Overview of Structural Health Monitoring

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What is Structural Health Monitoring (SHM)

- SHM is the concept of using the structural response of a system to determine if there is a fault in the structure (ie, loose joint, crack, delamination, etc) *while* the structure is in service.
- It is like non destructive evaluation (NDE) except the measurement and analysis is done while the system is in service with hardware that is integrated into the structure.
- What are the components of an SHM system?
  - A sensor and an actuator (usually piezoelectric) for exciting and the structure and for measuring its response
  - An algorithm (many types) for extracting some sort of damage metric
  - A computing device (microcontroller) for running the algorithm and managing the system
  - A method of broadcasting the results (telemetry)
  - An energy source (battery, energy harvesting or hard wired)

What are the main methods?

- Comparative Methods (base line methods) which compare the response of the system when healthy to the response of the system, any difference indicating damage
  - Vibration based using low frequency vibration signals
  - Lamb wave based using higher frequency wave propagation
  - Impedance based using changes of electrical impedance
  - Acoustic Emission using sound propagated from damage
- No Base Line Methods
  - Acoustic emission
  - A topic of research
  - Using models as the base line

Review of Key Ideas in Structural Health Monitoring (SHM)

- SHM can be split up into passive and active method
  - The main methods are
    - Vibration based which requires low frequency excitations and sensing
    - Impedance based which requires high frequency excitations and self sensing
    - Wave based which requires high frequency excitations and sensing
  - The main passive method is acoustic emission which requires a broad range of frequency sensing.
- These four methods differ in the following ways:
  - Each operates in a different frequency range, hence can discern different sizes of damage
  - Each requires a different circuitry
  - Each uses a different amount of energy

But they can each use the same sensing transducer: MFC

Structural Health Monitoring and Damage Detection Problem Levels

1. Detect the existence of damage
2. Detect existence and locate damage
3. Detect, locate and quantify damage
4. Detect, locate, quantify and predict remaining life (*Damage Prognosis*)
5. Combine Level 4 with smart structures and onboard computing to form intelligent sensors
6. Combine Level 5 with smart structures to form self-healing systems (smart bolt)

There are several methods of using vibration and vibration like data to perform SHM

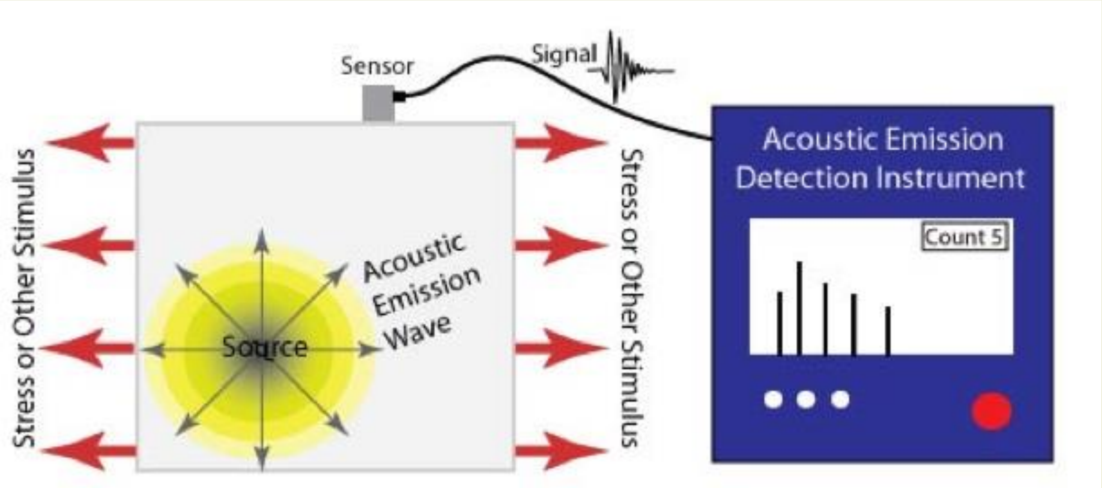
- Since some damage models suggest that mass and stiffness should change when a system is damaged, many methods look for changes in frequency or modal data
- Another approach is to use Lamb waves to “bounce” of off flaws
- Others use
  - Acoustic emission
  - Ultrasonic frequencies

I-95, 1989

I-35 W, 2007

Acoustic Emission Systems

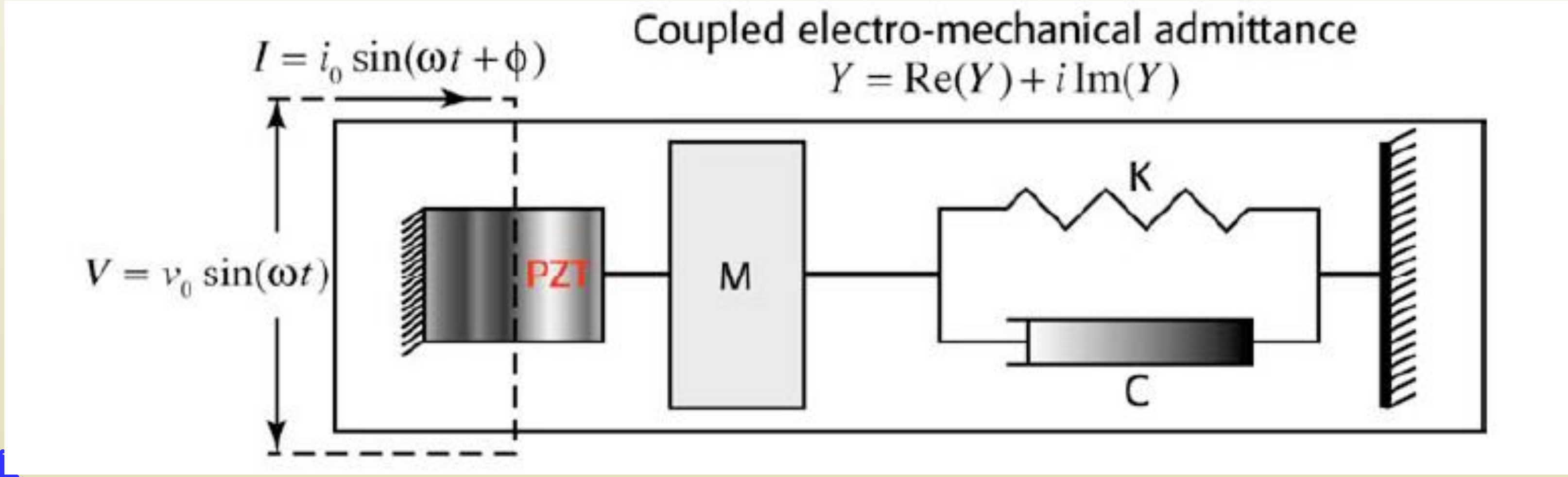
- A passive method based on the fact that the response to an impact an elastic wave results from the induced small displacement.
- Acoustic Emission methods (0 to 100 MHz)
  - Can detect an event by reading the signal from a PZT sensor
  - AE systems can only qualitatively gauge how much damage is contained in a structure
  - Signal discrimination and noise reduction are crucial.



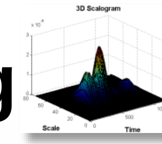
The impedance-based SHM method utilizes piezoelectrics as self-sensing actuators

PZT patches are generally actuated at high frequencies (30 – 400 kHz)

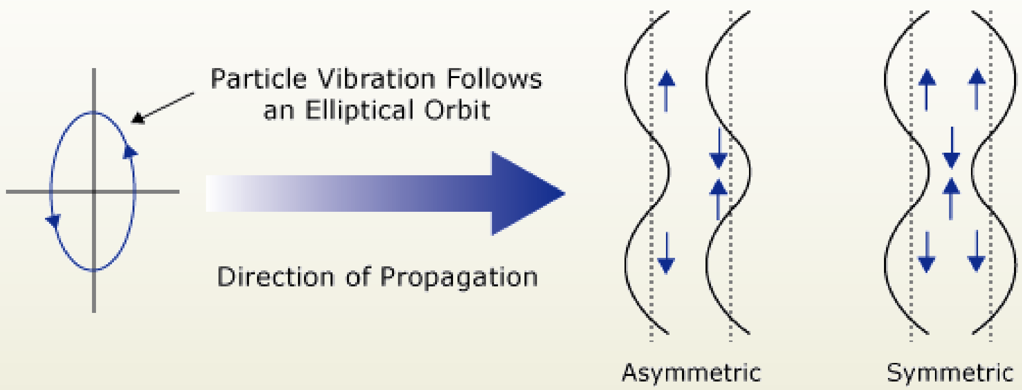
The mechanical impedance of the structure is related to the electrical impedance of the PZT

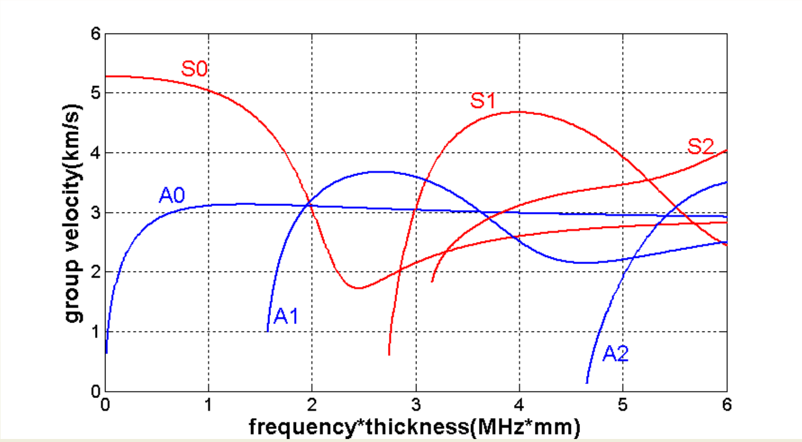


Lamb wave-based Structural Health Monitoring



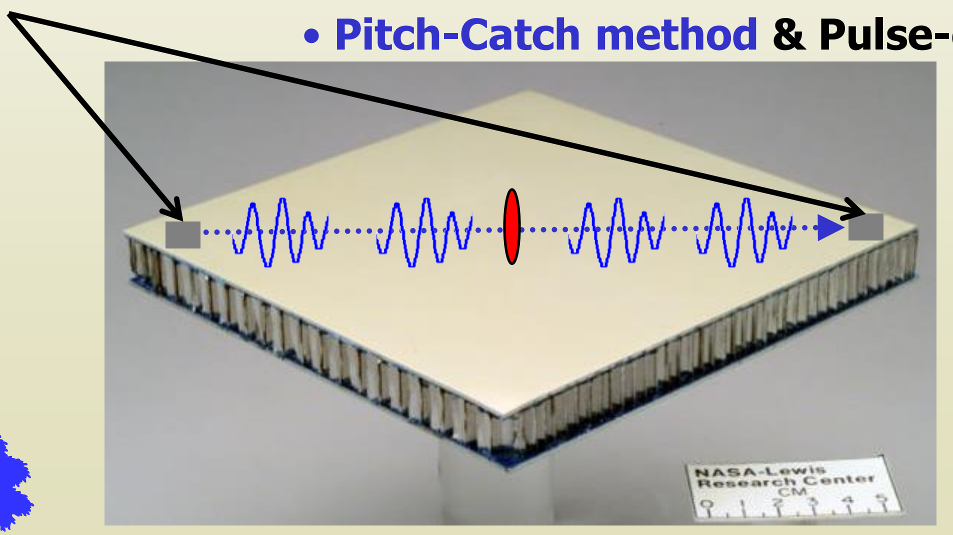
- **Elastic Perturbation that propagates in Plate-type Structures**
- **Two types of Lamb waves - Anti-symmetric (A) and Symmetric (S) Modes**
- **Described via Dispersion Curves: Group (Phase) Velocity vs. Frequency and Thickness**





PZT

- **Pitch-Catch method & Pulse-echo method**



Lamb waves are influenced by defects on the wave path

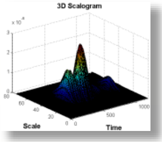
We can then infer damage locality and severity information

Principles of the impedance method are described

- Not model based
- Qualitative approach to damage detection
- Uses small PZTs as co-located actuators and sensors
- Can be remotely controlled and automated
- High frequency excitation provides:
  - Detection of incipient structural faults, such as cracks or loose bolts
  - Localized sensing area
  - Insensitivity to changes in boundary conditions, loading, or operational vibrations
- Low excitation forces produce low power requirements:

1 volt rms, 1 mA, about 10 mW

There are many other good methods in the literature



Impedance and Lamb wave techniques share many similarities

Both can use the same piezoelectric patches

Both operate at high frequencies (>10 kHz), but Lamb wave techniques are more material and dimension dependent

Lamb wave techniques look at a transient response, while the impedance method use steady state results

Impedance in more sensitive to incipient damage, while Lamb waves are more useful for damage location

Lamb waves have difficulty with boundary conditions

The ability to combine this methods on one platform is an enabling advance in SHM

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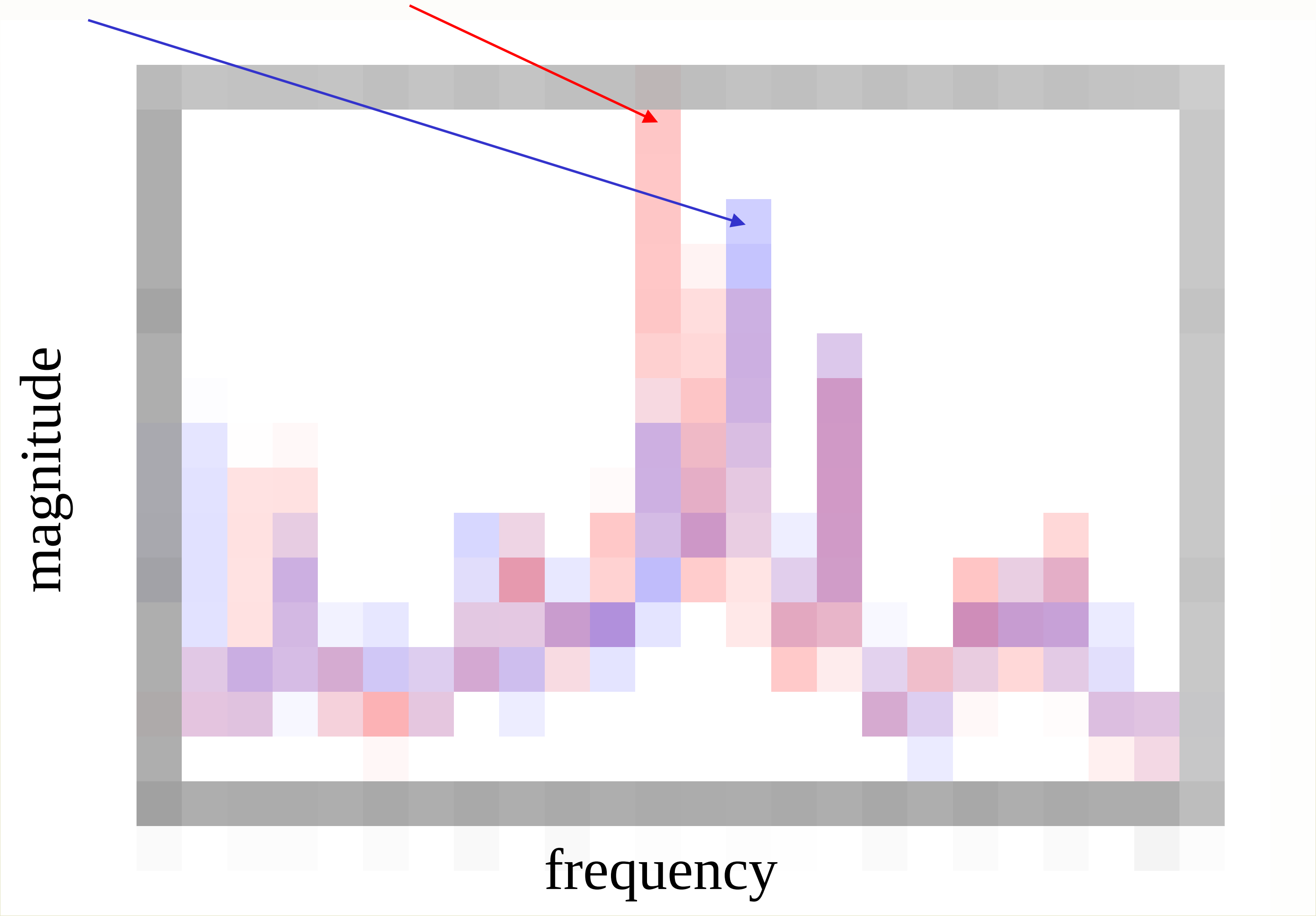
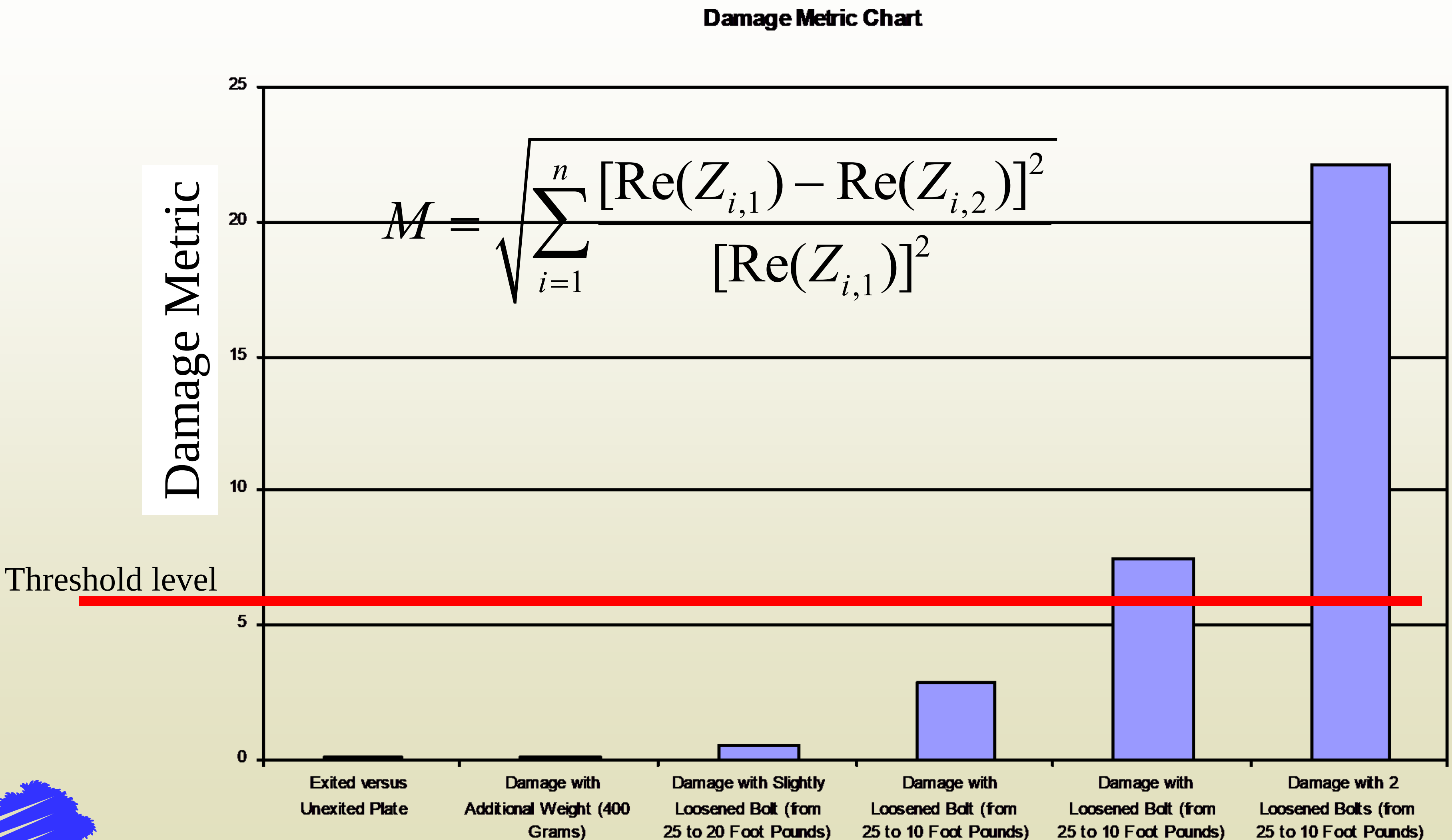
A sample Impedance Signature

undamaged: blue, damaged : red (two bolts loosened to 10 foot pounds)



Damage detection threshold allows automation of method



$$M = \sqrt{\sum_{i=1}^{n} \frac{[\mathrm{Re}(Z_{i,1}) - \mathrm{Re}(Z_{i,2})]^2}{[\mathrm{Re}(Z_{i,1})]^2}}$$

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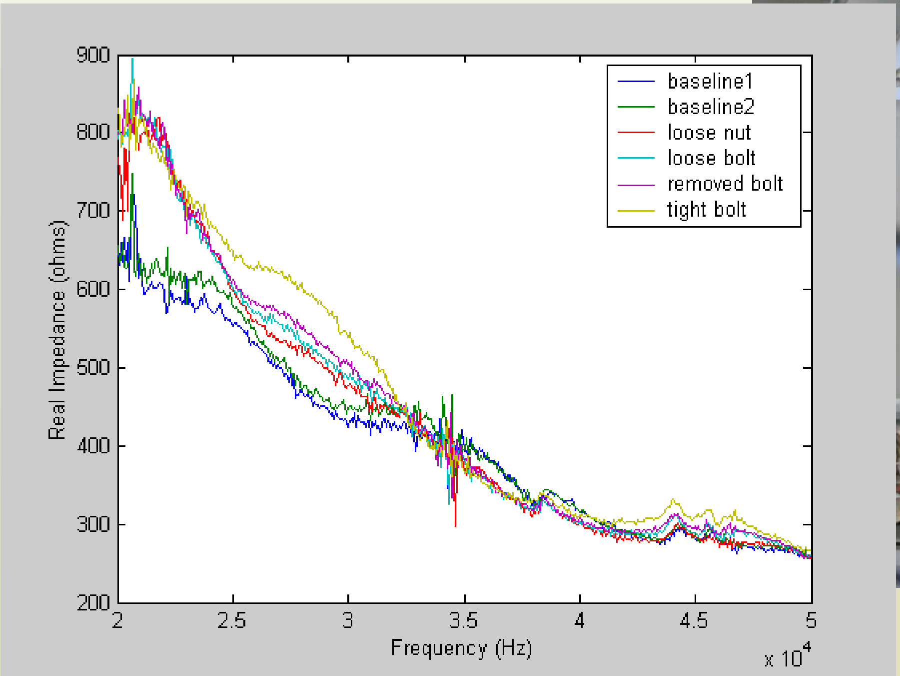
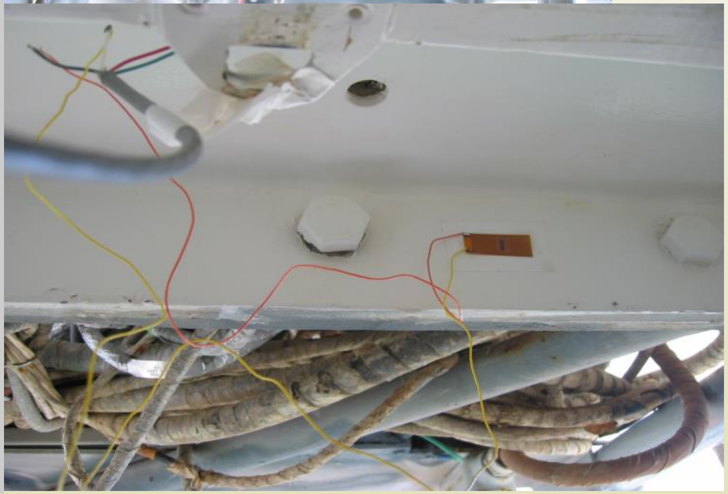
Application to NASA Kennedy Launch Facilities

- Several NASA support structures are past their design life
- Many have bolted joints which should be monitored

White Room Bolted Joint Testing

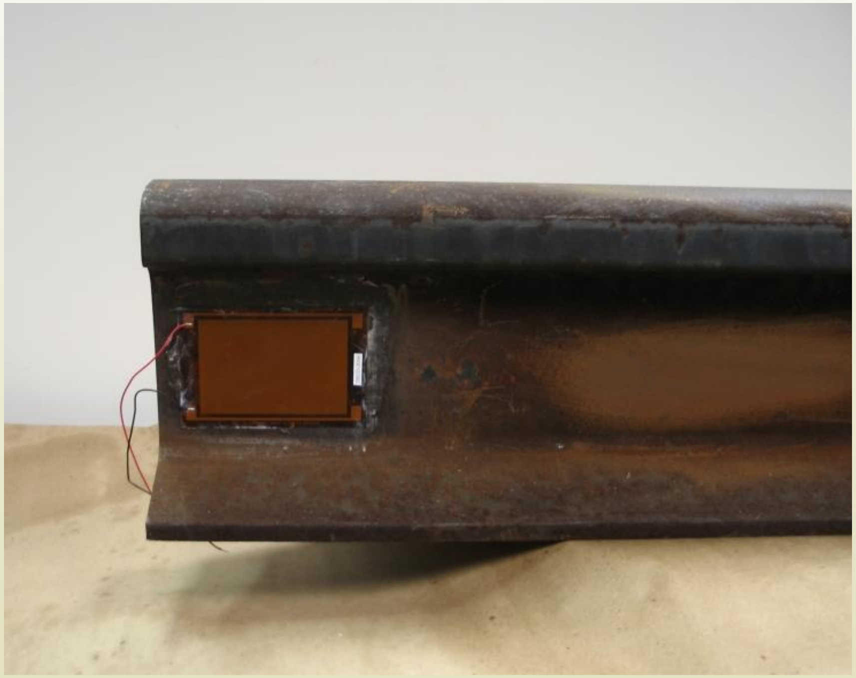
- Monitor Bolted connection of “white room” to launch pad structure for increased astronaut safety





Sample applications to rail systems

Rail Crack SHM



Switch point SHM

System Implementation

- TI MSP430 low-power microcontroller evaluation board
- Radio transceiver at 2.4GHz with 250kbps data rate
- 170 mAh Polymer Li-Ion battery
- Total size: 4.5 cm × 7 cm × 3 cm (not including MFC)