metis design

mechanical design
composites engineering
structural health monitoring

Certifying Structural Health Monitoring Systems

Characterizing Durability, Reliability & Longevity

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Introduction

- Structural Health Monitoring (SHM) denotes a system with the ability to detect and interpret adverse “changes” in components in order to reduce life-cycle costs and improve safety
- Involves integrating a non-destructive evaluation (NDE) device, or collection of devices, into a vehicle to collect prognostic data
  - can be embedded or surface mounted
  - benefits to both wired and wireless systems
  - detection methods can be active (excitation) or passive (witness layer)
  - integrate into new vehicles or retrofit ageing vehicles to facilitate CBM
  - interrogation of system can occur continuously or intermittently






Problem Statement

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- Greatest benefits can be achieved by the Aerospace industry

- Limited vehicle monitoring capabilities available presently
  - black-boxes on civil aircraft (record metrics such as velocity, altitude, etc)
  - health usage monitoring (HUMS) on newer military air and rotorcraft
  - most current SHM research has focused on detection methods, sensor optimization and interpretation algorithm development
  - evaluation has largely been limited to laboratory-scope testing

- Characterization standards are necessary for SHM certification
  - measure durability in realistic operating conditions
  - design for static and dynamic mechanical limitations
  - calculate reliability and longevity of integrated devices

Durability

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- Durability describes the response of a material, component or system to its operating environment over time

- Failure of aircraft subsystems have catastrophic consequences

- Several areas of concern need to be addressed
  - environmental susceptibility
  - electromagnetic interference
  - mechanical loading

- Standards in place to regulate durability of aircraft components
  - maintained by aircraft manufacturers and government officials
  - describe experimental setup, conditions, and rationale behind the test
  - provide charts to determine the test intensity and passing criteria

Current Standards

- RCTA/DO-160
  - "Environmental Conditions and Test Procedures for Airborne Equipment"
  - Recommended by the FAA to show compliance with environmental airworthiness requirements (FAR AC21-16D)
  - Defines procedures and criteria for airborne equipment ranging from light aircraft to commercial jets and transports
- MIL-STD-810
  - "Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests"
  - provides guidance for environmental tests to qualify DoD components
  - adds conditions such as ballistic, pyro and tethered landing shock
- MIL-STD-461
  - "Department of Defense Interface Standard Requirements for the Control of Electromagnetic Interference Characteristics of Equipment"
  - Describes test protocols for evaluating conducted and radiated emissions from DoD electronic components, as well as EMI susceptibility

Temperature

- Operational testing
  - simulates exposure extremes for storage and designed flight conditions
  - sensors are saturated at the peak temperature for 3 hours
  - followed by functional testing for two hours at the extreme peak
  - cold extreme of -55^{o}C for anticipated aircraft SHM conditions
  - hot extreme of 85^{o}C

- Thermal shock testing
  - simulates takeoff from a desert climate to a cruise at a high altitude
  - test begins with the specimen at its cold extreme of -55^{o}C
  - followed by a ramp of 10^{o}C/min to 85^{o}C and held for 2 minutes
  - then ramped back down to -55^{o}C where the sensor is tested for one hour
  - lastly a 30 minute hold time before a second identical cycle is performed

Pressure

- Altitude test
  - decrease pressure to maximum operating altitude of 30km (1.10kPa)
  - performance is tested for 2 hours at low pressure

- Emergency decent
  - decompress from 2.4km (75.36kPa) to 30km (1.10kPa) in 15 seconds
  - performance is tested for 10 minutes at low pressure

- Overpressure
  - simulates routine testing of pressurization system
  - pressure equivalent to -4.6km (169.73kPa) is maintained for 10 minutes
  - performance is tested at ambient pressure

Moisture

- Humidity
  - specimens are placed at 85% relative humidity and 30^{o}C
  - raise to 95% humidity and 60^{o}C over 2 hours, maintain for 6 hours
  - gradually reduce to 85% humidity at 38^{o}C over next 16 hours
  - complete two cycles then test performance of the sensor within 1 hour

- Condensation
  - specimens are placed in a cold -10^{o}C chamber for 3 hours
  - transferred to a warm 40^{o}C chamber at 85% relative humidity
  - test performance of the sensor for 10 minutes in warm chamber

Fluid Susceptibility

- Fluids grouped into two major categories
  - oil-based fuels, hydraulic fluids, lubricating oils
  - water-based cleaners, disinfectants, coolantants, fire extinguishants
- Spray testing
  - specimens are sprayed to remain wet in 4 hour intervals (minimum)
  - conducted over 24 hours, test performance of the sensor for 10 minutes
  - one fluid group is tested at a time
- Saturation testing
  - following spray test, store specimens at 65^{o}C for 160 hours
  - return to room temperature for performance testing over 2 hour period

Vibration

- Mechanical vibration
  - sinusoidal sweep is applied to specimens for 1 hour per axis
  - sweep range begins at 5Hz with an amplitude of 2.5mm peak-to-peak
  - sweep range ends at 2000Hz with an amplitude of 2.5μm peak-to-peak
  - performance of sensors is continuously tested

- Acoustic noise
  - specimens are placed in a reverberation chamber
  - overall sound pressure level of 160dB applied for 30 minutes
  - random frequencies excited up to 10,000 Hz
  - performance of sensors is continuously tested

Acceleration

- Maneuvering
  - centrifuge spun up to 27g, and held for 1 minute at each orientation
  - performance of specimens tested at conclusion of spin
- Operating shocks
  - simulate shocks such as hard landings and carrier takeoff and landing
  - spectrum approximating a terminal saw tooth wave, duration of 11ms
  - peak value of 6g applied three times in each orientation
- Crash safety
  - assure the equipment does not detach and become projectile in crash
  - terminal saw tooth wave with a peak value of 20g in each orientation

Electromagnetic

- EMI susceptibility & emissions
  - 4 measurements of conducted susceptibility through external cables
  - measurement of conducted emissions through external cables
  - measurement of radiated susceptibility (both wired and wireless)
  - measurement of radiated emissions (both wired and wireless)

- Other EMI effects
  - performance following typical voltage spikes through main power bus
  - electrostatic-discharge (arcing)
  - lightning strike (power spike, heating, acoustic wave)

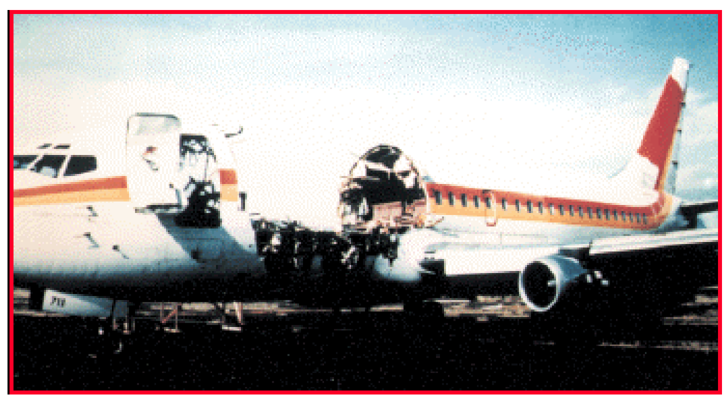
Combined Loading

- No combined tests are explicitly specified in the standards
  - need for application dependant combined tests is expressed
  - actual combined test procedure left to the discretion of testing engineers

- SHM environments dictate the need for custom testing
  - tests should be designed to expose sensors to probable environments
  - simulate take-off with high temperature and moisture along with vibration
  - simulate cruise with low temperature and pressure along with vibration
  - many other application specific conditions exist

Mechanical Design

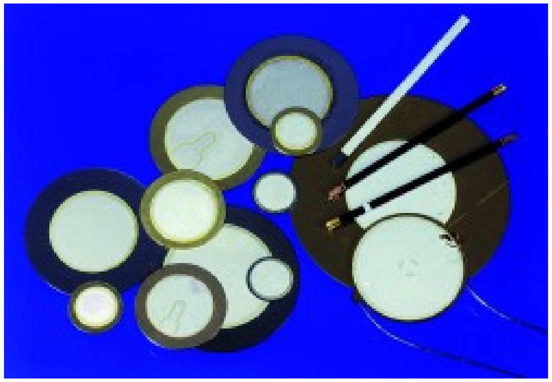
- SHM is predicated on the ability to intimately integrate sensors with a structure, whether surface mounted or embedded
  - exposed to many of the same loading conditions as the host structure
  - includes peak static stress and strain, as well as mechanical fatigue
  - sensor elements and adhesives can disbond, crack, soften, or decouple
- Design criteria listed for major aircraft components in FAR 25, however no standards directly specify mechanical design criteria for sensors or actuators bonded to components



Self-Imposed Fatigue

- Many SHM systems rely on high-frequency actuation for wave propagation or modal excitation that endure millions of cycles
  - mechanical fatigue of actuator element can become an issue
  - fatigue of attached subcomponents such as bonded electrodes, etc.

- Additional issues piezoelectric wafers and shape memory alloy
  - electromagnetic fatigue can degrade actuation properties over time
  - can also relax or alter poling and memory orientations



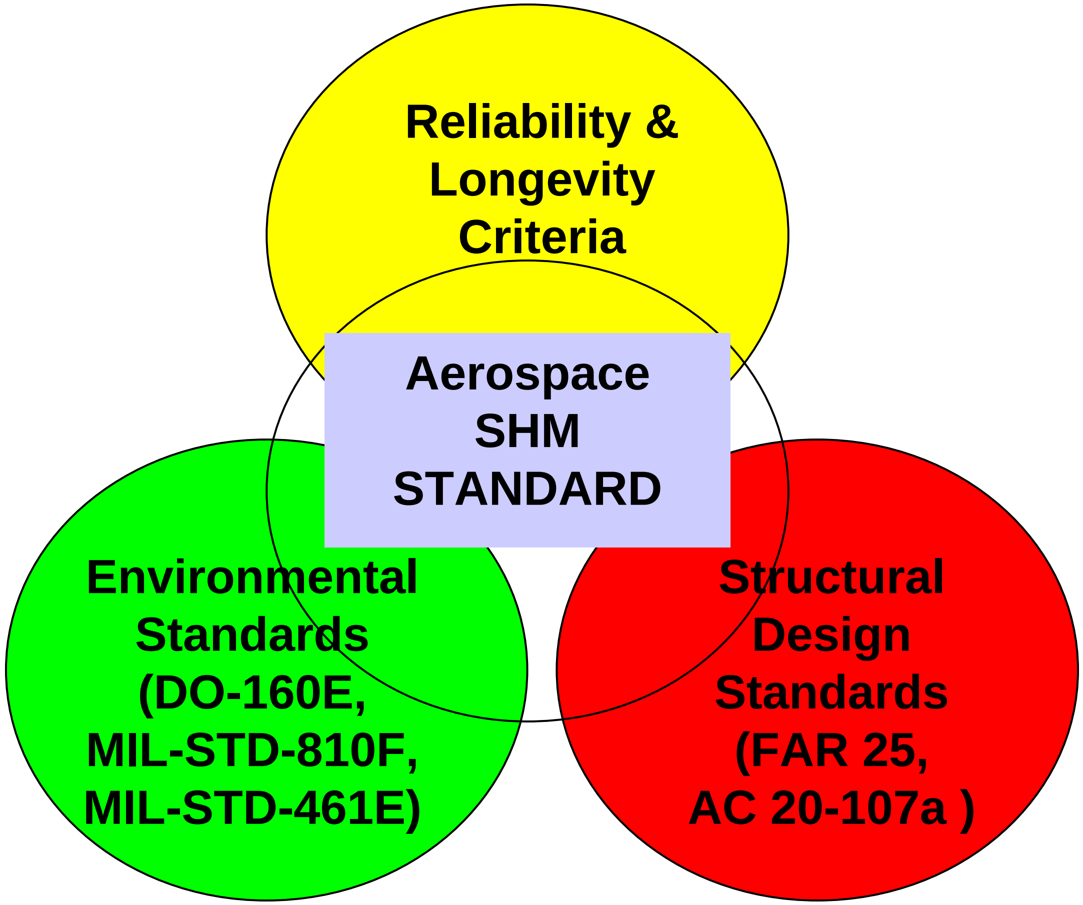
Reliability & Longevity

- To achieve the cost benefits of condition-based maintenance, sensors must be sufficiently reliable so as not to require replacement within the life of the component being monitored

- Reliability describes the probability of a device failing to perform to its required specifications over its expected lifetime
  - manufacturing variability (quality control)
  - installation conditions and preparation procedures
  - algorithms and logic robustness in software are also important

- Longevity relates to the ageing of components over time
  - “death by natural causes” – gradual degradation leads to a safe-life limit
  - repetitive environmental and mechanical factors wearing away at parts

Aerospace SHM Standard



- Gaps exist in regulating criteria for intimately integrated devices
- Need for standard to characterize and certify smart structures
  - suitable durability, reliability, longevity and mechanical criteria
  - SHM systems would be a subset of a smart structure standard
  - application dependant test matrix (e.g. vacuum and radiation for space)

Acceptance

- Despite certification procedures, acceptance of SHM systems by end users (such as airlines & DoD) will still be a challenge
  - inertia of current manual inspection interval procedure (if it's not broke…)
  - reluctance to trust new technology with minimal service data
  - potential upfront cost implications for hardware, software and training
- Staggered introduction of SHM systems
  - initially systems can be used to monitor damage for off-line comparison
  - second phase would include use of SHM to expedite manual inspection
  - third tier would give monitoring responsibilities over limited components
  - complete implementation once large volume of service data is collected
- Better economic models are necessary for convergence
  - most current models include discontinuities in value stream
  - end–users' desire for 3-year return-on-investment easily achievable

Summary

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- SHM devices must withstand conventional operating conditions to avoid failure within the life of the component being monitored
- Federally regulated standards currently provide characterization requirements for aircraft components
- Need exists for comprehensive reliability, longevity and mechanical loading requirements (static & dynamic)
- Suggest the development of a standard specifically suited to smart structure certification for the aerospace industry
- Work remains for acceptance prior to viable commercialization
- Integrated SHM systems will be an important component in future aircraft designs to reduce costs and improve safety

M.E.T.I.-Disk SHM Devices

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- Common device characteristics
  - concentric PZT actuator/sensor elements
  - flexible circuit for power and shielding
  - encapsulation to protect components
  - 2-part liquid adhesive bond to structure
  - nominal drive of 20Vpp, sense of 20mVpp
  - Lamb wave, modal analysis, AE capable
- M.E.T.I.-Disk 2 Analog SHM Device
  - co-axial cables for data & power
- M.E.T.I.-Disk 3 Digital SHM Device
  - 1MHz 16-bit ADC & 1MS/s 8-bit DAC
  - USB connectors for data & power, CAN bus
- M.E.T.I.-Disk 4 Wireless SHM Device
  - integrated wireless chip & rechargeable battery
  - removes cables, connectors, weight and cost