Integration of Structural Health Monitoring Solutions onto Commercial Aircraft Via the FAA SHM Research Program

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Abstract. The Federal Aviation Administration (FAA) started a research program in structural health monitoring (SHM) in 2011. The program's goal was to understand the technical gaps of implementing SHM on commercial aircraft and the potential effects on FAA regulations and guidance. The program evolved into a demonstration program consisting of a team from Sandia National Labs Airworthiness Assurance NDI Center (AANC), the Boeing Corporation, Delta Air Lines, Structural Monitoring Systems (SMS), Anodyne Electronics Manufacturing Corp (AEM) and the FAA. This paper will discuss the program from the selection of the inspection problem, the SHM system (Comparative Vacuum Monitoring-CVM) that was selected as the inspection solution and the testing completed to provide sufficient data to gain the first approved use of an SHM system for routine maintenance on commercial US aircraft.

INTRODUCTION

Structural Health Monitoring (SHM) is a growing technology that offers many benefits to airline operators, aircraft OEMs and regulators. There are many people pushing to get SHM installed on commercial aircraft in the United States and the Federal Aviation Administration's (FAA) Transport Aircraft Directorate (TAD) was interested in understanding what SHM is, which SHM systems may be close to be fielded, how will SHM affect existing rules, regulations and guidance and if any new documents need to be created. The TAD developed a SHM research requirement that started in FY11 with the desire to have the questions above answered. The research is being managed at the FAA William J Hughes Technical Center in Atlantic City, NJ. Personnel from the Airworthiness Assurance NDI Center (AANC) from Sandia National Labs was hired to perform SHM research because of their past 30 years' experience supporting the FAA's NDI Inspection program providing validation and verification of various NDI projects. AANC personnel reviewed all of the published documents related to SHM topics and summarized the information including a technology readiness level (TRL) analysis. They solicited input on SHM from hundreds of folks from airlines, OEMS, regulators and any potential SHM impact and collated the data. They performed a gap analysis and developed a recommended roadmap for the FAA to review. They also reviewed the existing FAA rules, regulations, guidance and commercial specifications and made recommendations to which may be revised to accommodate SHM. They were also tasked to make a recommendation of a demonstration program that could be performed with an airline operator and OEM to further understand the process, procedures and data required to get an SHM system approved for commercial transport aircraft use. AANC made agreements with the Boeing Company and Delta Air Lines to work as a team to define a problem, a SHM system that could be used and develop the program to move through the process and develop the procedures and collect the data to certify the methodology. Boeing and Delta spent a lengthy review of problems in their fleet and potential solutions. They ultimately chose the 737NG center wing box fitting cracking problem which Boeing had issued a service bulletin (SB). This paper will explain the application of SHM to this problem and the steps taken to gather information to get Boeing approval.

Comparative Vacuum Monitoring (CVM)

The Boeing and Delta team chose the Comparative Vacuum Monitoring (CVM) system made by SMS in Australia and currently licensed to AEM in Vancouver. It is a self-adhesive elastomeric sensor with alternating channels of vacuum and atmospheric pressure which are in contact with the surface as shown in Figure 1. The CVM sensor has connectors which allows the system (define) to interrogate the sensor and attempt to check the vacuum and atmospheric pressures. If a crack has breached a vacuum channel and either an atmospheric channel or a through material crack, the vacuum channel pressure cannot be achieved as shown in figure 2. The CVM sensor is ideal because it requires no power to operate, and has a self-checking ability to know that the sensor is performing correctly.

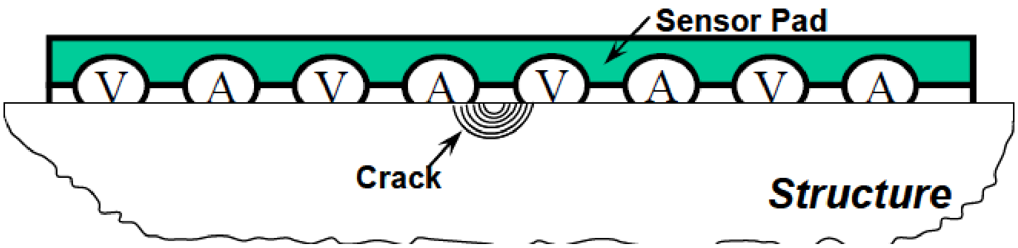

Figure 1

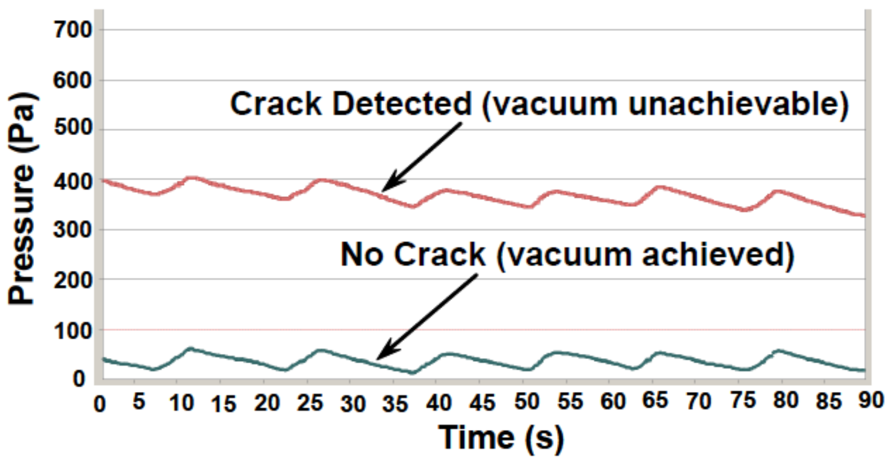

Figure 2

The sensor has been tested for several years under the FAA NDI program and AANC personnel. They were installed on Delta and Northwest Airline aircraft for 2-3 years (2004-2006) to test the sensor's long term ability to work in an aircraft environment (figure 3). The sensors were checked periodically by the operators and the data was provided to AANC for analysis.

Aircraft	Tail	Operator	Date	# Sensors	Status
DC-9	9961	NWA	Feb 04	6 (4 remaining)	2 sensors removed by NWA
DC-9	9968	NWA	Apr 05	6	3 sites
B757	669	Delta	Apr 05	8	4 sites in empennage on stringers, frames & near APB
B767	1811	Delta	Apr 05	6 (4 connected)	3 sites in empennage

Figure 3

In 2009, AANC personnel started a pilot program with Air Canada and Bombardier to test the CVM on their CRJ fleet which had a cracking problem on an engine pylon. The purpose of the program was to determine any issues with the sensor's design, surface preparation, access to the problem area, connection routing, and quality control. They monitored for 4 months and successfully found a crack as was shown in a liquid penetrant inspection in figure 4. The fleet tests with Delta, Northwest and Air Canada provided supporting data to the future use of CVM in the FAA certification process.

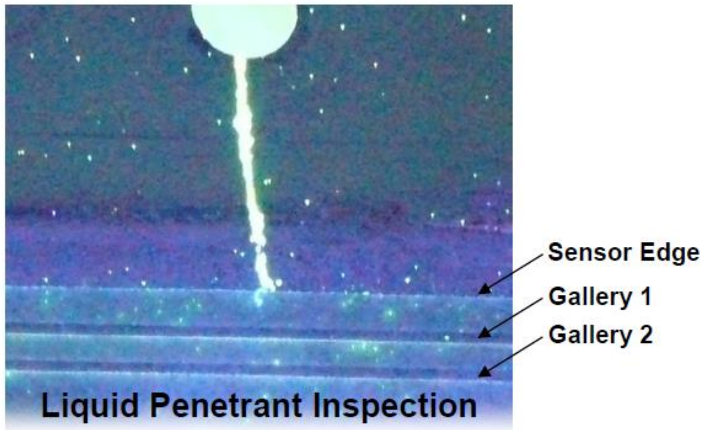

Figure 4

Certification and Validation Initiatives

Boeing issued a service bulletin (SB) to inspect the shear fittings on the 737NG center wing section for cracking shown in figure 5. The SB requires a high frequency eddy current (HFEC) and visual inspection for aircraft with more than 21k cycles. This SB requires the operator remove the seats, disassemble the floor panels to access the fittings in question. To perform the inspection, the fittings need to have the fuel vapor barrier and paint/primer removed.

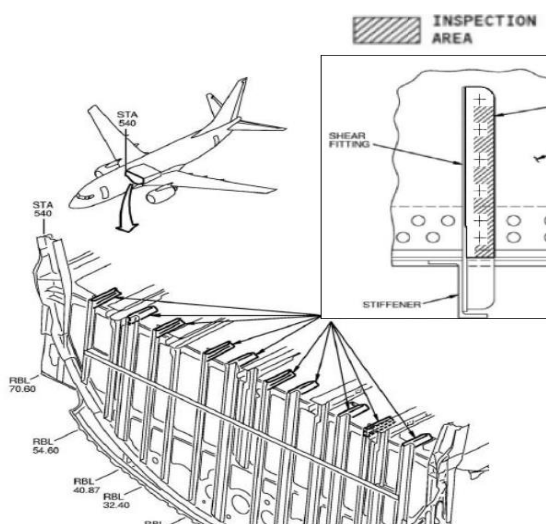

Figure 5

As part of the FAA's research program on SHM, the FAA Airworthiness Assurance Center (AANC) at Sandia Labs, in conjunction with Boeing, Delta Air Lines, Structural Monitoring Systems and Anodyne Electronic Manufacturing, is conducting a study to develop and carry out a certification process for SHM. By conducting a focused assessment of a particular aircraft application, all aspects of SHM integration are being addressed. While it is important to recognize the unique validation and verification tasks that arise from distinct differences between SHM and nondestructive inspection (NDI) deployment and flaw detection, it should be recognized that some portions of the methodology needed to determine NDI performance can be adapted to the validation of SHM systems. In this study, statistical methods were applied to laboratory and flight test data to derive Probability of Detection (POD) values for SHM sensors in a fashion that agrees with current NDI requirements.

Delta and Sandia National Labs, in conjunction with Boeing, SMS and AEM have partnered to conduct the first installation of Comparative Vacuum Monitoring (CVM) sensors onto a fleet of aircraft, ultimately resulting in a change to the Maintenance Program. This undertaking moves past the 'prototype' experiments of the past and will provide a recommended certification path for SHM future adoption. This effort focused on the 737NG Wing Center Section Shear Fittings as the initial application. This work can serve as the 'blueprint' for the industry to follow: airlines, MROs, regulatory agencies, vendors and academia.

CVM Performance Assessment

Some portions of the normal POD methodology needed to quantify NDI performance can be adapted to the validation of SHM systems. However, it is important to recognize the unique validation and verification tasks that arise from distinct differences between SHM and NDI deployment and flaw detection. SHM reliability calculations will depend greatly on the complexity of the structure and geometry of the flaw profile. For example, corrosion damage has a widely-varying flaw shape, both in the surface dimensions and in the changing depth. Contrast this with 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 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. 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%).

Because of physical, time or cost constraints, it is often impractical to inspect an entire population. Instead, a small sample of the total population is tested and the data is used to gauge how well the entire population conforms to specifications. In traditional statistical process control, a significant number of data points are required in order to get a reasonably accurate estimate of process capability. This is because capability is usually calculated to cover a fixed multiple standard deviations. But this percentage only holds true for larger sample sizes; that is, greater than 50. As the sample size decreases, there is greater uncertainty in knowing the true location of the mean and the true magnitude of the population variance. Therefore, the estimate of the range of values encompassing a given percentage of the population must necessarily increase to compensate. In order to maintain a reasonably accurate estimate of the capability of a process for smaller sample sizes, it is necessary to adjust the number of multiple sample standard deviations used to define the region covering the desired proportion of the population distribution with a given confidence. An OSTI can be used for this purpose.

The data captured is that of the flaw length at the time for which the CVM provided sustainable detection. With these assumptions there exists a distribution on the flaw lengths at which detection is first made. In this context, the probability of detection for a given flaw length is just the proportion of the flaws that have a detectable length less than that given length. That is, 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. Assuming that 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 γ 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 shown in equation (1). There may also be situations where the process capability is measured relative to a single-sided limit. These situations arise when a product characteristic need only meet a minimum specification limit or remain below a maximum specification limit. In this case, the desired POD value is the maximum crack length associated with the 90% POD level so the one-sided tolerance interval is used. 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:

$$T\ POD(90, 95) = X + (K\ n,ɣ,\alpha)(S) \qquad (1)$$

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
ɣ = 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 ensure the validity of a log-normal, or Gaussian, distribution on the flaw lengths, the data should plot linearly on a semi-log scale and the data should be clustered near the 50th percentile. The assumption of normality can also be tested by applying the Anderson-Darling test. The Anderson-Darling test yields a P-value that can be compared to the chosen significance level to determine whether or not the assumption of normality should be rejected. The significance level, a, is chosen to be 0.05. Any value of P less than a = 0.5 indicates that there is sufficient evidence to reject the assumption of normality. A normal probability plot was created using Minitab® statistical software. In addition, the Anderson-Darling test returned the required value of P > 0.05.

With the same parameters described above, the maximum likelihood estimate describing the upper bound or optimal performance on the Probability of Detection for the OSTI approach can be calculated as:

$$\mathbf{POD}(\text{Max Likelihood Est}) = \frac{1}{xS\sqrt{2\pi}} EXP\left(\frac{-(\ln(x) - X)^2}{2S^2}\right) \qquad (2)$$

Data acquired from CVM fatigue tests were used to calculate the 90% POD level for CVM crack detection on 0.1" thick 2024-T3 aluminum structure subjected to tension-tension fatigue loading. Twelve data points (bare surface) and ten data points (primer surface) were used in lieu of the 51 or greater that are required in conventional POD calculations. Due to the limited number of data points, the reliability calculations induce a penalty by increasing the magnitude of the K (probability) factor. As a result, while most of the crack detection levels were less than 0.015", the overall POD value (95% confidence level) for CVM crack detection was calculated from equation (1) as 0.023". The K values correspond to the desired ɣ (confidence level) of 95%. The maximum likelihood estimated POD function, representing the optimum performance for CVM crack detection, was calculated from equation (2) and is plotted alongside the 95% confidence bound. As the number of data points increases, the K value will decrease and the POD numbers could also decrease. In this particular instance, it was desired to achieve crack detection before the crack reached 0.1" in length so this goal was achieved. In over 150 fatigue tests conducted using CVM sensors there were no false calls produced by the sensors in any of the tests. Figure 6 shows the POD curve for CVM on primer panels.

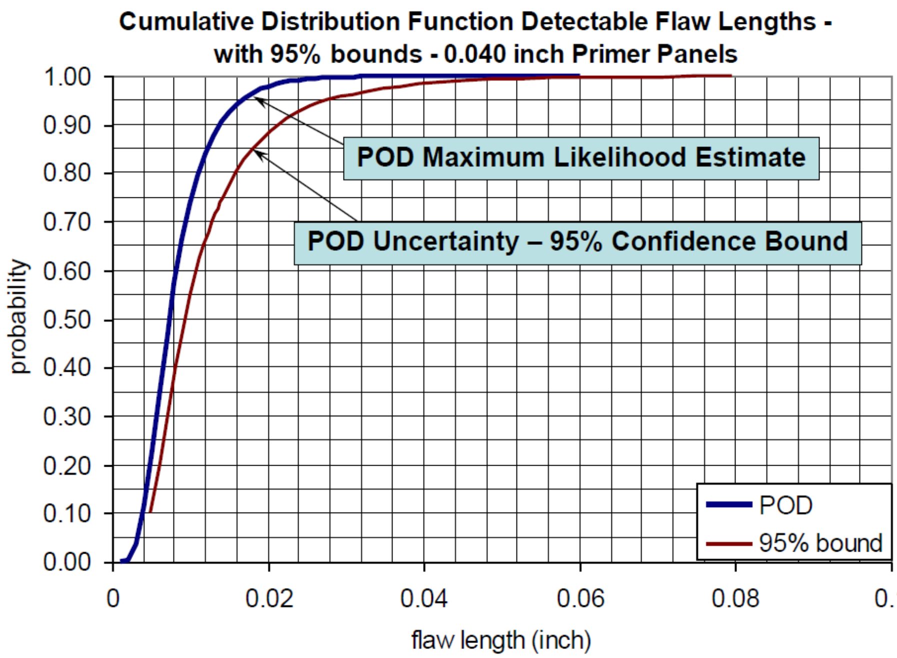

Figure 6

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 specific aircraft applications. 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 CVM sensors on aircraft. 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 flaw detection curves that can be used to propose CVM sensors for aircraft crack detection. The test specimens were wing box fittings from the Boeing 737 which was the chosen CVM application from Delta's fleet. The figures below show the details of the wing box fitting application and installation of CVM sensors for the flight test program. Fatigue tests were completed on the wing box fittings using flight load spectrums 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.

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. Crack detection lengths ranged from 0.145" to 0.245" in length for the wing box fitting application. The crack detection lengths correspond to permanent alarm levels for cracks engaging CVM sensors with the structure in an unloaded condition.

Numerous tests were required to gather the data needed to feel comfortable to approach the FAA and Boeing Corp for review and approval of the CVM on the 737 wing box fitting. Tests included lab tests as well as flight tests. The lab tests included fatigue testing of the CVM sensor while installed on the wing box. Figure 7 shows the model of the wing box fitting in tension loading for fatigue testing as loaded during normal flight and figure 8 shows the actual test setup. Another lab test was testing the CVM with fuel vapor barrier (FVB) because the fitting fasteners are covered in FVB and the CVM sensors would need to operate while covered with it as well. FVB seals the fasteners and the CVM sensors from the atmosphere and therefore affect who the CVM functions. Tests showed that the CVM could detect a crack once it broached the first 2 galleries. The next set of lab tests included environmental testing of the CVM sensor installed on test specimens which will prove the durability of the CVM sensor. Tests include heat, cold and humidity. The test profile is shown in figure 9. The CVM sensors showed no degradation due to environmental issues. The final set of lab tests was to test the effects of corrosion inhibiting compounds (CIC) on the CVM.

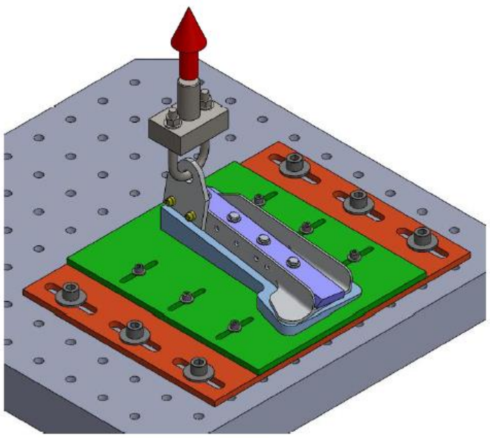

Figure 7

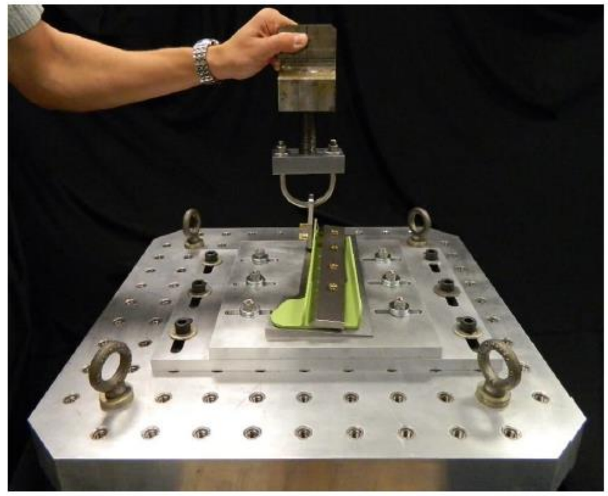

Figure 8

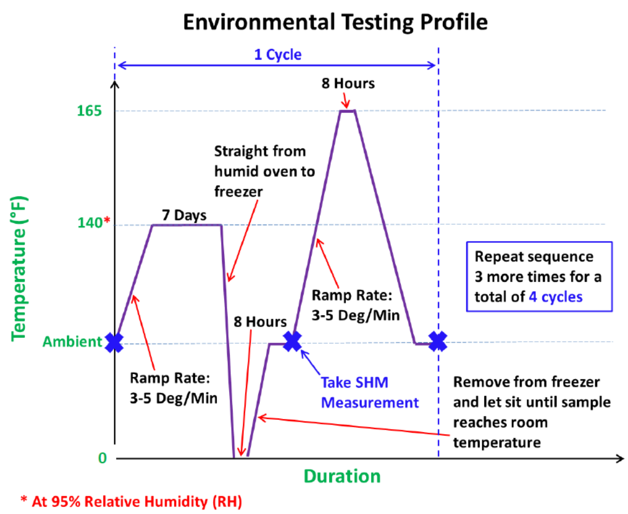

Figure 9

Flight testing was accomplished by Delta Air Lines with the intent to step through the formal process of integrating SHM into an airline maintenance program to include management approval, job cards and installation and operational training. Delta engineers developed the job cards to lead the maintenance personnel in installing the CVM sensor. AANC trained the Delta mechanics in installation of the sensors. Delta picked 7 aircraft that were coming into Atlanta for a five day check. Their mechanics successfully installed 68 of the70 sensors on the wing box fittings as shown in figure 10. The CVM connectors were routed into a luggage compartment to allow for the sensors to be checked overnight while they were in Atlanta. The sensors have been monitored every 90 days for the past 18 months, producing 385 sensor response data points. These flight tests demonstrated the successful, long-term operation of the CVM sensors in actual operating environments.

Figure 10

Conclusion

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. In addition, the costs associated with the increasing maintenance and surveillance needs of aging structures 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 through the use of sensor networks, can be used to assess overall performance (or deviations from optimum 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.

Through the use of in-situ CVM sensors, it is 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.

This study showed the viability of using the One-Sided Tolerance Interval (OSTI) approach to determine the Probability of Detection for a fixed sensor detecting a crack which is propagating in a known direction in the vicinity of the sensor. The OSTI approach yields a reasonable estimate for the CVM crack detection capability even with small data sets. In several structural categories studied, the CVM sensors provided crack detection well 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.

This program is also establishing an optimum OEM-airline-regulator process and determining how to safely adopt SHM solutions. Close consultation with regulatory agencies is being used to produce a process that is acceptable to both the aviation industry and the FAA. The activities conducted in this program facilitate the evolution of an SHM certification process including the development of regulatory guidelines and advisory materials for the implementation of SHM systems via reliable certification programs. Formal SHM validation will allow the aviation industry to confidently make informed decisions about the proper utilization of SHM.

In December 2015, the team presented the data package to Boeing DERs. Delta requested CVM be an alternate means of compliance to the existing service bulletin for all 737 aircraft. In June 2016, Boeing revised and published the service bulletin with CVM as an approved alternate means of compliance making this the first commercially approved use of SHM in the U.S. commercial transport fleet.

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