Assessing the Performance CVM Sensors for Monitoring the 737 Aft Pressure Bulkhead

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ABSTRACT

Current maintenance operations and integrity checks on aircraft require personnel entry into normally-inaccessible or hazardous areas to perform necessary nondestructive inspections. To gain access for these inspections, structure must be removed, sealant must be removed and disassembly processes must be completed. The use of in-situ sensors, coupled with remote interrogation, can be employed to overcome a myriad of inspection impediments stemming from accessibility limitations, complex geometries, the location and depth of hidden damage, and the isolated location of the structure. Reliable Structural Health Monitoring (SHM) systems can automatically process data, assess structural condition, and signal the need for specific maintenance actions. This paper presents an OEM-airline-SHM vendor-regulator effort to realize these benefits by moving Comparative Vacuum Monitoring (CVM) technology into routine use in airline maintenance programs. A certification program has been completed to validate CVM sensors for surface crack detection on the 737 Aft Pressure Bulkhead (APB). Formal and comprehensive CVM technology validation and certification was guided by a recently-released FAA Issue Paper which addresses the full spectrum of issues including design, deployment, durability and performance. For accurate SHM validation to occur, all relevant environments - which may include separate fatigue and environmental response components - were properly simulated in the tests. Flight tests also played an important role in assessing overall CVM system performance under normal aircraft operations. Validation tests were designed to address the CVM equipment, the health monitoring task, the resolution required, the sensor interrogation procedures, the conditions under which the monitoring will occur, and the potential inspector population. The test results will be presented in light of the overall CVM certification plan. Such SHM deployment programs are allowing the aviation industry to confidently make informed decisions about the proper utilization of SHM. These programs also streamline the regulatory actions and certification measures needed to ensure the safe application of SHM solutions.

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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 Structural Health Monitoring (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 approach 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]. This requires the use of reliable structural health monitoring systems that can automatically process data, assess structural condition, and signal the need for specific maintenance actions. The use of in-situ sensors for monitoring the condition of aircraft structure, coupled with remote interrogation, can be employed to overcome a myriad of inspection impediments stemming from accessibility limitations, complex geometries, and the location and depth of hidden damage. Furthermore, 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]. 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.

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 [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. It is important to note that the sensor detects surface breaking cracks once they interact with the vacuum galleries.

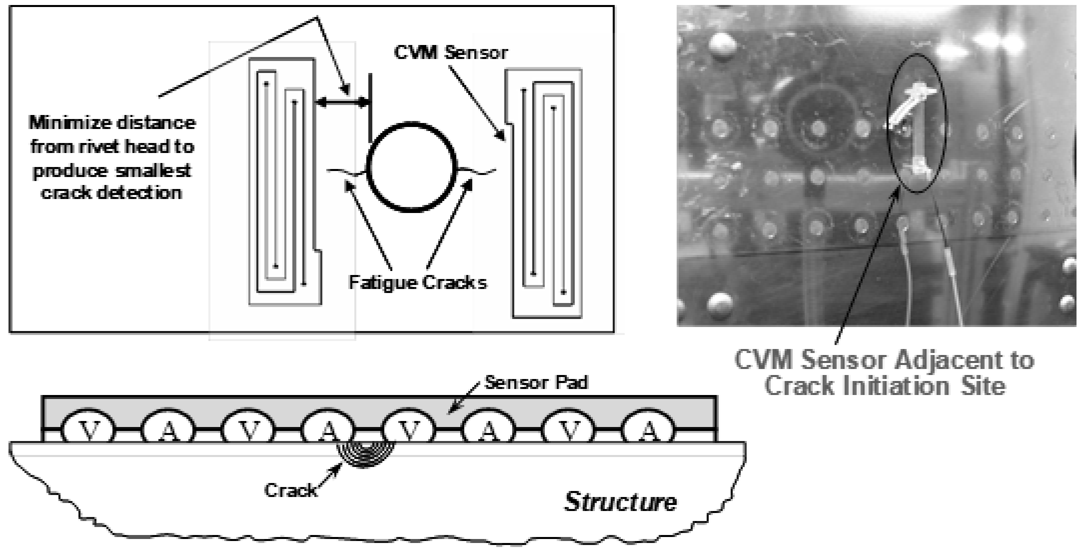

Figure 1. Schematics depicting operation of CVM sensor mounted on the outer surface of a riveted lap joint.

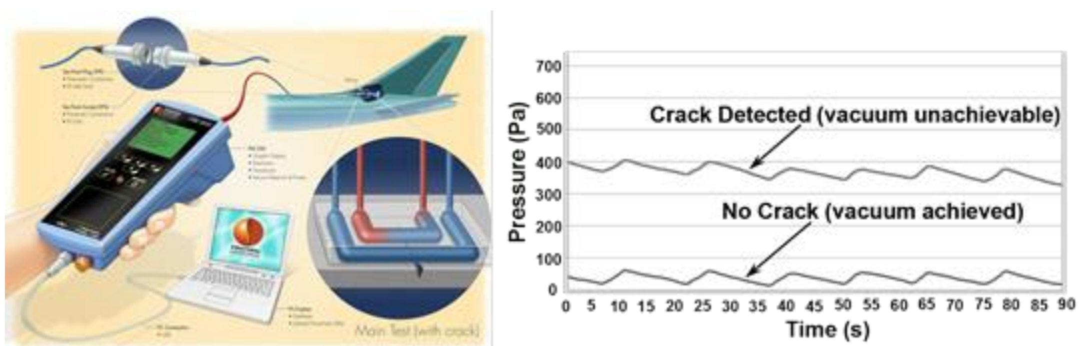

Figure 2. Crack detection monitoring with CVM system and pressure response used to indicate the presence of a crack.

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 [5, 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 test and data acquisition methods that produce the accurate SHM performance assessment results. Such tests include the validation assembly, load application, stress levels and data type acquired for each damage detection test. 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 the device, sensor spacing, data acquisition process, data analysis, data interpretation, and use of baselines, 2) the structural configuration including the geometry, material type, number of layers, fastener types and spacing, hole geometry, assembly specifics, surface condition, and coatings, 3) the damage condition including the type, location, depth, orientation, dimensions, and morphology, 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; Condition Based Maintenance and Prognostic Health Management considerations, 6) calibration of sensor responses needed to delineate damage signatures, 7) data requirements to assess applicability/limitations of SHM, and 8) aircraft maintenance practices and the ability to properly deploy SHM solutions. Other considerations for producing viable SHM performance data include: 1) obtaining baseline signals to properly represent the undamaged structure, 2) setting Damage Thresholds that consider signal-to-noise (S/N) levels that avoid false positives. The "Damage Threshold" pertains to the CVM signal threshold that is established to properly assign damage detection. It is associated with the change in system response compared to a Baseline (signals from an undamaged component) over its monitored lifetime. The goal is to simplify damage detection such that the CVM sensor response provides a Green Light/Red Light ("GO" – "NO GO") decision on the presence of damage.

PERFORMANCE TESTING OF CVM SENSORS

The goal of this project was 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 assessments 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 using one-sided tolerance intervals were employed to derive Probability of Detection (POD) levels for SHM sensors. The result is a series of crack detection values that were used to propose CVM sensors for aircraft crack detection in lieu of the existing eddy current (EC) inspections. By demonstrating that the CVM sensors provided equivalent crack detection performance as the alternative EC inspections, it was 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. Figure 3 shows the details of the APB application and installation of CVM sensors for the flight test program. Fatigue tests were completed on representative APB test specimens using realistic flight loads while the vacuum pressures within the various sensor galleries were simultaneously recorded. A fatigue crack was propagated until it engaged one of the vacuum galleries such that crack detection was achieved and the sensor indicated the presence of a crack by its inability to maintain a vacuum.

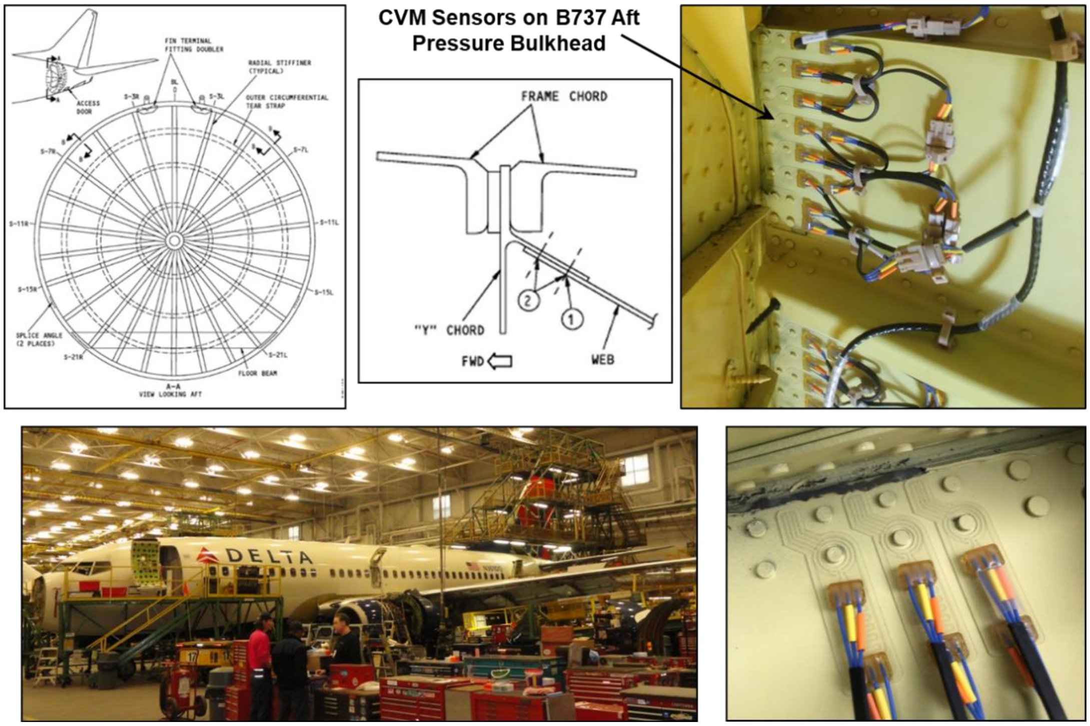

Figure 3. 737 Aft Pressure Bulkhead application with custom CVM sensor network installed.

DATA ANALYSIS USING PROBABILITY OF DETECTION MODELS

<u>One Sided Tolerance Intervals</u> - A fatigue crack that grows in a known propagation path such that the damage scenario can be described in a single parameter: crack length. In this latter case, the simplicity of such a one-dimensional entity allows for a more direct calculation of the reliability of the SHM system detecting such damage. The Probability of Detection for a fixed sensor detecting a crack which is propagating in a known direction in the vicinity of the sensor can be determined using the One-Sided Tolerance Interval (OSTI) approach [7, 8]. The OSTI estimates the upper bound which should contain a certain percentage of all measurements in the population with a specified confidence. Since it is based on a sample of the entire population (n data points), the confidence is less than 100%. Thus, the OSTI is greatly affected by two proportions: 1) the percent coverage which is the percent of the population that falls within the specified range (normally chosen as 90%), and 2) the degree of confidence desired (normally chosen as 95%).

The data captured is that of the flaw length at the time for which the SHM provided sustainable detection. With these assumptions there exists a distribution on the flaw lengths at which detection is first made. In this context, the reliability analysis becomes one of characterizing the distribution of flaw lengths and the cumulative distribution function is analogous to a Probability of Detection (POD) curve. If the distribution of flaws is such that the logarithm of the lengths has a Gaussian distribution, it is possible to calculate a one-sided tolerance bound for various percentile flaw sizes. To calculate a one sided tolerance bound, it is necessary to find factors $K_{n,\gamma,\alpha}$ to determine the confidence ɣ such that at least a proportion (α) of the distribution will be less than $X + (K_{n,\gamma,\alpha})S$ where X and S are estimators of the mean and the standard deviation computed from a random sample of size *n*. The K factor for an OSTI can be obtained from standard statistical tables. From this reliability analysis a cumulative distribution function is produced to provide the maximum likelihood estimation (POD). This stems from the one-sided tolerance bound for the flaw of interest using the equation:

$$T_{POD(90,\,95)} = X + (K_{n,\gamma,\alpha})(S) \qquad (1)$$

Where,

T = Tolerance interval for crack length corresponding to 90% POD with a 95% confidence
X = Mean of detection lengths
K = Probability factor (~ sample size and confidence level desired)
S = Standard deviation of detection lengths
n = Sample size
α = Detection level
γ = Confidence level

The formula in equation (1) is set-up to produce the upper bound for the tolerance interval which represents the actual POD value.

In order to properly consider the effects of crack closure in an unloaded condition (i.e. during sensor monitoring), a crack was deemed to be detected when a permanent alarm was produced and the CVM sensor did not maintain a vacuum even if the fatigue stress was reduced to zero. Figure 4 shows the fatigue test set-up used to grow cracks and a close-up photo of a fatigue crack as it engages the first vacuum gallery of a CVM sensor. CVM sensor monitoring was conducted at room temperature, elevated temperatures (104 ^{o}F), cold temperatures (39 ^{o}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. Twenty APB specimens were tested and the CVM crack detection lengths ranged from 0.124” to 0.153” in length with an average crack detection length of 0.137”. The crack detection lengths correspond to permanent alarm levels for cracks engaging CVM sensors and the structure in an unloaded condition.

Data acquired from CVM fatigue tests were used to calculate the 90% POD level for CVM crack detection on 0.032” thick 2024-T3 aluminum structure in a lap joint configuration and subjected to tension-tension fatigue loading (see Fig. 4). To complete the testing using a realistic number of data points, the reliability calculations induce a penalty by increasing the magnitude of the K (probability) factor as the specimen set gets smaller. As a result, while most of the crack detection levels were less than or equal to 0.153”, the overall POD value (95% confidence level) for CVM crack detection was calculated from equation (1) as 0.153”. In the APB application, it was desired to achieve crack detection before the crack reached 0.2” in length so this goal was achieved. In over 250 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.

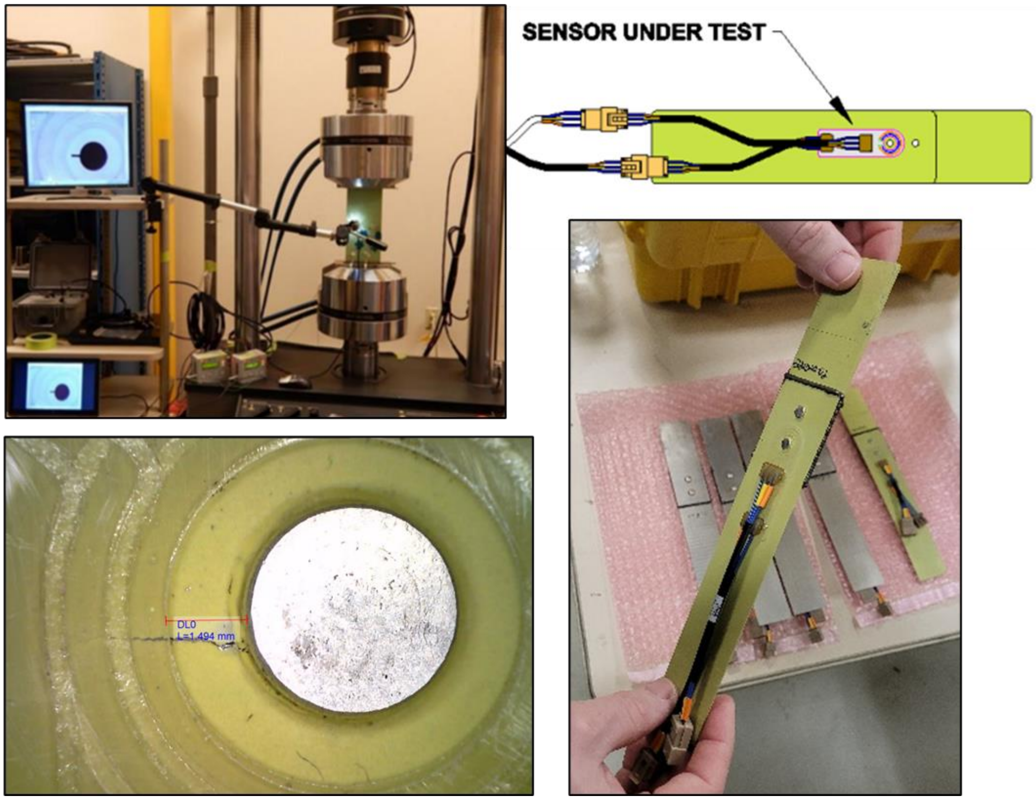

Figure 4. Fatigue testing to assess CVM performance in 737 Aft Pressure Bulkhead application.

In addition to the lab-based certification tests, the custom CVM sensor network was installed on 24 Aft Pressure Bulkheads in the Delta Air Lines 737 fleet. These installations took place over the past three years and the sensors have been monitored periodically since installation, producing hundreds of 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 multiple aircraft applications have produced over 1.5 million successful flight hours over the past 20 years. These 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.

CONCLUSIONS

The costs associated with the increasing maintenance and surveillance needs of aging aircraft are rising. 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. 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 engineering interval, a reading will be taken from an easily accessible point on the structure. Each time a 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. In the APB application described here, the CVM sensors provided crack detection before the crack propagated to the critical length determined by damage tolerance analyses. In addition, there were no false calls experienced in the fatigue crack detection tests. The sensitivity, reliability, and cost effectiveness of the CVM sensor system was demonstrated in both laboratory and field test environments. 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.

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