# Durability Assessment of Lamb Wave-Based Structural Health Monitoring Nodes

**Jeff Chambers**, Brian L. Wardle, Seth Kessler

Technology Laboratory for Advanced Materials and Structures
Dept. of Aeronautics and Astronautics
Massachusetts Institute of Technology

# Outline

- Introduction
- Framework for SHM Durability Testing
- SHM System for this Work
- Existing Test Standards
- Durability Testing Specifics and Procedures
- Experimental Results
- Conclusions and Recommendations

# Introduction

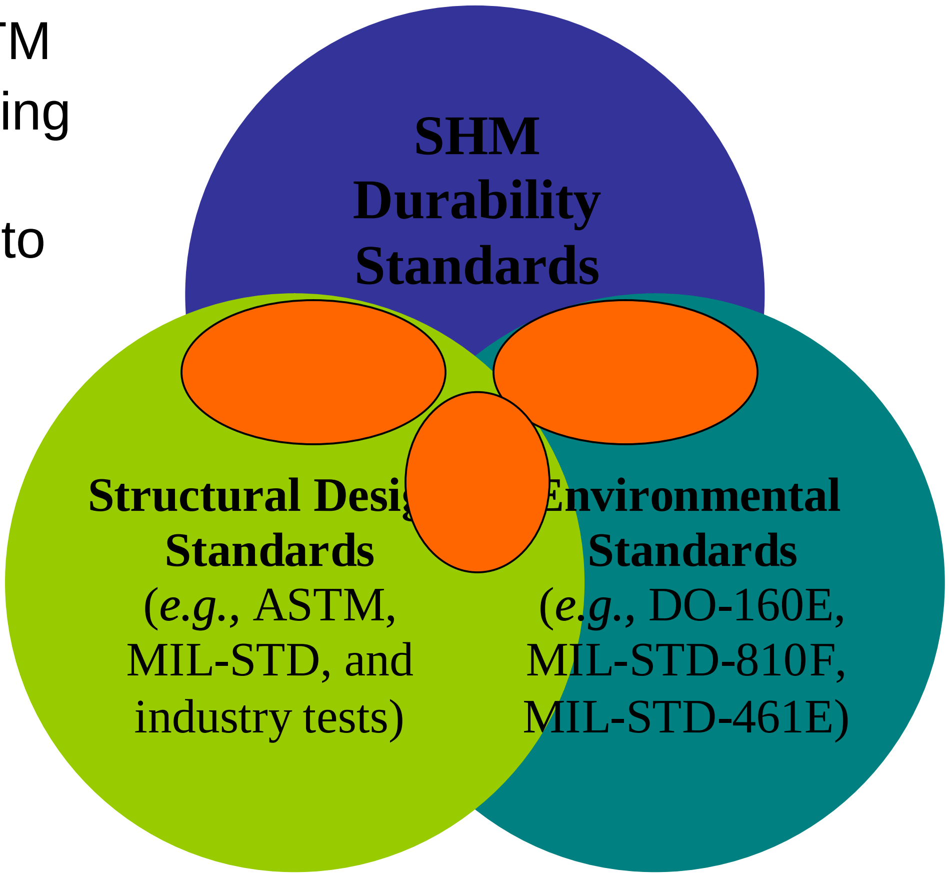
- Structural health monitoring (SHM)
- SHM denotes a system with the ability to detect and interpret (adverse) changes in components
  - Most current SHM work is on sensors/damage detection
  - Increased reliability/safety and reduced life-cycle costs
- Lack of testing standards and certification procedures
- This research presents a framework for developing testing standards, application of the framework to our system to generate specific tests/procedures, results from such tests





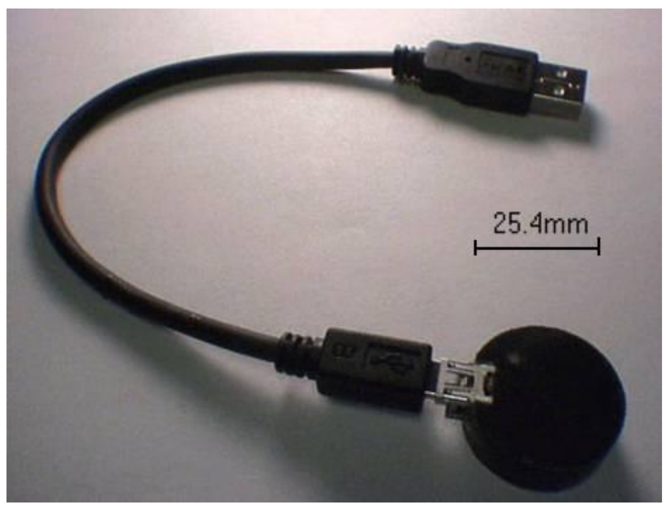

# Framework for Developing SHM Durability Standards

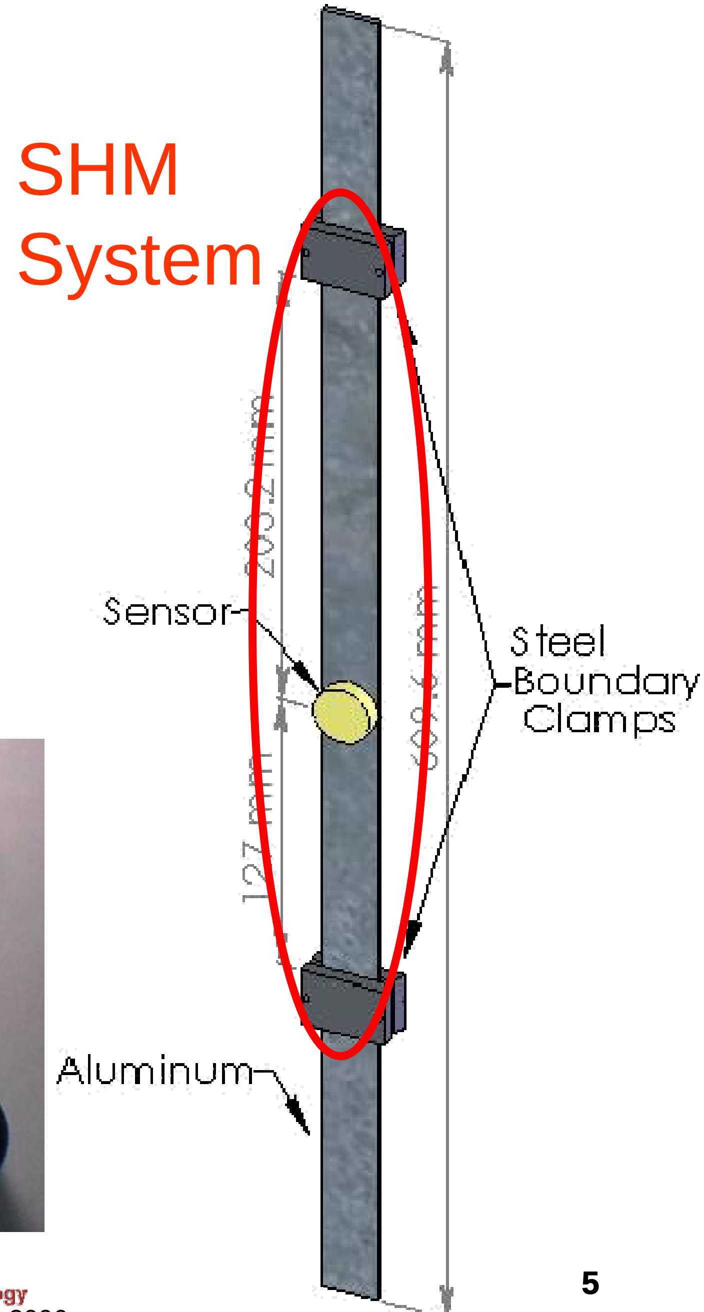
- Use of existing standards for independent environmental or structural testing
  - RTCA/DO-160E, MIL-STDs, ASTM
  - Environmental and structural testing overlap
  - Additional development required to be SHM specific
    - Combined testing
- SHM and smart structures
  - Specific standards needed
    - Embedded
    - Surface mount
  - Systems are integral part of structure
  - Define performance degradation



# SHM System

- Surface-mounted Ultrasonic Transducers
  - Surface bonding
  - Ultrasonic Lamb-waves
  - Pulse-echo operation
  - Inspection of structure’s state away from node
- 2024-T4 aluminum coupons
- Wave characteristics allow
  - ID type of damage
  - Location of damage
- Delta metrics to assess performance

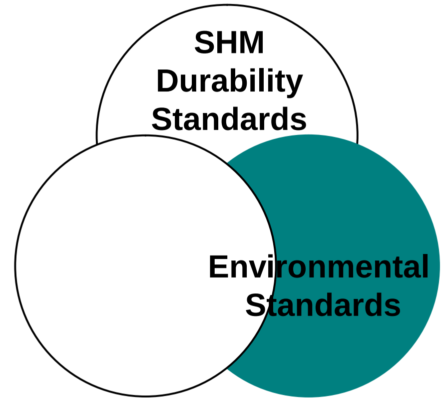


# Research Approach

- Objective:
  - To assess durability of a specific SHM system
- Approach:
  - Define a framework and the specifics (tests & metrics) to meet this objective
  - Tailor current standards to form the framework
  - Define test matrix for initial set of tests
  - Define ‘delta’/change metrics to evaluate system performance
  - Experimental testing of SHM system

# Current Standards - Environmental




- RTCA/DO-160E
  - "Environmental Conditions and Test Procedures for Airborne Equipment"
  - Identified by the FAA as an acceptable test standard for compliance with certain environmental airworthiness requirements (FAR AC21-16E)
  - Defines procedures and criteria for airborne equipment ranging from light aircraft to commercial jets and transports
- MIL-STD-810F
  - "Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests"
  - Guidance for environmental tests to qualify DoD components
- MIL-STD-461E
  - "Department of Defense Interface Standard Requirements for the Control of Electromagnetic Interference Characteristics of Equipment"
  - Describes test protocols for EMI testing of DoD electronic components

# Down-Selection Example

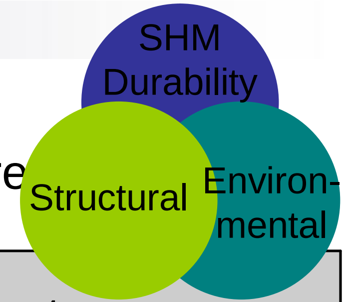
- RTCA/DO-160E test categories
  - Down-selected test categories
  - Eventually, all categories must be addressed

Grey = Selected

| | |
|---|---|
| 4.0 | Temperature and Altitude |
| 5.0 | Temperature Variation |
| 6.0 | Humidity |
| 7.0 | Shock |
| 8.0 | Vibration |
| 9.0 | Explosion Proofness |
| 10.0 | Waterproofness |
| 11.0 | Fluids Susceptibility |
| 12.0 | Sand and Dust |
| 13.0 | Fungus Resistance |
| 14.0 | Salt Spray |
| 15.0 | Magnetic Effect |
| 16.0 | Power Input |
| 17.0 | Voltage Spike Conducted |
| 18.0 | Audio frequency Conducted Susceptibility |
| 19.0 | Induced Signal Susceptibility |
| 20.0 | RF Susceptibility |
| 21.0 | Emission of RF Energy |
| 22.0 | Lightning Induced Transient Susceptibility |
| 23.0 | Lightning Direct Effects |
| 24.0 | Icing |
| 25.0 | Electro-Static Discharge |
| 26.0 | Fire, Flammability |
| 27.0 | Smoke Density, Toxicity |

# Test Matrix

✓ = Completed and re



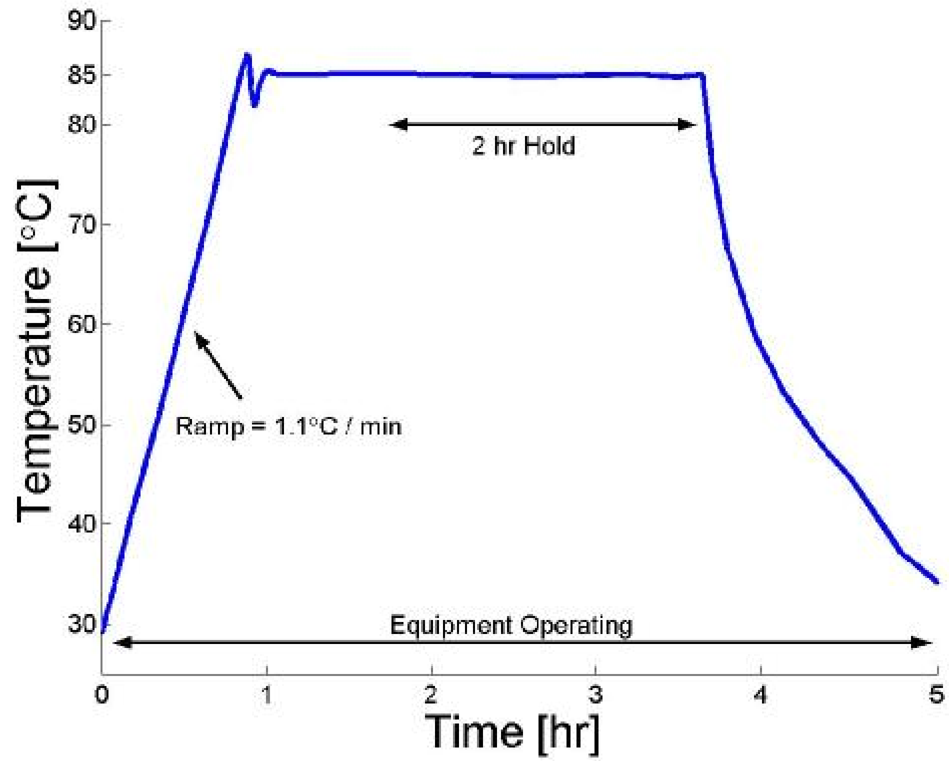

| Test Type | Test Specifics | # of Test Types | Samples/ Test Type | Comments |
|---|---|---|---|---|
| ✓ High Temperature | Ramp to operating high temp. | 1 | 3 | Extreme high operating temp = 85˚C. |
| Low Temperature | Ramp to operating low temp. | 1 | 3 | Extreme low operating temp = -55˚C. |
| Thermal Shock | 10˚C/min. minimum change rate. | 1 | 3 | Ramp between high and low extreme. |
| Humidity | 65˚C and 95%RH. | 1 | 3 | Pure water (no salts). |
| Fluid Susceptibility | Oil based and water based fluids tested. | 2 | 3 | Fuels, oils, hydraulics, etc. |
| Low Pressure | Simulate high altitude. | 1 | 3 | Altitudes = -4,572 m to 21,336 m. |
| EMI | - | - | - | Testing to be done by MDC. |
| ✓ Static Strain | Static mechanical strain. | 1 | 1 | Tensile tests to 0.2% strain. |
| Fatigue | Dynamic mechanical strain. | 1 | 3 | Tailored from ASTM E466-96. |
| Low Velocity Impact | Barley visible damage and visible damage. | 2 | 3 | Impact to produce BVID and VID. |
| Vibration | - | 1 | 3 | Defined by DO-160E §8. |
| **Total** | **-** | **12** | **34** | **-** |

# Temperature - Two Test Types

- High Temperature
  - simulates exposure to extreme elevated temperatures for storage (desert regions) and designed flight conditions
  - extreme temperature defined as 85˚C (185˚F)
  - specimen begins at ambient conditions and continuously operating
  - temperature ramped to elevated temperature and stabilized
  - held for 2 hours before returning to ambient temperature
  - performance of sensors tested after test.
- Low Temperature
  - simulates exposure to reduced temperatures for storage (artic regions) and flight conditions (high cruise).
  - same procedure as high-temperature test
  - extreme defined as -55˚C (-67˚F)

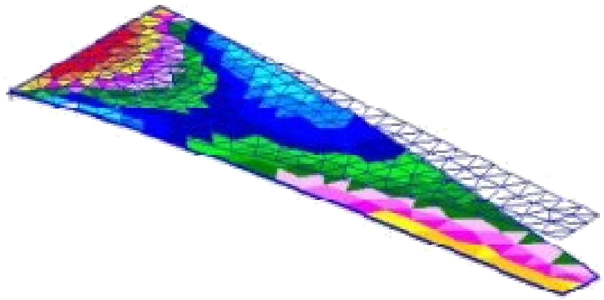
# Experimental Specifics - Temperature

- High-temperature tests
  - specimens placed in oven
  - ramped to operating high temperature
  - stabilization period followed by 2 hour hold
  - operating entire test
  - performance assessed periodically throughout test



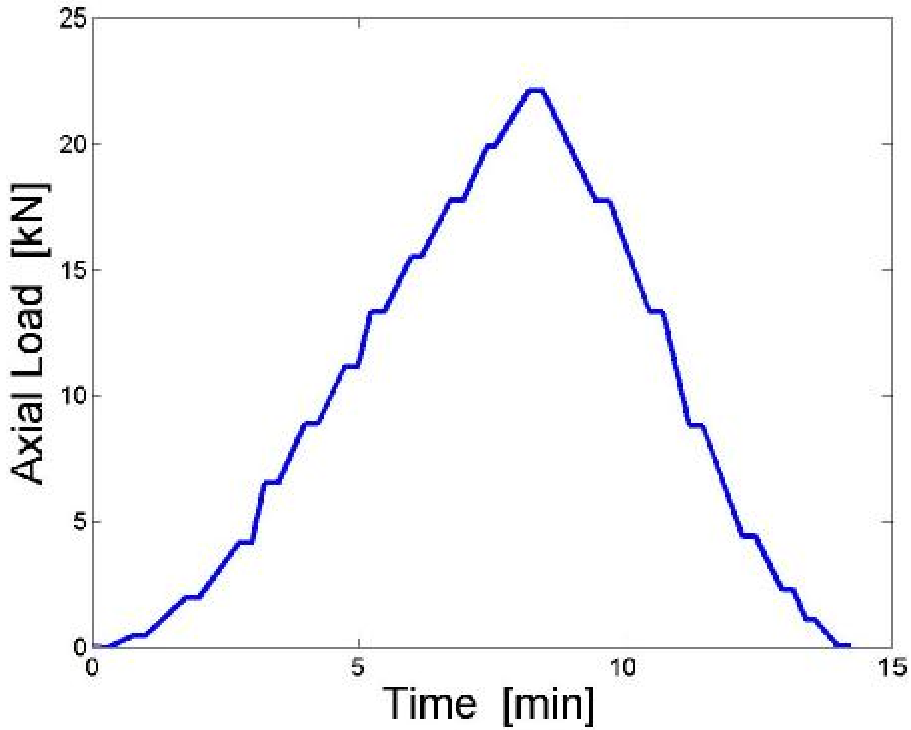
# Static and Fatigue Structural Tests

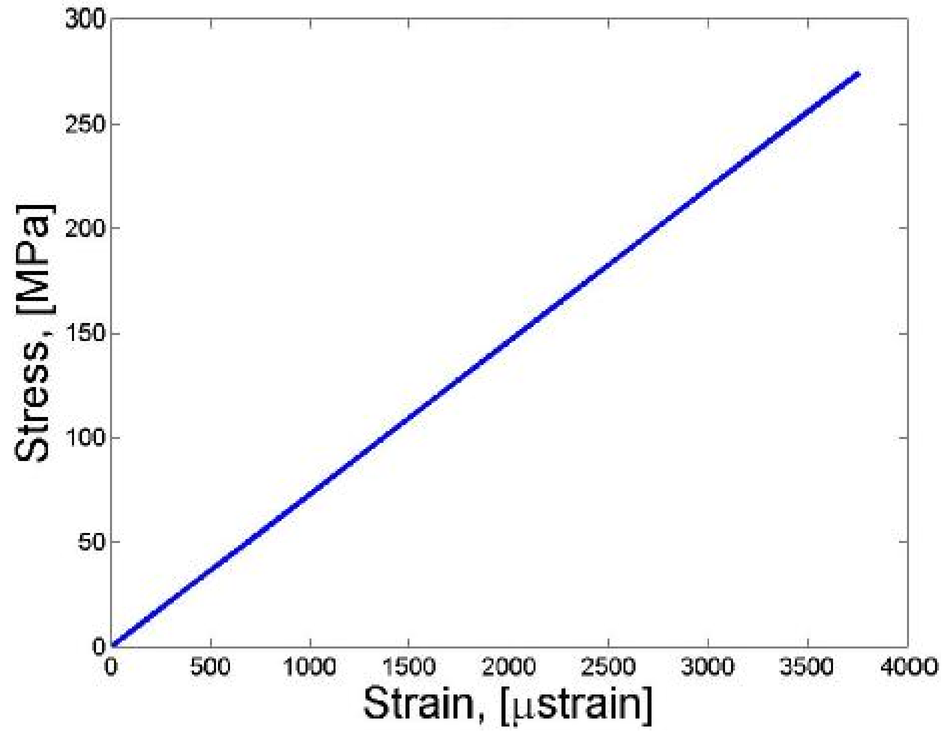
- Static Strain
  - simulates normal strain levels experienced during operation
  - step strain level to tensile yield strain (0.2% offset) testing performance at each step
  - relax strain by stepping down strain and testing performance at each step
- Fatigue
  - simulates the cyclical strains experienced by structural components over the life of an aircraft



# Experimental Specifics – Static Strain Test

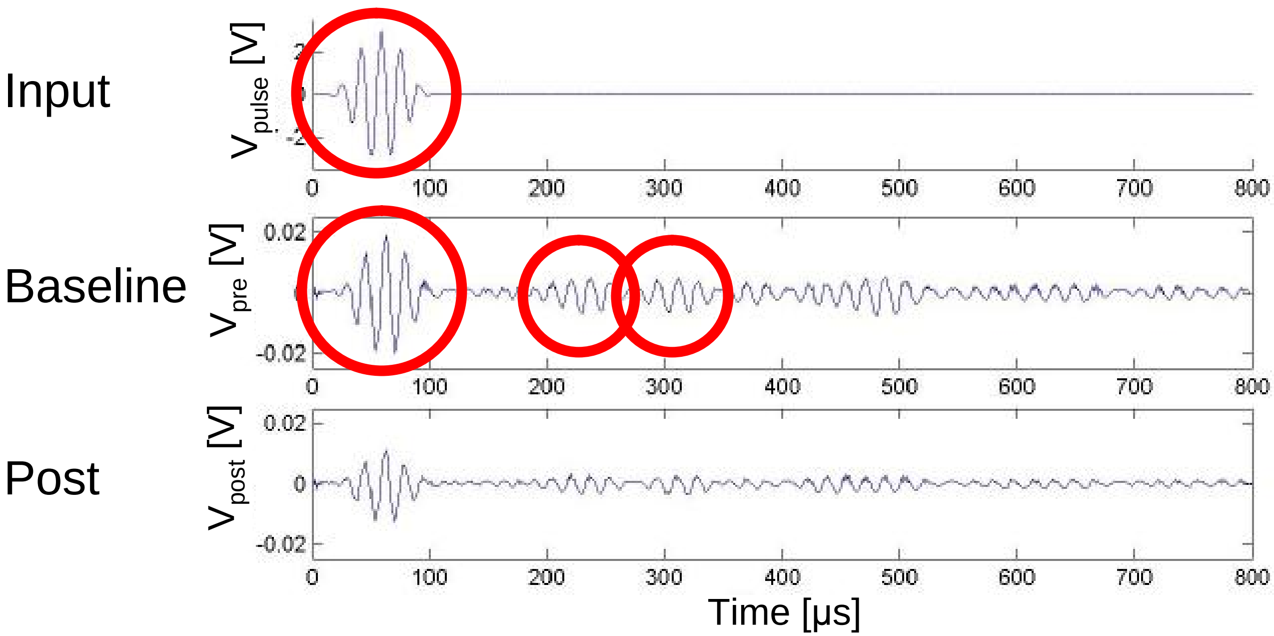
- MTS tensile-compression machine with Instron controller
- displacement controlled test
- loaded near yield strain
- performance assessed at each step

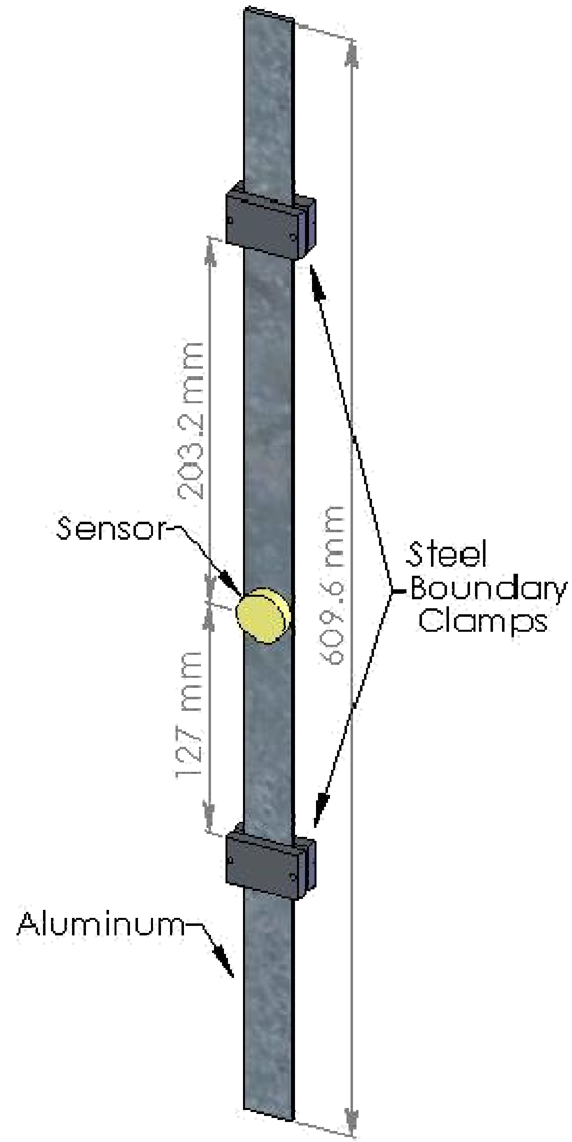


# Performance Criteria to Assess Change in SHM System

- Time-of-flight (TOF)
- Peak Voltage

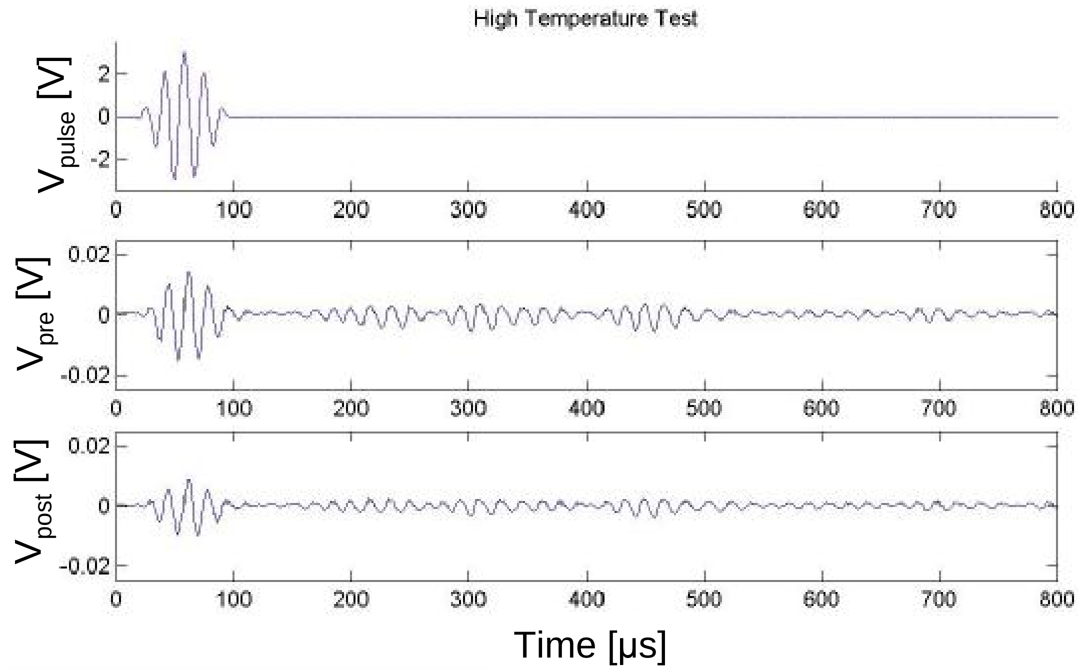


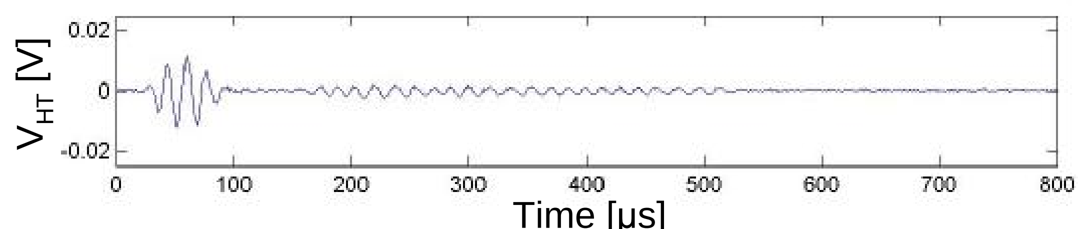

*4 quantitative metrics to assess SHM system change

# Results – High-temperature Testing

- 3 tests conducted
- No visual damage
- -0.5% TOF change
- -14.7% voltage change
- Shear couplant flowed, likely the source of change in voltage.

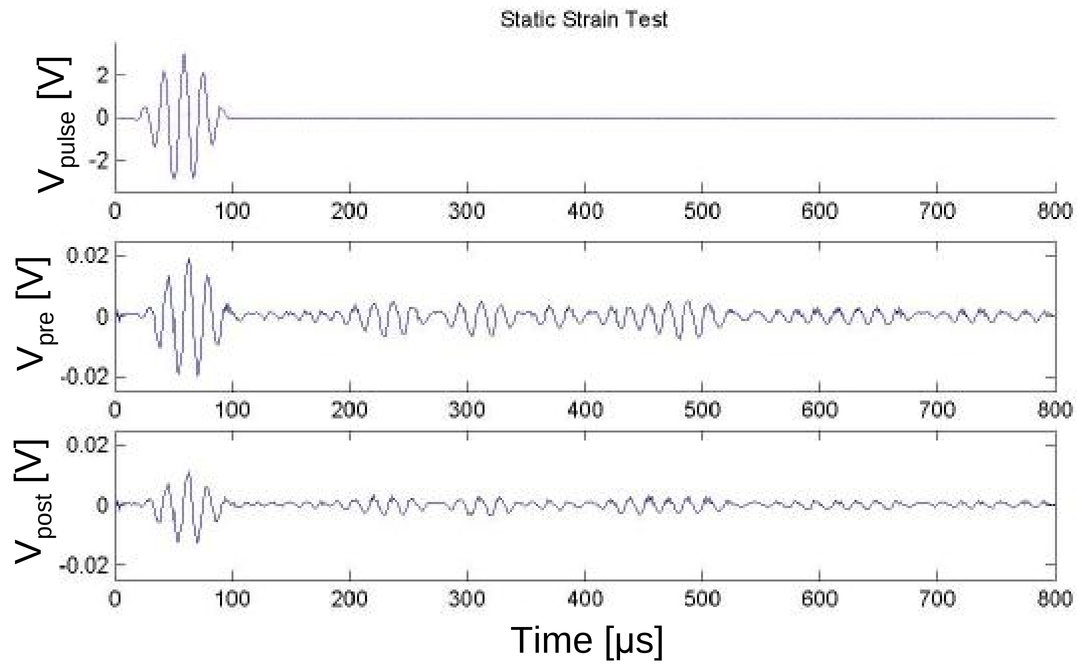



| | TOF | | Peak Voltage | |
|---|---|---|---|---|
| | $1^{st}$ wavepacket | $2^{nd}$ wavepacket | $1^{st}$ wavepacket | $2^{nd}$ wavepacket |
| **Baseline** | 221 μs | 308 μs | 4.620 mV | 3.495 mV |
| **Post-test** | 220 μs | 306 μs | 3.619 mV | 4.027 mV |

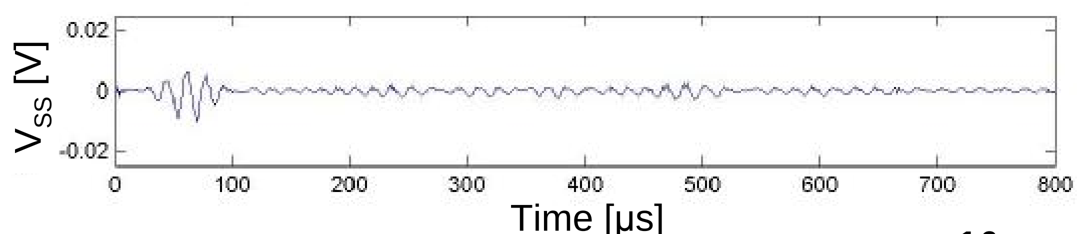


# Results – Static Strain Testing

- 0.5% TOF change
- -46% voltage change
- No visual damage
- Source of large voltage change currently under investigation




| | TOF | | Peak Voltage | |
|---|---|---|---|---|
| | 1st wavepacket | 2nd wavepacket | 1st wavepacket | 2nd wavepacket |
| **Baseline** | 228 μs | 311 μs | 6.635 mV | 6.403 mV |
| **Post-test** | 229 μs | 313 μs | 3.513 mV | 3.541 mV |



# Conclusions and Recommendations

- Current testing and certification standards can serve as foundation for SHM standards
- SHM system tested is affected by thermal and strain excursions
  - Sensors and system survived both excursions
- Difficult to define “system”
- Combined environmental/structural tests
- Contributions from SHM community, government, and commercial and military aircraft manufacturers necessary

# Acknowledgements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