Implementation of Structural Health Monitoring (SHM) into an Airline Maintenance Program

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ABSTRACT

Delta Air Lines has partnered with Sandia National Labs, FAA, Boeing, Anodyne Electronics Manufacturing Corp. (AEM), and Structural Measurement Systems (SMS) on a novel SHM program using Comparative Vacuum Monitoring (CVM) sensors. The goal is to produce regulatory guidance that will enable widespread adoption of SHM across the commercial aviation industry. This “blueprint” is required since current regulations do not define SHM, nor validation and certification of SHM required for implementation.

INTRODUCTION & BACKGROUND

Delta has investigated Structural Health Monitoring and sensors for many years. Two main hurdles were identified as an impediment to incorporation: 1) business case, and 2) Lack of regulatory guidance and a need for industry education. CVM technology has been widely researched, analyzed, and even incorporated into Boeing’s general practices; however mainstream adoption was lacking. Therefore, Delta partnered with the FAA, Boeing, Anodyne Electronics Manufacturing Corp., Structural Monitoring Systems, and Sandia National Laboratories on a program to use CVM sensors to move beyond a traditional prototype and move into mainstream, industry-wide adoption of SHM. The goal is to produce regulatory guidance that will enable widespread adoption of SHM across the commercial aviation industry [1].

Comparative Vacuum Monitoring (CVM) sensors were applied to seven B737-700s on the 10 Wing Center Section Shear Fittings, a known area of cracking. This flight test program is designed to provide ample data which can be used to provide an approval basis for the maintenance program changes. The passive system has been flown since February 2014 and periodic interrogation occurs through the Cargo bin. The data is downloaded from the sensors via a handheld device during

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overnight checks, on what is currently a 90-day repetitive schedule. The objective is to produce the data package within 12-18 months of monitoring, consisting of 5-6 readings following installation on the aircraft. In total, 70 installed sensors would be involved, providing hundreds of data points. The data from the sensors is being monitored and tracked in conjunction with performance tests at Sandia National Laboratories to identify aircraft structural maintenance items earlier and more efficiently.

APPLICATION SELECTION

The selection of the application was done carefully and purposefully. Since the regulatory guidance was to-be-determined, the application could not be a safety critical area. These ‘hot-spot’ areas, often mandated by Airworthiness Directives, are indeed a large focus for the future. The bulk of the ~20 proposed applications fell into this category. Instead, the B737NG Wing Shear Fittings were selected since it was determined by Boeing to be an ‘economic’ application and not a critical area (see Figure 1) [1]. Since finding the damage required a time-consuming and logistically complex repair, Boeing suggested inspecting or replacing these fittings at Heavy Maintenance. This program would serve as an alternative to the visual inspection without requiring onerous access.

The selection of the application drove a unique CVM sensor design. The shear fitting was known to crack and propagate between fasteners; therefore, the sensor was designed with ‘fingers’ to fit in between each of the fasteners (see Figure 2) [1]. This ultimately was significant since manufacture and installation were generally without any issues despite the complex design (versus circular or rectangular ‘patches’).

Figure 1. An illustration of the 737NG Wing Shear Fittings.
Cost-benefit

This program was cost neutral to Delta in part by subsidized funding from the FAA. Future programs must meet a strict cost-benefit analysis, the trickiest parameter of which is payback. Full payback for a typical ‘alternate inspection’ program would not be until the first repetitive inspection, which may be years. Several previous attempts of SHM applications failed at this point at Delta, and contributed to the reasoning behind the FAA program.

The cost-benefit to the airlines will be directly proportional to the industry acceptance and comfort level. For example, in order for the FAA and aircraft OEMs to approve SHM, they may require a period of time of ‘side-by-side’ inspections of the SHM inspection and the current inspection before granting approval. From the airlines’ perspective, this means double the cost for that period of time, which typically means the program will not go forward. It is imperative that this industry comfort level is established quickly and solidly. This will require extensive cooperation between the OEMs, the airlines, and the sensor vendors.

A proactive program designed to be an ‘early warning system’ would have economic value as well, but this is complicated by the pervasive philosophy ‘if you find it, you must fix it before further flight’. This philosophy must be changed in order for a ‘monitoring’ program (active or passive) and true condition-based-maintenance program to be approved. For the airline, the largest cost-benefit lies in going to true condition-based-maintenance. However, to get to that point, this program must be completed, and subsequent regulatory guidance recommendations endorsed by the FAA. Thus, Delta is making small steps but is taking a longer term view of SHM, hoping to compress the timeline needed for acceptance and widespread adoption.

INSTALLATION APPROVALS

Approval for this program saw a multitude of hurdles, including financial, logistical, and technical. The Engineer first begins with a project overview and financial form. Coordination meetings lead to signatures and approvals from Engineering Management, Finance, Maintenance, Demand Planning, and Materials
Planning. If successful, the project is presented to the Operational Reliability Team for consideration. Finally, the project is approved by the Project Approval Board. Then the Engineer may write the Engineering Documentation and associated Job Cards. Internal Engineering Documents and Job Cards were approved as a ‘minor alteration’ under Delta’s authority under the Code of Federal Regulations, Part 14, 121.379(b).

Upon completion of the paperwork, it is submitted for checking and approval before submitting to “Process Control”. This forms a double-check of the previous coordinations with maintenance, materials, inspection, etc., prior to the project being allowed to ‘go open’. Once the project is open, Scheduling begins assigning the work to specific aircraft, location of the work, and determines time of accomplishment.

Since Delta has an extensive and lengthy process for authoring or revising Engineering documents, a job aide called “Technique Sheets” were utilized for both the installations and the monitoring. While these are not the actual ‘sign-off’ documents, they cover ‘what-if’ scenarios, include schematics, and other details. These are date and revision controlled and approved by the Level III, and are easier to revise, if needed.

CHALLENGES

Internal

Challenges experienced during the project were numerous. A cost-benefit analysis had to be tabulated and vetted by Finance: a program with a payback longer than 6-12 months is problematic. This hurdle was only passed by obtaining Senior Management buy-in to the longer-term vision, plus the funding provided by the FAA. Additionally, due to the Delta merger with Northwest and resulting integration, all Job Cards and engineering documents required a ‘dual process’. Beginning the project in the throes of integration was unfortunate timing that continued to plague the project throughout. The installation approval process had to be repeated four times due to changing organizational structure and approval requirements during the lengthy timeframe. Ultimately, success was reached in seven months.

Once approved, the coordination of logistics continued to be a challenge. Twice, the project was ‘frozen indefinitely’ due to mandatory milestones associated with integration of computer systems due to the merger of Delta and Northwest. Integration took so many resources, only the top priority projects were able to be worked. Finally, after three additional months, the project was ready and installations could begin.

Time pressure and task descriptions provided further challenges. The installations were conducted during a 5-day visit instead of a traditional heavy maintenance visit. The heavy maintenance visit was attempted, but was not successful due to crack findings on the fittings prior to installation. The CVM sensors were installed by Maintenance personnel, but will be inspected/monitored by Inspection personnel. The different job categories had to be accounted for in the Job Cards, sign-off requirements, and Engineering documentation.
External

Extensive external coordination was required to ensure the success of the project. Sandia National Labs provided a ‘test bed’ to practice on before ‘going live’ at a “CVM Workshop”. SMS and AEM provided the equipment and installation expertise. Boeing and the FAA provided technical oversight at key points. Training required coordination of all parties, especially the required surface preparation. A change in location (where the aircraft was located) complicated this training, but ultimately was successful in Atlanta during January-February 2014.

MAINTENANCE PROGRAM APPROVALS

In order to take credit for the sensor inspections versus the Maintenance Program, approval is required from Boeing and the FAA. This is completely separate from installation approval, which was conducted internally at Delta. Boeing and FAA approval is needed to substitute the alternate (CVM) inspection for the existing inspection. An example of this would be not opening up an area for a HFEC or visual inspection and instead use the CVM sensors. This ‘hot-spot’ monitoring as an alternate inspection is the first step required to transition from a scheduled maintenance system, to a true Condition Based Maintenance Program.

ADOPTION BY AIRLINES

One of the main goals of the program is to determine obstacles, solutions and new processes needed for wide-spread industry adoption. As the case with most new technologies, the largest obstacle is philosophical: persuasion to do something different than what is currently being done. This will first be conquered through ‘hot-spot’ alternate inspections, typically approved on a case-by-case basis, and still conducted at the scheduled intervals (i.e., S-SHM). A much more difficult and lengthy road must be undertaken in order to transition to condition-based-maintenance and monitoring/prognostics (A-SHM). The duration of that transition is dependent upon the comfort level of the industry, in particular the regulatory agencies.

Financial obstacles were discussed previously. Different solutions are available, such as partnering, and various creative financial arrangements. Therefore, this obstacle can be overcome, though is highly dependent upon the industry acceptance discussed above.

Technical obstacles were also present in the form of Probability of Detection (POD) analysis, environmental durability, surface preparation, and training. POD trials were previously generically conducted using CVM, with application specific POD determined with the laboratory testing at Sandia National Labs [1]. Environmental durability was met by Delta (and previously Northwest) flying CVM sensors on various aircraft for approximately 7 years [1]. These were in ‘decal mode’, meaning they were placed in locations which damage was not anticipated, and served to confirm the sensors would still function in the harsh environment.
Surface preparation and training were obstacles, but we overcome with effective support from Sandia National Labs and AEM. Maintenance personnel were able to install the sensors with a minimal learning curve.

LESSONS LEARNED

There were several lessons learned during the installation process. The CVM sensor requires a delicate installation, and surface preparation cannot be rushed. This application was a challenging install with a complex sensor design (non-symmetric and size of sensor) in a difficult-to-access area with tight geometry (free edges). Re-installation of several sensors was needed. A template was designed for easy installation, but due to the geometry, it was found that hand application was best.

The 5-day time window for installation during a minor check was challenging. This forced adjacent work near the sensor installation, creating possible contamination of the prepared surface. Minimizing adjacent movement and air flow in the cabin helped reduce sensor failures. Cabin interior crew was in and out of the area, requiring some coordination, but SHM installation did not impede progress on adjacent tasks.

Surface preparation was key to a successful CVM sensor installation. The CVM Install Workshop at Sandia was a good activity. The use of a spray-on primer provided a better surface than brushed primer. After sensor installation, fasteners were sealed and fuel vapor barrier reapplied to the entire area. Diluted application of fuel vapor barrier and use of smaller and more delicate reapplication of rivet sealant (smaller, artist paint brush) could allow for better visual inspections with the sensor in place (in-case both inspections were required to obtain the ‘comfort level’).

Once the sensors were placed, tubing and SLS connectors were routed down the front spar to a bracket for convenient access through the cargo bin during future repetitive inspections. More detail was needed describing the tie-down points of the CVM tubing. The PM200 also required software programming for the SLS connectors, which is better done prior to aircraft arrival.

The paperwork associated with the CVM sensor installation was well thought out. The use of a “Technique Sheet” made things more flexible rather than changing the Job Cards and Engineering documentation and going back through the full approval process. However, the education Process within Delta needed to be broader and more efficient. Many different departments had to be involved, creating complexities for coordination. Changing approval requirements and rotation of personnel due to merger integration made this even more important.

SHM RELIABILITY REQUIREMENTS

For commercial aviation acceptance, SHM systems must meet reliability requirements (validation, verification, qualification). Most importantly, for ‘hot-spot monitoring’ or S-SHM, the system must provide an ‘equivalent level of safety, or better’. This means the Probability of Detection must be equal or better than the current inspection it is replacing. However, the sensitivity must be appropriate for
the application (i.e., don’t find a 0.010” crack when the visual inspection is looking for 2.0”). This is primarily a result of the philosophy ‘if you find it, you must fix it before further flight’. This philosophy must be changed in order for a ‘monitoring’ program (active or passive) and true condition-based-maintenance program to be approved. For the airline, the largest cost-benefit lies in going to true condition-based-maintenance.

Other parameters are critical to commercial aviation industry acceptance. The ‘false calls’ must be minimal as they result in substantial cost to access the area, leading to decreased confidence in SHM. Additionally, the sensor must have a ‘fail-safe’ similar to CVM. If the sensor is not functioning, then the signal/result should be different from a potential defect finding. CVM has this functionality.

Various other important airworthiness requirements must be met. Whatever is placed on the aircraft must meet the same safety standards as other equipment, furnishings, etc. These include flammability, environmental, vibrational and electromagnetic interference. Therefore, it is easier for a ‘passive’ system (data interrogated on the ground) to be approved than an ‘active’ system (data taken during flight, likely transmitted in-flight).

FUTURE PLANS FOR GLOBAL ADOPTION

Delta envisions three distinct phases of SHM acceptance for the commercial aviation industry. The initial phase will be a ‘hot-spot’ phase where a SHM application will be approved as an ‘alternate inspection’ for a particular local application (case-by-case basis). Then, there will be a phase where larger areas are generically examined with SHM, but on the same schedule as current maintenance (S-SHM). This is primarily due to the philosophy ‘if you find it, you must fix it before further flight’. The ‘early warning’ stage will help bridge the gap to the final phase, where true condition-based-monitoring phase will see ‘monitoring of damage’, ‘maintenance planning’ and even ‘prognostics’.

Delta will complete the current program by soliciting Boeing and the FAA for final approval to use the CVM system instead of the current visual inspection required in the 737NG Maintenance Program. Next, Delta will compare the program to SAE’s ARP 6461 for improvements in the next revision [2]. It is noted that the FAA has not recognized ARP 6461 as an accepted industry document yet. Delta will then coordinate with the FAA to ensure regulatory requirements and certification path are appropriately disseminated throughout the commercial aviation industry via a ‘policy memo’. Once this occurs, the industry would then be free to embark on ‘hot-spot’ SHM applications and gradually move to condition-based-maintenance.

REFERENCES


2. SAE ARP 6461.