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mechanical design
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structural health monitoring

How to Commercialize Structural Health Monitoring:

Characterization, Certification and Acceptance

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Outline

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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)
  - interrogation of system can occur continuously or intermittently

Aerospace Applications

- Countless viable applications for SHM systems
  - integrate into new vehicles for need-based maintenance and repair
  - retrofit into existing or ageing vehicles to monitor damage growth
- Greatest benefits can be achieved by the Aerospace industry
  - advantage for both military & civil vehicles (fixed wing & rotorcraft)
  - manned aircraft (passenger, cargo, carrier, super/hypersonic, etc.)
  - unmanned aerial vehicles (UAV & UCAV's)
  - expendable & reusable launch vehicles
  - spacecraft (satellites, space stations, space exploration vehicles, etc.)

Airline Inspection Practice

- Current requirements from FAA FAR AC43.13-1B
  - “walk-around” pre-flight for obvious visual damage
  - detailed visual inspection of most components every 150 flights
  - tear-down of critical metallic components every 6,000-12,000 flight hours, ultrasonic or eddy-current inspection
  - composite parts designed to survive with any invisible damage, visually inspect for no growth over two scheduled intervals

- Example: Airbus A300/310
  - composite vertical stabilizer
  - no specific inspection requirement
  - Airworthiness Directive (FAA-AD) immediate visual inspection for “delamination, cracks, splitting, moisture damage or frayed fibers”

NTSB report on American Airlines Flight #587

Concept of Operations

Starting from taxi, monitoring methods can begin collecting data on state of structural health

In flight, can passively monitor for events, intermittently perform tests, or actively notify operators and ground crews

Upon landing flight data can be collected and analyzed during normal pre-flight servicing time, and can perform complete system diagnostic prior take-off.

System Data Utility

- Black box augmentation
  - record additional critical data in the event of an accident
  - witness maximum strain/stress in vehicle for future design/analysis use
- Maintenance checks
  - expedite scheduled inspections, reduce manual labor with in-situ system
  - offer surface penetrating methods without tear-down of sub-structure
- Ground support
  - continuously monitor vehicle in-flight for threshold strain/stress values
  - perform complete pre-flight diagnostic inspection for safety assurance
- Supply/demand
  - provide component data for state-based maintenance and replacement
  - smoother, quicker and cheaper supply and demand of components

Other Applications

- Ground vehicles
  - automobiles & trucks
  - tanks
  - rail cars

- Naval
  - ships
  - submarines
  - ocean platforms (oil drilling & sea-launch)

- Civil infrastructure
  - bridges
  - buildings
  - pipelines
  - energy facilities (wind turbines, nuclear plants & oil refineries)

- Variety of environments and loading conditions

Problem Statement

- 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
  - need exists for more elaborate structural health monitoring methods to reduce life-cycle costs of aircraft, extend safe operational life

- Most current SHM research has focused on detection methods
  - sensor optimization and interpretation algorithm development
  - evaluation has largely been limited to laboratory-scope testing
  - The durability, reliability, longevity of SHM components need to be characterized along with the static and dynamic mechanical limitations for future certification and eventual implementation

Durability

- 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

RCTA/DO-160

- “Environmental Conditions and Test Procedures for Airborne Equipment” was first released as DO-138 in 1958
- Current version is RCTA/DO-160E issued by the Radio Technical Commission for Aeronautics in 2005
- 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
- Recognized as the de facto international standard ISO-7137

	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	Flammabilty

MIL-STD-810

- "Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests" was first released in 1959
- Current version is MIL-STD-810F issued in 2000, with 3 subsequent change notices released between 2000-2003
- Provides guidance for tailoring environmental tests to qualify components to be used in DoD applications
- Similar in scope to DO-160, omits EMI testing
- Adds other conditions only found in DoD applications such as ballistic, pyro and tethered landing shock

	MIL-STD-810
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

MIL-STD-461

- “Department of Defense Interface Standard Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment” first released as SCL-49 in 1934

- Current version is MIL-STD-461E issued in 1999

- Describes test protocols for evaluating conducted and radiated emissions from DoD electronic components, as well as EMI susceptibility

	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

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°C for anticipated aircraft SHM conditions
  - hot extreme of 85°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°C
  - followed by a ramp of 10°C/min to 85°C and held for 2 minutes
  - then ramped back down to -55°C where the sensor is tested for one hour
  - lastly a 30 minute hold time before a second identical cycle is performed

Pressure

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- 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°C
  - raise to 95% humidity and 60°C over 2 hours, maintain for 6 hours
  - gradually reduce to 85% humidity at 38°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°C chamber for 3 hours
  - transferred to a warm 40°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°C for 160 hours
  - return to room temperature for performance testing over 2 hour period

Vibration

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- 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

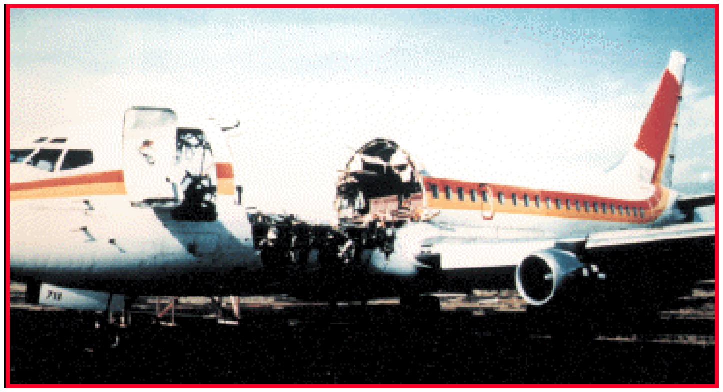
- SHM is predicated on the ability to intimately integrate sensors with a structure, whether surface mounted or embedded
  - exposed to many of the same loading conditions as the host structure
  - includes peak static stress and strain, as well as mechanical fatigue
  - sensor elements and adhesives 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

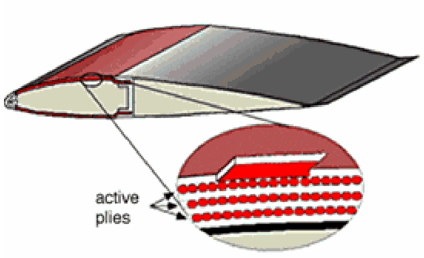
- Reliability describes the probability of a device failing to perform to its required specifications over its expected lifetime
  - manufacturing variability (quality control)
  - installation conditions and preparation procedures
  - algorithms and logic robustness in software are also important

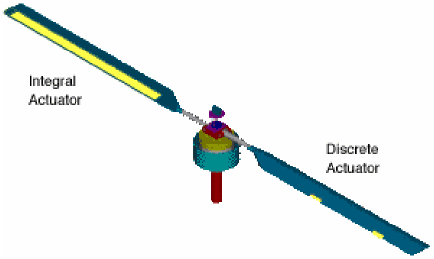
- Longevity relates to the ageing of components over time
  - "death by natural causes" – gradual degradation leads to a safe-life limit
  - repetitive environmental and mechanical factors wearing away at parts

Smart Structure Standard

- Gaps exist in regulating criteria for devices that are intimately integrated with aircraft, or more generally smart structures
  - provide detection, shape control, integrated antenna or power capability
  - widely accepted as the future direction for aerospace vehicles

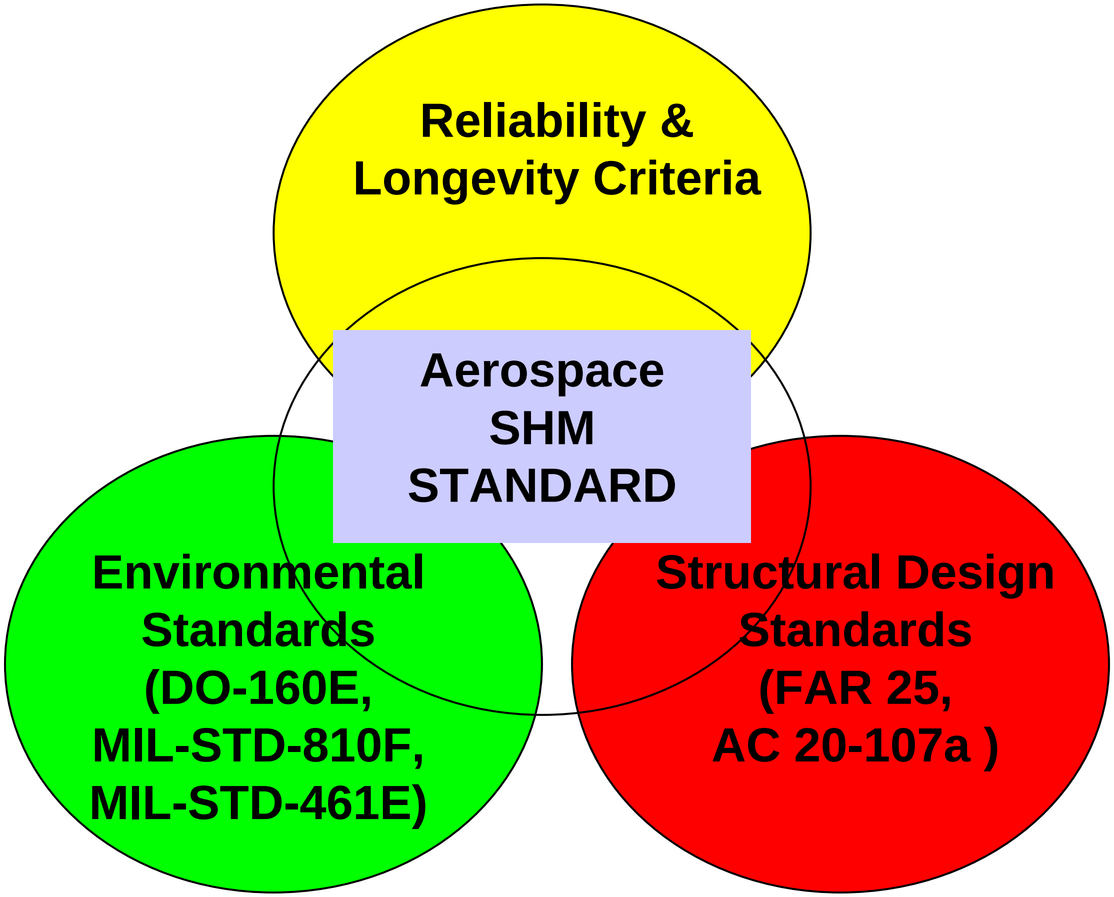
- Need exists for unique standard specifically for smart structures
  - characterization procedures for certification and regulation
  - suitable durability, reliability, longevity and mechanical criteria
  - written in a similar style to current industry standards presented
  - both commercial and defense versions of this new standard necessary





Figures provided by MIT Active Materials & Structures Laboratory

Aerospace SHM Standard



Reliability & Longevity Criteria

Aerospace SHM STANDARD

Environmental Standards (DO-160E, MIL-STD-810F, MIL-STD-461E)

Structural Design Standards (FAR 25, AC 20-107a)

- Framework for developing a comprehensive SHM standard
  - 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

Benefits to End-Users

- Inspection and maintenance expenses significantly reduced by SHM
  - inspections account for roughly 25% of an aircraft’s life cycle cost
  - commercial airlines spend a combined $10 billion/year on maintenance
  - condition based maintenance could reduces these costs by 33%
  - tremendous savings compared with elimination of meals and pillows

- Reliability of damage detection and failure prediction increased
  - much of the airline and military fleet are ageing aircraft, fatigue issues
  - can catch damage that may have occurred between scheduled intervals
  - most inspection is currently visual, overlooks some forms of damage
  - prevent catastrophic loss of equipment and life

Summary

- 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

Acknowledgments

- This research conducted by MDC was sponsored by the Air Force Office of Scientific Research under STTR Phase II award FA9550-05-C-002 entitled “Intelligent Multi-Sensing Structural Health Monitoring Infrastructure”

- Guidance from Air Force program managers:
  - Mark Derriso (AFRL) & Captain Clark Allred, Ph.D. (AFOSR)

- Contributions from subcontractors
  - Professor Brian Wardle (MIT) & Jeffrey Chambers (MIT)
  - Grant Gordon, Ph.D. (Honeywell)

- Special thanks to Dr. Kevin Amaratunga (MDC)