

# Technical and Oversight Considerations for Reliable SHM Utilization

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DENNIS ROACH and TREVOR LYNCH-STANTON

## ABSTRACT

As the use of Structural Health Monitoring (SHM) systems continues to expand, the key elements associated with proper performance assessments and oversight requirements are becoming very well-defined. Similarly, supporting developments such as SHM guidance, regulatory measures, quality assurance and training are progressing to build a firm foundation for SHM deployment. Extensive SHM studies have highlighted the viable use of in-situ sensors for real-time health monitoring of a myriad of structures across multiple industries. SHM use can overcome inspection impediments stemming from accessibility limitations, complex geometries, and the location and depth of hidden damage. A critical aspect to applying SHM solutions is determining the operational requirements for SHM systems and the full array of variables that must be considered in the assessment process. In the case of the aviation industry, OEMs, airlines, regulators and researchers have worked together to define a detailed process for determining how to safely adopt SHM solutions. Multiple, formal SHM certification efforts have been completed to exercise and define the process of validating SHM systems. SHM certification must address the full spectrum of issues ranging from design to performance and deployment to continued airworthiness. This paper will provide an update on SHM deployment and certification in several aircraft applications, streamlined processes for airline adoption and recent FAA and industry initiatives to aid thorough evaluations of SHM systems. An FAA Issue Paper now provides essential guidelines for SHM system designers and procedures for assessing the performance of SHM systems. Formal documents have been issued by aircraft manufacturers to accommodate SHM usage. The Aerospace Industry Steering Committee for SHM has published multiple, essential standards for integrating and certifying SHM use on aerospace structures. These efforts are allowing SHM solutions to quickly and properly support maintenance activities while establishing policies and guidance to ensure the safe, uniform and comprehensive certification of SHM systems. Furthermore, this foundation will foster expanded regulatory and industry guidance as SHM efforts ultimately move towards Condition Based Maintenance programs.

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Structural Monitoring Systems and subsidiary Anodyne Electronics Manufacturing Corp (AEM), Kelowna, BC Canada

## INTRODUCTION

Multi-site fatigue damage and hidden cracks in hard-to-reach locations are among the major flaws encountered in today's extensive array of aging structures and mechanical assemblies. The costs associated with the increasing maintenance and surveillance needs of aging structures are rising. The application of SHM systems using distributed sensor networks can reduce these costs by facilitating rapid and global assessments of structural integrity. These systems also allow for condition-based maintenance practices to be substituted for the current time- or cycle-based maintenance approaches thus optimizing maintenance labor. Other advantages of on-board distributed sensor systems are that they can eliminate costly and potentially damaging disassembly, improve sensitivity by producing optimum placement of sensors, and decrease maintenance costs by eliminating more time-consuming manual inspections. Through the use of in-situ sensors, it is possible to quickly, routinely, and remotely monitor the integrity of a structure in service [1]. Prevention of unexpected flaw growth and structural failure could be improved if on-board health monitoring systems are used to more regularly assess structural integrity [2, 3].

Comparative Vacuum Monitoring (CVM) is a simple pneumatic sensor technology developed to detect the onset of cracks. CVM sensors are permanently installed to monitor critical regions of a structure. The CVM sensor is based on the principle that a steady state vacuum, maintained within a small volume, is sensitive to any leakage [3, 4]. A crack in the material beneath the sensor will allow leakage resulting in detection via a rise in the monitored pressure. Figure 1 shows top-view and side-view schematics of the self-adhesive, elastomeric sensors with fine channels etched on the adhesive face along with a sensor being tested in a lap joint panel. When the sensors are adhered to the structure under test, the fine channels and the structure itself form a manifold of galleries alternately at low vacuum and atmospheric pressure. Vacuum monitoring is applied to small galleries that are placed adjacent to the set of galleries maintained at atmospheric pressure. If a flaw is not present, the low vacuum remains stable at the base value. If a flaw develops, air will flow from the atmospheric galleries through the flaw to the vacuum galleries. When a crack develops, it forms a leakage path between the atmospheric and vacuum galleries, producing a measurable change in the vacuum level. This change is detected by the CVM monitoring system shown in Figure 2.

Multiple CVM deployment programs have been conducted to establish the viability of CVM use for routine maintenance while also facilitating the evolution of a process for certifying SHM systems. As a result, supporting activities such as SHM validation guidance, regulatory measures, training programs and quality assurance procedures have already progressed to build a firm foundation for SHM certification. These CVM certification programs will be discussed to show the progress in obtaining complete credit for SHM use and the critical tasks needed to establish the complete performance of SHM systems.

The requirements for certifying SHM systems will vary by industry and by the damage tolerance and failure assessments of the specific structural application. This paper will emphasize the most regulated industry, aviation, since the belief is that

other industries (e.g. civil) will be less stringent and contained within the requirements imposed by the aviation industry [5].

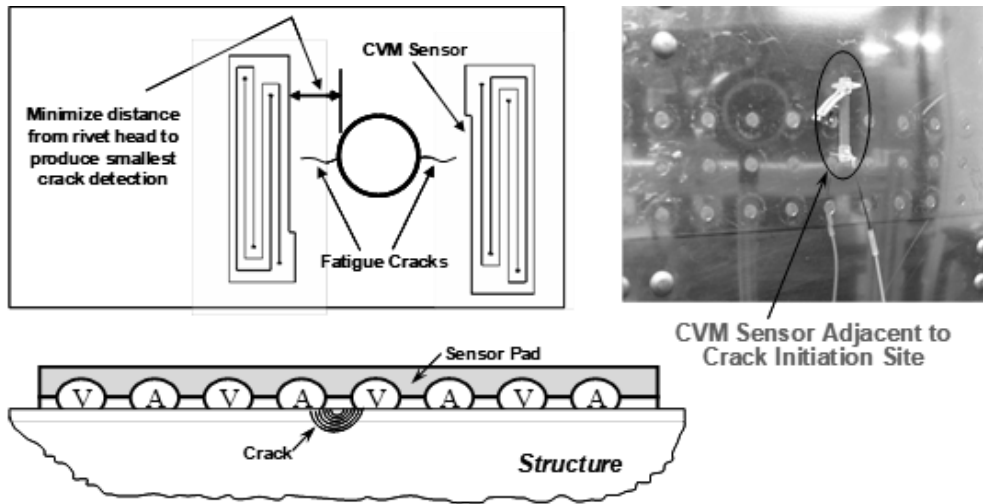


Figure 1. Schematics depicting operation of CVM sensor mounted on the outer surface of a riveted lap joint.

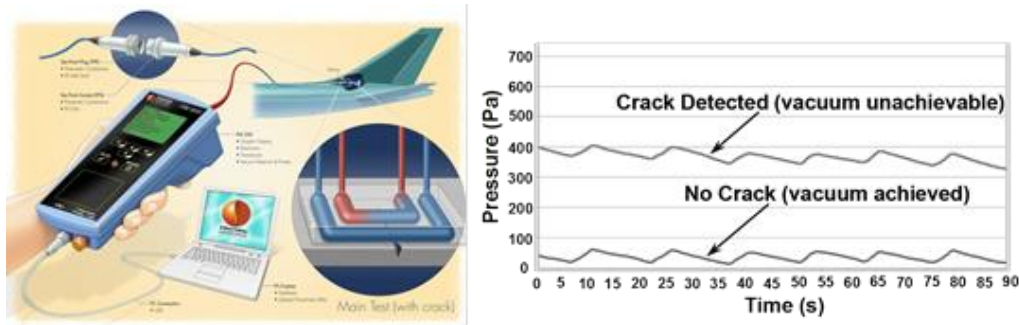


Figure 2. Crack detection monitoring with CVM system and pressure response used to indicate the presence of a crack.

## CERTIFICATION OF CVM SENSORS FOR MULTIPLE APPLICATIONS

A number of detailed studies have already been completed to formally introduce CVM sensors as an alternate health monitoring procedure. All programs were used to certify CVM SHM systems for conducting inspections in lieu of traditional eddy current methods. Figure 3 shows a summary of the three 737 applications:

### 737NG Center Wing Tank Fitting (Approved 2016)

- 7 Delta A/C monitored (10 sensors each) every 90 days (avg) for 6 years
- Delta continued data collection beyond initial period until A/C retirement
- Usage approved via Alternate Means of Compliance in Service Bulletin

### Wi-Fi Antenna Installation (Approved 2021)

- Basis for the FAA generic Issue Paper

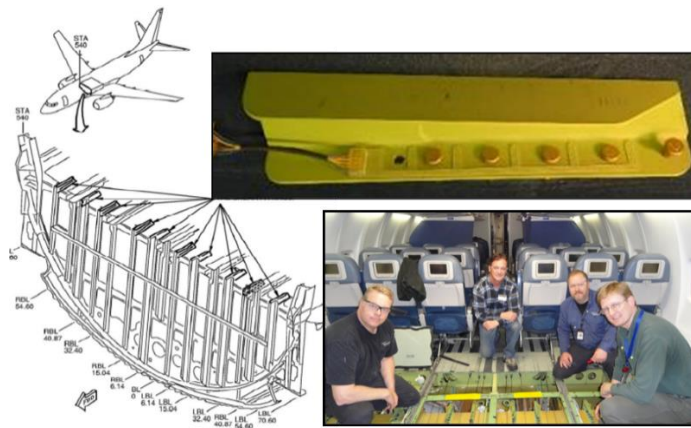
- 1st type design change approved by FAA for CVM use (Supplemental Type Certificate)

#### **737NG Aft Pressure Bulkhead (2019-present)**

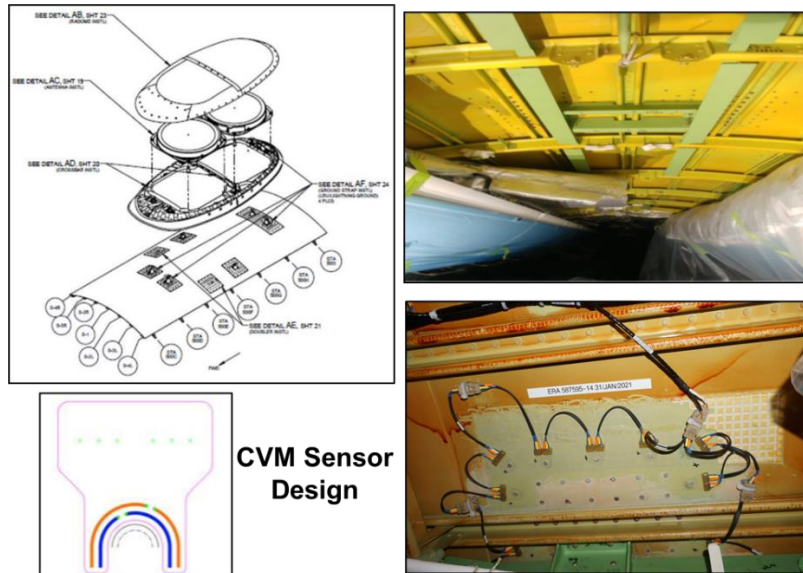
- 60+ Delta A/C have CVM system installed beginning in 2019
- MTBF based on 16 A/C (21-23 sensors each) monitored every 90 days
- Data collection since 2019 compared to existing EC inspection results
- Usage approved via new Service Bulletin (in-process)

Each of the three applications summarized above has come with increasing scrutiny due to the relative safety concerns attached to them. In the case of the APB, this application involves CVM sensors installed on a Principle Structural Element of a Commercial Fixed Wing Aircraft. As a result, an FAA Airworthiness Directive mandates the inspection for 737 operators instead of a Supplemental Type Certificate application. To obtain full maintenance credit, SHM systems must be certified and integrated into the aircraft's maintenance and inspection program. This requires that SHM systems demonstrate compliance with title 14, Code of Federal Regulations 14 CFR § 25.571 - Damage-tolerance and fatigue evaluation of structure and 14 CFR § 25.1529 - Instructions for Continued Airworthiness.

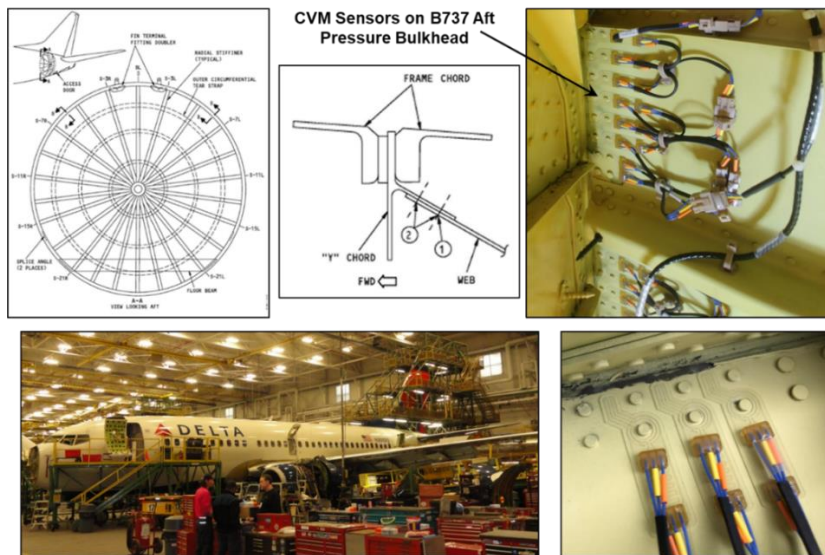
The comprehensive CVM technology validation and certification process used in the programs discussed here, have been guided by an FAA Issue Paper (IP) which addresses the full spectrum of required operation parameters including design, deployment, durability and performance. Similarly, the Aerospace Industry Steering Committee on SHM, composed of aerospace experts from around the world, recently produced an Aerospace Recommended Practice 6821 “Guidance for Assessing the Damage Detection Capability of Structural Health Monitoring Systems” to guide SHM technology validation and certification processes and to comprehensively support the evolution and adoption of SHM practices [6]. For accurate SHM validation to occur, all relevant environments - which may include separate fatigue and environmental response components - were properly simulated in the tests. It allows for the use of pertinent, existing data and outlines the process for conducting “gap” testing to ensure that the system meets the safety standards and performs reliably under normal and abnormal operating conditions. Validation tests were designed to address the CVM equipment, the health monitoring task, the resolution required, the sensor interrogation procedures, and the conditions under which the monitoring will occur. In-service data from CVM installations on operating aircraft, also plays an important role in assessing performance. The resulting documentation must include all design and testing data, as well as the system's installation, operating, and maintenance procedures.



(a) CVM application to monitor the 737 Wing Box Fitting



(b) CVM application to monitor the 737 WiFi installation



(c) CVM Application to Monitor the Aft Pressure Bulkhead

Figure 3. Use of custom CVM sensor networks in lieu of traditional aircraft NDI methods.

## SHM PERFORMANCE FACTORS IN VALIDATION TESTING

When considering the most straightforward application of SHM solutions, on-board sensors may be viewed as in-situ nondestructive inspection (NDI). The data requirements for certification will naturally be similar to those that pertained to the existing NDI method when it was originally certified for the same application. Thus, the core of the validation program stems from the need to establish that the SHM system is “effective if it will readily detect the damage” as required by the Damage Tolerance Analysis [6]. That is, the SHM system must be proven to be “as good or better” than the existing NDI approach. It is necessary to design validation tests that produce the accurate SHM performance assessment results. The validation assembly should be a structure that adequately represents the important aspects of the actual aircraft structure. Its shape and stress field should produce realistic damage to adequately establish the damage detection capability of the SHM sensor system.

Some key factors that can affect the performance of SHM systems are: 1) the SHM solution including sensor layout, data acquisition process, data analysis, data interpretation, and use of sensor signal baselines, 2) the structural configuration including the geometry, material type, number of layers, fastener types, assembly specifics, and coatings, 3) the damage condition including the type, location, depth, and orientation, 4) the environmental conditions including the stress/temperature/vibration load scenario to generate damage, and operating environment to establish durability, 5) usage mode including local versus global monitoring, 6) calibration of sensor responses needed to delineate damage signatures, 7) data requirements to assess applicability of SHM, and 8) aircraft maintenance practices and the ability to properly deploy SHM solutions.

Validation testing must address any effects on the sensor response produced by geometry variations in the sensors and local airplane structure and allowable variations in the structural assembly. For example, variations in structural assembly could potentially change signal transmission/reflection to the degree that SHM performance is dependent on a particular assembly tolerance. If so, then this must be specified up-front and use of this SHM system must be limited to assemblies that fall within an established, allowable tolerance.

Once you decide on the type of data to acquire to properly establish SHM performance, a key follow-on decision is determining how much data is needed. How many data points are needed to statistically prove each performance parameter? How do you properly integrate lab-based testing with in-service data in light of the fact that it is extremely difficult to acquire SHM damage detection occurrences on in-service aircraft. Thus, laboratory testing must be accepted to establish certain performance measures.

## QUALIFICATION AND PERFORMANCE TESTING OF CVM SENSORS

**Damage Detection** - To determine the reliability, sensitivity, and repeatability of the CVM system, and to ensure that the proposed technology meets or exceeds the required crack detection length for the current accepted NDI methods for aircraft, a series of laboratory qualification tests were performed on representative specimens. All factors that affect SHM sensitivity, durability, reliability and repeatability were

included in the suite of validation tests. The goal of the ongoing APB effort is to produce sufficient data and to conduct the proper interface with regulatory agencies to certify CVM sensor technology for detecting cracks in the Boeing 737 Aft Pressure Bulkhead (APB) structure. Towards that end, probability of flaw detection tests were coupled with on-aircraft flight tests to study the performance, deployment, and long-term operation of custom-designed CVM sensors for the APB structure. Statistical methods - including Size of Deterioration at Detection (SODAD)/One-Sided Tolerance Interval (OSTI) [6, 7] - were employed to derive Probability of Detection (POD) levels for SHM sensors. The overall POD value (90% probability, 95% confidence level) for CVM crack detection on the APB was 0.153". The allowable POD crack length using standard eddy current NDI techniques (as per Boeing Service Bulletin 737-53A1248) is 0.200". Thus, CVM exceeded the requirements for the Service Bulletin. In over 300 fatigue tests conducted using CVM sensors for multiple aircraft applications, there have been no false calls produced by the sensors in any of the tests. CVM sensor monitoring was conducted at room temperature, elevated temperatures (104 °F), cold temperatures (39 °F), high humidity (95% RH) and at high altitude (10,000 ft. =10.2 psi) to ensure that the sensors produced proper crack detection after and during exposure to expected monitoring environments.

Flight tests, which will likely not include statistically-relevant damage detection opportunities, still play an important role in assessing overall SHM system performance and long-term durability under an aircraft operator's control. So, the custom CVM sensor network has been installed on over 60 Aft Pressure Bulkheads in the Delta Air Lines 737 fleet. The sensors have been monitored periodically since installation, producing thousands of CVM sensor response data points. These flight tests demonstrated the successful, long-term operation of the CVM sensors in actual operating environments. An assortment of flight tests covering the set of aircraft applications listed here have produced over 2.5 million successful flight hours over the past 20 years.

**Durability and Reliability** - Environmental conditions experienced by the aircraft during flight and ground maintenance activities could affect the reliability and sensitivity of the CVM system. These must be properly understood, evaluated and quantified as do the long-term effects of sensor coatings and operational stress/vibrations. The document used to establish the operational environmental test conditions is "Environmental Conditions and Test Procedures for Airborne Equipment" revision DO-160G developed by RTCA. These standards provided a means of determining the performance characteristics of the CVM system in environmental conditions representative of those which would be encountered during airborne operation. The aviation industry has determined that testing to DO-160 properly simulates aircraft operational environments and captures the 'real' performance of sensors over time. Extensive environmental survivability tests determined that CVM sensors maintained the performance noted above even after exposure to the extreme environments of RTCA DO-160G.

**CVM Installation, Operation and Continued Airworthiness** - In addition to the performance considerations discussed above, there are a many other issues that must be addressed to certify SHM systems as an alternative to other aircraft health monitoring methods. The CVM certification efforts presented here also included formal documents addressing CVM system design, installation and monitoring, training for all personnel involved in SHM deployment, an assessment of false

positives with associated response actions and Instructions for Continued Airworthiness. Systems intended to ensure the airworthiness of an aircraft require thorough analysis of every potential failure method. The analysis provides the system and airplane level effects of failure for each functional block of the CVM system. Each time a CVM reading is taken, the system performs a self-test. This inherent fail-safe property ensures the sensor is attached to the structure and working properly prior to any data acquisition. This fundamental fail-safe design of CVM is essential for SHM of commercial aircraft as false negatives cannot be tolerated. Finally, there is the important SHM education for all players involved in the certification process. This includes not only general education regarding SHM, its proper design and use but also specific information regarding the CVM system in particular and all the validation and supporting documentation for each application. This process is critical to ensuring a fully-informed FAA certification team so that they can complete their review and approval process without any uncertainties in the CVM system's capabilities.

## **REGULATORY REQUIREMENTS**

By demonstrating that the CVM sensors provided equivalent crack detection performance as an alternative for EC inspections, it is now possible to accommodate remote interrogation of the CVM sensors, thus eliminating the removal of the galley to access the structure for the manual EC inspections. The CVM damage detection results were combined with lab-based environmental durability studies and the laboratory flaw detection testing described above to form a critical portion of the overall CVM certification effort. Overall, the goal is to clearly establish the performance of the CVM system to eliminate any unknowns and avoid stacked conservatism that pushes the CVM performance outside of the required levels.

There are 45 documents included in the CVM APB certification effort, including: 1) APB Stress Analysis, 2) Structures Compliance Summary Report, 3) FAA Certification Plan, 4) APB CVM Qualification Analysis, 5) Electrical Compliance Summary Report, 6) Damage Tolerance Analysis, 7) Similarity Report to accommodate use of prior test results, 8) Failure Modes and Effects Analysis, 9) Probability of Detection Report, 10) CVM Installation and Use Tech Sheets, 11) Flammability Compliance Summary Report, 12) Instructions for Continued Airworthiness, 13) Issue Paper Compliance Summary Report, 14) multiple Boeing CVM Performance Test Reports, 15) APB In-Service Data, and 16) new Boeing Service Bulletin 737-53-1418 to introduce CVM use.

Even with the step-by-step guidance provided by the FAA IP for SHM certification, various interpretations of the instructions, uncertainties on the part of regulatory entities and compounding conservatism are hindering the complete adoption of SHM systems for full maintenance credit. For example, regulators are concerned that the 737 APB in-service experience did not record a crack detection on an operating aircraft. However, an in-service crack detection is not a requirement in the FAA IP. It is worthwhile to note that a CVM on-aircraft crack detection was recorded in 2009 on a Bombardier CRJ engine mount beam. The crack was verified by x-ray and eddy current. The view of the Boeing-Delta-AEM team that conducted the CVM performance study is that the use of in-service data provides a basis that

should be used with engineering judgement and other reliability tools (MTBF, Failure analysis) to assess the effectiveness of sensors.

A critical consideration is determining the required substance and pedigree of the in-service data to include it in the certification package. In-service testing on operating aircraft is used to support the proof of durability by establishing SHM system performance on an actual aircraft. Since it is not realistic to require SHM in-service damage detection as a prerequisite to formal use of SHM, the intentions and value of any in-service testing must be addressed by the applicant. The applicant should address why in-service damage detection is not necessary to establish SHM performance. Specific formalities (documentation, inspector signatures, activity witnessing) and FAA involvement in the in-service testing should be discussed with the FAA to ensure the acceptability of the resulting in-service data.

If any portion of the APB laboratory performance testing and the 2.5 M hours of successful CVM in-service data is not accepted for use in the certification package, then a conservative “Belt and Suspenders” approach may be required that uses both the CVM sensors and original EC NDI. Both inspections could be performed at staggered intervals. This reduces the economic advantage of SHM by still requiring the onerous inspection and access. Frequent access to inspection areas also increases the risk for accidental damage to aircraft structure during removal for access. Currently, the FAA and industry is working on guidance relative to SHM in-service detection requirements and clarifications on when “Belt and Suspenders” approaches are required and when they can be terminated. For example, for a specific USAF application of SHM (safety critical), the controlled entry into service period of performance is 24 months (belt and suspenders) at various base locations with no requirement for an in-service detection. After this period, the traditional NDI is performed only at major maintenance checks.

## **CONCLUSIONS**

The effect of structural aging and the dangerous combination of fatigue and corrosion has produced a greater emphasis on the application of sophisticated health monitoring systems. Meanwhile, the costs associated with the increasing maintenance and surveillance needs of aging aircraft are rising. Corrective repairs initiated by early detection of structural damage are more cost effective since they reduce the need for subsequent major repairs and may avert a structural failure. Global SHM achieved with sensor networks, can be used to assess overall performance of large structures such as aircraft, bridges, pipelines, large vehicles, and buildings. The ease of monitoring an entire network of distributed sensors means that structural health assessments can occur more often, allowing operators to be even more vigilant with respect to flaw onset.

The use of in-situ CVM sensors makes it possible to quickly, routinely, and remotely monitor the integrity of a structure in service and detect incipient damage before catastrophic failures occur. These sensors can be attached to a structure in areas where crack growth is known to occur. On a pre-established inspection interval, a reading can be taken from an easily accessible point on the structure. In the aircraft applications described here, the CVM sensors were proven to detect cracks before they propagated to the critical length determined by damage tolerance analyses. The

sensitivity, reliability, repeatability, and durability of the CVM sensor system were demonstrated in both laboratory and field test environments.

A complete understanding of the parameters involved in the SHM system's response and the effect of those parameters on the resulting POD and other performance items was used to properly apply the established POD models. This allowed all validation testing to be completed using suitable structures that produced representative damage growth under realistic flight environments. In addition to CVM sensitivity assessments, all performance measures were determined while considering all inspection requirements, fail-safe features, continued airworthiness tasks and regulatory compliance issues regarding CVM system production, installation and operation.

The activities conducted in this program facilitated the evolution of the CVM certification process including the development of regulatory guidelines and advisory materials for the safe implementation of CVM systems. Current certification processes are being further evolved via the programs described here so that there are no remaining uncertainties surrounding SHM use. Key to this endeavor is assembling robust, trusted validation data to avoid stacked conservatism and the addition of maintenance tasks that do not fully rely on SHM for damage detection. These efforts will allow for a full realization of the economic and technical advantages offered by SHM systems.

## **ACKNOWLEDGEMENTS**

This program was a joint effort involving Boeing, Delta Air Lines, AEM and the FAA. The contributions from these agencies were essential to successful CVM certification. Specific thanks go to Walt Jarecki and Zeb Tidwell at Boeing, David Piotrowski at Delta Air Lines and Ivan Li, Kam Zaman, Greg Schneider, Walt Sippel, Michael Gorelik, Catalin Dumitrescu, Bill Vickers, and Patrick Safarian at the FAA. Critical hardware testing and on-aircraft installation support were provided by Brian Shaigec and Derrick Formosa at AEM and Steven Crummack at Testia.

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