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Federal Aviation Administration

Task 228: Magneto-Elastic Sensing for Structural Health Monitoring

Andrei Zagrai and Warren Ostergren

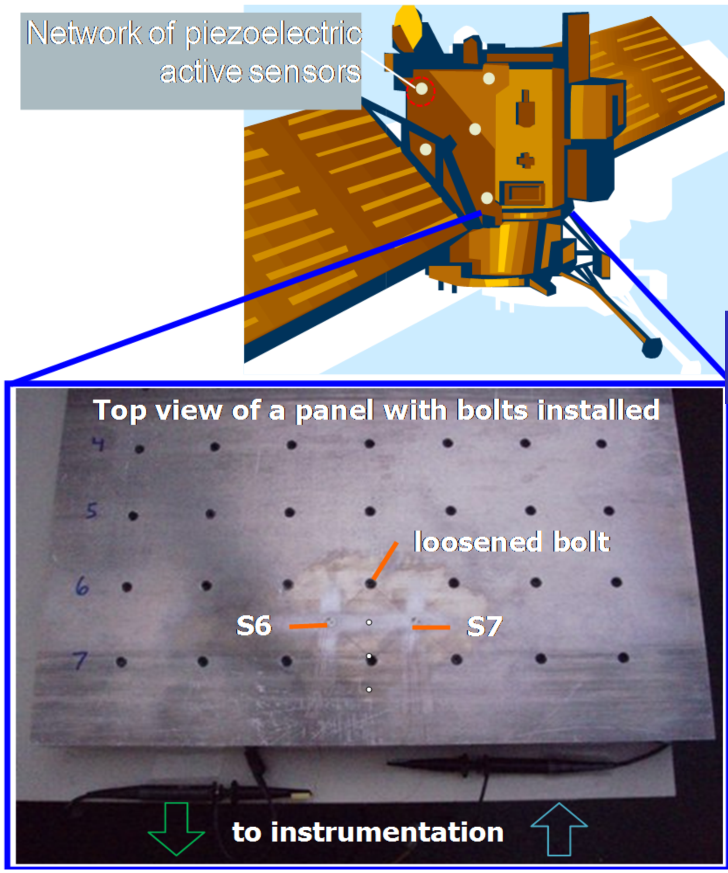
November 10, 2011

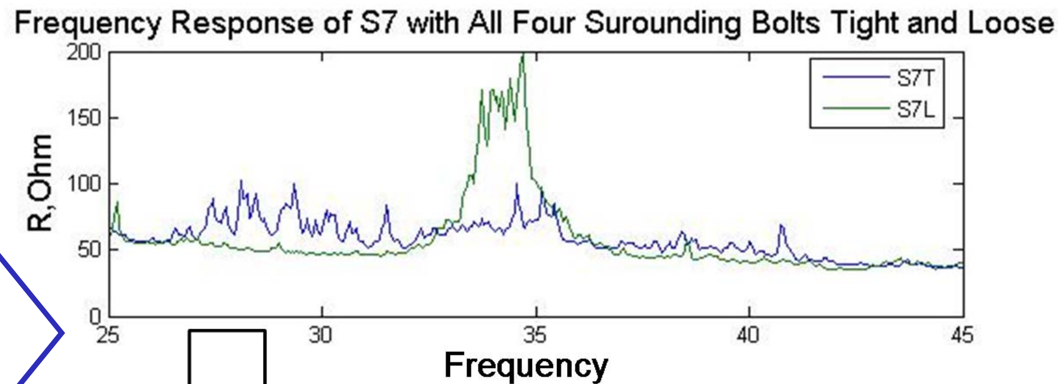
CST

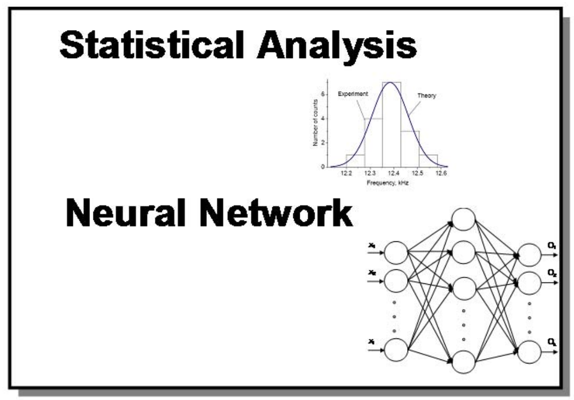
Overview

- Structural Health Monitoring (SHM) of Space Vehicles
- Motivation, needs and objectives
- Research team
- Tasks progress
- Schedule & Milestones
- Next Steps
- Contact Information

Structural Health Monitoring

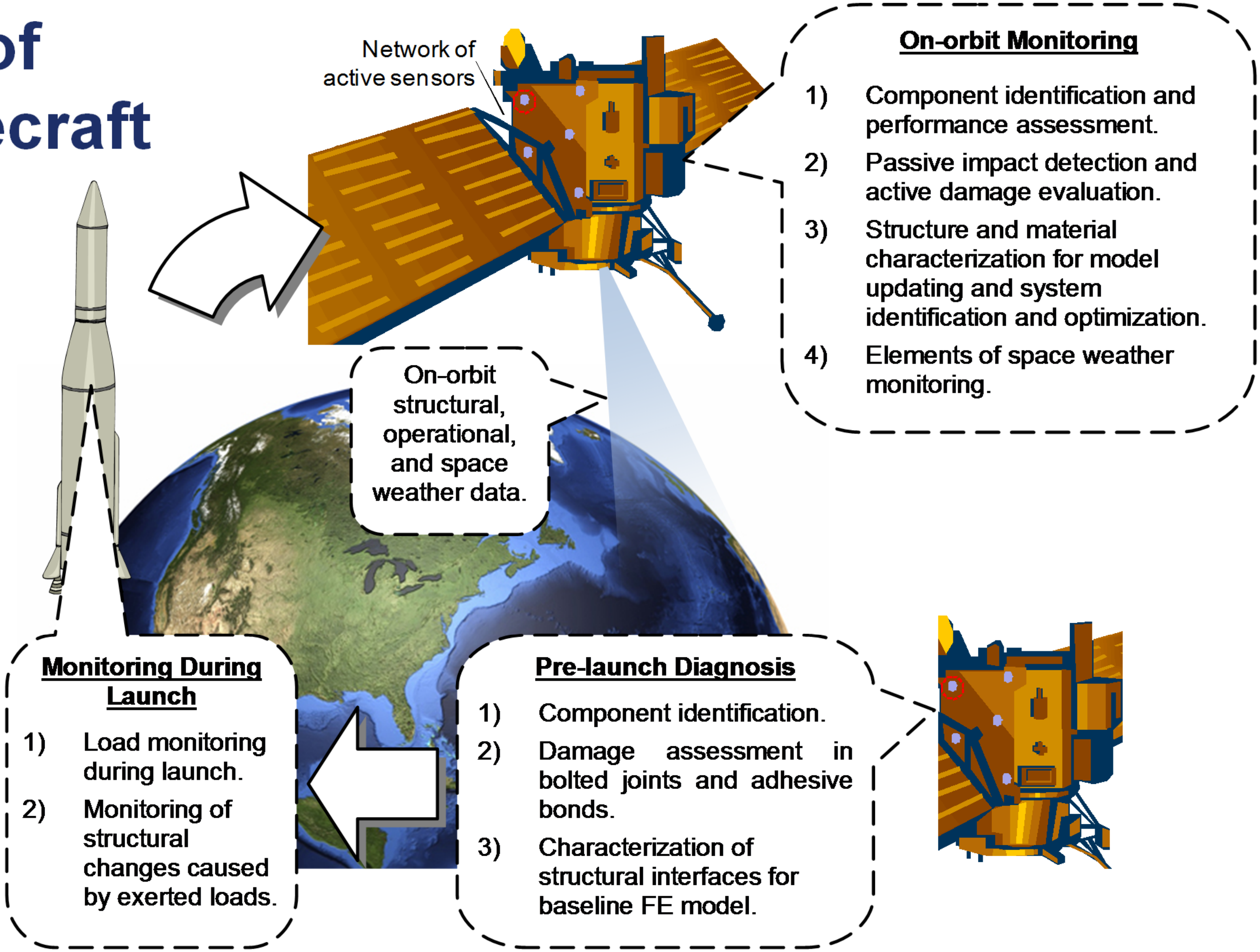




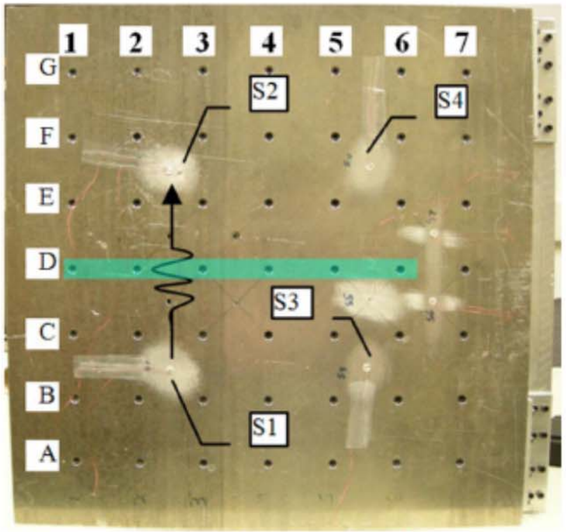


Damage
Detection
and
Classification
Results

SHM of Spacecraft



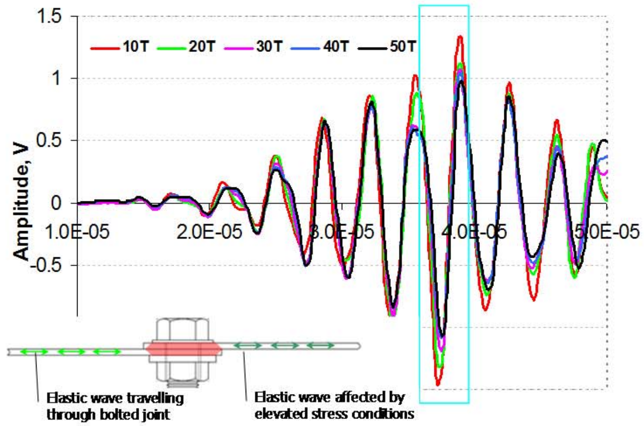
Example: Monitoring of Bolted Joints

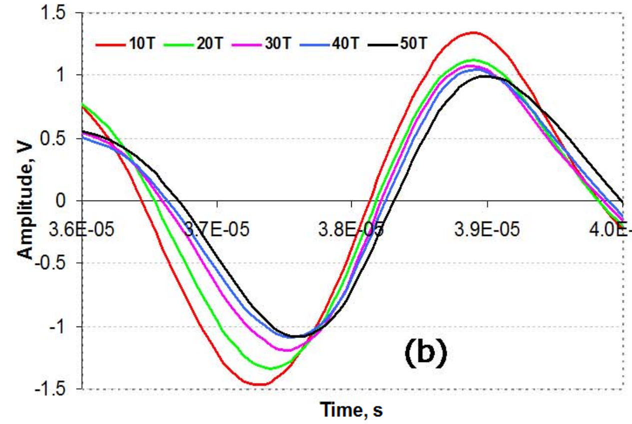


Sound speed Stress

$$\rho c_{l\perp}^2 = \left(K+\frac{4\mu}{3}\right)+\frac{\sigma}{3K}\left(4K-\frac{8\mu}{3}+\frac{2(K-2\mu/3)^2}{\mu}+\frac{K-2\mu/3}{\mu}\cdot A+\frac{2(K+5\mu/3)}{\mu}\cdot B-2C\right)$$

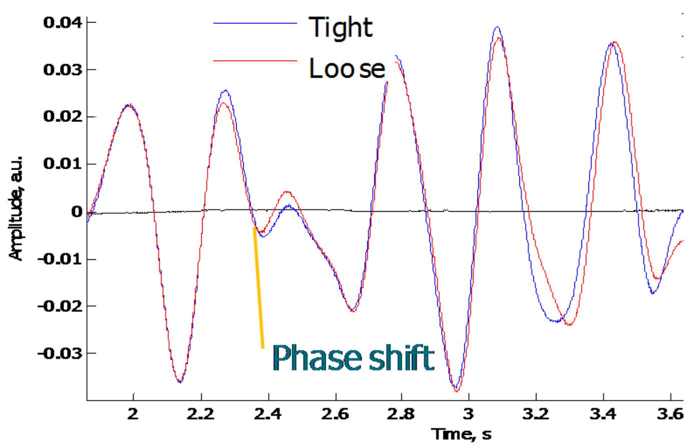
Linear parameters (bulk and shear moduli) Non-linear parameters

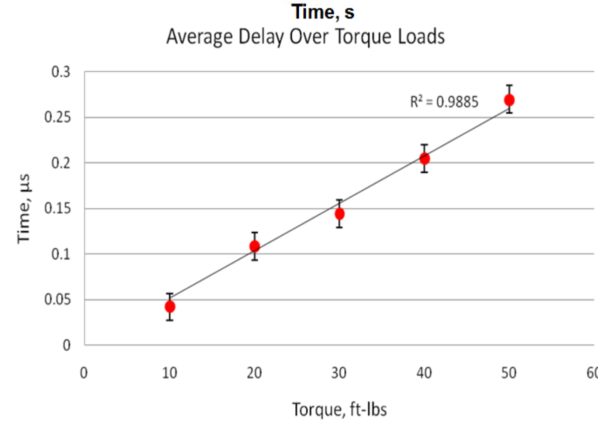




Key Issues:

- Structural complexity
- Many interfaces
- Classification of nonlinear source

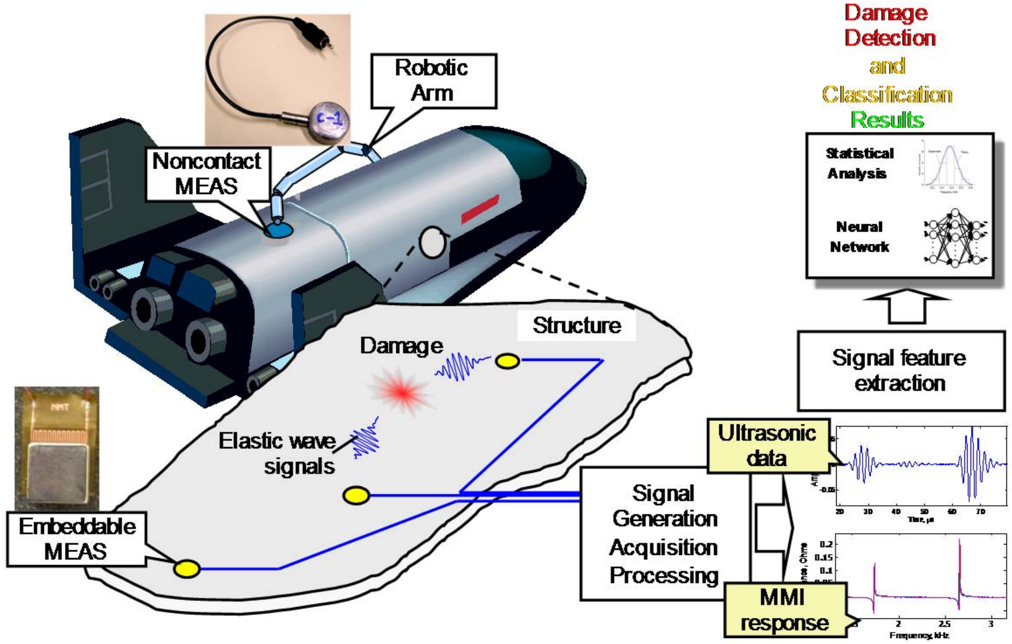


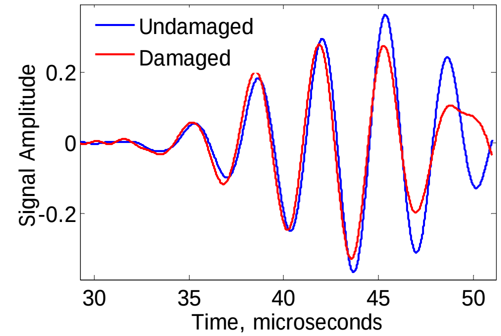


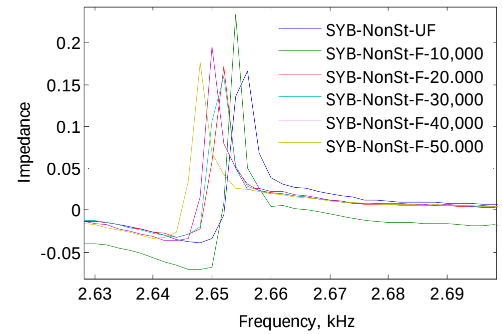
SHM Tasks for Space Vehicles

- Rapid assembly and launch
  - Validating the condition of stored (in a warehouse) structural elements
  - Facilitating rapid assembly of spaceship components,
  - Insuring that no structural damage occurred during spaceship assembly and handling
  - Minimizing or eliminating pre-flight tests, e.g. thermavac, vibration
  - Model update using SHM data
  - Monitoring during transport
- Monitoring system condition and dynamics during launch,
- In-orbit / mission monitoring
  - Component deployment and wakeup
  - Mission parameters and associated loads
  - Assessing in-service variation of structural properties suitable for model updating and in-orbit system optimization.
  - Micro-meteorite / debris impact detection and characterization
  - Electrical signature, electronics, space weather – indirectly.

SHM Tasks for Reusable Spacecraft







- Re-entry
  - Structural integrity and material deterioration
  - Breakup (if any)
  - Components deployment

BLACK BOX FOR SPACECRAFT !

Re-launch

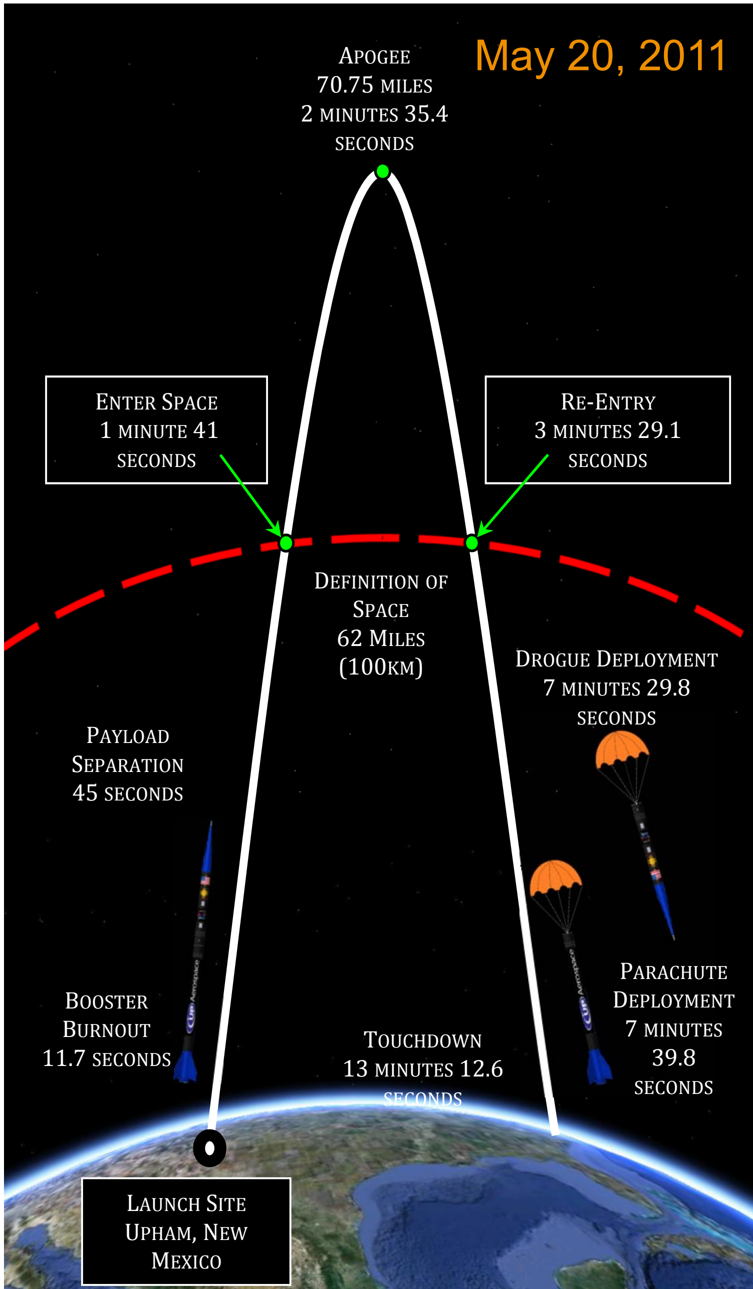
- Fatigue data from previous mission
- Assisting in re-qualification pre-launch tests.
- Spacecraft degradation model update. GO/NO-GO?

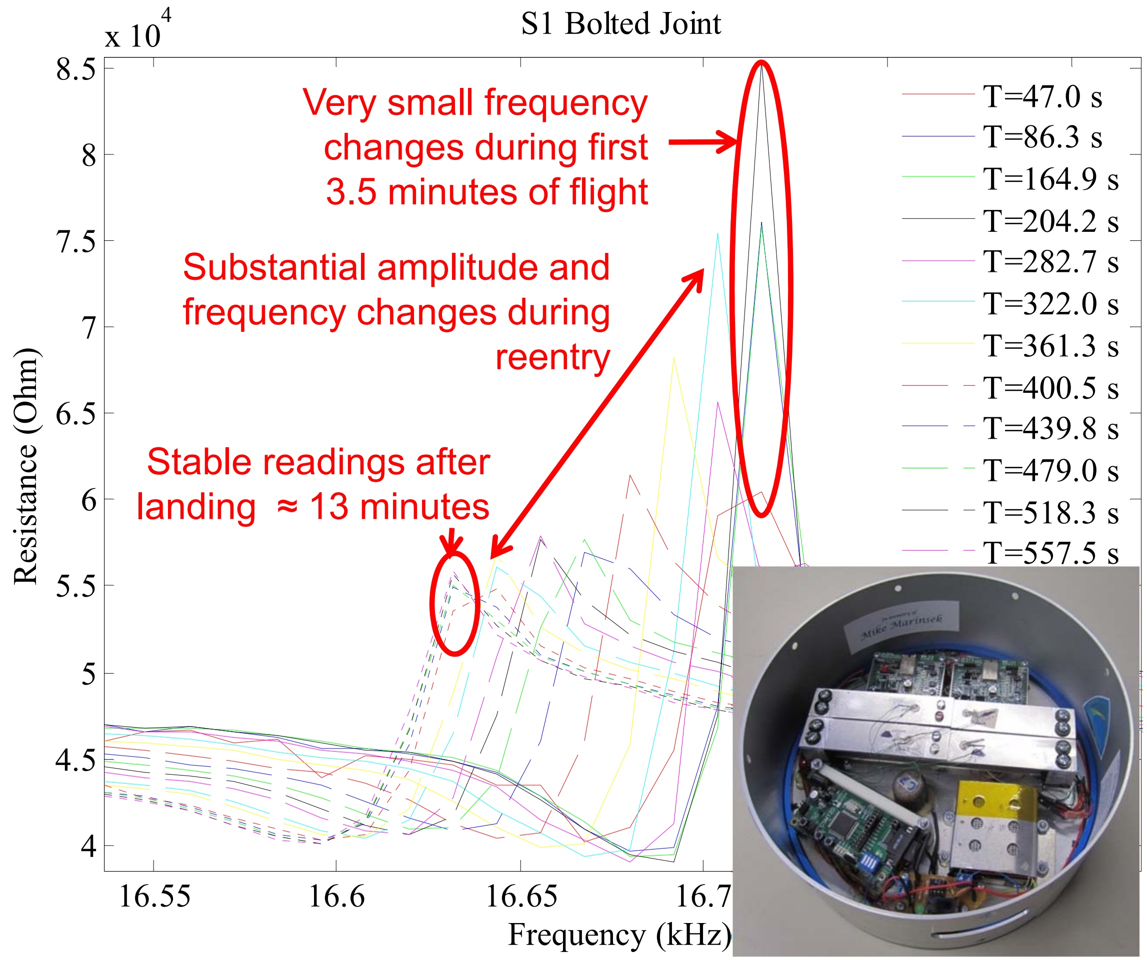
NMT Current Space Activities ME&EE

PRACTICAL TESTS AND HARDWARE

- Validation of SHM on AFRL's PnP Sat, 2009
- SL5 suborbital 2011
- Swiss PnP Sat Langmiur probe mech. design (scheduled for launch later this 2011 year)
- ELANA New Mexico Sat (NASA)
- Nano-sat program/competition: Boston Univ. Sat
- New Mexico Tech Sat (NASA EPSCoR)
- SL7 suborbital 2013

SHM During Suborbital Flight of Spaceloft Rocket

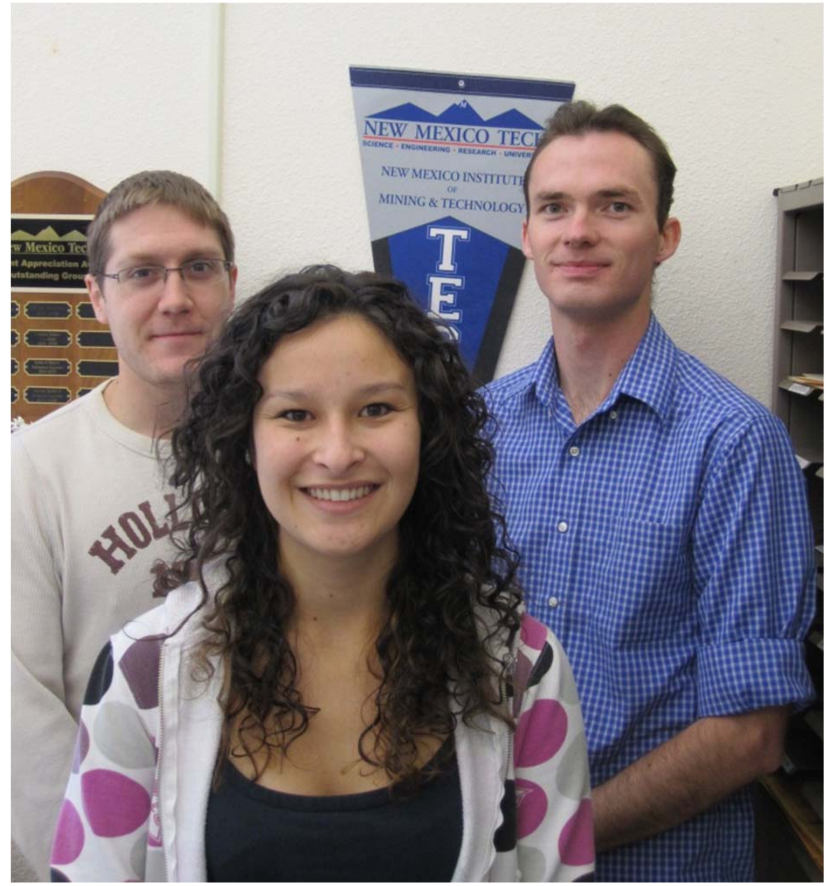




Needs

- Reliable multi-purpose sensing technology with
- Very robust durable sensors that would have long lifespan in space environment and can:
- Detect and characterize impact damage from space debris
- Assess structural integrity of a spacecraft
- Provide information on structural interfaces
- Explore spacecraft electrical signature
- Enable reusable component requalification for flight
- Possibly conduct non-contact inspection in space.

Team Members



Task 228 NMT Team

- Jaclene Gutierrez (UG ME)
- Daniel Meisner (GR ME)
- David Conrad (GR ME)
- Andrei Zagrai
- Warren Ostergren

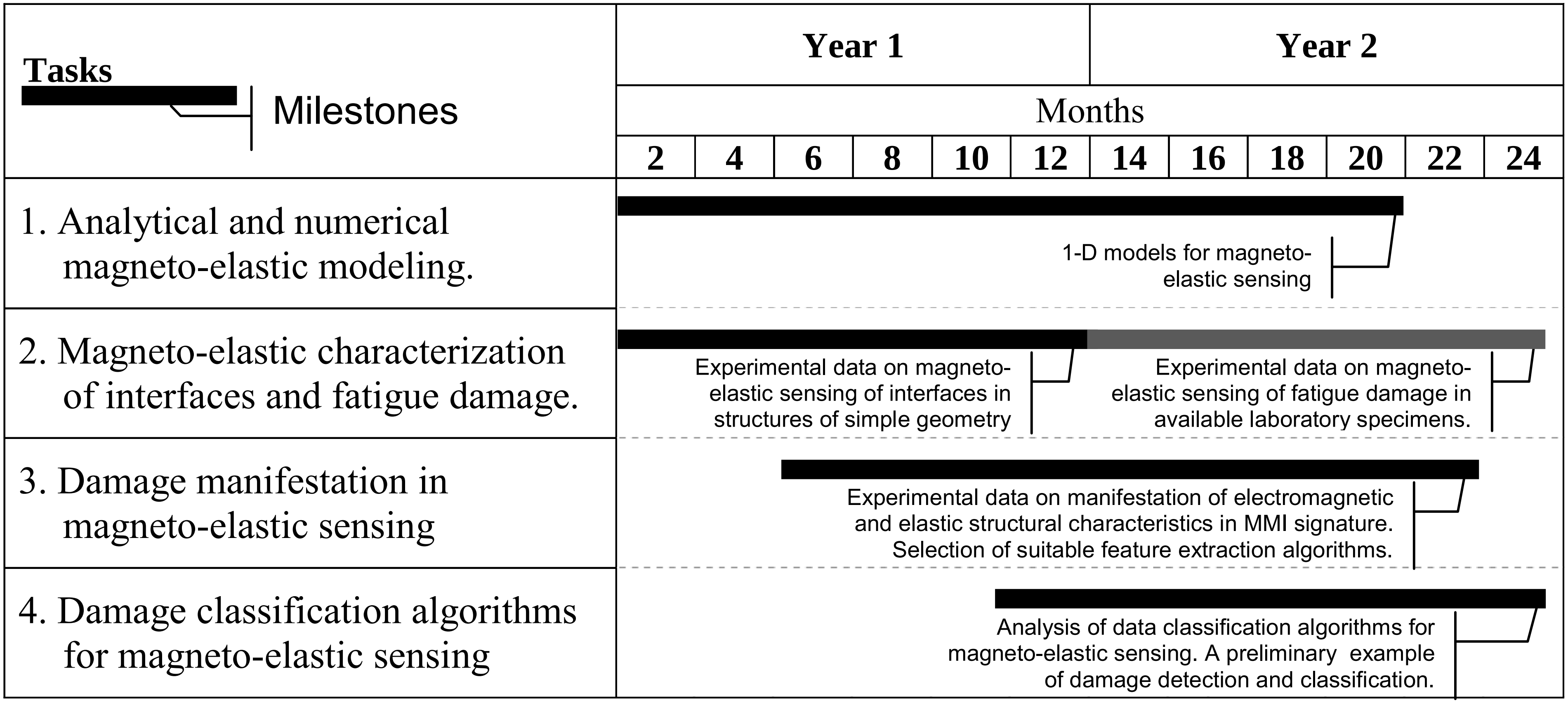
Collaborators

- Igor Sevostianov (MAE NMSU)
- Whitney Reynolds (AFRL Space Vehicles)

Purpose and Objectives

- The objective of the proposed project is to develop innovative magneto-elastic sensing technologies for structural diagnosis of space vehicles.
- In achieving this objective, the investigation team conducts both theoretical and experimental research on the physical mechanism of sensing, its practical realization in the engineering system, information inference from the magneto-elastic response and automatic data classification / decision support.
- A separate objective of this research is educating young aerospace professionals at the undergraduate and graduate levels as well as broadening participation of minority groups such as students with disabilities and Hispanics.

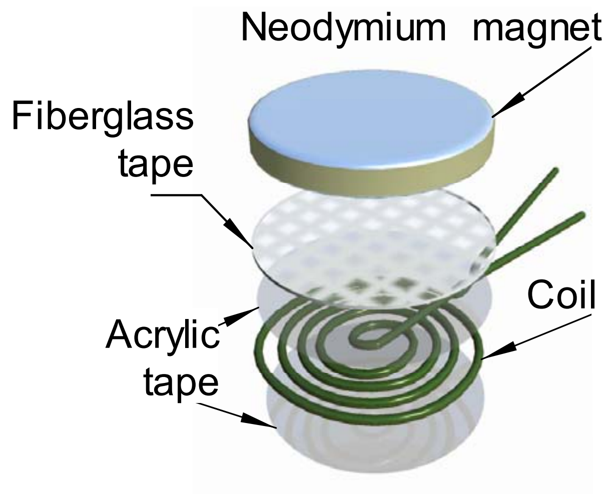
Schedule/Milestones

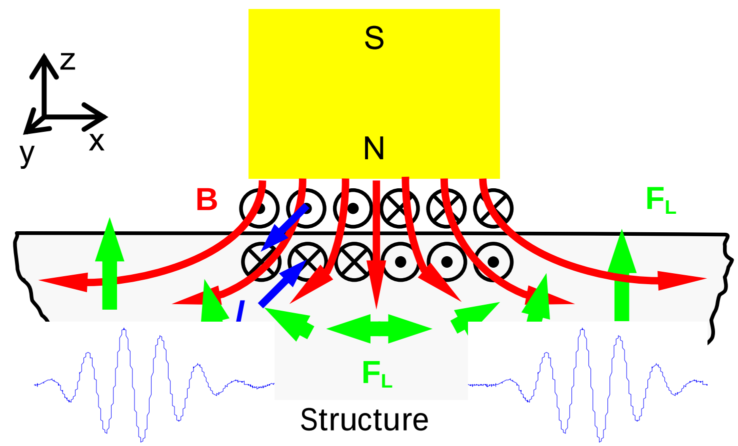


Presentation and a full paper in Proceedings of ASME 2011 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, September 2011:
Conrad, D. and Zagrai, A. (2011) "Active Detection of Structural Damage in Aluminum Alloy Using Magneto-Elastic Active Sensors (MEAS)," SMASIS2011-5219.

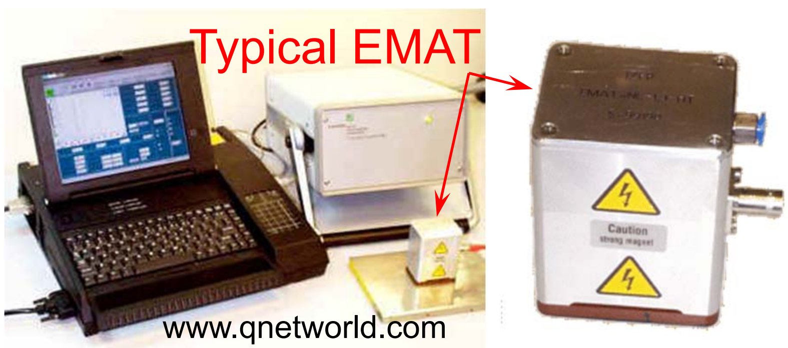
Magneto-elastic Active Sensors (MEAS)

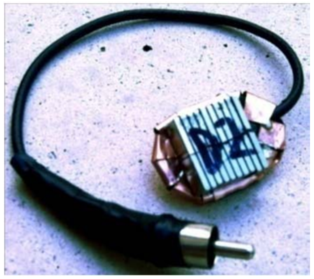
Capable of NON-CONTACT excitation INSIDE material - NO COUPLING MEDIUM NEEDED





Electric current passing through the coil induces eddy currents in the structure. The eddy currents interact with the applied static magnetic field, resulting in Lorentz forces, responsible for generating elastic waves.

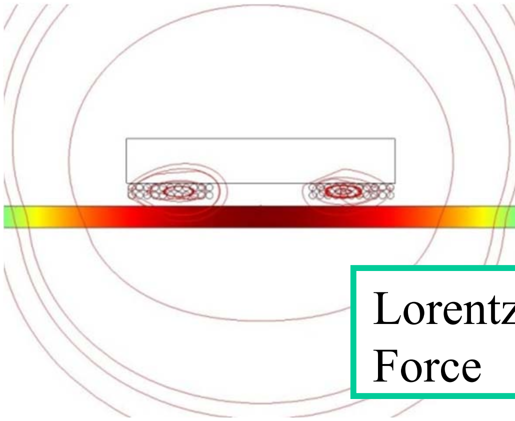


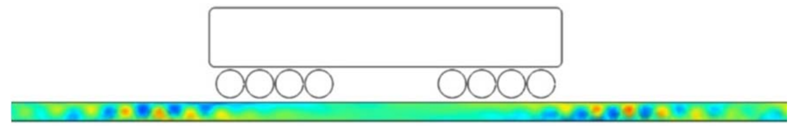


MEAS Damage Detection Methodologies

MEAS Electromagnetic Response

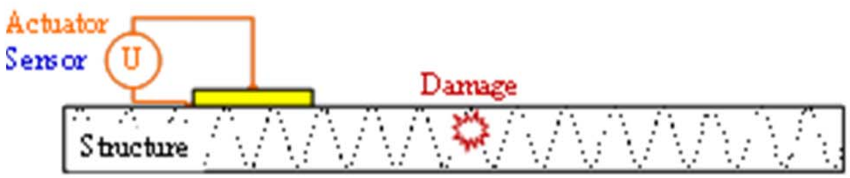
MEAS Mechanical Response

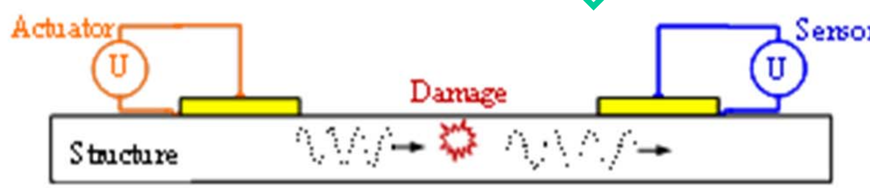




Lorentz Force

Elastic Wave

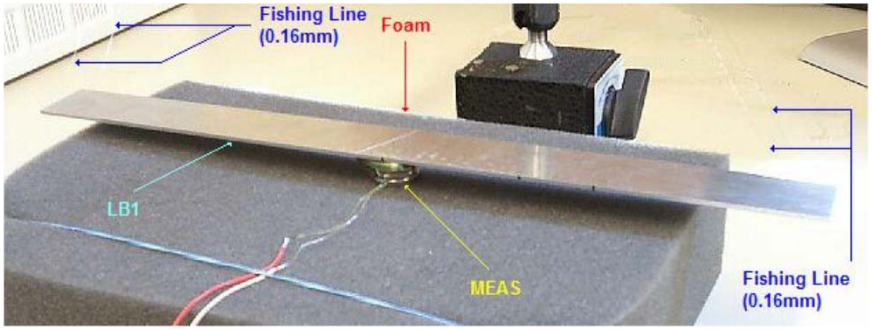




Continuous Wave – Magneto-mechanical impedance (MMI)

Pulse Wave – Pitch-catch ultrasonics

Task 1: MEAS SHM Theory



$$\rho A \cdot \frac{\partial^2 w(x,t)}{\partial t^2} + EI \cdot \frac{\partial^4 w(x,t)}{\partial x^4} = F_L(x,t)$$

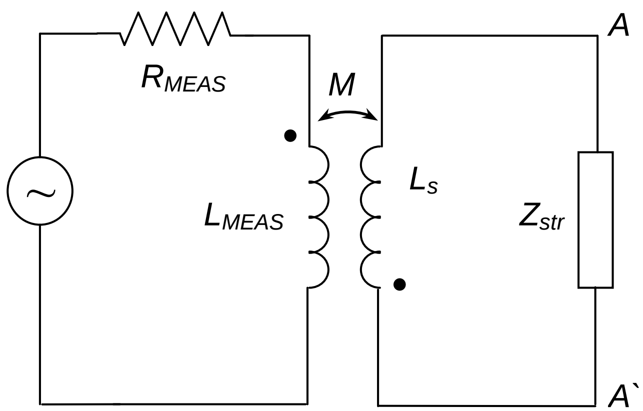
Lorentz excitation force

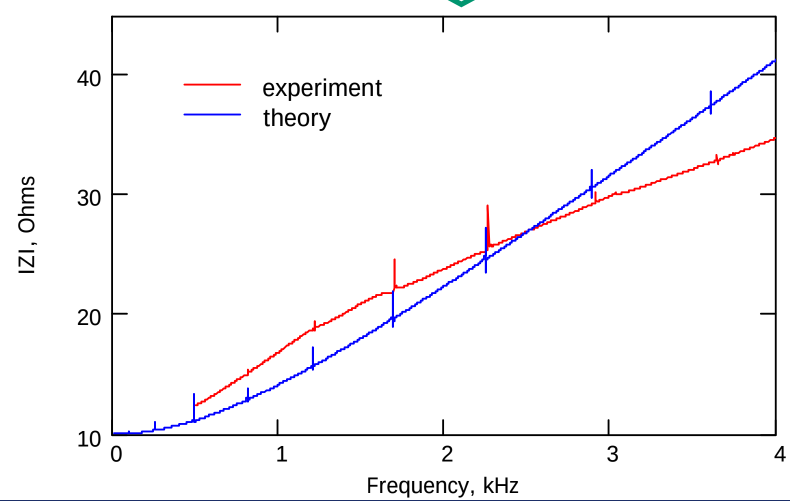
$$F_L(x,t) = I \cdot B \cdot b_a \cdot \delta(x - x_a) \cdot e^{i\omega t}$$

$$Z_{str}(\omega) = \sum_{n=0}^{\infty} \frac{i\omega \cdot (W_n(x_a) \cdot b_a \cdot B)^2}{\rho A \cdot \left(\omega_n^2 + 2i\varsigma_n \omega \omega_n - \omega^2\right)}$$

$$Z(\omega) = R_{MEAS} + i\omega L_{MEAS} + \frac{\omega^2 L_{MEAS} L_S \cdot k_C^2}{i\omega L_S + R_S + Z_{str}(\omega)}$$

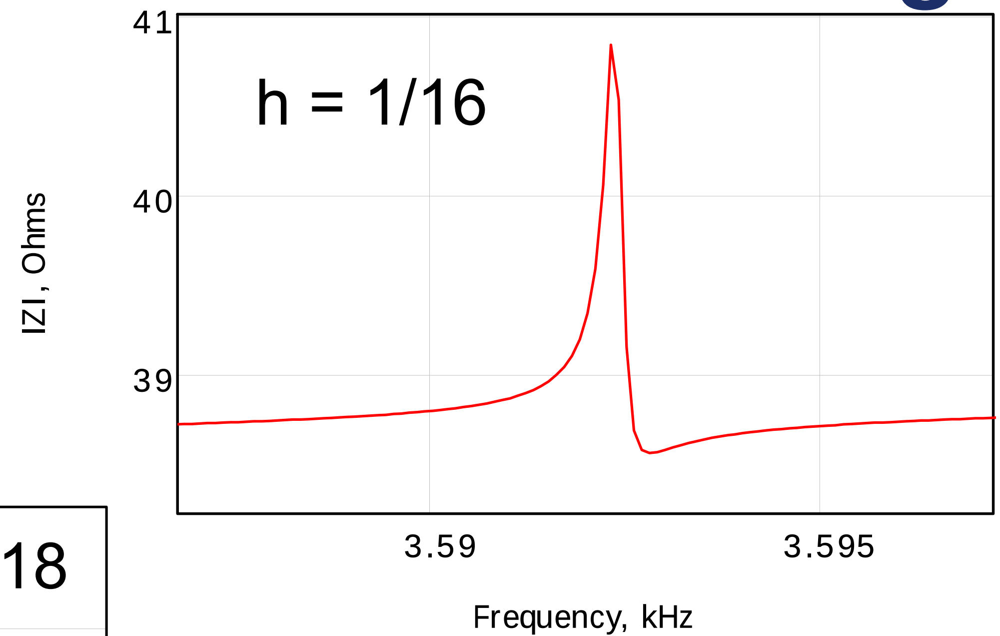
Electro-magnetic interaction between MEAS and structure is represented as a transformer

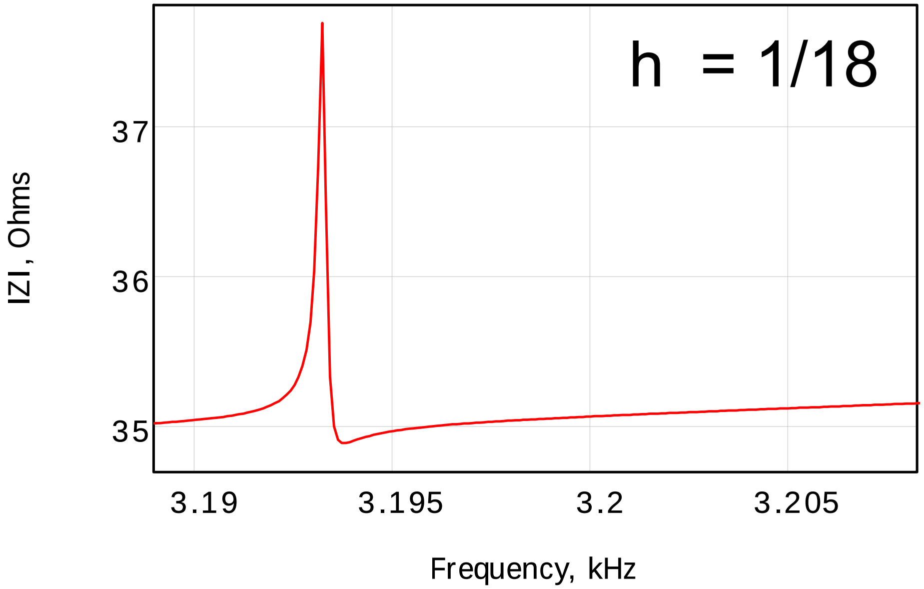




Mechanical Manifestation of Damage

Damage was imitated by considering reduction of specimen thickness from h1 = 1/16 in to h2 = 1/18 in.

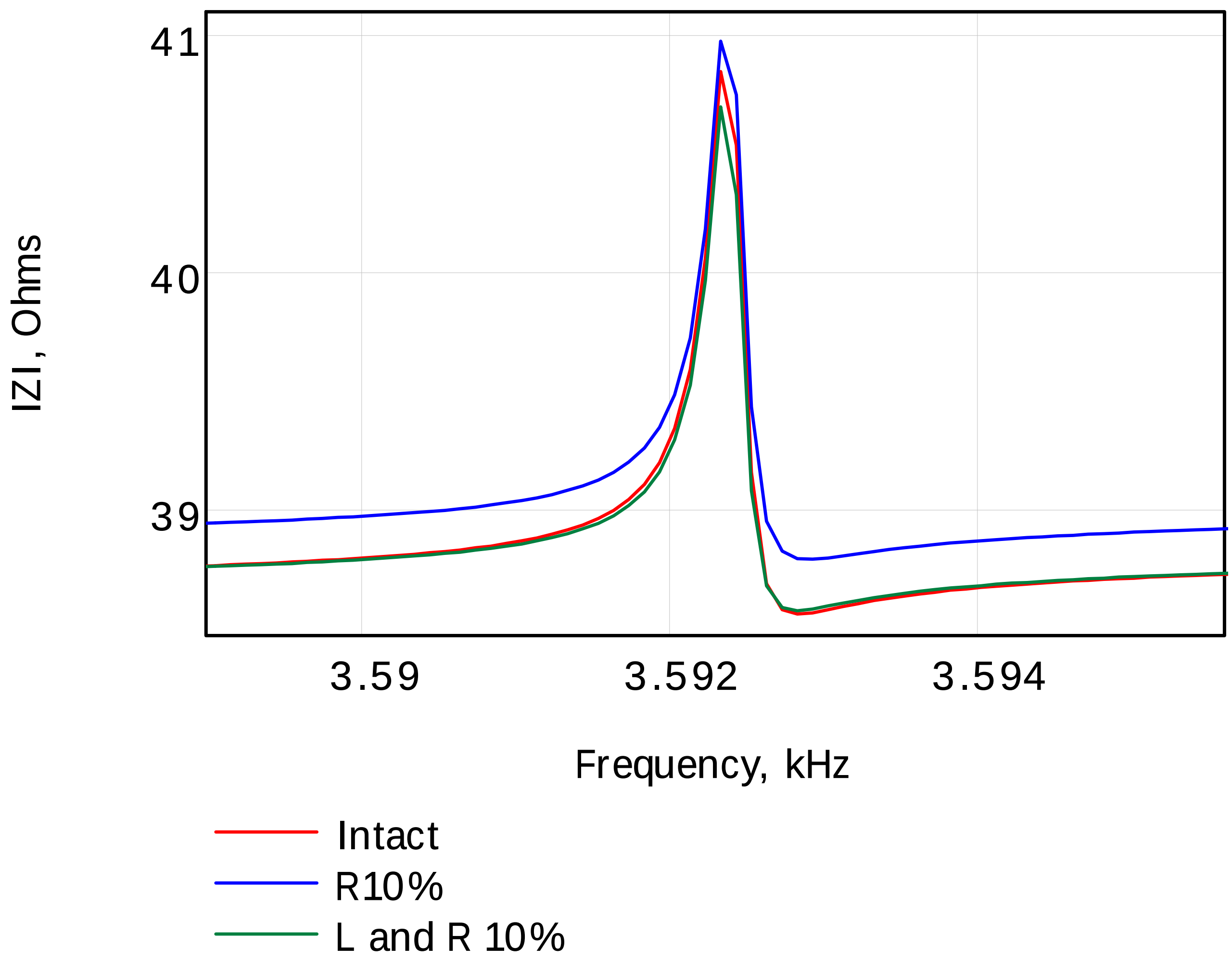




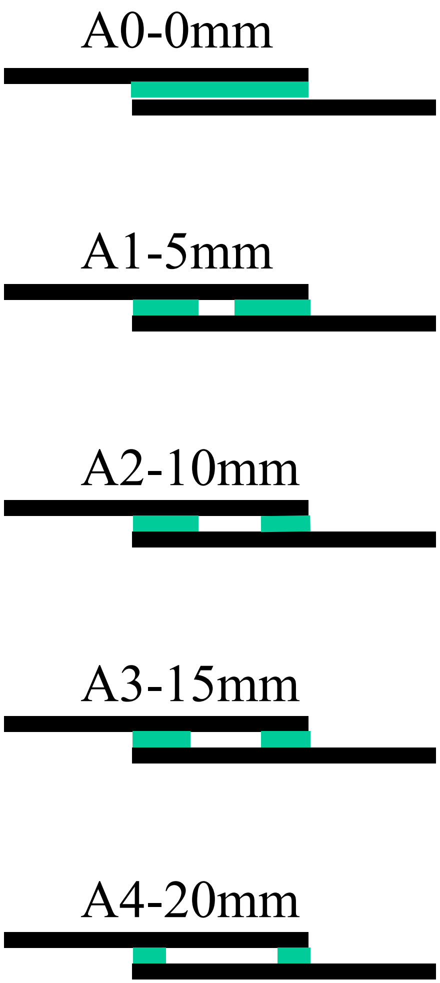
Due to reduction of specimen thickness:

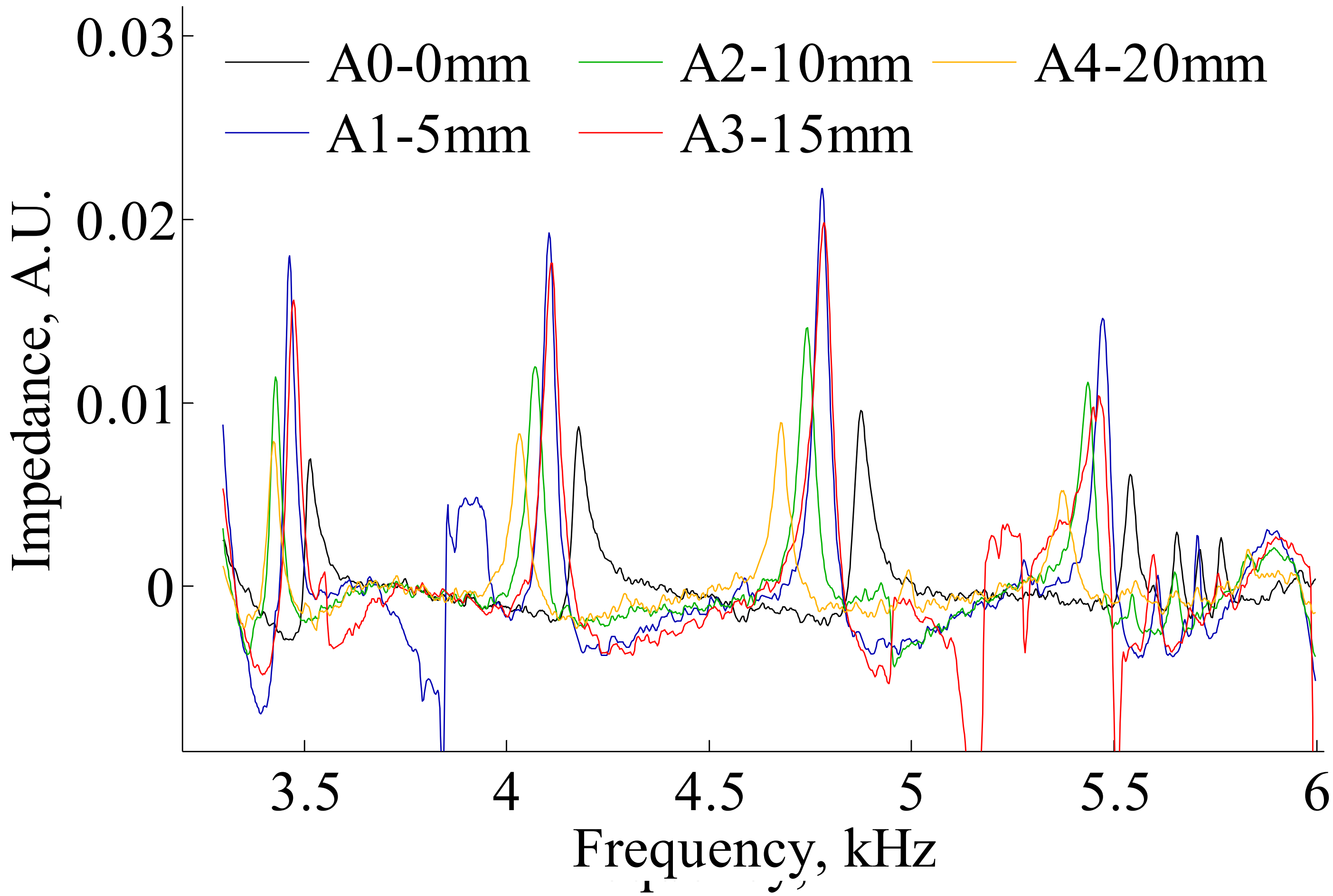
1. Frequency shifted from 3.592 kHz to 3.193 kHz, i.e. $\Delta f = 400$ Hz.
2. Impedance amplitude increased slightly: 0.5 Ohms.
3. Impedance slope has changed.

Electrical Manifestation of Damage



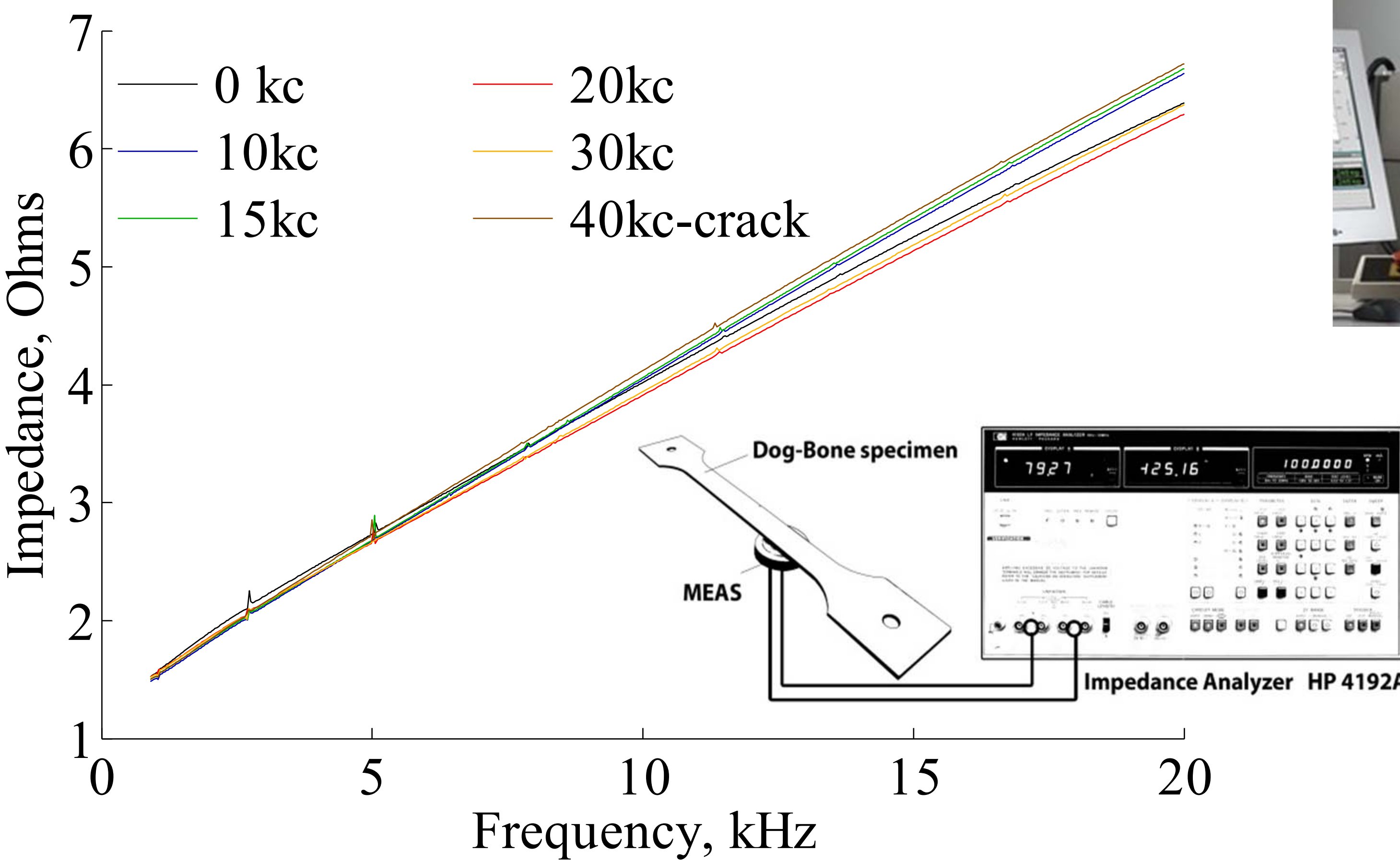
Task 2: Damage in Adhesive Interfaces



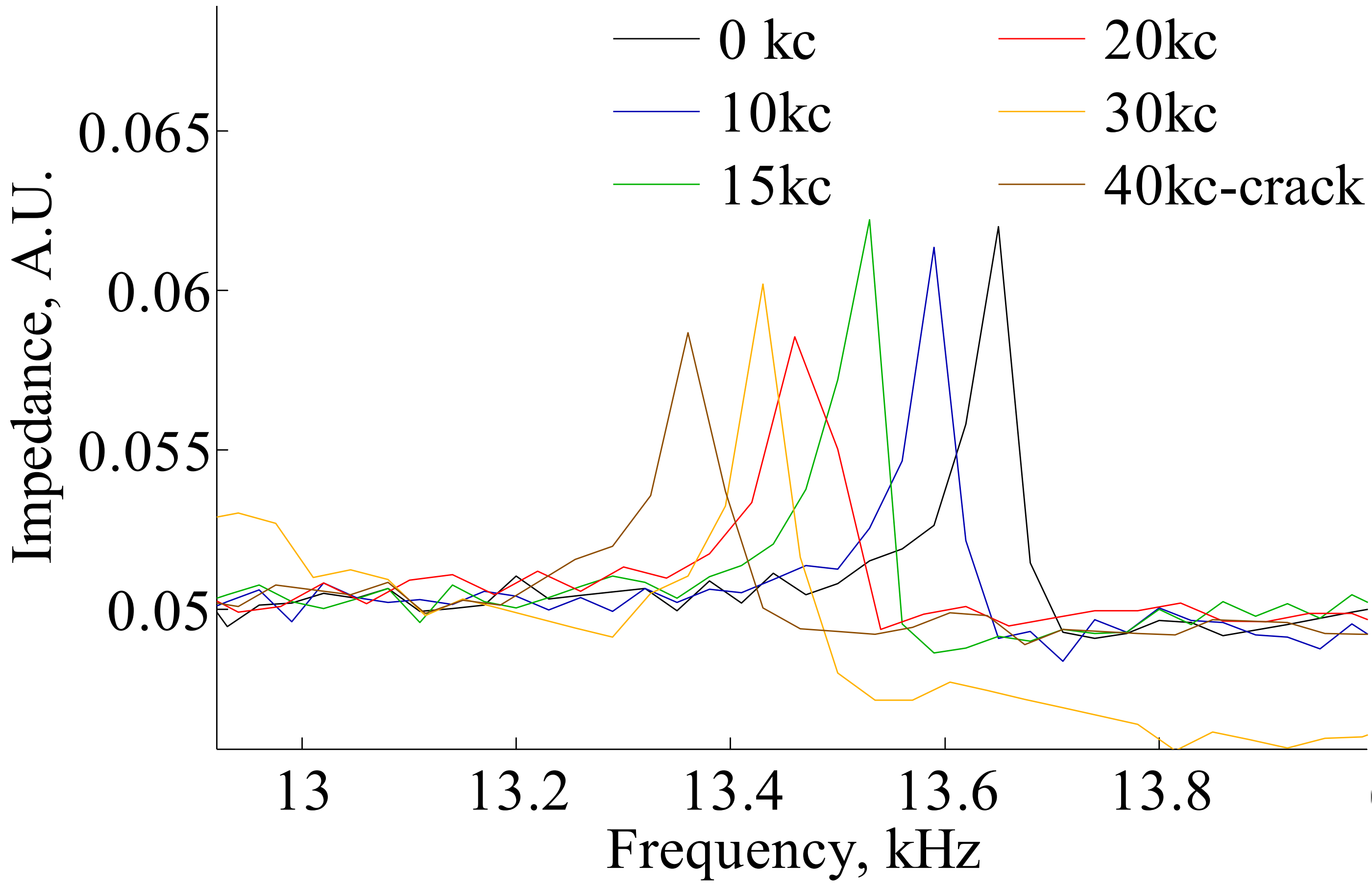


Task 2: Fatigue Testing

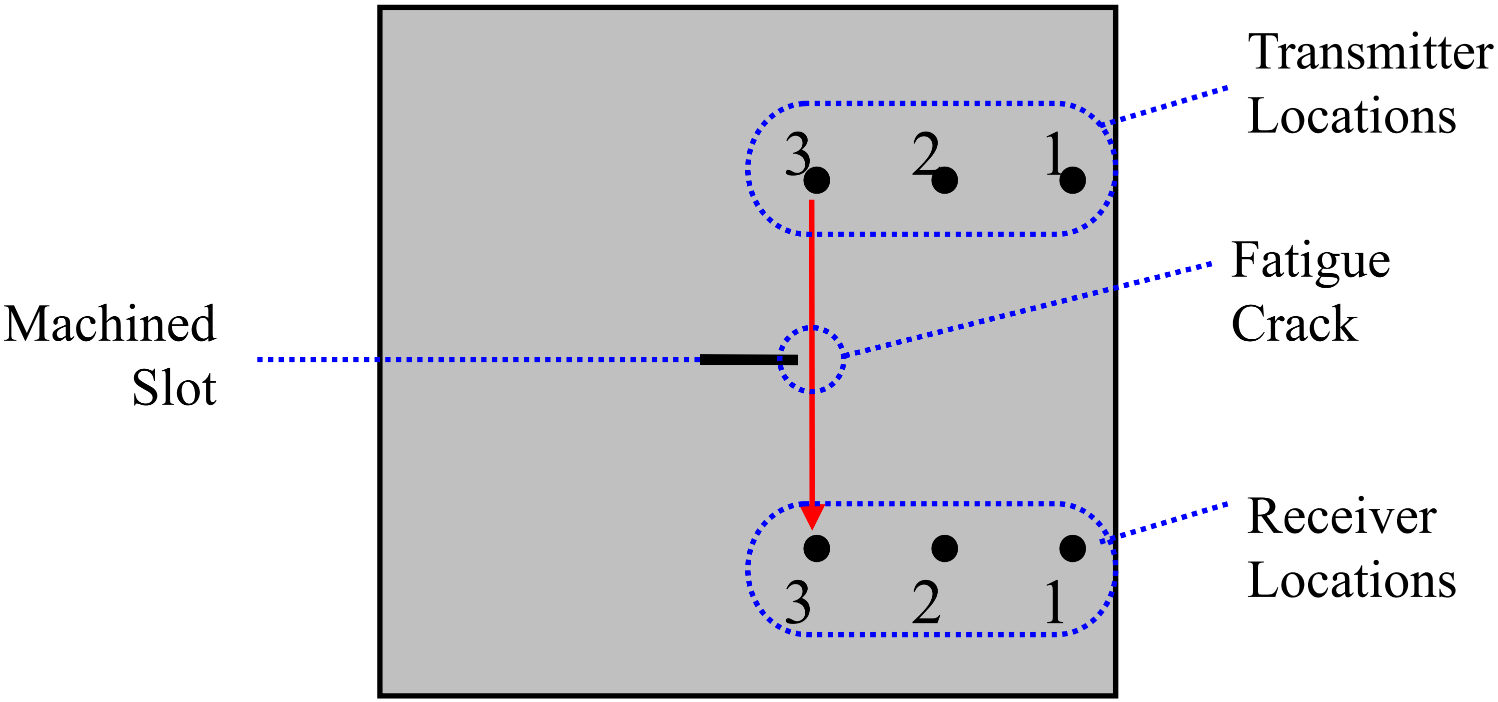
ASTM standard: Parameters



Task 2: Fatigue Testing



Task 3: Damage Manifestation in MEAS Signal

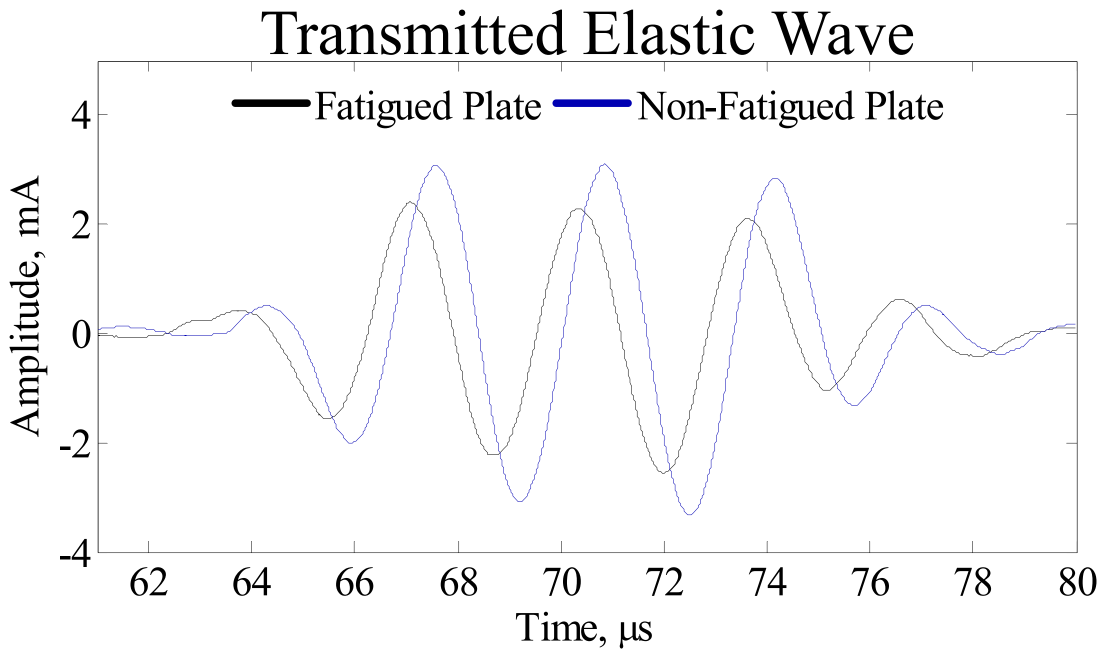


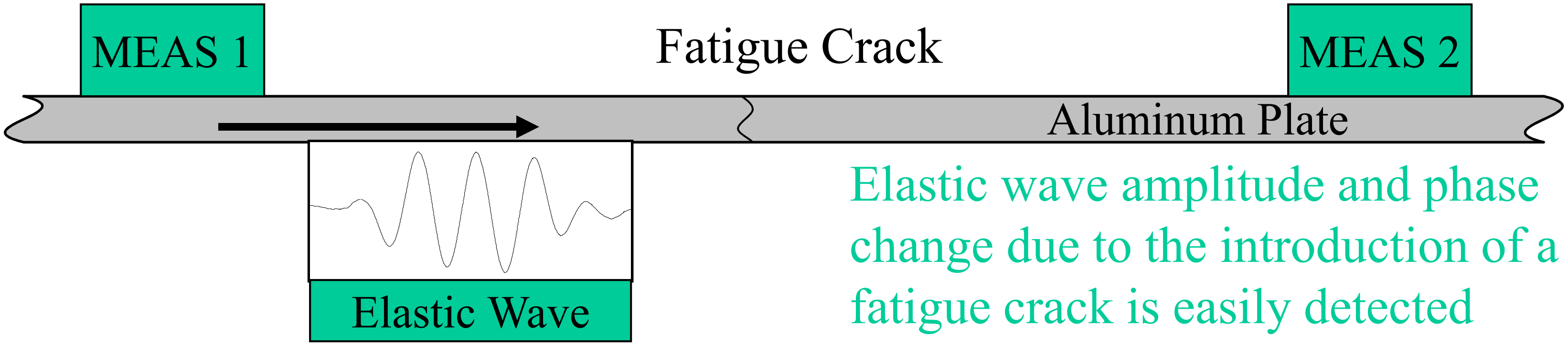
- Two Aluminum alloy plates (1mm thick), each with a machined slot
- One plate was to subjected to 185kcycles of loading from 1.7-17.8kN at which point a fatigue crack was visible on both sides of the slot
- The same sensor pair was used on both fatigued and non-fatigued specimens

Task 3: Damage Manifestation in MEAS Signal

Sensor Location	Mean Amplitude Reduction, %
1	3.0
2	4.5
3	15.5

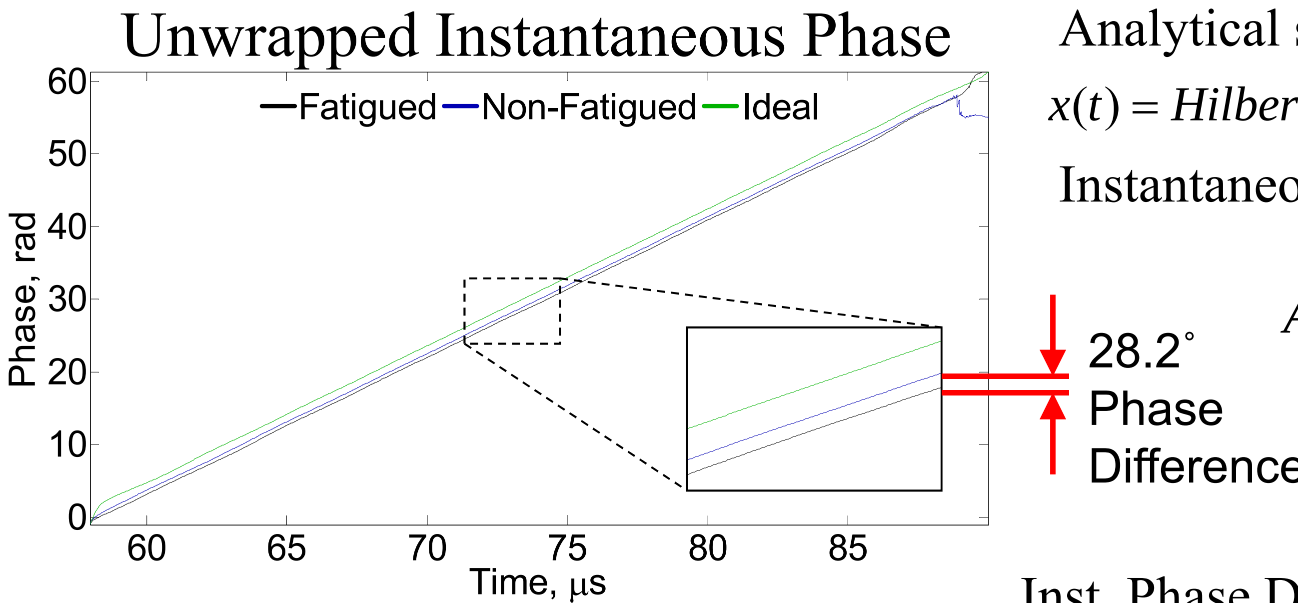
Sensor Location	Mean Phase Shift, deg
1	32.6
2	32.5
3	32.2





Elastic wave amplitude and phase change due to the introduction of a fatigue crack is easily detected

Task 3: Damage Manifestation in MEAS Signal



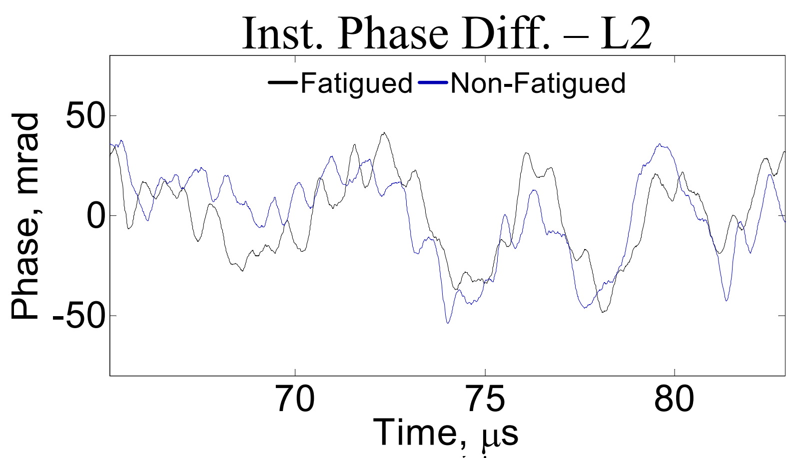
Analytical signal

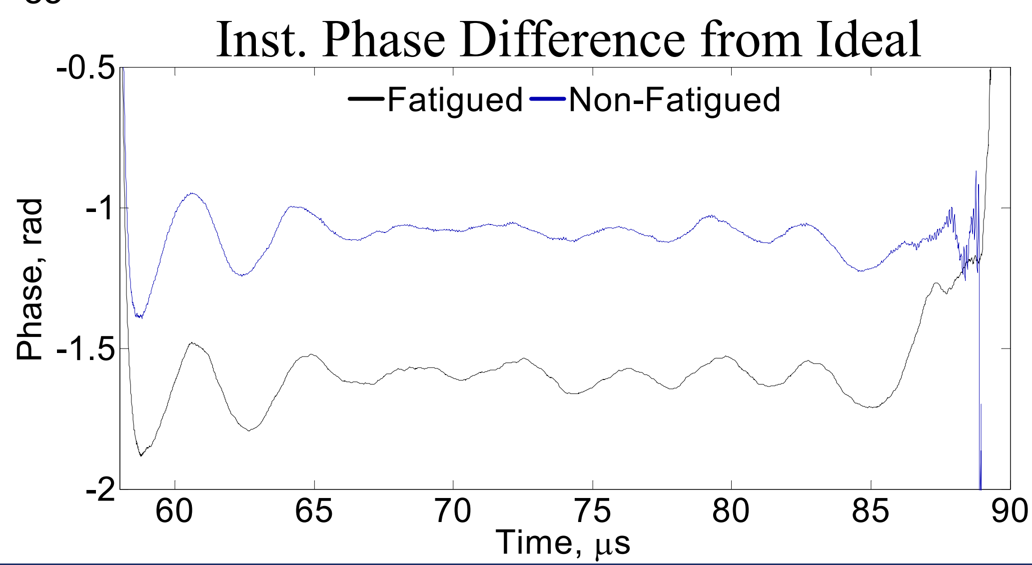
$$x(t) = Hilbert(s(t)) = \mathrm{Re}(x(t)) + i \cdot \mathrm{Im}(x(t))$$

Instantaneous amplitude and phase

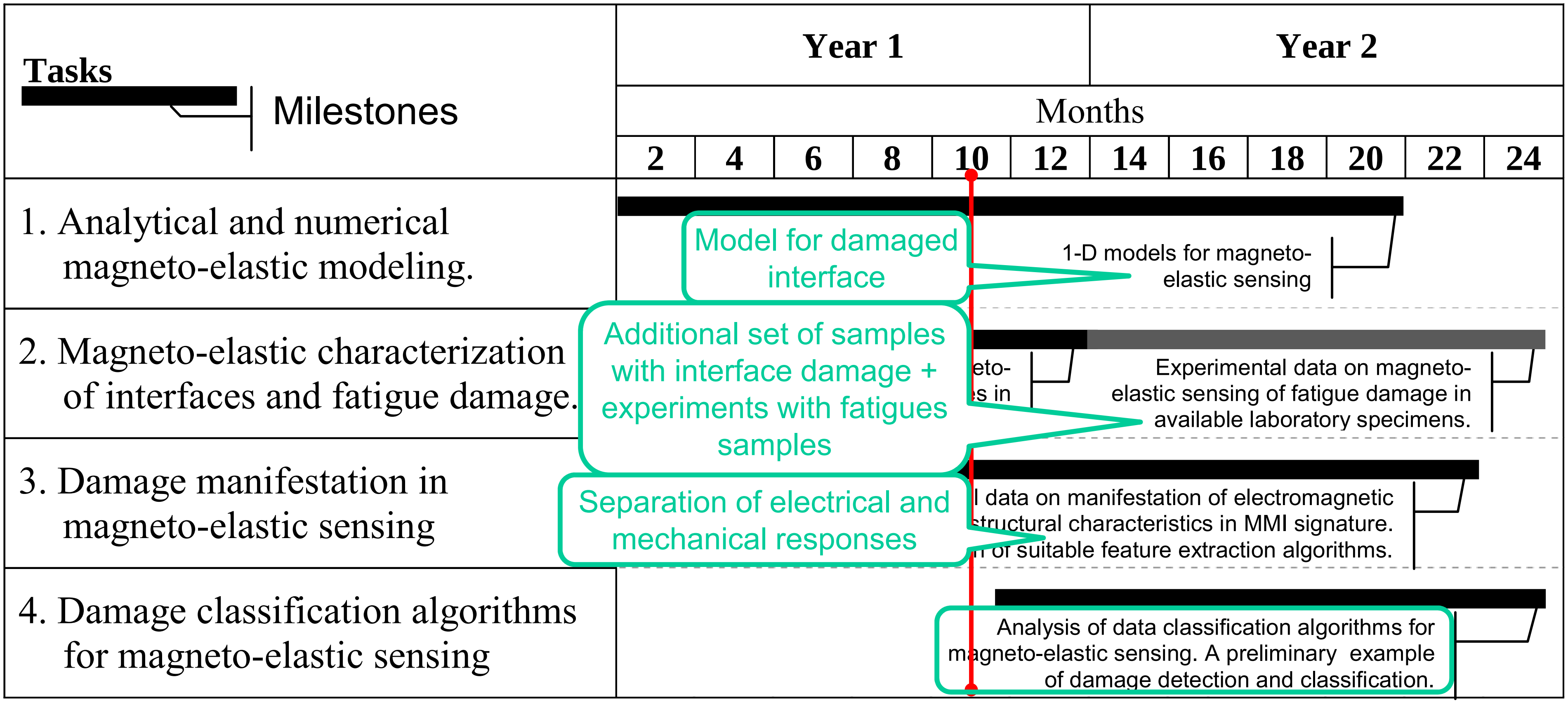
$$A(t) = |x(t)| = |Hilbert(s(t))|$$

$$\varphi(t) = \tan^{-1}\left(\frac{\mathrm{Im}(x(t))}{\mathrm{Re}(x(t))}\right)$$





Next Steps



Long term goal:

Black box for spacecraft with integrated SHM data

Contact Information

- Andrei Zagrai
- Department of Mechanical Engineering
- New Mexico Institute of Mining and Technology
- 801 Leroy Pl., Weir Hall, Room 124, Socorro, NM
- Ph: 575-835-5636;
- Fax: 575-835-5209;
- E-mail: azagrai@nmt.edu