Lessons Learned from a Broad Durability Study of an Aerospace SHM System

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ABSTRACT

Structural health monitoring (SHM) systems are beginning to be implemented on a variety of aerospace structures. As the application of SHM systems increase, it will be important to define standardized procedures to test durability, reliability, and longevity of the systems. Following a framework (built upon existing durability standards for commercial and military aircraft avionics) developed in previous work, a durability test matrix and testing specifics were developed for a specific sensor system. The lessons learned from a broad range of testing of a surface-mounted piezoelectric Lamb-wave SHM system are presented. Durability testing included mechanical (mechanical strain, hi-cycle actuator fatigue) and environmental (temperature extremes, thermal shock, high humidity, fluid susceptibility, altitude/pressure) loading. Criteria were defined for the tested SHM system to establish whether it had been affected by the various tests. These lessons can help in forming standards specific to SHM systems, such as a supplemental standard geared specifically toward smart structure technologies that would address SHM and other embedded or surface mounted smart structure components and systems. Such a new standard will require contributions from the SHM community, aircraft manufacturers, and regulatory agencies.

INTRODUCTION

Structural health monitoring (SHM) systems have reached a maturity level that enables them to be tested on experimental flight tests [1-5]. These systems have potential to offer economic benefits by reducing maintenance time and improving safety across multiple industries. However, aerospace structures have one of the highest payoffs for SHM systems since damage can lead to catastrophic and expensive failures, and the vehicles involved undergo regular costly inspections [6]. There are many different approaches to designing a SHM system (surface-mounted

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vs. embedded, piezoelectric, strain-gauge, fiber optic, etc.), but the goal of these systems is the same: monitoring a structure's state relative to a baseline. SHM systems have been described as a nervous system for aircraft [7], allowing operators to know if and where a structure has become damaged. With this knowledge, operators can make repair decisions on a prognostic basis. Before these systems can be implemented on a large scale in commercial and military vehicles, standardized procedures to test durability, reliability, and longevity of the systems must be developed.

This paper presents several lessons learned from a broad durability study of an aerospace SHM system. A framework previously developed was used to form a durability test matrix and testing procedures [8]. The foundation of this framework came largely from existing related standards that were tailored to SHM systems. The SHM system studied during this work was the surface-mounted piezoelectric Lamb wave-based sensor nodes from Metis Design Corporation. Detailed testing procedures, system specifics, and test data can be found in [9]. One issue that arose during testing was the necessity of clearly defining the SHM 'system' under test. Most SHM systems use the monitored structure as an integral part of the system, and therefore the structure must be tested as a component of the SHM system. As durability tests were completed, the results often identified additional SHM tests to include in the original framework. An example is the hi-cycle actuator fatigue test, which was identified from initial testing and added to the test matrix. It was learned that the fatigue of the sensor actuator should be considered independently of the mechanical and environmental loading. Additional testing results that followed initial testing are presented. Finally, overall lessons learned from the durability testing are summarized.

DEVELOPING SHM STANDARDS

There are currently no established standards for durability testing or certification of SHM (or smart structures) systems for commercial or military aerospace structures. In order to create such standards, the complete process of health monitoring must be addressed: installation, credit validation, and instructions for continued airworthiness. The Federal Aviation Administration (FAA) has recently developed certification guidance for health usage monitoring systems (HUMS) in rotorcraft as part of Advisory Circular (AC) 29-3C [10]. However, there have not been similar documents released for SHM systems to be used on aircraft/spacecraft.

The SHM community is aware of the need for standards and certification procedures before their technologies can be fully implemented. One group has recently (November 2006) formed the Structural Health Monitoring – Aerospace Industry Steering Committee (SHM-AISC). This committee has representatives from industry (Airbus, BAE Systems, Boeing, EADS, Embraer, Honeywell), aircraft regulatory agencies (EASA, FAA), government agencies (DoD, NASA), and a subset of the SHM community developing the sensors (Sandia National Labs, Stanford University). The mission of the SHM-AISC is to begin developing standardized integration and certification requirements for SHM systems on aerospace structures [7, 11].

The void in SHM standards stems in part from the difficulty in identifying what the system is, and what it is not: in many cases, even the simplest actuator/sensor is integrally connected to the structure (or embedded in the structure) such that durability testing becomes a subcomponent task. The SHM system is *not* simply the sensor node. In the case of the surface-mounted Lamb-wave type sensors studied in this work, the sensors' performance required an integral connection to the structure: the Lamb-waves are initiated at the sensor/actuator, propagate through the structure, and return to the sensor/actuator. The structure itself is part of the SHM system in conjunction with the sensor node. Further, the bondline between the sensor node and the structure, the electrical connections, and the software for processing data form components of the SHM system. SHM developers are beginning studies to better understand each aspect of their SHM system. One group is looking specifically at the bond and piezoelectric material characteristics of a typical surface-mounted SHM system exposed to stresses and thermal loads [12]. Other groups are starting environmental testing, but the lack of accepted standards has the result of *ad hoc* test procedure development.

To develop a durability standard for aircraft SHM (and smart structures in general), a practical approach will make use of relevant existing standards, but will require additional development to recognize that the SHM system is both sensor and structure [13]. Taking such a view, the framework for developing SHM durability standards shown in Figure 1 incorporates existing standards for structures (Structural Design Standards) and avionic equipment/electrical components (Environmental Standards). Existing standards that were used to form the foundation of the environmental SHM test matrix here include: RTCA/DO-160E, MIL-STD-810F (environmental testing), and MIL-STD 310 (global climatic data) [18-17]. Both military and commercial structural standards exist or are evolving to meet certification requirements (*e.g.*, FARs) for both metal and composite structures (*e.g.*, ASTM, MIL-STD, and industry proprietary standards). The lessons learned during this work focused on the overlaps in Figure 1 between the SHM durability and the structural design standards (region A) and the SHM durability and the environmental standards (region B). The central overlap (region C) is

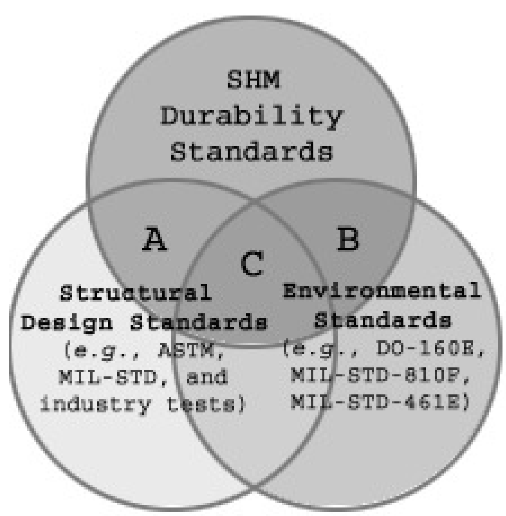

Figure 1. Framework for identifying SHM or smart structure testing standards.
Regions A and B are the focus of the current work.

important for SHM systems but was unexplored in our own first-round testing. Additional considerations beyond the existing standards (SHM-only considerations) will need to be developed.

Initial Testing

The framework led to the initial durability test matrix shown in Table 1 (excluding the hi-cycle fatigue test) after down-selecting from among a long list of potential test conditions [9]. This matrix served as a starting point for SHM durability testing and does not include all environments necessary to fully test SHM systems. The testing environments chosen for the initial testing included: static-strain, temperature extremes, thermal shock, high humidity, fluids susceptibility, and altitude (pressure). To gauge the performance of the Lamb wave-based SHM system, a useful performance metric was developed (see Figure 2). This metric was based on a difference/change in the peak sensed signal voltage compared to a baseline value. For details on the framework, test matrix, testing procedures, and initial test results, please refer to [9].

Additional Testing

Upon completion of the initial testing, 3 additional tests were identified and added to the test matrix (see Table 1). This type of iterative process will continue as relevant tests are identified until a complete SHM durability and certification process is fully developed. The 3 tests were selected for investigation based on the initial test findings: a water-based fluids susceptibility test using deionized/distilled water, a water-based fluids susceptibility test with the original water-based fluids and a sealed electrical connection, and hi-cycle actuator fatigue tests.

WATER-BASED FLUIDS SUSCEPTIBILTY TESTS

The initial water-based fluids susceptibility tests were found to have a significant effect on the operational and post-test signal voltages (an average

TABLE 1: SHM DURABILITY TEST MATRIX.

Test Type	Extreme Condition	Samples / Test Type
High Temperature	85˚C operating high temp	3
Low Temperature	-55˚C operating low temp	3
Thermal Shock	10˚C/min minimum change rate	3
Humidity	Pure water, 65˚C, 95%RH	3
Oil-based Fluids Susceptibility	24 hour immersion in fluids	3
Water-based Fluids Susceptibility	24 hour immersion in fluids	3
Altitude (Low-Pressure)	Altitude of 21 km (4.4 kPa)	3
Decompression	Rapid decompression to 21 km	3
Overpressure	Pressurize to -4.6 km (170 kPa)	3
Static-strain	Strain coupon to near yield	1
Hi-cycle Fatigue*	Operate actuator for long duration	2
Additional Water-based Fluids Suscept.*	24 hr immersion in deionized water	1
Additional Water-based Fluids Suscept.*	24 hr immersion with sealed connection	1
Total	-	32

*Added after initial testing

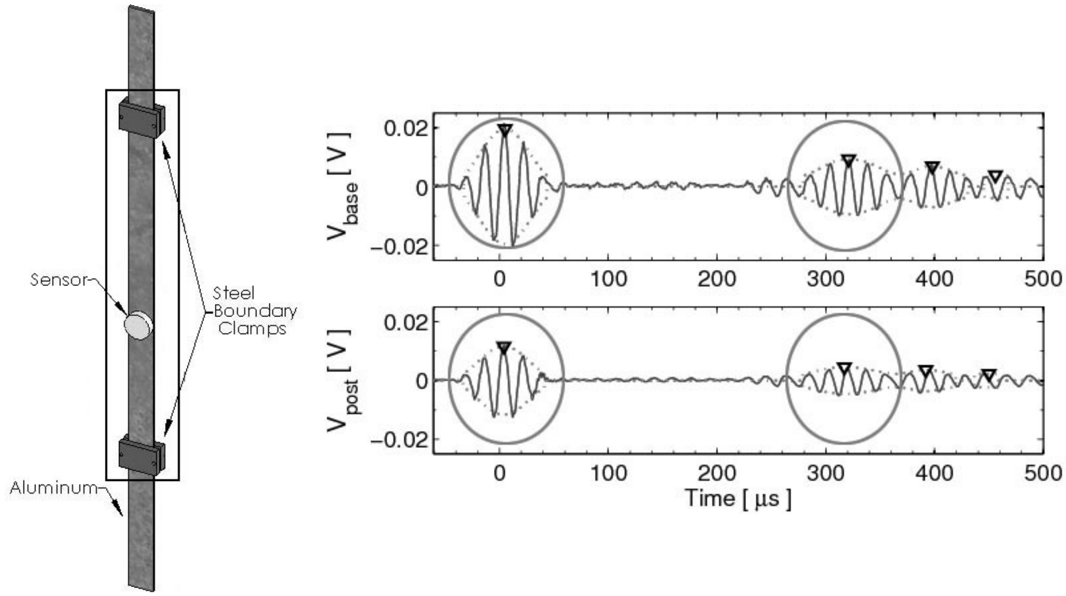

Figure 2: SHM system and performance metrics [9].

decrease of 48% from baseline). A hypothesis was that one (or more) of the water-based fluids was able to permeate the node or bondline, or affect the USB electrical connection. Two tests were conducted to test the hypothesis. The first was to conduct the fluids susceptibility test using deionized/distilled water, which has relatively low electrical conductivity (conductivity of typical drinking water is 50,000 μS/m while deionized/distilled water is typically 5 μS/m). The results of the test showed a consistent decrease in signal voltage of only 4.3%, which is within the expected normal variance of the SHM system [9]. This test suggested that the water-based fluids were not permeating the node or bondline. The second test conducted used a sealed USB connection (to prevent fluids from entering the electrical connection) and the original water-based fluids (equal parts of isopropyl alcohol, denatured alcohol, and antifreeze/coolant (ethylene glycol)). The results from this test showed an increase in signal voltage of 12.3%. These findings suggest that one (or more) of the water-based fluids was adversely affecting the USB electrical connection in the initial tests.

HI-CYCLE ACTUATOR FATIGUE TEST

The hi-cycle actuator fatigue test was conducted to examine the effects of stress/strain from ultrasonic waves produced during operation of the nodes. This can be considered a pure-SHM test (upper portion of Figure 1). In 77% of the original tests, an overall trend of signal voltage degradation was observed. Many of the initial tests required the nodes to operate for long time durations, accumulating large numbers (4.5 million to 5.4 billion) of actuation cycles. The hi-cycle actuator fatigue test investigated the signal voltage degradation as related to the number of actuation cycles with the SHM system operating at ambient conditions (no structural or environmental loads applied). Two nodes were tested. The results from these tests did not show signs of affecting the performance of the SHM system

(4.1% voltage increase) up to the limits tested (240 hours of continuous operation). At this limit, the node had actuated approximately 5.4 billion cycles. This suggests that the trends observed during the initial testing were caused by the environmental or structural loading interacting with the node, not from fatigue of the piezoelectric sensor/actuator, bond, or structure.

LESSONS LEARNED

The lessons learned during this work are summarized below. These lessons include decisions made when tailoring existing standards to observations made during testing. The summary of these lessons should be used in the continued development of SHM durability testing and certification procedures. It is suggested that others doing similar SHM testing write summaries of the lessons they have learned to help fully develop SHM specific standards.

DEFINING THE SHM 'SYSTEM'

It is crucial to carefully define the SHM 'system' and recognize that for most SHM systems, as in this work, the structure being monitored for health is part of that system. Defining a clear and precise 'system' allows the test to be accurate. In our work, the system was defined between two rigid boundary clamps (see Figure 2), however, the clamped boundary condition allowed some wave propagation through and reflections from the free ends of the aluminum bars were observed. It is also necessary to decipher between degradation of the sensors (smart components) and the structure. Environmental aging of materials, such as composites, should be considered in the durability of SHM systems.

SYSTEM POWERED VS. OPERATING

Traditional avionic equipment typically has two states, on or off. An example would be an altimeter, which when operating will display altitude. The existing standards for avionic testing call for the equipment being tested to be cycled between not operating and operating. However, SHM systems are often more complex. The system studied in this work can be operated in two modes, active and passive. In the active mode, the system is powered and the actuator is producing pulses while the sensor records disturbances. This state was referred to as the system "operating". In the passive mode, the system is powered but the actuator is not producing pulses. This state was referred to as the system "powered". Therefore, SHM specific standards will need to address the various operating states of systems when defining testing specifics.

ENVIRONMENTS

The environments selected in the test matrix were taken from the environmental extremes defined in the existing standards. These standards often contained multiple categories (with less extreme conditions) with each category corresponding to the maximum operating environment to be regularly experienced by the tested component. SHM standards should contain similar levels of certification depending on the application. As aerospace vehicles continue to develop and their missions evolve, the environmental operational categories will need to be reevaluated.

DEFINING PERFORMANCE CRITERIA

Performance criteria will need to be defined to assess the affects of environments on SHM systems. In our SHM system, received voltage and time-of-flight from the sensor output were used to assess system changes. These metrics are SHM system specific and it is likely that no global metrics (across all different sensor types) can be defined.

INFLUENTIAL TESTS

The 3 tests that had the largest influence on the SHM system tested were the high-temp, humidity, and water-based fluids susceptibility tests. Beginning with the uncoupled tests, regions A and B in Figure 1, usefully guided subsequent tests.

TEST RATES

The rate of loading (structural or environmental) was shown to have influence on the performance of the studied SHM system. The test data between the altitude tests (which imposed an ascent to an altitude of 21 km in 30 minutes) and the rapid decompression tests (which imposed an ascent to 21 km in less than 15 seconds) showed a change in system performance. Therefore, an SHM standard should capture the change rate the systems will experience.

EXPANDING THE TEST MATRIX

As additional durability testing is completed on SHM systems, additional environments will be identified and added to the durability test matrix. The test matrix included in this work contained only a subset of the total environments listed in existing standards. Eventually, combined (mixed) environments should be considered that simulate typical environments encountered by the system (*e.g.*, combined temperature, pressure, and humidity).

ECONOMICS

As SHM adds additional tests and additional interactions (regions A, B, and C in Figure 1), establishing durability and longevity of each SHM system experimentally will be a time and expense consuming process beyond typical avionic equipment. However, the value added by the SHM systems is expected to outweigh these and other costs [14].

FLUIDS SUSCEPTIBILITY TESTS

Current standards state that a fluid susceptibility test should only be performed when the system is installed in areas where fluid contamination might be encountered [15]. However, the intent of SHM is to monitor an entire vehicle, and therefore the test will need to include all fluids used in and around such vehicle. The large number of fluids used can make this test long and expensive and often fluids are difficult to obtain due to government regulations (*e.g.*, de-icing fluid). The testing done in this work combined all water-based fluids and all oil-based fluids to reduce testing time and cost. It may be necessary to investigate conducting individual fluid tests instead of the mixed (water- and oil-based) tests to identify the 'problem fluid'.

CONCLUSIONS

The benefits of SHM include significant cost savings and safer aircraft. It is critical that testing and certification standards for SHM systems are formed so that such benefits can be realized. It is recommended that current testing and certification standards for avionic equipment be used as the foundation for SHM standards, following the path taken in [9]. This paper has summarized key lessons learned from initial durability testing of a surface-mounted Lamb wave-based SHM system. The SHM community, aircraft manufactures, and regulatory agencies have taken an important first step to large scale implementation of SHM in aircraft by organizing a committee (SHM-AISC) to develop SHM specific standards.

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