Certification of CVM™ Sensors for Monitoring 737 Aft Pressure Bulkhead

TREVOR LYNCH-STAUNTON, BRIAN SHAIGEC,
DERRICK FORMOSA and DENNIS ROACH

ABSTRACT

Structural health monitoring (SHM) systems are a desired solution to provide aircraft operators information on the health of aircraft structures. The Federal Aviation Administration (FAA) is responsible for ensuring the safety of the air transportation system in the United States and its certification of SHM systems is essential to ensure that these systems meet safety standards and do not compromise aircraft safety. This paper provides an overview of the efforts undertaken to supply the necessary data and analysis for certification of a CVM SHM system, including the regulatory requirements and the steps involved in the certification process. Additionally, this paper discusses the benefits of SHM systems for the aviation industry and their potential impact on safety.

Cost and time savings are driving the demand for certification of a CVM™ SHM system that satisfies the requirements of Boeing SB-737-53A1248 along with the guidance of an FAA Issue Paper. This certification would be the first for any SHM system in a safety critical Principle Structural Element of a Commercial Fixed Wing Aircraft, the Aft Pressure Bulkhead (APB), where an FAA Airworthiness Directive is mandating the inspection for 737 operators.

The existing Service Bulletin allows for two inspection options, Option 1: LFEC and detailed inspection (aft side) every 1,200 flight cycles or Option 2: HFEC and detailed inspection (fwd side) every 3,800 flight cycles. The approval of the revised service bulletin would allow for Option 3: CVM™ inspection (fwd side) every 1,200 flight cycles, thus reducing the inspection time from 24 hr to 15 min[1].

INTRODUCTION

The goal of this work is to provide the required certification elements to submit for approval of the CVM™ Sensor system on the Boeing 737 APB. The performance capabilities and specific design details for sensor configurations that intend to show compliance with FAA and Boeing requirements as well as the specific FAA Issue Paper for this application.

The CVM™ sensor design for the Boeing 737 Aft Pressure Bulkhead (APB) application was successfully evaluated and tested in accordance with the Test Plan. Flight testing, lab testing, and qualification by similarity to previous designs was conducted to satisfy requirements.

A Probability of Detection study, along with Reliability and Durability with environmental testing was conducted on specimens. Data collected from CVM™ Sensor Systems in-flight, and lab tests was collected and analyzed to satisfy relevant sections of the Issue Paper. The documentation package including the Installation and Monitoring Procedures, Service Bulletins, Failure Modes and Effects Analysis and Mean Time Between Failure reliability analysis, as well as Qualification Test Reports were provided and reviewed during the approval process.

Lynch-Staunton, Shaigec, Formosa, Roach, Anodyne Electronics Manufacturing Corp., Kelowna, BC Canada

The application of Structural Health Monitoring (SHM) could provide significant cost savings to an aircraft operator[2]. To utilize SHM on a commercial aircraft, certification approval must be obtained. The path to certification follows guidance provided by a specific FAA Issue Paper for the qualification of Structural Health Monitoring on the 737 Aft Pressure Bulkhead, this issue paper was derived from a generic Issue Paper previously written on SHM.

The goal is certification of a CVM™ SHM solution that satisfies the original intent of Boeing SB-737-53A1248 while satisfying the guidance of the FAA Issue Paper. This will be the second safety critical certification achieved for CVM™ but this time, the application is installed on a Principle Structural Element of a Commercial Fixed Wing Aircraft, the Aft Pressure Bulkhead (APB), with an FAA Airworthiness Directive mandating the inspection for 737 operators instead of a Supplemental Type Certificate application.

REGULATORY REQUIREMENTS

The FAA Issue Papers provided guidance for two CVM™ applications, the Gogo Wi-Fi STC for Delta Air Lines aircraft and the Boeing 737 Aft Pressure Bulkhead. The Issue Papers provide guidance on how to show compliance with Federal Aviation Regulations (FAR) Part 25. For maintenance credit, SHM systems must be certified and integrated into the aircraft's maintenance and inspection program.

CERTIFICATION PROCESS

The certification of SHM systems require demonstration of 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 involves several aspects. If existing allowable data is available and it can be shown to be similar to the proposed system, a similarity analysis may allow the use of existing data for substantiation instead of testing. The validity and pedigree of the data will need to be supported, as the opportunity for specimen and test conformity, as well as test witnessing would no longer be available. If no similar admissible data exists, testing must be conducted to ensure that the system meets the safety standards and performs reliably under normal and abnormal operating conditions. Any in service data for these systems or similar systems is also considered. Additionally, installation, maintenance, and troubleshooting documentation is reviewed. The documentation must include all design and testing data, as well as the system's installation, operating, and maintenance procedures.

QUALIFICATION TESTING OF CVM™ SENSORS

To determine the reliability, sensitivity, and repeatability of the CVM™ system, and to ensure that the proposed technology meets or exceeds the equivalent POD length for the current accepted SHM methods for aircraft, a series of laboratory qualification tests were performed on various specimens. These specimens included Sensor and test coupon designs that were representative of the on-aircraft installation for the B737 Aft Pressure Bulkhead, as well as generic designs that met the material and functional requirements of the CVM™ system. The document used to determine the standard environmental test conditions was *"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. In addition to this standard, AEM worked closely with Sandia National Labs[2] in Albuquerque, New Mexico, and Boeing Engineers to determine specific environmental conditions, and physical conditions of the aircraft during both flight and ground maintenance cycles that could affect the reliability and sensitivity of the CVM™ system.

To qualify the CVM™ Sensors, a Probability of Detection (POD) study was performed to quantify the CVM™ Sensor's ability to detect a fatigue crack. By placing Sensors on aluminum test coupons with a starter notch, we were able to grow a crack on a Fatigue Testing Machine (FTM) to the point of detection by applying a sinusoidal stress equivalent to what the Sensors could experience during flight cycles. Once detection was achieved, the test specimens were exposed to the environmental conditions and interrogated as per the standard AEM test procedures for CVM™ Sensors. The analysis of the results was conducted in concert with Boeing statistical experts and included Length at Detection (LAD)/One-Sided Tolerance Interval (OSTI).

Qualification Testing Categories

The Environmental Survivability standards determined that CVM™ Sensors mounted on aluminum test coupons demonstrated survivability and compliance to environmental test condition performance under the standards of RTCA/DO160G, or the specified test conditions. The specimens used for these conditions did not have a detectable flaw.

Testing was required to be performed after exposure to each environmental condition (as per RTCA and AEM test standards) and was performed using the same equipment that's used in the field during on-aircraft CVM™ interrogations. Although data monitoring was not required during exposure, this data was still recorded to determine the live response of a sealed CVM™ system.

Temperature (DO-160G, Sec. 4.5, Cat. C4):
Low Temp: -67° F (-55° C) for 3 hours

High Temp: +158° F (+70° C) for 3 hours

Altitude (DO-160G, Sec. 4.6. Cat. C4):
Maximum Operating Altitude: +35,000 ft. (+10,700 m) for 2 hours

Humidity (DO-160G, Sec. 6.0, Cat. A):
Humidity Cycle: 95% RH for 48 hrs.

Stress (determined in concert with Boeing):
Stress on Coupon: 24 KSI (Far Field)
3 Cycles held for 5 seconds

Hot/Wet/Freezing Cycle (determined in concert with Sandia National Labs): 32-day profile:

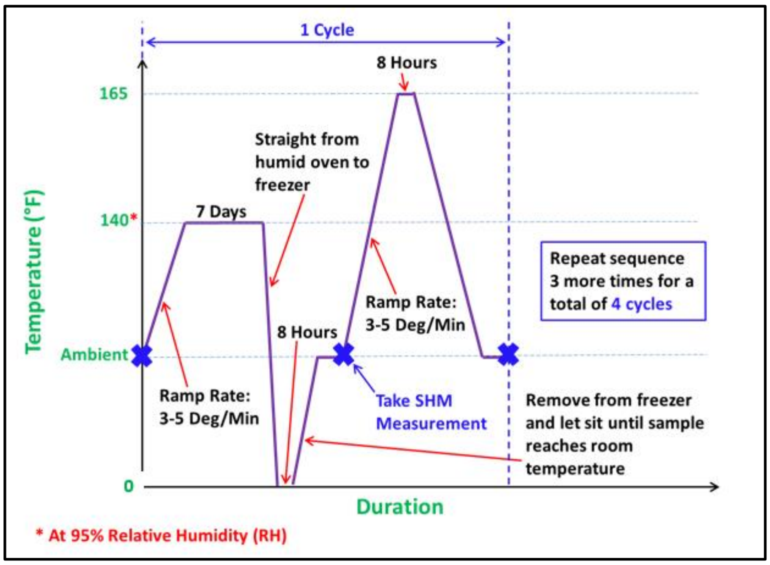

Figure 1: . Hot/Wet/Freezing Cycle

All Testing performed on the CVM^{TM} System during and after exposure to the survivability conditions listed above resulted in all tests passed.

Environmental Performance

The Environmental Performance standards determined that CVM^{TM} Sensors mounted on aluminum test coupons that were equivalent to the on-aircraft installation for the B737 Aft Pressure Bulkhead and have a detectable fatigue crack demonstrated compliance to environmental test condition performance under the standards of RTCA/DO160G, or the specified test conditions, without affecting the detection threshold limits. The environmental conditions listed below are typical conditions that could be seen in the aircraft hangar during maintenance cycles. The test specimens were tested after stabilized at each environmental condition.

Temperature (DO-160G, Sec. 4.5, Cat. C4):
Operating Low Temp: 39° F (+4° C)

Operating High Temp: 104° F (+40° C)

Altitude (determined in concert with Boeing):
Maximum Operating Altitude: +10,000 ft. (+3,048 m)

Humidity (determined in concert with Boeing):
Humidity Cycle: EUT stabilized at 40°C @ 95 %RH

All Testing performed on the CVM^{TM} System during exposure to the performance conditions listed above resulted in all tests passed.

POD ANALYSIS

The POD analysis quantified the ability of CVM^{TM} Sensors to detect a fatigue crack, and the sensitivity and reliability of repeated interrogation cycles when exposed to various environmental conditions. The test data was used to calculate POD data and false positive estimates to compare with existing NDT systems detecting comparable flaws.

The application used for the POD study fatigued 20 specimens that were indicative of the CVM^{TM} system installed on the web of the AFT Pressure Bulkhead (APB), sections S5L – S7L, and S5R – S9R on Boeing 737 aircraft. The POD study resulted in a 90% probability, with 95% confidence, that a 0.153" long crack would be detected with the CVM^{TM} system. The allowable POD crack length using standard NDT techniques (as per Boeing Service Bulletin 737-53A1248) is 0.200", thus CVM^{TM} exceeds the requirements for the Service Bulletin.

INSTALLATION, MAINTENANCE, AND SUPPORT

Installation Overview

Aircraft specific technique sheets and sensor drawings are developed for each individual application. CVM^{TM} installation packages contain 2 main components: the sensors and sensor lead socket connectors. The sensor lead socket provides a remote interrogation location in an easy to access space. Prior to installing CVM^{TM} sensors, traditional non-destructive testing (typically eddy current test) is completed to ensure sensors will not be installed on damaged aircraft structure.

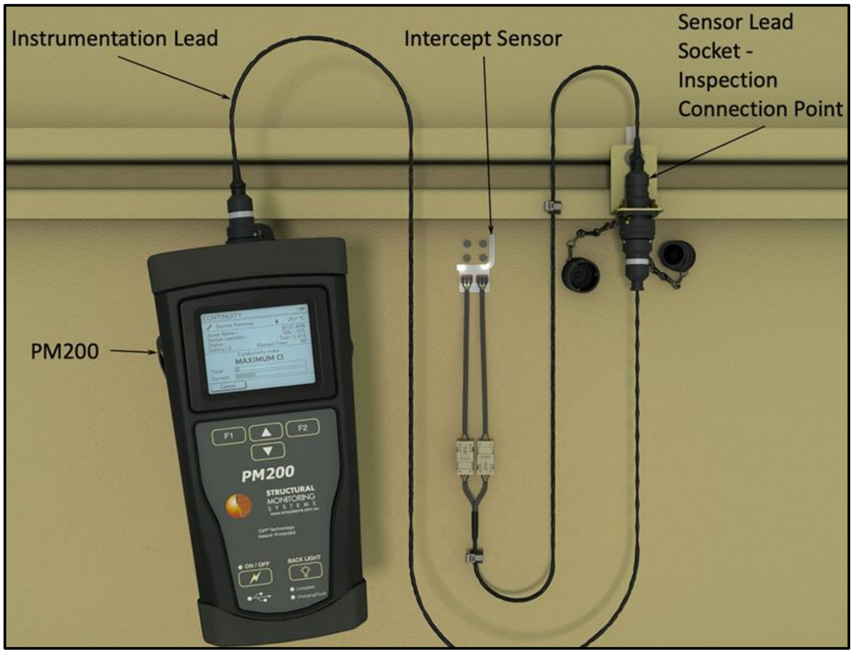

Figure 2. CVM™ System

The installation of CVM™ sensors requires strict adherence to CVM™ engineering drawings and technique sheets. Sensors detect surface breaking cracks when the crack contacts sensor vacuum galleries, therefore successful installation depends on thorough surface preparation as a fundamental step to maintain vacuum.

Installation techniques were developed to produce smooth surfaces free of flaws prior to sensor installation; surface flaws can require the sensor be replaced if the flaw is large enough to become a leakage path which will display as false positive crack detection. Dust and fibers can become entrapped between the sensor and substrate; this can lead to a reduction in strength and may cause sensor malfunction. If applicable, sealant must be removed prior to sanding the surface for installation. To achieve the required finish for both sensor sensitivity and bond strength, 600 grit sandpaper adhered to different shaped pieces of acrylic are used to prepare the surface. The surface is washed with isopropyl alcohol, then with distilled water. A 15-minute waiting period after the water wash is necessary to ensure the surface is dry before a sensor is installed. In addition to surface preparation, attention to sensor placement is critical; installed sensors detect cracks that intersect a vacuum gallery and therefore placement must physically intersect inspection sites within specified distances. The distance must meet POD and crack length inspection requirements for each location. The installation of a sensor is permanent for the duration of SHM, sensors are removed only to replace a failed sensor or the conclusion of SHM at the inspection location.

Training Installation Personnel

Installation training involves trainers traveling to the maintenance facility where the aircraft undergoes a routine maintenance check (typically a heavy check) to demonstrate correct procedures. Day one of the training is classroom style, typically in a conference room. The technique sheets are displayed, and each step is explained in detail. After the technique sheet is presented, each trainee is given a physical mock-up of a sensor installation location to practice surface preparation, sensor installation, and sensor testing. In the days following, trainees witness the full system installation performed by the trainers. After classroom and on-aircraft witnessing of the installation procedures and testing, trainees will complete their own full system installation on another aircraft, that is directly supervised by the trainers. Once the second aircraft installation is complete, the trainees are certified to continue CVM™ installations without direct supervision.

In field training of aircraft maintenance personnel has been fundamental for repeated installations as there are many procedures which are new to maintenance personnel. Training teaches the installers to test each single sensor after it is placed. Doing so ensures the Sensor has been adhered correctly and allows for a simpler troubleshooting process after all Sensors have been connected in series. Once the large Sensor network is connected, the entire system is tested together. As with single sensor tests, the network test consists of connecting a PM200 to one of the sensor lead sockets and performing an inspection. Should the inspection fail, it is likely not due to a damaged aircraft component as the NDT inspection has confirmed there were no defects in the area prior to installing sensors. If troubleshooting a CVM network is required, the installer will begin by confirming the sensor lead socket is functional by disconnecting it from the sensor network and connecting the male/female connectors of the sensor lead socket into one another, creating a loop back to the PM200. If this test fails, a new sensor lead socket is obtained and connected to the sensors network, and the test is repeated. Should the sensor lead socket pass inspection when looped to the PM200, the Sensor network is the suspected failure point. The installer will separate the network into two smaller networks to narrow the problem. The network can be split further until the failing sensor or connection is located. The failing sensor or connection is then replaced and the full sensor network test is repeated to achieve a passing test. To ensure the PM200 is operating withing specified limits, a verification test is run at the beginning and end of each install day. A failed verification test requires all the inspections between the failing verification tests to be repeated with a new PM200 that has a passed verification test.

Programming the sensor lead sockets with a computer takes place on the final training, or installation day. Each sensor lead socket has an identification chip which contains a unique serial number, CVM™ parameters for the specific install location, the tail number of the aircraft, and the installation location of the sensors (typically a station and stringer callout). The programming is completed by connecting a PM200 to a laptop with a USB cable and a sensor lead socket to the

PM200. Specifically designed software is used to access the identification chip which allows the installer to enter the required information. Programming times are determined during the development of each CVM™ application. The times are limits set for vacuum monitoring duration and conductivity index (CI) limits. Vacuum monitoring times vary based on the total volume of the system; a long sensor lead socket with many sensors in a single network will require longer times than a single sensor with a short lead. Conductivity index is a proprietary unit of measurement that was developed for the CVM technology and provides the detection limits of the system. A CI value outside of a set limit will constitute as a failed test, which results in either a sensor requiring replacement during installation or indicating the need to gain access during a routine inspection.

Development of Installation Procedures

Determining placement of CVM™ sensor installation relies on a clear definition of both the expected flaw location and orientation. This information may be available in the form of damage tolerance analysis and fatigue test results. From the available information a sensor installation package is developed to cover the inspection locations. An interrogation site is identified near the sensor installation in a location easily accessible for upcoming inspections. An access panel/door is selected where available. Gaining access to perform mandated, non-destructive inspections without CVM™ can be hazardous as well as time consuming. Some locations require fuel to be vented, while others require the removal of sealant and other disassembly with the risk of damage. Determining which inspection sites qualify for CVM™ installation requires collaboration between aircraft operators, OEMs, and regulatory bodies.

RELIABILITY AND FAILURE MODES ANALYSIS

Systems intended to support the continued airworthiness of an aircraft require thorough analysis of each and every potential failure method. The fundamental fail-safe design of CVM™ lends itself well to be suited for structural health monitoring of commercial aircraft. The analysis provides the system and airplane level effects of failure for each functional block of the CVM™ system. Predicted failures, failure severity, and detection probability are shown for each functional block, for loss of function and for erroneous function.

False Positives

The design of the CVM™ sensor provides a fail-safe such that if the sensor disbonds or leaks from any one gallery, the detection indicates as a crack or Unstable Vacuum indication. The possible false positive indication of a crack would be considered a nuisance, but not a safety concern as in these cases, traditional NDI techniques would then be used to verify the structure after receiving such an indication.

The CVM™ system has a built-in test to determine gallery continuity, testing to see if particulate or physical damage has blocked of the air within a gallery from one end to the other. The use of the PM200-9 Verification Block checks the PM200's ability to measure a predetermined flow rate prior to conducting a set of tests.

The Analysis

Methods of showing compliance with FAR 25.1309 and the guidance of AC 25.1309-1A. The CVM™ system consists of a limited number of unique parts, and therefore leads itself well to a Component Level qualitative approach for the FMEA. The components are, the PM200, the interconnection pneumatic tubing, and the sensors.

In addition to the PM200-9 Verification Block that checks the operation against a physical reference, the PM200 firmware has built in self-tests covering the following possible error codes. The Verification Block takes priority, and the user will not continue without a successful Verification Block test. The list of PM200 Self Checks are listed in the PM200 user manual, these codes are displayed on screen if they occur.

PM200 Instrument is verified with the Verification Block at the beginning and after test, it is possible to postpone this check and complete it at the end of each shift or inspection set, but all inspections prior to a Verification Block check pass are considered suspect. In the FMEA, "Check with Verification Block, before and after test" the after-test check may be postponed for efficiency and convenience but sign off of the inspection should not occur until a Verification Block check has been successfully completed. The Verification Block check is performed after acclimatization to the same ambient environmental conditions as the inspection location. On screen PM200 temperature reading allows easy comparison between internal and ambient temperatures. The Verification Block is calibrated annually, and provides a verification of the system's ability to seal, as well verifies both galleries continuity measurement through a known value flow restrictor.

CONCLUSION

The certification process for SHM systems is critical to ensuring the continued safety and reliability of aircraft structures when using SHM systems to replace conventional inspection methods. SHM systems offer several benefits to the aviation industry, reduced maintenance costs, more efficient use of their fleet, and improved performance. As SHM technology continues to evolve, it is expected that these systems will become even more prevalent in the aviation industry, allowing operators more efficient use of their fleet.

REFERENCES

1. Jeong-Beom Ihn (JB) Ihn, P. (n.d.). Introduction to Boeing Structural Health Managment., (p. 6).
2. Dennis Roach, Tom Rice, Sandia National Laboratories. 2020. “Application and Certification of Comparative Vacuum Monitoring Sensors for Structural Health Monitoring of 737 Wing Box Fittings”