Field Operation of PZT Sensor Based SHM System on Commercial Aircraft in Detecting Cracking Around Chem-Mill Areas

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ABSTRACT

The integrity of Boeing 737 aircraft structures, particularly at the edges of chemically milled pockets between stringers and frames on the interior skin surface, is compromised by the occurrence of multiple crack formations. These cracks, often initiated at the chem-mill line, have prompted regulatory agencies and manufacturers to enforce rigorous inspection protocols, including Eddy Current and Phased Array Ultrasonic Testing (PAUT). While effective, these NDT methods are labor-intensive, costly, and often necessitate extensive aircraft disassembly, posing safety risks to inspectors, creating logistical challenges, and incurring significant operational downtime. The sheer volume of inspection sites, coupled with the limited availability of qualified personnel and the difficulty of accessing critical areas, underscores the need for more efficient, reliable, and less invasive inspection techniques. To address these challenges, Delta Air Lines has shown interest in investigating Structural Health Monitoring (SHM) as a cost-effective solution that could eliminate the need for extensive access requirements. This study presents an evaluation of SHM technology's feasibility in detecting cracks along the chem-mill line on Boeing 737 structures in service condition.

INTRODUCTION

Acellent Technologies, a leading supplier of SHM solutions, in collaboration with Stanford University is studying the feasibility of SHM technologies to identify cracking in the complex geometry of a chem mill pocket by utilizing SMART layer technology

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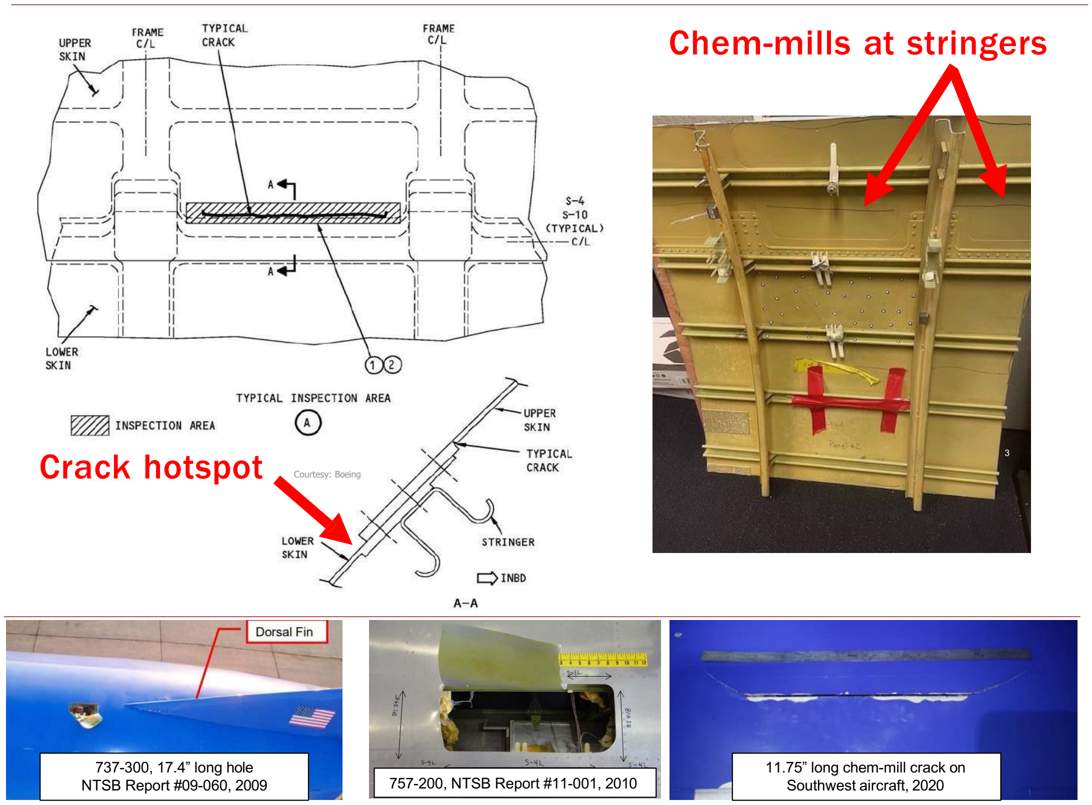
to establish a sensor network for real-time damage assessment through Damage Index (DI) analysis. [1].

The SMART Layer SHM system developed by Acellent Technologies is a versatile solution comprising a network of PZT sensors integrated into a thin carrier film, integrated with built-in wiring and connectors. This system allows for effortless installation on a wide range of structures, offering choices between individual sensors, standard layers, and customized configurations to meet various needs. Known for their robustness and utility in structural health monitoring, and adaptability to different shapes and surroundings, these layers stand out for their durability and practicality. This approach enables precise crack detection and localization, utilizing signal feature changes estimated as Damage Index (DI) values from sensor generated guided wave data to monitor crack progression and identify structural irregularities. The research highlights the potential of SHM systems in enhancing maintenance efficiency and improving aircraft safety targeting chem-mill areas of Boeing 737 structural elements. The results emphasize the significant advantages of SMART layer based SHM systems in transforming aircraft maintenance practices by enabling proactive and accurate structural health assessments.



737-300, 17.4” long hole
NTSB Report #09-060, 2009

757-200, NTSB Report #11-001, 2010

11.75” long chem-mill crack on
Southwest aircraft, 2020

Figure 1. Example of Chem-mill cracks

The research involved sensor installation on Delta Air Lines aircraft components at critical chem-mill locations for flight trials. An example representation of the chem-mill inspection area is shown in Figure 1. Preliminary results demonstrate that SMART Layer-based SHM systems can reliably identify and localize cracks, facilitating ondemand access to diagnostic results as opposed to traditional NDI inspection thus improving maintenance in terms of efficiency, safety, and cost.

Ongoing flight testing and further development are expected to solidify their role in future aircraft maintenance paradigms, ultimately contributing to safer, more efficient, and cost-effective aviation operations.

ACELLENT'S SHM SYSTEM

Structural Health Monitoring (SHM) systems encompass various disciplines such as sensors, materials, signal processing, and system integration, aiming to provide valuable data throughout a structure's lifespan while assisting in health assessment and maintenance planning through advanced data interpretation software. A critical aspect of SHM is the effective integration of strategically placed network of PZT sensors onto the structures. One innovative approach is the SMART Layer (see Figure 2), which embeds a network of miniature piezoelectric (PZT) transducers within a thin dielectric film. This integrated layer simplifies installation by reducing wiring and allows comprehensive damage detection across the entire structure, not just along direct sensor paths. It can be embedded during fabrication or retrofitted onto existing structures and can incorporate various sensors, such as strain, temperature, and moisture gauges, for structural state monitoring.

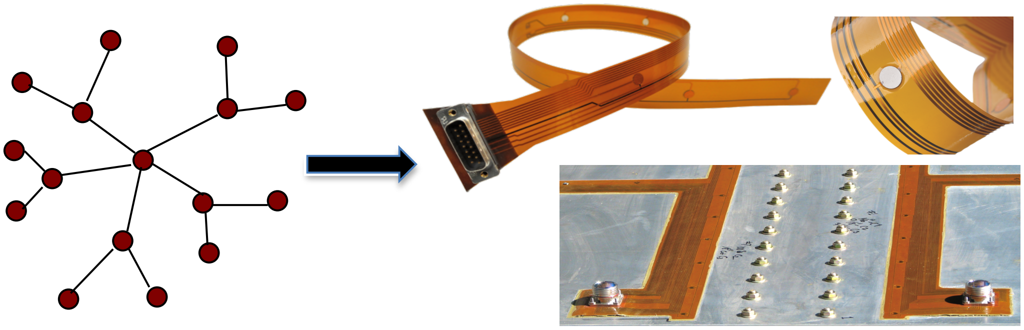


Figure 2. Sensor network based SMART Layer
[courtesy Acellent Technologies Inc.]

Data collection is performed using specialized hardware and software, and damage detection often involves active sensing. In the active mode, PZTs generate elastic waves that travel through the structure andwhen these waves encounter damage, they scatter. Analyzing the scattered waves against the original incident waves enables the detection and characterization of flaws. Understanding how different damages affect wave scattering is essential for accurate damage identification in SHM systems.

SHM INSTALLATION FOR CHEM-MILL APPLICATION

In this investigation, specific regions on the chemically milled components of Delta's Boeing 737 aircraft were carefully identified for the installation of Structural Health Monitoring (SHM) sensors during flight testing, as shown in Figure 3. The selection of these preliminary zones was driven by multiple considerations, including historical data on high occurrence of cracking, the spatial constraints of the aircraft structure, the feasibility of sensor installation, and the potential for effective damage detection and monitoring. The primary objectives of targeting these areas were to evaluate the most suitable methods for installing the sensors, to ensure ease of establishing reliable connections, and to verify the detection capabilities of the SHM system in operational flight conditions.

To address these objectives, SMART Layers were custom-designed for each targeted area. The design process accounted for available space limitations, routing pathways for cabling, and the specific detection requirements dictated by the structural features and expected operational stresses. The finalized SMART Layers, which integrate multiple sensors into a compact form factor, are shown in Figure 3.

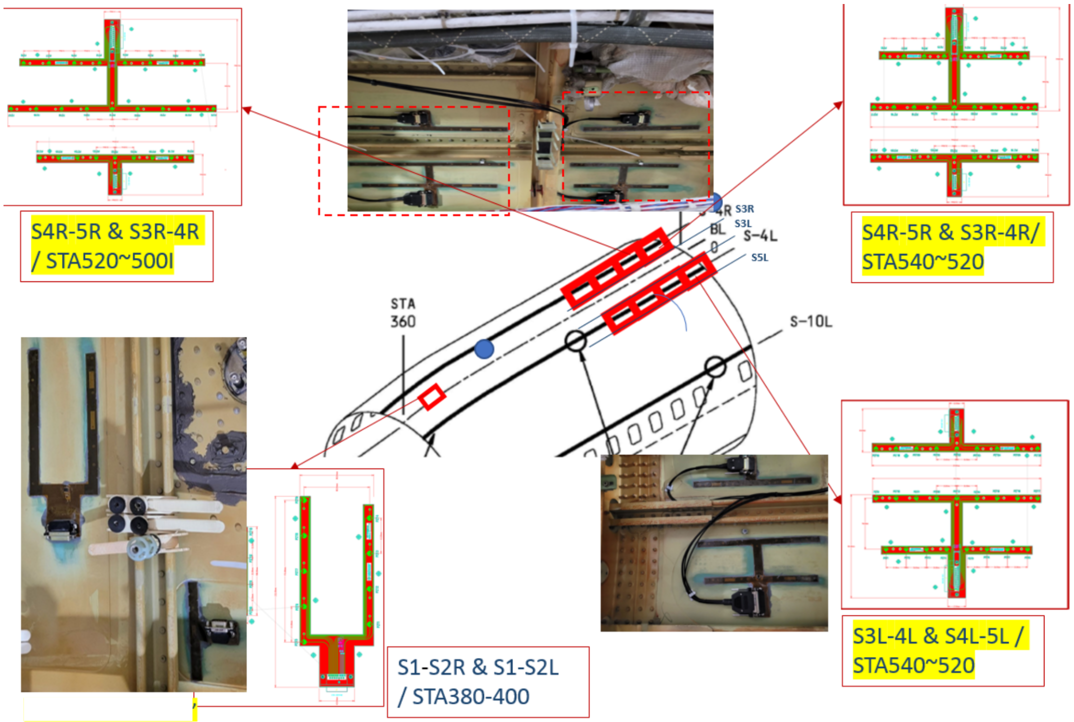
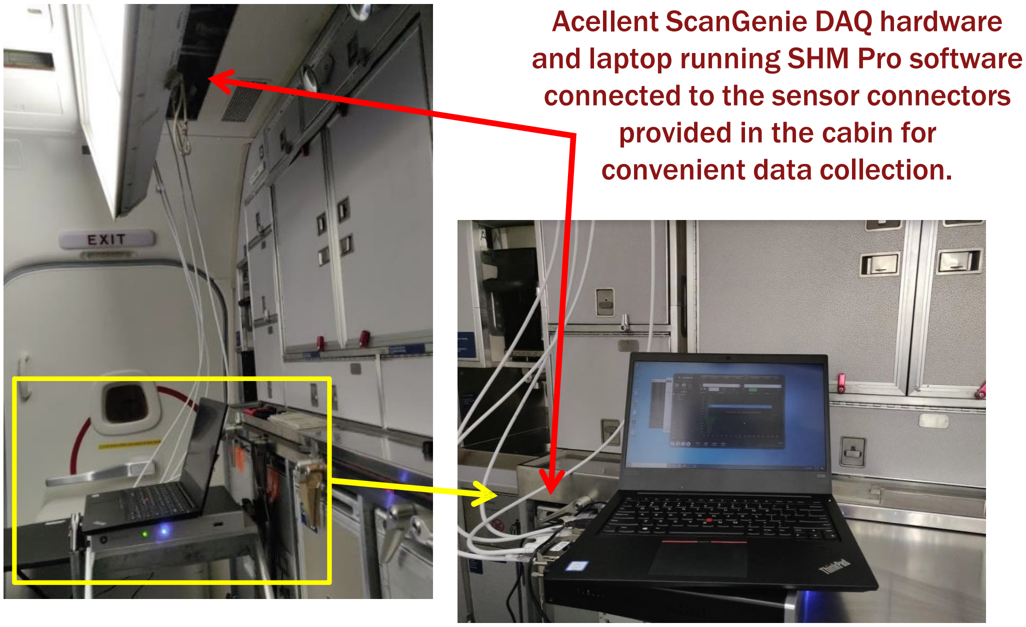


Figure 3. SMART layer design for installation on Chem-mill areas

To facilitate installation, Acellent provided specialized installation kits that included all necessary components and instructions. The SMART Layers were bonded directly onto the aircraft structure a high-performance epoxy known for its strong bonding properties and durability. Following bonding, the layers were vacuum-cured to ensure a uniform and robust attachment, minimizing the risk of sensor detachment during flight operations. Figure 4 shows a typical installation kit components.

Cabling design was a critical aspect of the installation process, aiming to route all connections toward accessible locations above the cabin area. This routing strategy was implemented to facilitate future data acquisition, maintenance, and troubleshooting activities. The cabling layout ensured minimal interference with existing aircraft systems and maintained compliance with safety standards, as shown in Figure 5.

Figure 4. Acellent's SMART Layer installation kit



Acellent ScanGenie DAQ hardware and laptop running SHM Pro software connected to the sensor connectors provided in the cabin for convenient data collection.

Figure 5. Data collection with Acellent's Software, Hardware and Cabling

Post-installation, a comprehensive system integrity check was conducted utilizing Acellent's SHM Patch software and the ScanGenie Data Acquisition System (DAQ). This validation process confirmed that all sensors were functioning correctly and that the data acquisition system was properly configured for real-time monitoring during flight. The results, depicted in Figure 6, demonstrated that the sensors responded as expected and that the installation did not compromise the structural integrity or operational safety of the SHM system with onboard sensor installation.

SYSTEM INTEGRITY CHECK REPORT

Hotspot Name [redacted]

Sensor Layout File [redacted]

Date Time [redacted]

USB CONNECTION PASSED

MEMORY CHECK

CONTROLLER	STATUS
ADC MEMORY	Passed
WGC MEMORY	Passed
VGC MEMORY	Passed

PZT SENSOR HEALTH

SENSOR NO.	STATUS	CHANNEL NO.
1	Good	1
2	Good	2
3	Good	3
4	Good	4
5	Good	5
6	Good	6
7	Good	7
8	Good	8

TEMPERATURE SENSORS HEALTH

TEMP SENSOR NO.	STATUS
1	Good
3	Good
5	Good

SWITCH HUB AND SA BOX

COMPONENT	STATUS	CHANNEL START	CHANNEL END
1	OK	1	32
2	OK	33	64
3	OK	65	96
4	OK	97	128

Figure 6. System integrity check after sensor installation and cable connections

Currently, the SMART Layers have been successfully installed on three (3) Delta (Boeing 737) aircraft. Flight testing is ongoing, with data being systematically collected to evaluate the performance of the SHM system in detecting structural responses and potential damage signatures under real-world operating conditions. The insights gained from this phase are expected to inform future deployment strategies and to enhance the overall safety and maintenance efficiency of the aircraft fleet through advanced, sensor-based structural health monitoring.

FLIGHT DATA REVIEW

The sensor data used for this study was collected utilizing Acellent's SHM Patch software, which is specifically designed for fatigue induced cracking in aerospace applications. Following installation, data collection was carried out regularly and evaluated for a comprehensive assessment of the system's performance and the stability of the sensors over time. Figure 7 provides a comparative review of the sensor signals recorded at two different points in time. Importantly, both measurement dates were characterized by similar environmental conditions, with recorded temperatures of 14.2°C and 13.9°C respectively, as also noted in Figure 8. This careful consideration of temperature consistency ensures that any observed differences in sensor signals are unlikely to be influenced by environmental variations, thereby enabling a more accurate assessment of sensor stability over time.

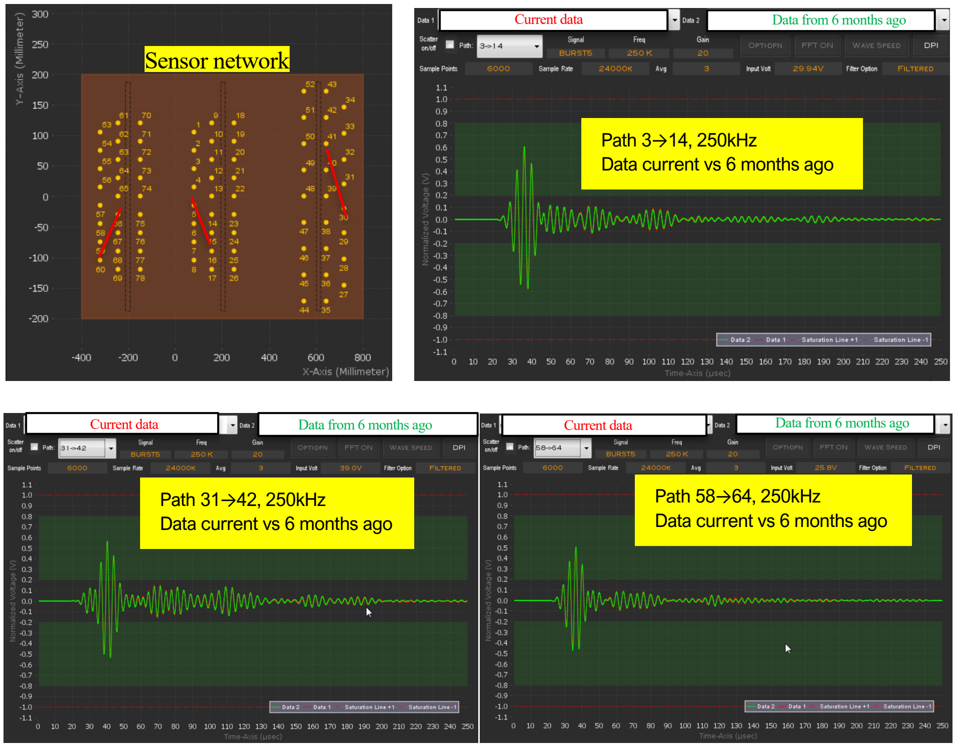


Figure 7. Acousto-ultrasonic data review for various sensor paths (250kHz)

The analysis focuses on measurements obtained from multiple sensor paths located within the chem-mill inspection area. The results reveal that the sensor signals remained remarkably stable over the six-month period, with only minor fluctuations observed between the two data sets. This high degree of consistency indicates that the sensors maintained their calibration, sensitivity, and overall performance without significant drift or degradation. Such stability is crucial for the reliability of long-term structural health monitoring systems, as it ensures that any observed changes in sensor readings are genuinely reflective of structural conditions rather than sensor performance issues.

Building on this, Figure 8 showcases a qualitative evaluation of the data's integrity by calculating the Damage Index (DI) values, as outlined in reference [2]. The DI values are visualized in a histogram, which illustrates that all measured paths have maximum DI values below the established threshold of 0.025. This low damage index across the entire sensor network confirms the absence of any significant structural changes or damage in the monitored area during this six-month interval. Collectively, these analyses reinforce the conclusion that the sensor system exhibits robust stability and consistent performance over extended periods, thereby validating its suitability for continuous structural health monitoring in critical areas of the aircraft. This comprehensive evaluation underscores the reliability of the sensor network and supports its application for early damage detection and maintenance planning.

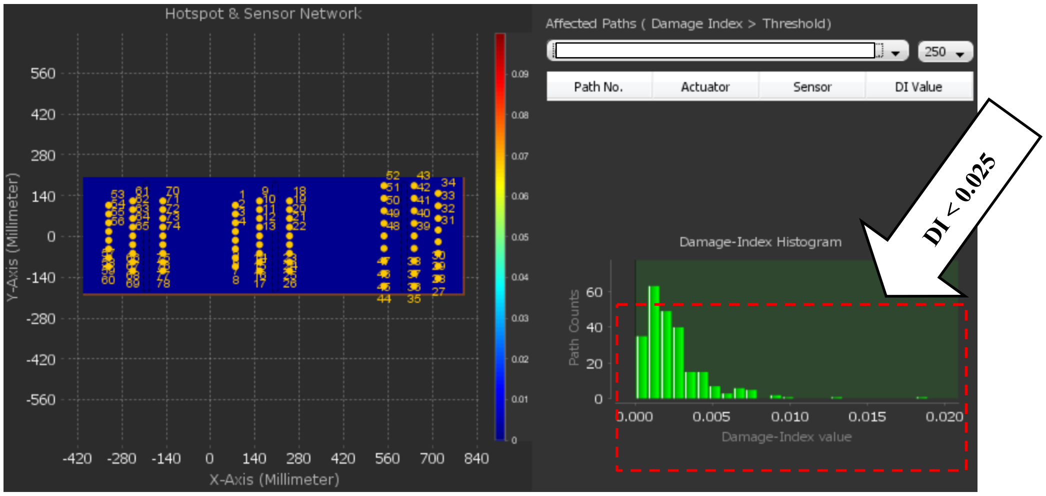


Figure 8. Damage-Index histogram across sensor paths

In summary, the review of the flight data demonstrates that the SHM system and its sensors performed reliably during aircraft operation. The consistent impedance readings across all sensors, along with the stable measurements observed over a six-month span, confirm that the sensor network remained functional and accurate. This high level of stability is essential for the credibility of the structural health monitoring system, ensuring that any detected changes or anomalies are genuine indicators of structural condition rather than sensor errors. These findings reinforce the effectiveness of the deployed SHM system for continuous, long-term monitoring, providing valuable insights for maintenance planning, safety assurance, and structural integrity management of the aircraft.

SUMMARY

This study presents the ongoing efforts to evaluate Structural Health Monitoring (SHM) systems for the detection of cracks in chemically-milled components on Boeing 737 aircraft. Initial observation demonstrated the feasibility of successful installation of PZT sensor based SHM system on three Delta aircrafts to facilitate flight testing. The data obtained from these operations will serve to assess the effectiveness and reliability of SHM technologies in identifying mill-line crack scenarios. Furthermore, the findings will inform potential updates to industry standards and guidance, supporting operators in adopting SHM-based inspection methods for enhanced structural integrity assessment.

ACKNOWLEDGEMENTS

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