An Assessment of Durability Requirements for Aircraft Structural Health Monitoring Sensors

Seth S. Kessler and Kevin S. Amaratunga
Metis Design Corporation

Brian L. Wardle
Massachusetts Institute of Technology

SHM-2005

ABSTRACT

In recent years, the Structural Health Monitoring (SHM) market has expanded, both in the quantity of applications as well as the number of technology providers. While most research has focused on optimizing detection methods themselves, an important area that has not been sufficiently addressed is durability requirements for SHM sensors. This paper presents a framework for considering smart structure durability and discusses the various applicable existing durability standards for commercial and military aircraft components, and how they relate to SHM systems. This work is part of a larger current investigation aimed at developing infrastructure to provide power, data collection, communication and protection from operational environments for a specific SHM system. The reliability and longevity requirements of SHM systems are discussed, as well as the need for a supplemental standard geared specifically towards smart structure technologies. 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 with minimal human intervention to reduce life-cycle costs. There are several components required to design a complete SHM system, including sensor elements, processing and communication chips, power supply, and packaging to integrate and protect these components. Current SHM efforts have focused mainly on sensing methods for damage detection, however the infrastructure needed to employ these methods has not been sufficiently addressed. Under AFOSR funding, the Metis

Seth S. Kessler, Metis Design Corporation, 222 Third St., Cambridge, MA 02142
Kevin S. Amaratunga, Metis Design Corporation, 222 Third St., Cambridge, MA 02142
Brian L. Wardle, Massachusetts Institute of Technology, Cambridge, MA 02139

Design Corporation (MDC) has developed infrastructure components to facilitate surface-mounted damage detection, including optimized actuators and sensors, integrated electronics that provide signal excitation, data collection and communication, protective packaging and software to collect and interpret data. MDC's damage detection research has focused on piezoelectric-based methods such as Lamb waves since they provide reliable information about damage presence and location. Lamb waves are a form of elastic perturbation that propagate in a plate with free boundaries [1-3]. More detailed Lamb wave research results by the present authors can be found in several journals and conference proceedings [4-18]. Now that detection methods have been demonstrated in laboratory conditions, the present research has focused on assessing durability requirements for sensors, so that they can be implemented practically in commercial and military applications. This paper presents results from AFOSR funded research conducted at MDC in conjunction with MIT investigating the durability of SHM components. Applicable standards were consulted to select suitable tests, including thermal exposure, pressure, susceptibility to water and other contaminants and electromagnetic interference. Suggestions are also presented for other necessary tests.

DURABILITY STANDARDS

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" [19]. 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 [20]. 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" [21, 22]. 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" [23]. 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.

DURABILITY TESTING FOR SHM SYSTEMS

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.

FURTHER REQUIREMENTS

While tests described above are reasonably comprehensive, there are several issues not specifically addressed that are directly applicable to SHM systems. First, the mechanical strength of the sensors is not discussed. While the FAR 25 lists acceptable engineering design criteria for major aircraft components, there are no standards that directly specify mechanical design criteria for sensors that are bonded to these components. SHM is predicated on the ability to intimately integrate sensors with a structure, whether surface mounted or embedded, thus exposing the sensors to many of the same loading environments as the host structure. This includes peak static stress and strain, as well as cyclic mechanical environments leading to fatigue. Of concern are the sensor elements, which can be quite brittle in the case of piezoelectric wafers for example, and adhesives that can disbond, crack, soften, or decouple from the host structure by some other mechanism.

Second, reliability and longevity are not mentioned. Reliability relates to the probability of components failing over time due to "natural causes," basically a safe-life design limit. 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. While often difficult to quantify, these phenomena are essential when considering an SHM system to reduce life-cycle costs. To achieve condition-based maintenance cost-effectively, the sensors themselves must be sufficiently reliable so that they do not require replacement at intervals less than the economic lifetime of the components they are monitoring.

The last area where additional attention should be placed is operational fatigue. Most SHM 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, such as piezoelectric wafers or shape memory alloys there is also the possibility of electromagnetic fatigue, where the preferred poling orientation can degrade.

Overall, while investigating the standards for aircraft subcomponent design, it has become 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 to create a unique standard specifically prepared for smart structures. This standard should be written in a similar style to the ones this paper references, citing relevant environmental and EMI requirements, however it should also capture the additional issues discussed in this section. As is the case with current standards, there likely is a need for both a commercial and defense version of this new standard. A framework for developing a complete SHM and/or smart structure standard is presented in **Figure 1.**

CONCLUSIONS

This paper presents results from a portion of recent AFOSR funded research conducted at MDC and MIT investigating durability requirements for SHM systems. 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. MDC is currently using the criteria described in this paper to qualify their M.E.T.I.-Disk 3 and 4 digital and wireless SHM nodes for conventional aircraft conditions. Future work will aim to further harden these nodes and subsequently test them in more extreme conditions such as vacuum and radiation exposure for space applications. Integrated SHM systems will be an important component in future aircraft designs.

ACKNOWLEDGEMENTS

This research was sponsored by the Air Force Office of Scientific Research, under the Phase II STTR contract FA9550-05-C-0024. The work was performed at the MDC in Cambridge, MA, with a subcontract for testing to MIT.

REFERENCES

1. Lamb H. "On Waves in an Elastic Plate." *Proceedings of the Royal Society of London, Part A: Containing Papers of a Mathematical and Physical Character*, v.93, n.651, 1917, 293-312.
2. Viktorov I.A. *Rayleigh and Lamb Waves, Physical Theor*. Plenum Press, New York, 1967.
3. Nayfeh A.H. *Wave Propagation in Layered Anisotropic Media with Applications to Composites*. v.39, Elsevier, Amsterdam, 1995.
4. Kessler S.S. "Piezoelectric-Based In-Situ Damage Detection of Composite Materials for SHM Systems." Massachusetts Institute of Technology, Ph.D. Thesis, January 2002.
5. Kessler S.S., Spearing S.M., Atalla M.J., Cesnik C.E.S. and C. Soutis. "Damage Detection in Composite Materials using Frequency Response." Proceedings of the SPIE's 8th Symposium on Smart Structures and Materials, 4-8 March 2001, Newport Beach, CA, NDE 4336-01.
6. Kessler S.S., Spearing S.M., Atalla M.J., Cesnik, C.E.S. and C. Soutis. "SHM in Composite Materials using Frequency Response Methods." Composites Part B, v.33, January 2002, 87-95.
7. Kessler S.S., Spearing, S.M. and C. Soutis. "Damage Detection in Composite Materials using Lamb Wave Methods." Proceedings of the American Society for Composites, 9-12 September 2001, Blacksburg, VA, ASC01-043.
8. Kessler S.S., Spearing S.M. and C. Soutis. "Optimization of Lamb Wave Methods for Damage Detection in Composite Materials." Proceedings of the 3rd International Workshop on Structural Health Monitoring, 12-14 September 2001, Stanford University, SHM2002-071.
9. Kessler S.S., Spearing S.M. and C. Soutis. "SHM in Composite Materials using Lamb Wave Methods." Smart Materials and Structures, v.11, April 2002, 269-278.
10. Material Systems and Structures, December 2001.

11. Kessler S.S., and S.M. Spearing. "Design of a PiezoElectric Based SHM System for Damage Detection in Composite Materials." Proceedings of the SPIE's 9th International Symposium on Smart Structures and Materials, March 2002, San Diego, CA, NDE 4701-11
12. Kessler S.S., and S.M. Spearing. "In-Situ Sensor-Based Damage Detection of Composite Materials for Structural Health Monitoring Systems." Proceedings of the AIAA/ASME 43rd SDM Conference, April 2002, Denver, CO, AIAA-2002-1545.
13. Kessler S.S., Spearing S.M., and M.J. Atalla. "In-Situ Damage Detection of Composite Materials using Lamb Wave Methods." Proceedings of the European Workshop on SHM, July 2002, Paris, France.
14. Kessler S.S., and C.T. Dunn. "Optimization of Lamb Wave Actuating and Sensing Materials for Health Monitoring of Composite Structures." Proceedings of the SPIE's 10th International Symposium on Smart Structures and Materials, March 2003, San Diego, CA, NDE 5056-80.
15. Kessler S.S., Johnson C.E. and C.T. Dunn. "Experimental Application of Optimized Lamb Wave Actuating/Sensing Patches for SHM of Composite Structures." Proceedings of the 4th International Workshop on SHM, 15-17 September 2003, Stanford University.
16. Kessler S.S. and S.M. Spearing. "Selection of Materials and Sensors for SHM of Composite Structures." Proceedings of the MRS Fall Meeting, 1-5 December 2003, Boston, MA.
17. Kessler S.S., Spearing S.M., Shi Y. and C.T. Dunn. "Packaging of SHM Components." Proceedings of the SPIE's 11th International Symposium on Smart Structures and Materials, 14-18 March 2004, San Diego, CA.
18. Kessler S.S., and D.J. Shim. "Validation of a Lamb Wave-Based SHM for Aircrafts." Proceedings of the SPIE's 12th International Symposium on Smart Structures and Materials, 7-10 March 2005, San Diego, CA.
19. RTCA/DO-160E "Environmental Conditions and Test Procedures for Airborne Equipment." RTCA Paper No. 111-04/SC135-645, Washington, DC, 2005.
20. AC21-16D, US Department of Transportation, Federal Aviation Administration, Advisory Circular No: 21-16D, July 1998.
21. MIL-STD-810F "Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests." January 2000.
22. MIL-STD-810F Change Notices 1, 2 and 3 "Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests." 11/00, 08/02 and 5/03.
23. MIL-STD-461E "Department of Defense Interface Standard Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment." August 1999.

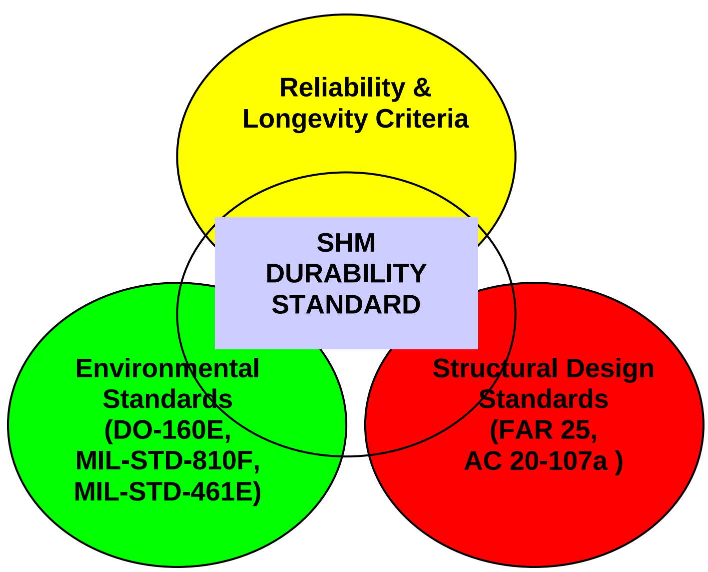

Figure 1: Framework for identifying SHM or smart structure durability standard.

Table 1: DO-160E*

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

Table 2: MIL-STD-810F*

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

Table 3: MIL-STD-461E*

		Highlighted
CE101	Conducted Emission Power lead 30hz-10khz	
CE102	Conducted Emission Power lead 10khz-10mhz	yes
CE106	Conducted Emission Antenna 10khz-40ghz	
CS101	Conducted Susceptibility Power lead 30hz-150khz	yes
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	yes
CS115	Conducted Susceptibility cable impulse	yes
CS116	Conducted Susceptibility Power leads 10khz-100mhz	yes
RE101	Radiated emissions magnetic field 30hz-100khz	
RE102	Radiated emissions electric field 10khz-18ghz	yes
RE103	Radiated emissions antenna 10khz-40ghz	
RS101	Radiated susceptibility magnetic field 30hz-100khz	
RS103	Radiated susceptibility electric field 2mhz-40ghz	yes
RS105	Radiated susceptibility transient electromagnetic field	

* Tables 1-3 are distilled from the testing standards referenced in this paper [19-23]. 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 nodes.