A Structural Health Monitoring System for Impact and Damage Detection in Space Structures

MARIYA POZHANKA, ANDREI ZAGRAI, ISABELLA WELLS, RAMON ROMERO, AMRITA KUMAR, ROSHAN JOSEPH, CODY GRAY and FRANKLIN LI

ABSTRACT

Space-based assets, such as satellites, are highly vulnerable to damage at all stages of their lifecycles. In particular, on-orbit events, such as impacts with space debris, micrometeoroids, and other vehicles, present major operational and logistical concerns. A Structural Health Monitoring (SHM) system deployed on satellite structures holds the promise of *in-situ* detection of impact events and monitoring of associated damage, thereby becoming a critical component of any On-orbit Servicing, Assembly, and Manufacturing (OSAM) strategy. The authors explored the feasibility of such an SHM system by instrumenting aluminum plates and a satellite panel with an integrated network of distributed piezoelectric sensors and then subjecting them to a series of impact tests with a wide range of forces. Satellite panels typically have a complex geometry due to stiffening ribs, and, consequently, variable stiffness. Therefore, signals obtained from the sensors were processed taking into consideration the geometry of the impacted areas, which allowed the location of the impact on the satellite panel to be accurately determined. The impact locations and force magnitudes estimated by the SHM system were compared with the actual values and found to have a high degree of correlation, with some avenues for additional improvement identified. In addition, the SHM system's damage-detection capability was validated in both test structures. The results show that SHM systems can be readily applied to space structures in order to provide both impact- and damage-detection capabilities.

Mariya Pozhanka, New Mexico Institute of Mining and Technology,801 Leroy Pl., Socorro, NM 87801, U.S.A.
Andrei Zagrai, New Mexico Institute of Mining and Technology,801 Leroy Pl., Socorro, NM 87801, U.S.A.
Isabela Wells, New Mexico Institute of Mining and Technology,801 Leroy Pl., Socorro, NM 87801, U.S.A.
Ramon Romero, New Mexico Institute of Mining and Technology,801 Leroy Pl., Socorro, NM 87801, U.S.A.
Amrita Kumar, Acellent Technologies, Inc., 835 Stewart Dr., Sunnyvale, CA 94085, U.S.A.
Roshan Joseph, Acellent Technologies, Inc., 835 Stewart Dr., Sunnyvale, CA 94085, U.S.A.
Cody Gray, Acellent Technologies, Inc., 835 Stewart Dr., Sunnyvale, CA 94085, U.S.A.
Franklin Li, Acellent Technologies, Inc., 835 Stewart Dr., Sunnyvale, CA 94085, U.S.A.
Ramon Romero, Acellent Technologies, Inc., 835 Stewart Dr., Sunnyvale, CA 94085, U.S.A.

INTRODUCTION

Space-based assets, such as satellites, form the backbone of modern communication, navigation, and defense industries. Yet, these assets are highly vulnerable in multiple ways, presenting a unique set of challenges to operators and maintainers. Space structures operate in harsh conditions and are regularly subjected to high velocities, acceleration, vibration, radiation, temperature swings, and impacts with foreign objects, yet must maintain structural integrity during their entire service life. Monitoring the condition of the constituent structures is critical to ensuring the safety, operability, and efficiency of space vehicles. Impacts with space debris, micrometeoroids, and other vehicles are among the key concerns, as congestion and debris increasingly threaten space logistics and the long-term sustainability of space-based assets. Information on mechanical impacts is essential to making decisions about a spacecraft's functionality, especially during in-orbit operations.

In-situ impact detection is a promising prevention practice that provides information about the location and characteristics of an impact event, helping to overcome unpredictable failures, increasing reliability, and reducing operational and maintenance costs. Impact detection is part of a broader and revolutionary new approach to structural inspection and logistics known as Structural Health Monitoring (SHM). Structural inspection and monitoring is well-known in the aerospace industry and highly regarded as one of the primary means for improving safety and reducing maintenance costs. By leveraging low-cost sensors that can be permanently installed on the structure, combined with precision data-acquisition electronics, efficient signal-processing algorithms, and state-of-the-art analytic techniques, SHM systems improve upon traditional Non-Destructive Evaluation (ND) techniques, providing the ability to monitor structures continuously during operation, with minimal or no human interaction, even in areas that are difficult or impossible to access. Therefore, On-orbit Servicing, Assembly, and Manufacturing (OSAM) operations serve as a novel and practical use-case for SHM technologies. The data provided by an SHM system may include details on the variation of structural conditions specific to vehicle's mission, mechanical events such as payload or component changes, and external factors such as micrometeorite impacts, which would then be communicated to the vehicle's control system and/or ground operators.

By strategically distributing sensors across the entire monitored structure and grouping them together in a network topology, the system becomes capable of not only detecting, but also locating and quantifying impacts. Although a distributed SHM system could utilize a variety of sensing approaches, the most common one includes embedded or surface-bonded piezoelectric (PZT) transducers, which are able to act as both sensors and actuators. For impact detection, SHM systems tend to utilize either a model-based [1]–[5] or data-driven approach (typically realized using tend to utilize either an artificial neural network) [6]–[8]. In addition to detecting impacts, PZT-based SHM systems could be employed to monitor vibration levels, as vibrations affect the quality of signals transmitted and received by the satellite [9]–[10].

In this paper, a commercially-available SHM system developed and supplied by Acellent Technologies, Inc., was used to investigate the feasibility of SHM on space structures. Laboratory samples (two aluminum plates of different thicknesses) and a real satellite panel were instrumented with the SHM system's distributed network of

PZT sensors, called the SMART Layer®. By using the appropriate data-acquisition hardware and software, the same sensor network can be operated in two different modes, each providing unique information on the state and health of the structure.

One is a "passive" listening mode, where the IMGenie Pro data-acquisition hardware simultaneously captures signals from all sensors at up to 30,000 samples per second. When impacted with a sufficiently large force (or some other significant event occurs), the PZTs respond to the resulting stress waves propagating through the structure. If an impact exceeds the configured "trigger" threshold, the Acellent Impact Monitor (AIM) software not only reports that an impact has occurred but also calculates and displays the precise location of the impact and an estimated force level. Thus, the "passive" operating mode provides impact detection, localization, and quantification abilities. The second operational mode is the "active" interrogation mode, provided by the ScanGenie series of data-acquisition hardware. In this mode, an individual PZT sensor is actuated in the ultrasonic range (200–700 kHz) while the response from a neighboring sensor is simultaneously captured at an extremely high resolution and sampling rate (up to 48 million samples per second). By automatically cycling through many combinations of sensors (termed "paths"), complete coverage of the monitored area is achieved. Such "active" acousto-ultrasonic interrogation provides the ability to detect, localize, and quantify damage within the structure using Acellent's SHM Patch software. Experimental testing included use of the "passive" mode to detect low-velocity impacts created with an impact hammer and a drop tower. In the latter case, the "active" mode was used to locate perforation damage. Additional experiments were conducted on an actual satellite panel, utilizing both "passive" and "active" modes to demonstrate multiple uses for an SHM system in space.

DETECTION OF IMPACTS ON METALLIC PLATES

Specimens

Three distinct specimens were used for testing the SHM system: two aluminum plates of differing thicknesses and one satellite panel. All test specimens and their dimensions are shown in Figure 1, including the surface-bonded PZT sensor networks. The two aluminum plates were each equipped with 21 sensors, and the satellite was equipped with a network of 9 sensors. The satellite panel featured an isogrid structure in which width of the thinner wall was 3.75 mm and width of the thicker wall was 9.8 mm.

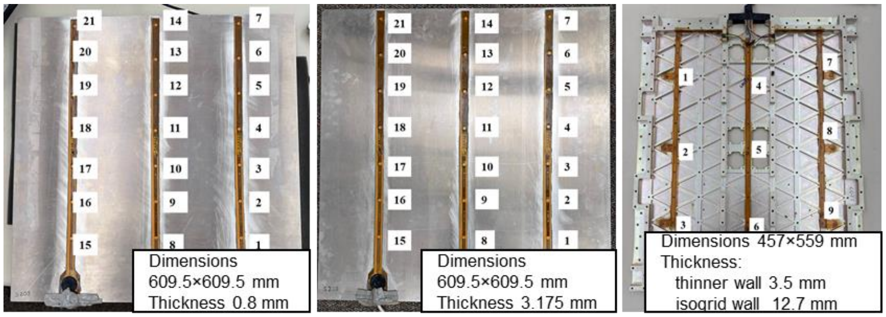


Figure 1. The three test articles, showing their dimensions and sensor network configurations.

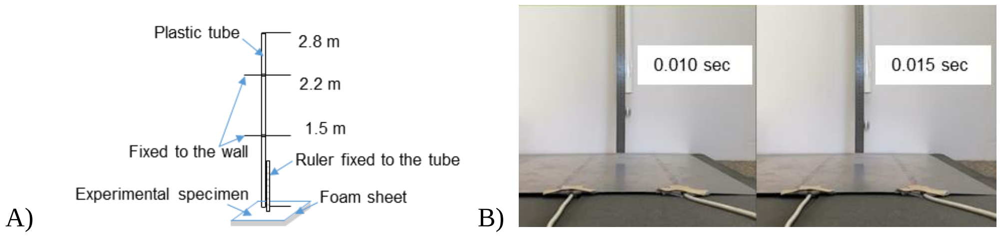


Figure 2. (A) Schematic of drop tower; (B) Screenshots from slow-motion movie of the test.

Experimental Setup

Experiments were conducted to examine two different types of low-velocity impacts: first, due to an impact hammer and, second, due to a steel ball dropped from a tower with gravity-induced acceleration. The experimental setup included the specimens described above, an IMGenie Pro (Acellent), a laptop computer running the AIM software (Acellent), an impact hammer with a force sensor (PCB Piezoelectronics, Type 086C01), and an oscilloscope (Tektonix TDS2024B) to record the force exerted by the hammer. The sensitivity of the impact hammer was 50 mV/lbf. A schematic of the drop tower is provided in Figure 2. In the drop tower experiments, a metal ball of diameter 1 in was dropped from three different heights: 1.5 m, 2.2 m, and 2.8 m.

Experimental Estimation of Impact Location

First, all PZT sensors were calibrated by applying impacts of varying intensity to the panel at a single location. By the averaging the value of the ratio of the force obtained from AIM to the force recorded by the impact hammer, the sensitivity coefficient was determined. Then, to estimate the error in determining impact location, the locations obtained from AIM were compared to the actual impact locations measured using an imprint made by the falling ball on the specimen after coating its surface with a thin layer of putty.

Experimental Estimation of Velocity and Force

Slow-motion videos were recorded during the drop-tower experiments and used,

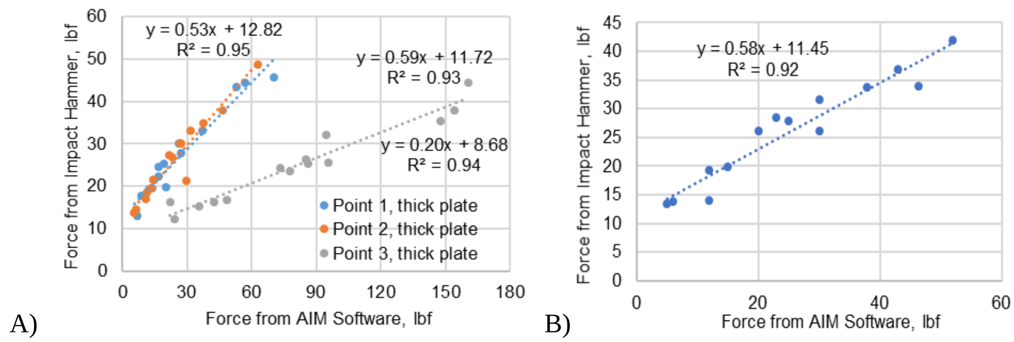


Figure 3. Calibration curves for the (A) thick and (B) thin aluminum plates.

along with physical laws, to compute the velocity and force of the impact. The initial velocity was calculated using the ball's location at the time points on the video timeline before the impact, and the same procedure was used to obtain the final velocity after the impact. The frame rate of the video was 240 frames per second. The duration of the interaction of the ball with the plate was calculated using temporal information from the recorded videos. The impact force was calculated using Newton's 2nd Law of Motion, $F=ma$, where m is the mass of the metal ball (67 g). The result estimated the impact force at 4.4 N.

Calibration Curves

Because individual PZT transducers generate different responses depending on the characteristics of the transducer itself, the strength of the bond, the thickness of the epoxy, etc., AIM allows the operator to define a sensitivity coefficient for each sensor. During the calibration process, impacts of various intensity were applied to experimental specimens, producing calibration curves relating actual (hammer) and estimated (AIM) impact magnitudes. For the thinner aluminum plate, only one point was tested in order to avoid damaging the experimental specimen. For this case, a ratio of the forces was obtained as ≈0.01, so the sensitivity coefficient was configured as 0.01. For the thicker specimen, three different points on the plate were tested. The ratio of forces obtained was ≈0.1, so the sensitivity coefficient was configured as 0.1. Figure 3 shows calibration curves and equations obtained by fitting the experimental data for both aluminum plates. The absolute error of localization for both X and Y coordinates was within 50.8 mm for both specimens.

DETECTION OF PERFORATION DAMAGE IN METALLIC PLATES

After installing the sensor network but prior to inducing any damage, a baseline profile for the undamaged specimen was obtained using the ScanGenie Mini data-acquisition hardware. Later, when a damage scan is performed, Acellent's SHM Patch software compares the ultrasonic signals obtained by interrogating the structure with this baseline measurement in order to detect the location and quantify the severity of damage. (A detailed discussion of the damage-detection algorithm and process is outside the scope of this paper; see [11].) Perforation damage was created

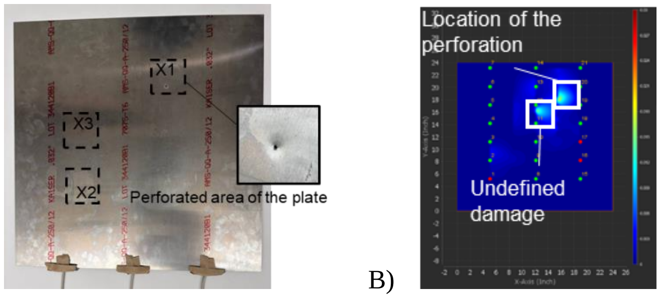


Figure 4. (A) Photograph of the thin aluminum plate, with a close-up of the perforated area; (B) Screenshot of the damage map, showing the detected damage and damaged sensors.

in the thinner aluminum plate specimen using the drop tower experimental setup, except that a sharply-angled metal pike having a mass of 316 g was used instead of a metal ball. The metal pike was dropped from the highest point of 2.8 m. Ultrasonic scans of the aluminum plate were performed before and after inducing the perforation. The system detected no damage before the perforation; Figure 4 B shows the results of damage detection after the perforation. It is notable that two areas of damage were detected on the plate. The first one matched the area of the perforation, but the second one could not be observed visually. It may have been caused by fatigue-induced distortion of the specimen during the prior set of impact tests, or it could have been the result of a signal reflection caused by the perforation damage. It should also be mentioned that, during the experiments where the panel was impacted with a steel ball, 3 out of 21 sensors on the thin aluminum plate
became partially disbonded. These 3 damaged sensors were detected by the SHM system and are marked in red on Figure 4 B.

DETECTION OF IMPACTS AND DAMAGE ON A SATELLITE PANEL

Impact Tests

To demonstrate the applicability of SHM to space structures, a real satellite panel was subjected to a series of impact tests. The satellite panel, in contrast to previously considered specimens, has a complex, non-uniform geometry, with ribs forming a triangular isogrid structure that had different widths depending on their location and function. Like most space structures, the geometry of this panel is designed to maximize its functionality and structural efficiency. Three different impact locations were chosen, taking into account the heterogeneity of the panel’s thickness: a thin area of the panel (X1) with the same thickness as the thick aluminum plate, a thin rib (X2) with a thickness of 3 mm, and thick rib (X3) with a thickness of 6 mm (Figure 5A). Sensor calibration was performed using the same experimental setup described for the aluminum plates. The ratio of forces obtained was ≈0.01, and the sensitivity coefficient for all sensors was configured as 0.05. The relationship between the force obtained from the oscilloscope and that reported by AIM is presented in Figure 5B; clearly, the force adjustment function depends on the location

A) B)

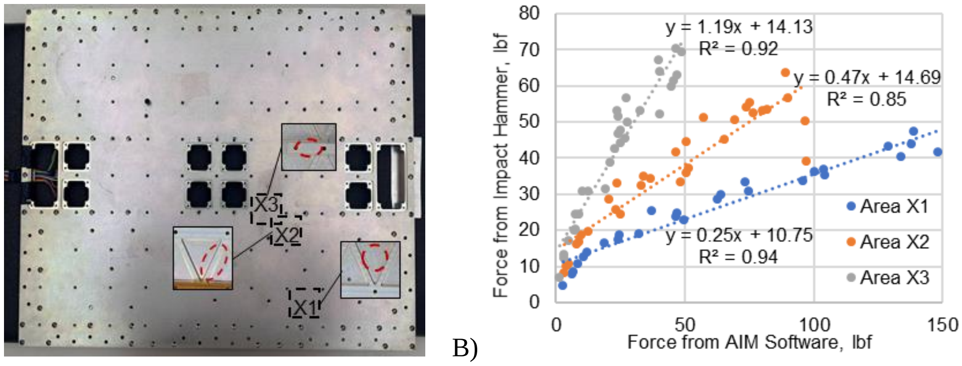


Figure 5. (A) The three locations on the satellite panel selected for impact tests; (B) Impact force calibration curves for the satellite panel.

of the impact. Experimental data suggests linear behavior in the considered range. Equations describing these linear dependencies are indicated on the plot and could be used to calculate the approximate value of the impact force.Tests with the impact hammer were conducted on the satellite panel at the same three locations. Experiments demonstrated that the absolute error for impact localization remained within 50.8 mm for the X coordinate, whereas it deviated within 63.5 mm for the Y coordinate. This increased error is likely caused by the complexity of the specimen's geometry, especially the ribs and isogrid structure, which affects signal propagation and is not currently compensated for by the localization algorithm (which assumes a uniform structural geometry).

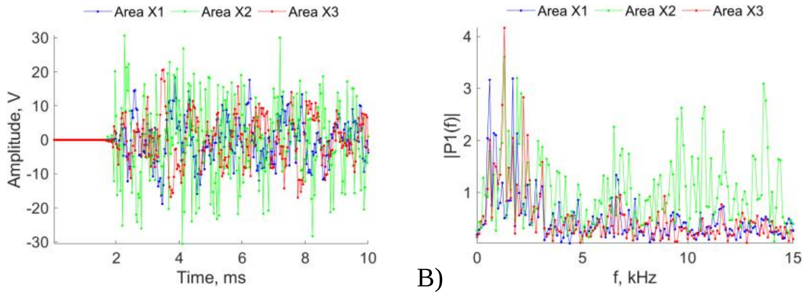
In order to examine higher-velocity impacts, the satellite panel was subjected to the same drop-tower tests as the aluminum panels. The metal ball was dropped from 3 different heights on the same 3 locations used for the impact hammer tests. As with the impact hammer tests, the absolute error for the drop-tower tests was within 2 inches for the X direction and within 63.5 mm for the Y direction.

Characterization of Signals from Different Locations

The geometrical complexity of the satellite panel provided the opportunity to characterize the effect of the underlying structural geometry on the waveform signals. Since time-domain signals were already recorded for impacts at three different points on the panel (Figure 6A), with each location exemplifying a different structural geometry, spectral characteristics of the signals recorded by the first sensor were analyzed using a Fast Fourier Transform (FFT) (Figure 6B). Impacts under the satellite panel's ribs excited frequencies in a wider range than impacts on a thin, uniform area. This is a preliminary study which could be potentially used for future improvements to the system. Impact localization could be performed extremely accurately using only signal-processing techniques, aided by a data-driven approach, perhaps with a neural network, rather than relying on a structural model.

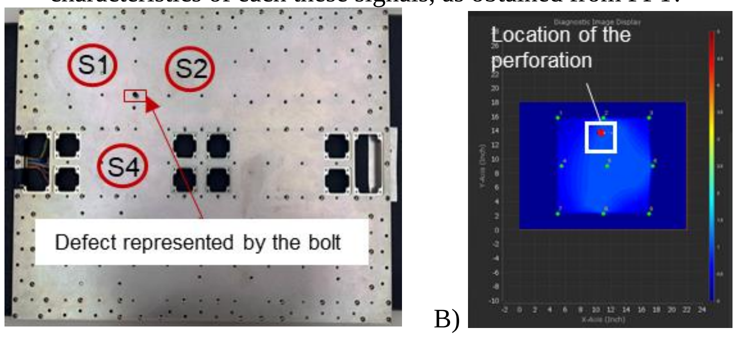
Damage Detection for Bolt Loosening

Since a loose or absent bolt is a common failure presentation in space structures,



A) B)

Figure 6. (A) Impact signals from 3 different locations on the satellite panel; (B) Spectral characteristics of each these signals, as obtained from FFT.



A) B)

Figure 7. (A) Photograph of the satellite panel, showing the location of bolt and sensors; (B) Screenshot of the damage map, showing the detected damage.

an experiment was conducted to explore the potential of an integrated SHM system to detect this type of damage. As with the earlier experiments in the aluminum panels, a baseline profile was obtained first. An ultrasonic scan before damage was induced detected no damage; after damage was induced by screwing a bolt into the panel (Figure 7A), the damage was successfully located and mapped by the SHM Patch software (Figure 7B). Comparing the damage map with the actual location of the bolt suggests that the damage location was detected with an error of ≈ 38 mm.

CONCLUSIONS

The results demonstrate the feasibility of an integrated SHM system to monitor and quantify impacts and damage in specimens of simple geometry as well as a real satellite panel. In hammer and drop-tower tests, the “passive” SHM system identified the location of with an accuracy of 25–50 mm and the force estimates linearly correlated with the measurements from the impact hammer. The impact localization algorithm can be improved to compensate for the structural geometry; one means for doing so might be a spectral analysis of the signals using a data-driven approach. Finally, the “active” SHM system was able to accurately detect and localize multiple types of damage, including perforations and the addition of a bolt to the structure.

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