Certifying a Structural Health Monitoring System: Characterizing Durability, Reliability and Longevity

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ABSTRACT

The market for SHM has been expanding rapidly, both in the quantity of applications as well as the number of technology providers. Most current research has focused on the development of new detection methods and optimization of sensors themselves, however an important area that has not been sufficiently addressed is how future SHM devices will be commercialized and regulated. This paper presents a framework for considering how to characterize and certify SHM systems. Specifically, the topics of durability, reliability, longevity mechanical design of these systems have not been sufficiently addressed. Existing standards for commercial and military aircraft components are identified, along with their relationship to SHM systems. While the aircraft component manufacturing and integration industry in general is well regulated, it is evident that there is a need for a supplemental standard geared specifically towards SHM technologies, in order to comprehensively address all of these regulatory concerns. The field of SHM has progressed significantly in recent years, and it will become critical to address these topics explicitly before SHM systems can be successfully commercialized and subsequently utilized in prognostic applications.

INTRODUCTION

Structural Health Monitoring (SHM) is an emerging technology leading to the development of systems capable of continuously monitoring structures for damage to improve safety and reduce life-cycle costs. SHM essentially involves integrating of one or more non-destructive test (NDT) method into a vehicle in order to facilitate quick and accurate damage detection with minimal human intervention. There are several advantages to using a SHM system over traditional inspection cycles, including reduced downtime, elimination of component teardown, and the potential prevention of failure during operation. 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 manual inspections. For both commercial and military aircraft, inspection and maintenance currently accounts for more than 27% of the vehicle life cycle cost. Current monitoring schemes such as "black-boxes" on commercial airliners and Health Usage Monitoring Systems (HUMS) on newer fighter-crafts record key measurements to provide information about the state of the vehicle between flights, however the value of such a system increases greatly if detailed, accurate data is accessible instantaneously. This would reduce the downtime of the vehicle, and increase the probability of damage detection prior to catastrophic failure.

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There are several components required to design a complete SHM system, including sensor and actuator elements, processing and communication chips, a power supply, and some form of packaging to integrate and protect these components. Current SHM efforts have focused mainly on methodologies, sensor optimization and algorithms for damage detection, however little attention has been placed on practical implementation of these systems within complex, built-up structures operating in harsh environments. Now that several viable SHM systems have been demonstrated in laboratory conditions, the research in this paper presents a framework for considering how to characterize and certify SHM systems for real-world commercial and military applications [1-8]. Specifically, the topics of durability, reliability, longevity mechanical design of these systems have not been sufficiently addressed. Applicable existing standards for commercial and military aircraft were consulted to assist in selecting suitable tests, and their relationship to SHM systems identified. These standards include susceptibility to environmental testing, mechanical durability, and electro-magnetic interference (EMI), as well as a host of other extreme aircraft conditions (shock, vibration, fluids, etc.). Currently, there is no standard specifically addressing these key issues for SHM.

DURABILITY FOR SHM SYSTEMS

Failures of aircraft subsystems could lead to catastrophic consequences; therefore stringent standards are in place to regulate the durability of these components. Three relevant standards were identified for this study, each of which was created by a committee consisting of aircraft manufacturers and integrators along with government officials. The test within these standards can be divided into three categories: environmental susceptibility, electromagnetic interference and mechanical testing. Each standard systematically lays out test conditions, the rationale behind the test, a detailed setup, charts to determine the test intensity and often some criteria to determine whether or not the component has passed the test.

The first standard examined, summarized in **Table 1,** was RCTA/DO-160E, “Environmental Conditions and Test Procedures for Airborne Equipment” [9]. This document, issued by Radio Technical Commission for Aeronautics, is recommended by the Federal Aviation Regulations AC21-16D, to show compliance with appropriate airworthiness requirements [10]. It states that the DO-160 is an acceptable means for any environmental qualification. This document defines procedures and criteria for testing airborne equipment aircraft ranging from light aircraft to large commercial jets and supersonic transport aircraft. Together with its precursor (DO-138), DO-160E has been used as a standard for environmental qualification testing since 1958. In addition it is recognized by the International Organization for Standardization (ISO) as de facto international standard ISO-7137.

The next significant standard, summarized in **Table 2,** is the MIL-STD-810, “Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests” [11]. First released in 1959, this document provides guidance for tailoring environmental tests similar to DO-160, as well as including several other shock and vibration conditions only normally found in military applications such as ballistic, pyro and tethered landing shock. This standard omits all of the EMI related testing, which can be found in MIL-STD-461E, “Department of Defense Interface Standard Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment” [12]. The first EMI standard was published by the US Army Signal Corps as SCL-49 in 1934, which was then replaced by the

DoD's MIL-STD-461, 2 and 3 in 1967. In 1999 these were consolidated into the present format. The requirements specified in this standard, summarized in **Table 3,** contain a detailed series of tests to measure both conducted and radiated emissions from electronic components, as well as to quantify their susceptibility to electromagnetic interference.

Temperature

Two temperature tests are specified: operational and shock. For operational testing, the sensors must first saturate at the peak temperature for 3 hours, followed by functional testing for two hours at that same extreme. For the cold extreme, -55^{o}C should be used, and for the hot extreme 85^{o}C. The thermal shock tests simulate takeoff from a desert climate to a cruise at a high altitude. The test begins with the specimen at its cold extreme, followed by a ramp rate of 10^{o}C per minute to its hot extreme with a 2 minute hold time. This is followed by another ramp down to its cold extreme where the sensor is tested for one hour followed by a 30 minute hold time before a second identical cycle is performed.

Pressure

Three types of pressure tests are specified: altitude, decompression and overpressure. For the altitude test, the pressure surrounding the specimen is decreased to the maximum operating altitude, which in this case is 30,000m (1.10kPa) where the performance is tested for 2 hours. Next, to test operation during and after an emergency decent, the specimen is decompressed from 2,400m (75.36kPa) to the maximum operating altitude within 15 seconds, where it is tested for 10 minutes. Lastly, to simulate routine testing of pressurization systems, an overpressure test is performed, where a -4,600m (169.73kPa) is maintained for 10 minutes, followed by operational testing at ambient pressure.

Moisture

Two moisture tests are specified: humidity and condensation. First, the specimen is placed at 85% relative humidity and 30^{o}C and then raised to 95% humidity and 60^{o}C over two hours. This is maintained for six hours, then gradually reduce to 85% humidity at 38^{o}C over next 16 hours to complete the cycle Once two cycles have been completed the performance of the sensor should be evaluated within 1 hour. For the condensation test, the specimens should be placed in a cold -10 ^{o}C chamber for 3 hours, then transferred in under 5 minutes to a warm chamber at 40 ^{o}C and 85% relative humidity and operationally tested for 10 minutes.

Fluids Susceptibility

The specimens should be tested for susceptibility to fuels, hydraulic fluids, lubricating oils, cleaning fluids, disinfectant, coolant dielectric fluid and fire extinguishants. These fluids should be grouped into oil-based and water-based for spray testing. Sensors should be sprayed in minimally 4 hour intervals to keep them wetted over a 24 hour period by each of the fluids in one group. The sensor should then be operated for 10 minutes before being stored at 65 ^{o}C for 160 hours, and finally returned to room temperature to be operationally tested over 2 hours.

Vibration

Two vibration tests are specified: stress and acoustic. For normal vibration, a sinusoidal sweep is applied to the specimen for 1 hour per axis while continuously testing performance. The sweep should range from 5Hz with an amplitude of 2.5mm peak-to-peak through 2000Hz with an amplitude of 2.5μm peak-to-peak. Next, acoustic noise is tested in a reverberation chamber using an overall sound pressure level of 160dB for 30 minutes, with random frequencies up to 10,000 Hz.

Acceleration

Three acceleration tests are necessary: maneuvering, operational shock and crash safety. First, normal maneuvering is simulated using a centrifuge spun up to 27g, and held for 1 minute at each orientation. Next, operating shocks such as hard landings are tested using a terminal saw tooth wave with pulse duration of 11ms and a peak value of 6g applied three times in each orientation. Last, a crash safety test is performed by applying a terminal saw tooth wave with a peak value of 20g once in each orientation to assure the equipment does not detach.

Electrical & Magnetic Effects

There are ten separate tests contained within the various standards that relate to electromagnetic testing. The first five, described in MIL-STD-461E, specify measurements of susceptibility and emissions conducted through external cables. These are followed by two similar tests for radiated susceptibility and emissions suitable for both wired and wireless sensors. Next, the DO-160E further recommends tests for the effects of voltage spikes both through the main power bus and through electro-static-discharge. Last, there is also a section on the direct (power spike) and indirect effects (heating, acoustic wave) of lightning strikes.

Combined Loading

While no combined loading tests are explicitly specified, the need for application dependant combined testing is expressed. SHM dictates combined temperature, pressure, moisture and vibration testing. Tests should be designed to simulate real probable environments, such as high temperature and moisture with vibration for take-off, or low temperature and pressure with vibration for cruise.

MECHANICAL DESIGN OF SHM SYSTEMS

SHM is predicated on the ability to integrate sensors within a structure; this requires not only that the sensors be able to detect the damage, but that the sensors themselves are robust enough to avoid replacement within the economic life of the component they monitor. As consequence, whether the sensor is embedded or surface mounted, these devices must endure unique loading conditions, including interactions with the aircraft structure itself in a dynamic environment. This exposes the sensors to many of the same loading environments as the host structure, including peak static stress and strain, as well as cyclic mechanical environments leading to fatigue. Of concern are brittle sensor elements, such as piezoelectric wafers, electrodes and adhesive layers that can disbond, crack, soften, or decouple from the host structure by some other mechanism. The FAA FAR 25 lists acceptable engineering design criteria for major aircraft components, however there are no standards that directly specify mechanical design criteria for sensors that are bonded or otherwise intimately attached to these components. In lieu of such standard, it would be prudent to assume that SHM system devices need to be designed to the identical static and dynamic load profiles as specified for its host structure by the FAR and/or airframe manufacturer.

In addition attention needs to be placed towards operational fatigue of the SHM devices themselves. Most SHM system designs rely on high-frequency phenomenon such as wave propagation or modal excitation, and any actuator used to excite these vibrations will endure millions of cycles through its lifetime. There is concern for mechanical fatigue not only for the actuator elements themselves, but also for any other subcomponent of the SHM device attached to the actuator such as electrodes and for any adhesive bonds present. Additionally, for certain types of actuators there is the potential for electromagnetic fatigue. For example, shape memory alloys can relax and the poling orientation and strength of piezoelectric wafers can degrade with cycles over time, both effects that can be accelerated by environmental factors such as temperature.

RELIABILITY AND LONGEVITY OF SHM SYSTEMS

Reliability and longevity are important in order to formulate appropriate architectures and economic models for SHM systems. Reliability describes the probability of a monitoring system failing to perform its function within a certain expected lifetime. This can be due to manufacturing variability, level of quality control, installation conditions or procedures, and robustness of error handling in firmware and software design. Longevity relates to the ageing of components over time; a “natural” degradation due to a combination of repetitive environmental and mechanical factors wearing away at parts. Longevity is used typically to define a safe-hours-of-usage or mean-time-to-failure (MTF) figure, so that devices can be retired prior to reaching an uncertain state of functionality. While often difficult to quantify, these phenomena are essential when considering an SHM system to reduce life-cycle costs. Again, while no formal standard regulates these criteria for SHM devices, to achieve condition-based maintenance in a cost-effective manner, the sensors themselves must be reliable enough with sufficient MTF so that they do not require replacement at intervals less than the economic lifetime of the components they are monitoring.

DISCUSSION

Overall, while sufficient standards currently exists to dictate design of typical aircraft subcomponents, it is apparent that gaps exist in regulating criteria for devices that are intimately integrated with aircraft such as SHM systems, or more generally smart structures. Smart structures can serve to detect damage such as SHM devices, to control shape for aerosurfaces or noise mitigation, or provide integrated antenna or power capabilities, and are widely accepted as the future direction for aerospace vehicles. While it is possible to sift through the environmental standards and subsequently devise suitable reliability, longevity and mechanical criteria on an individual device basis, it would more prudent for a unique standard to be created specifically prepared for smart structures. This standard should be written in a similar style to the existing ones, citing relevant environmental and EMI requirements, however it should also capture the additional issues discussed in this paper. SHM would be a subsection of a smart structure standard framework, and as the case is with current standards, there would be a need for application-dependant test matrices; for example there would be additional durability concerns for space vehicles regarding vacuum and radiation

CONCLUSIONS

This paper presents results from recent research investigating characterization requirements for SHM systems for certification. In order to commercialize SHM devices into viable products, they must be able to withstand conventional operating conditions so that they do not need to be replaced within the economic lifetime of the aircraft that they are meant to monitor. Requirements are extracted, condensed and consolidated from several government regulated standards, including the DO-160E, the MIL-STD-810F and MIL-STD-461E. Further requirements for reliability, longevity and mechanical loading are also specified. Lastly, the authors suggest to government and industry to develop commercial and defense smart structures standards that would specifically govern the issues addressed in this paper to regulate the large volume of smart structure designs for the aerospace industry that is anticipated for the near future. Integrated SHM systems will be an important component in future air and spacecraft designs, and characterization standards will play a large role in their commercialization, certification and eventual implementation.

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Table 1: DO-160E*

3	Combined loading
4	Temperature & pressure
5	Temperature variation
6	Humidity
7	Shocks
8	Vibration
9	Explosive atmosphere
10	Waterproofness
11	Fluids Susceptibility
12	Sand & dust
13	Fungus
14	Salt fog
15	Magnetic effect
16	Power input
17	Voltage spike
18	Audio frequency susceptibility
19	Induced signal susceptibility
20	Radio frequency susceptibility
21	Emission of radio frequency
22	Lightning transient susceptibility
23	Lightning strike
24	Icing
25	Electrostatic discharge
26	Flammability

Table 2: MIL-STD-810F*

500	Pressure
501	High temperature
502	Low temperature
503	Temperature shock
504	Contamination by fluid
505	Solar radiation
506	Rain
507	Humidity
508	Fungus
509	Salt fog
510	Sand & dust
511	Explosive Atmosphere
512	Immersion
513	Acceleration
514	Vibration
515	Acoustic noise
516	Shock
517	Pyroshock
518	Acidic Atmosphere
519	Gunfire vibration
520	Combined loading
521	Icing
522	Ballistic shock
523	Vibro-acoustic

Table 3: MIL-STD-461E*

CE101	Conducted emission power lead 30hz-10khz
CE102	Conducted emission power lead 10khz-10mhz
CE106	Conducted emission antenna 10khz-40ghz
CS101	Conducted susceptibility power lead 30hz-150khz
CS103	Conducted susceptibility antenna 15khz-10ghz
CS104	Conducted susceptibility antenna reject 30hz-20ghz
CS105	Conducted susceptibility antenna 30hz-20ghz
CS109	Conducted susceptibility current 60hz-100khz
CS114	Conducted susceptibility cable 10khz-200mhz
CS115	Conducted susceptibility cable impulse
CS116	Conducted susceptibility power leads 10khz-100mhz
RE101	Radiated emissions magnetic field 30hz-100khz
RE102	Radiated emissions electric field 10khz-18ghz
RE103	Radiated emissions antenna 10khz-40ghz
RS101	Radiated susceptibility magnetic field 30hz-100khz
RS103	Radiated susceptibility electric field 2mhz-40ghz
RS105	Radiated susceptibility transient electromagnetic field

* Tables 1-3 are distilled from the testing standards referenced in this paper [9-12]. The highlighted tests are considered SHM relevant. Note that the "conducted" EMI tests are only applicable for sensors with external cables, and not for wireless sensors.