlieren imaging was employed to visualize projectile impacts on test specimens inside a vacuum chamber. A collimated-light, lens-type schlieren setup was used to capture high-contrast images of the projectile and any resulting fragmentation without perspective distortion. Although traditionally applied to visualize compressible flow phenomena, the schlieren system here provided clear imaging of impacts even in vacuum conditions, aiding in the assessment of projectile behavior and structural response during testing. The example of the schlieren image for the orthogrid panel tested in air is provided in Figure 6.

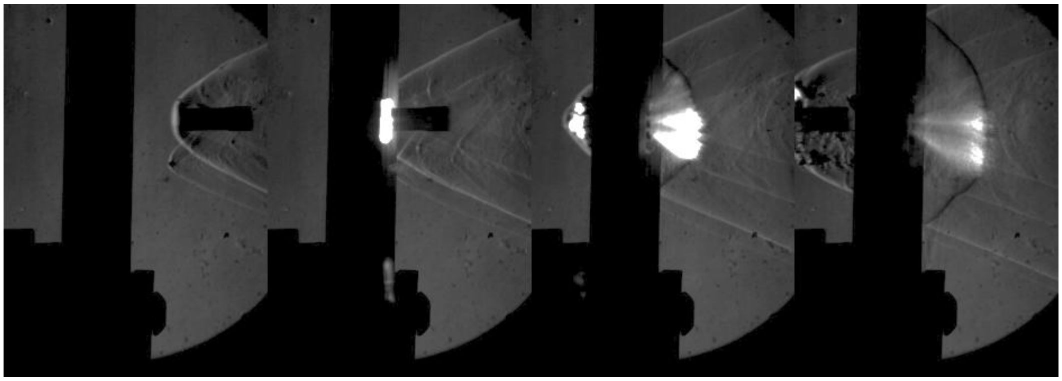


Figure 6. Successive schlieren image frames recorded at 50,000 Hz for orthogrid plate test in air

In the high-velocity impact tests, the effects of environment, panel structure, and impact angle were explored. Tests were conducted both in vacuum and atmospheric conditions using various panel configurations, including aluminum panels of uniform thickness, aluminum panels with orthogrid ribs, carbon fiber composite panels, and honeycomb panels. Additionally, tests were performed with the panels inclined at a 30-degree angle to assess the influence of impact angle.

A comparison of impacts at 0- and 30-degree angles for the aluminum panel of uniform thickness and the aluminum panel with orthogrid ribs, both tested under vacuum conditions, is presented in Figure 7 A, B. This figure illustrates a much richer acoustic response of the orthogrid panel and impacts at inclined angles resulted in diminished signal intensity that varied with the angle of impact.

As a result of the set of high-velocity tests, the SMART Layer sensor network demonstrated strong durability, with all piezoelectric sensors remaining securely bonded and showing no signs of debonding, damage, or signal degradation after impact. The SHM system successfully detected and located every impact, with reliable data acquisition confirming its suitability for high-energy impact events.

A)

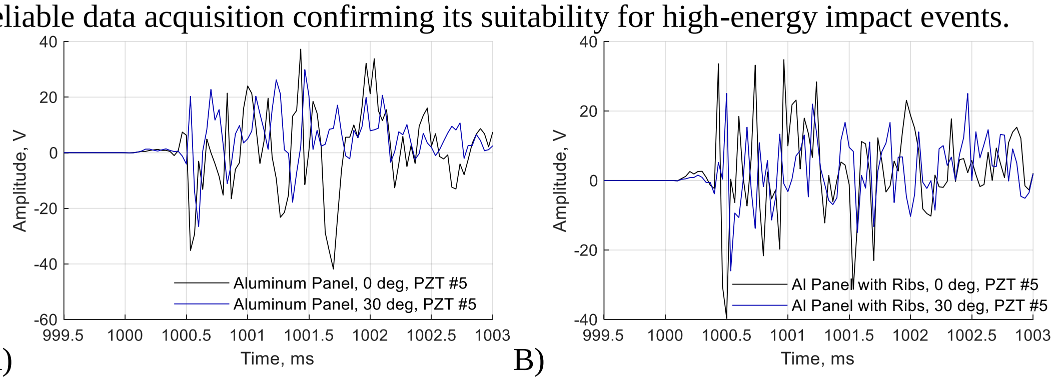


Figure 7. Comparison of impacts at 0- and 30-degrees angles under vacuum conditions for the A) Aluminum panel of uniform thickness; B) aluminum panel with orthogrid ribs.

The experiments also revealed that elastic wave signals were generally stronger in vacuum compared to air, due to higher energy transfer and reduced attenuation. Additionally, impacts at inclined angles produced lower signal amplitudes and cleaner waveforms. Overall, the results of high-velocity tests were consistent with trends observed in low-velocity experiments, supporting the use of low-velocity testing as a foundation for high-velocity impact analysis.

5. CONCLUSIONS

This study evaluated the performance of the Acellent's SHM system based on piezoelectric sensors under varying impact conditions, including changes in impact angle, velocity, environment, and structural configuration. Experimental results demonstrated that the SHM system effectively detected and localized impacts across different scenarios, maintaining robust signal acquisition and sensor integrity even after high-velocity impacts. Increasing impact energy led to higher signal amplitudes, while increasing the impact angle reduced signal intensity, reflecting lower energy transfer at oblique angles. Environmental effects were also observed, with stronger elastic wave signals in vacuum due to reduced attenuation. Comparisons between different panel structures highlighted a richer acoustic response in orthogrid panels. The SHM system exhibited consistent trends between low and high velocity impact tests, supporting the use of low velocity data for preliminary analysis of high velocity events. Overall, the results demonstrated reliable performance, durability, and sensitivity of the Acellent's SHM system, confirming its suitability for impact detection and structural monitoring in demanding aerospace applications, including on-orbit environments.

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