Federal Aviation Administration

Task 228: Magneto-Elastic Sensing for Structural Health Monitoring

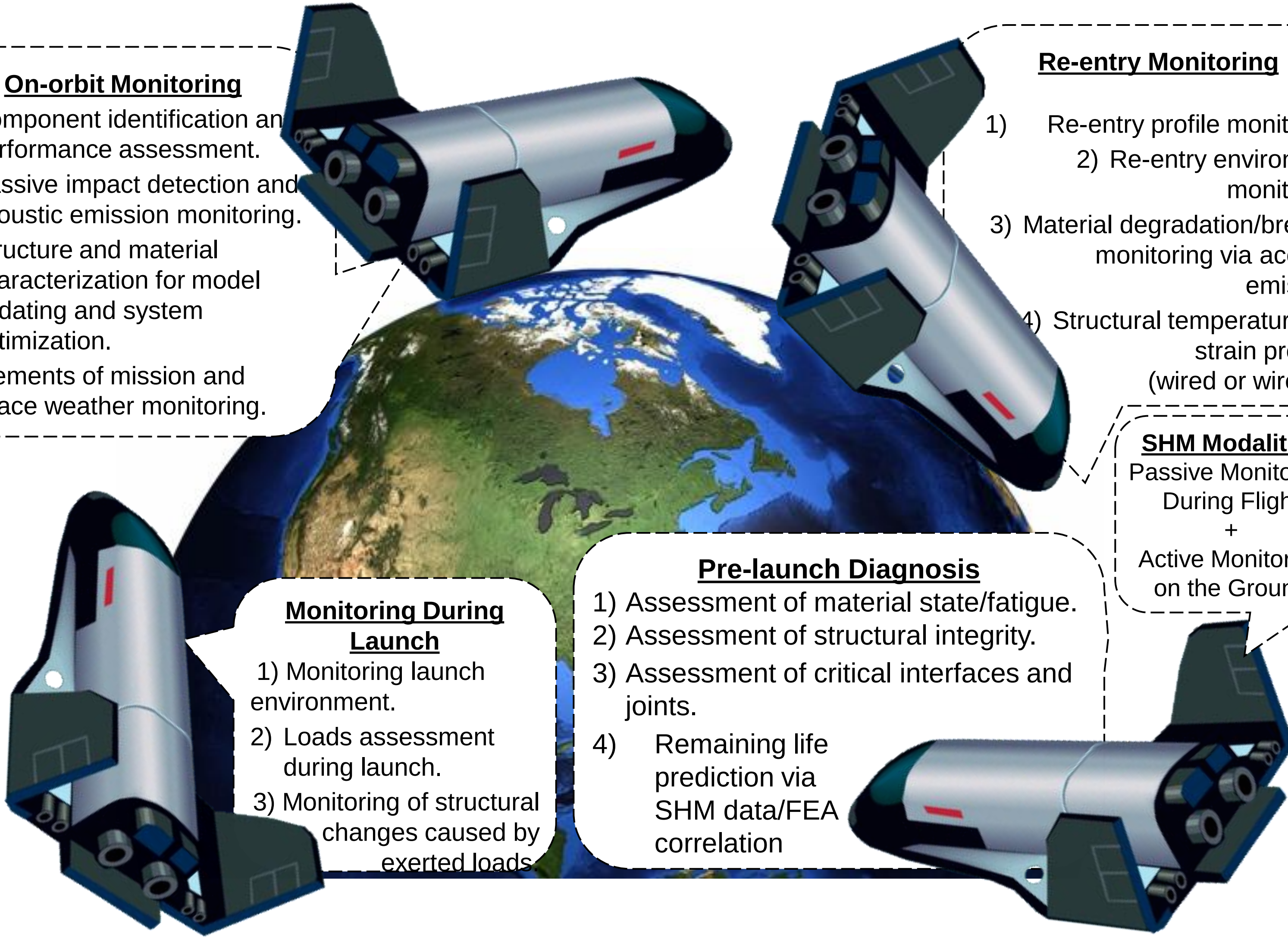
Andrei Zagrai and Warren Ostergren

October 31, 2012

Overview

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

Spacecraft Structural Health Monitoring



On-orbit Monitoring

1) Component identification an performance assessment.
2) Passive impact detection and acoustic emission monitoring.
3) Structure and material characterization for model updating and system optimization.
4) Elements of mission and space weather monitoring.

Re-entry Monitoring

1) Re-entry profile monitoring.
2) Re-entry environment monitoring.
3) Material degradation/breakup monitoring via acoustic emission.
4) Structural temperature and strain profiles. (wired or wireless)

SHM Modalities

Passive Monitoring During Flight
+
Active Monitoring on the Ground

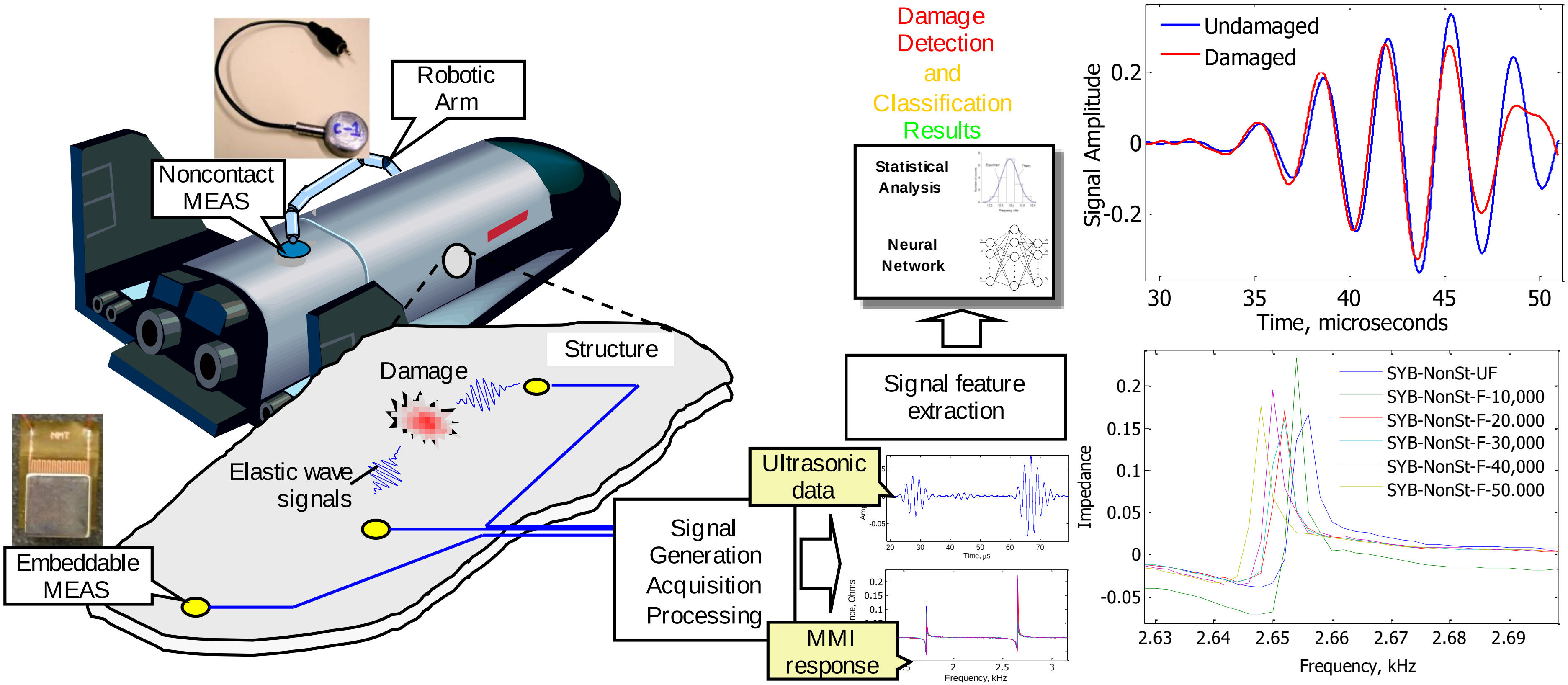
Monitoring During Launch

1) Monitoring launch environment.
2) Loads assessment during launch.
3) Monitoring of structural changes caused by exerted loads.

Pre-launch Diagnosis

1) Assessment of material state/fatigue.
2) Assessment of structural integrity.
3) Assessment of critical interfaces and joints.
4) Remaining life prediction via SHM data/FEA correlation

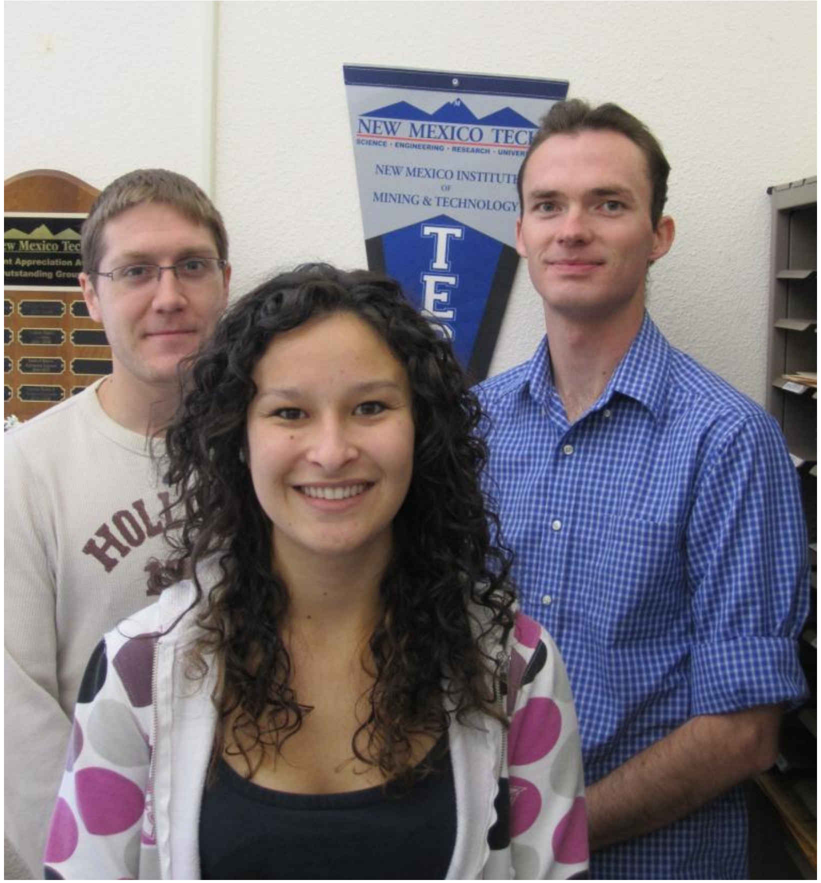
SHM System Engineering



Team Members

Task 228 NMT Team

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



Collaborators

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

Purpose and Objectives

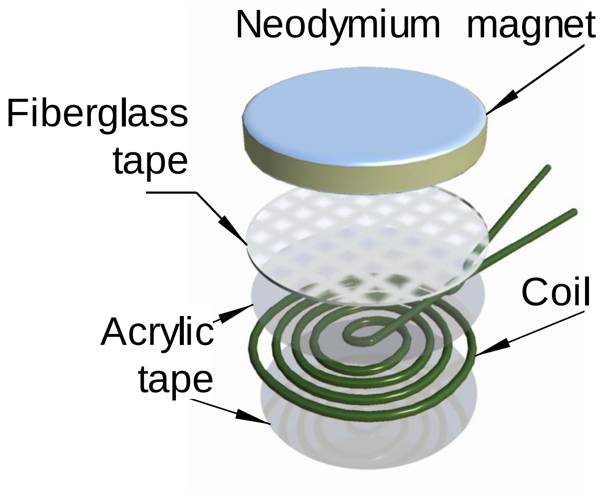
- The objective of the proposed project is to develop magneto-elastic sensing technologies for structural diagnosis of space vehicles.
- In achieving this objective, the investigation team conducts both theoretical and experimental research on the physical mechanism of sensing, its practical realization 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.

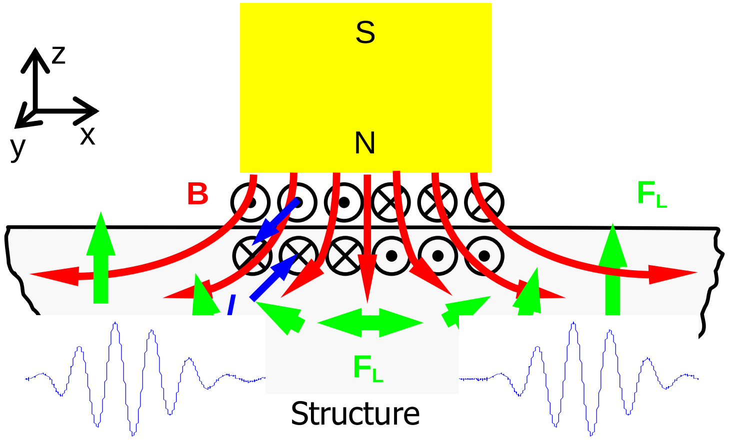
Schedule/Milestones

Tasks / Milestones	Year 1						Year 2					
	Months											
	2	4	6	8	10	12	14	16	18	20	22	24
1. Analytical and numerical magneto-elastic modeling.										1-D models for magneto-elastic sensing		
2. Magneto-elastic characterization of interfaces and fatigue damage.						Experimental data on magneto-elastic sensing of interfaces in structures of simple geometry						Experimental data on magneto-elastic sensing of fatigue damage in available laboratory specimens.
3. Damage manifestation in magneto-elastic sensing											Experimental data on manifestation of electromagnetic and elastic structural characteristics in MMI signature. Selection of suitable feature extraction algorithms.	
4. Damage classification algorithms for magneto-elastic sensing											Analysis of data classification algorithms for magneto-elastic sensing. A preliminary example of damage detection and classification.	

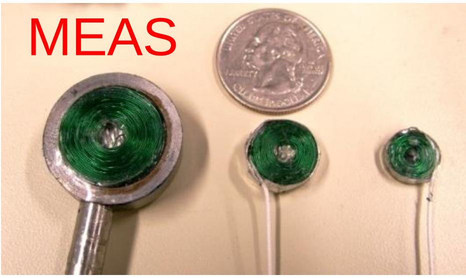
Magneto-elastic Active Sensors (MEAS)

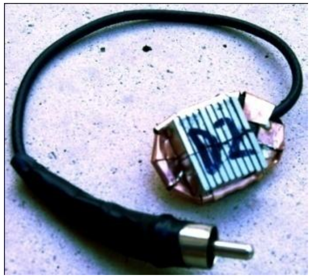
Capable of
NON-CONTACT
excitation
INSIDE material -
NO COUPLING
MEDIUM NEEDED





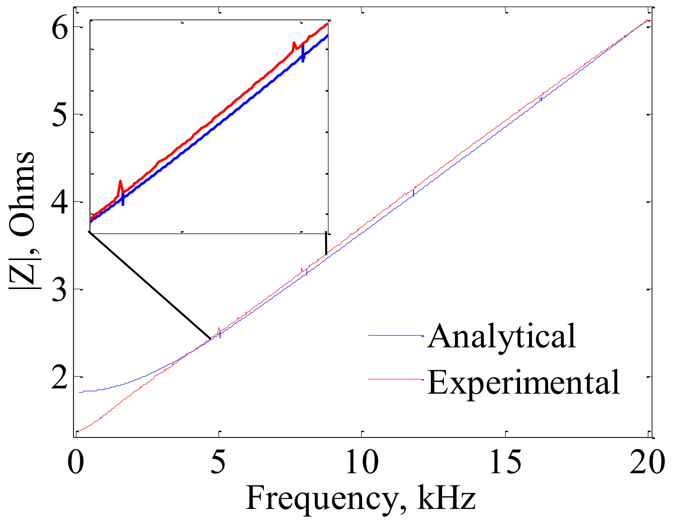
Electric current passing through the coil induces eddy currents in the structure. The eddy currents interact with the applied static magnetic field, resulting in Lorentz forces, responsible for generating elastic waves.

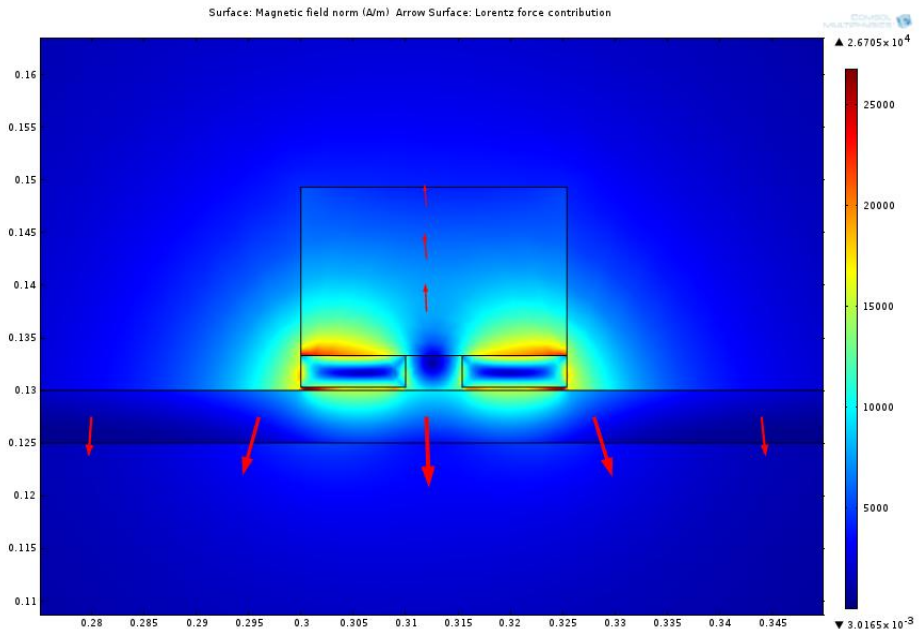




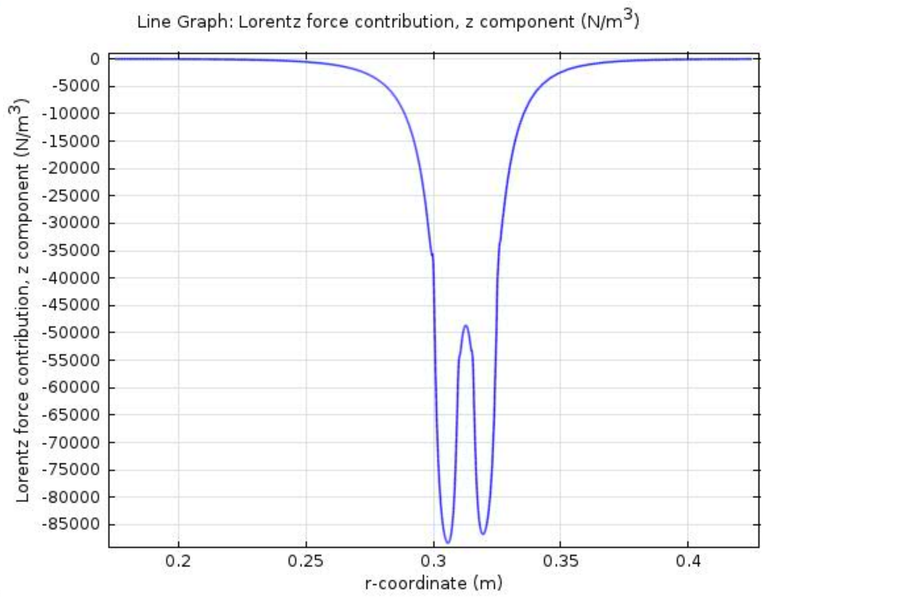
Analytical and Numerical Models

- Analytical models for 1D structures
- Numerical models using multi-physics finite element analysis



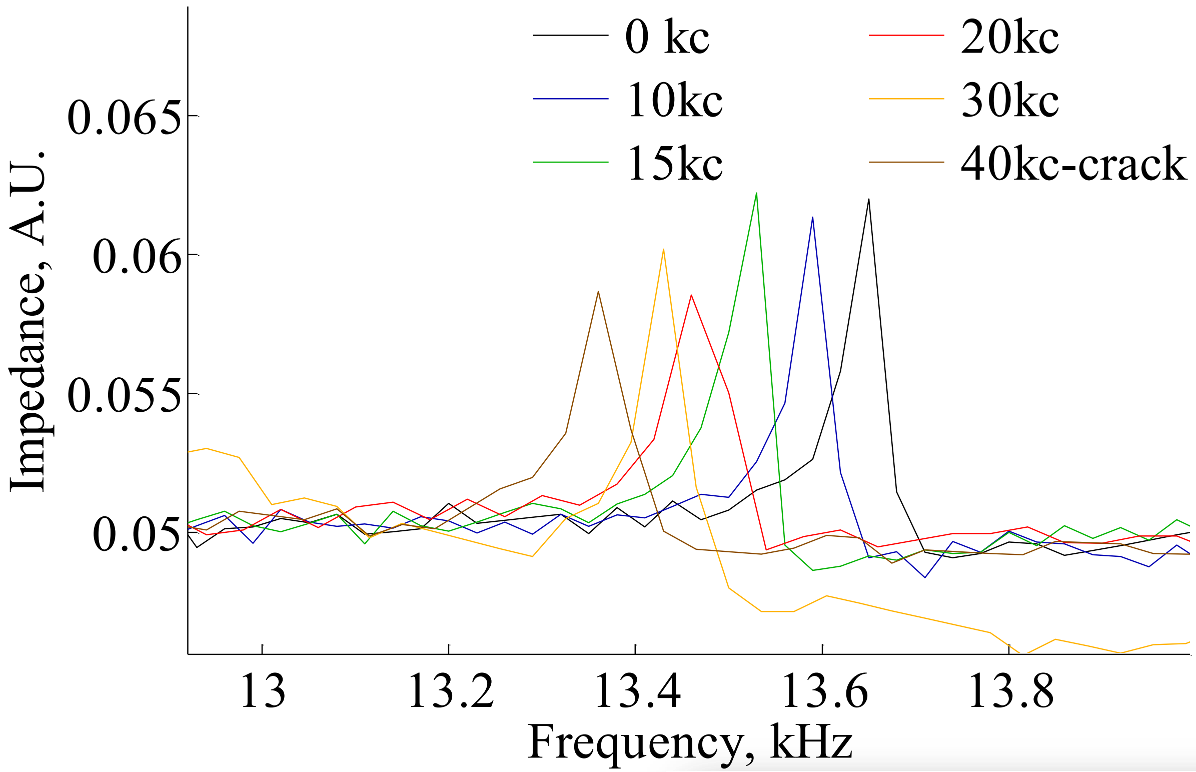


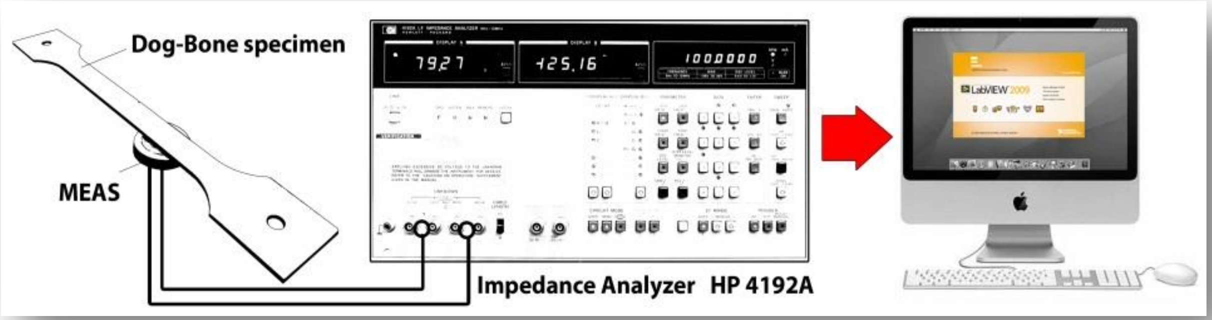
MEAS, magnetic field (shown in color), and Lorentz force (shown in arrows).



Spatial distribution of the Lorentz force on the surface of the specimen underneath MEAS.

Preliminary Fatigue Tests

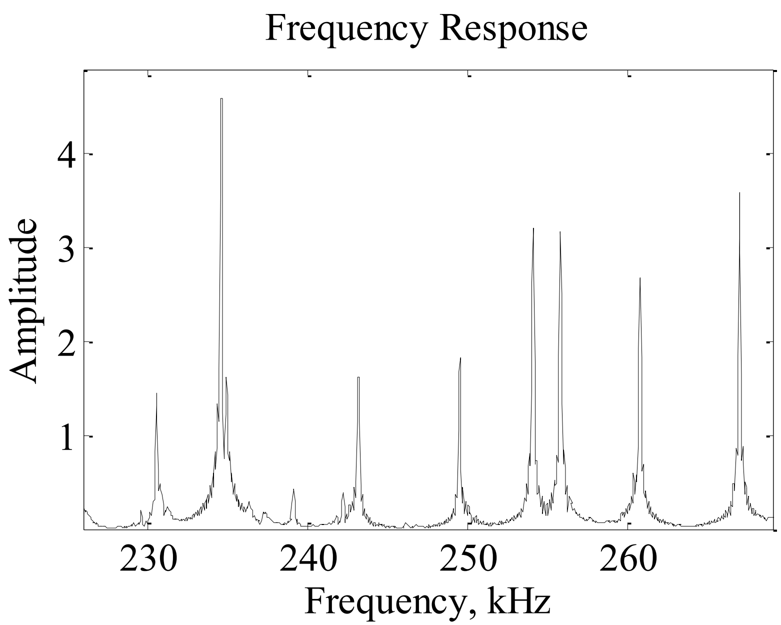




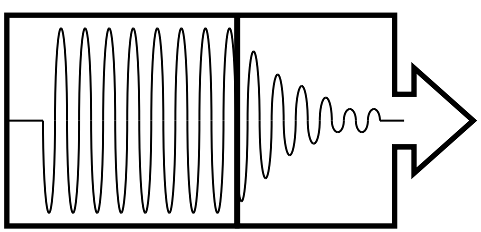
Damage Detection Methods

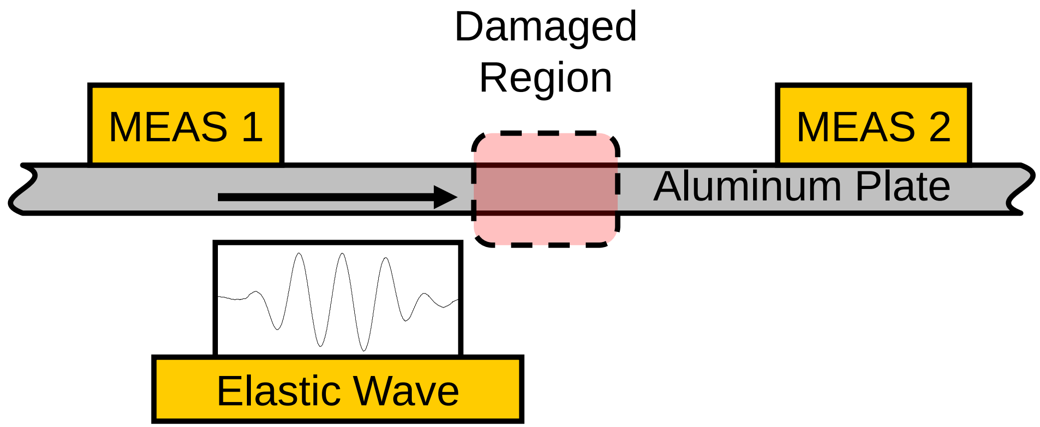
Wave Propagation

- Amplitude, Phase, and nonlinear characteristics



Received Signal





Frequency Response

- Amplitude and frequency of resonance peaks

Received Signal

$$x(t) = A(t)\sin(\omega t + \phi)$$

Analog Integration

$$I_1(t) = r\int_{t_1}^{t_2} D_1(t)dt$$

$$I_2(t) = \int_{t_1}^{t_2} D_2(t)dt$$

Quadrature Phase Detection

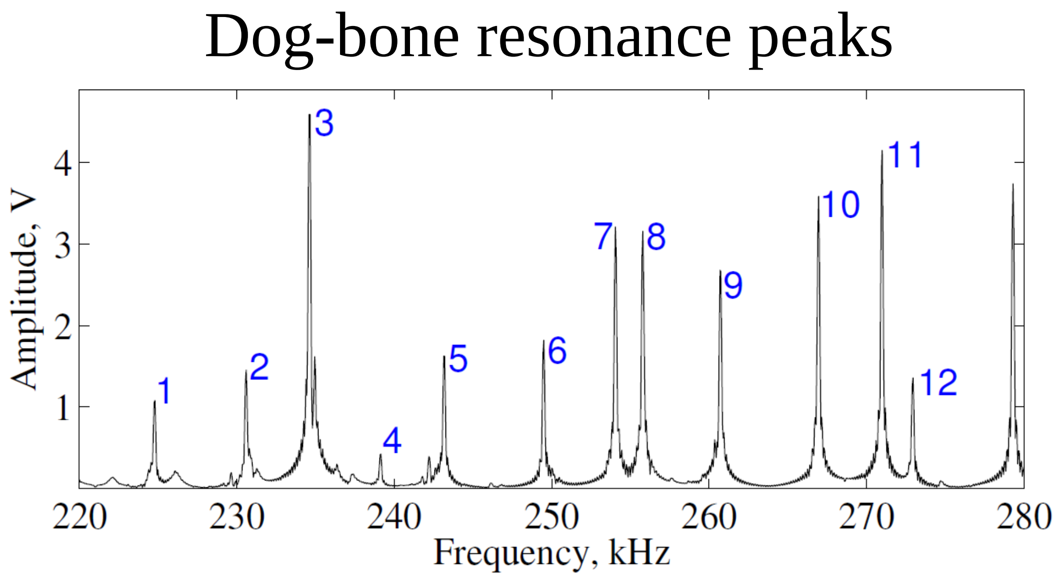
$$D_1(t) = g \cdot A(t)\sin(\phi)$$

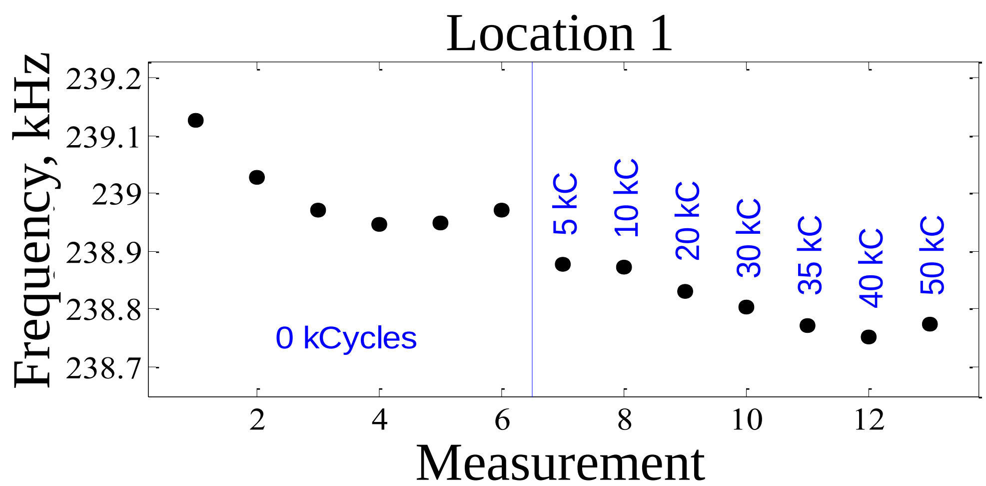
$$D_2(t) = g \cdot A(t)\cos(\phi)$$

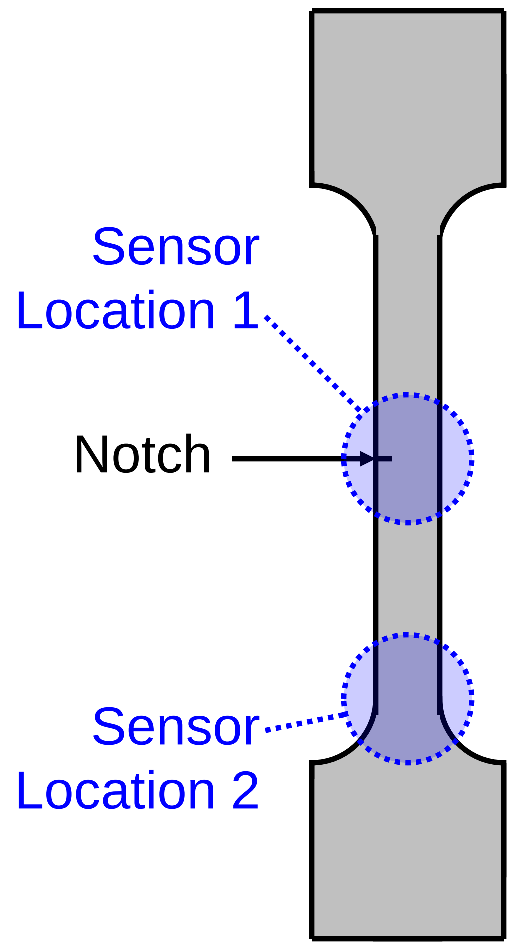
Magnitude Response

$$A = \sqrt{I_1^2 + I_2^2}$$

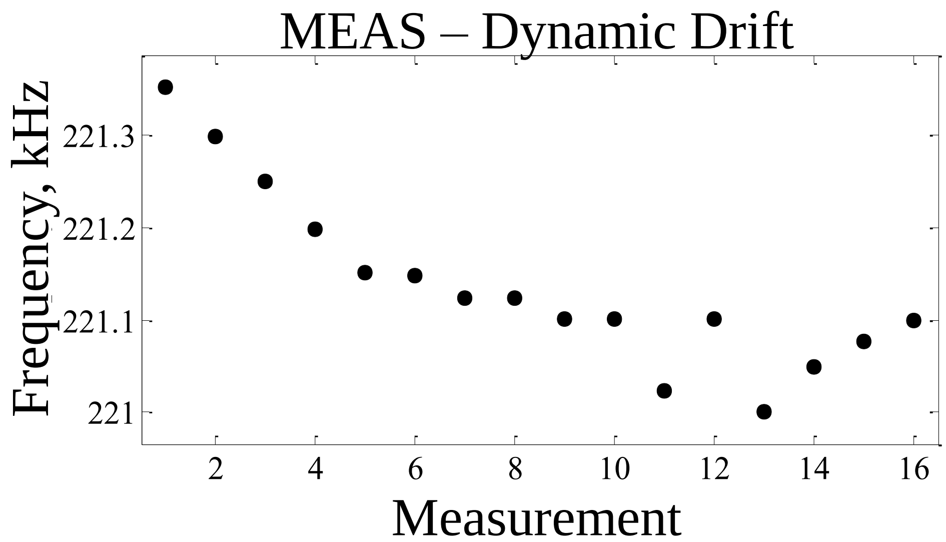
Dog-Bone Experimental Layout

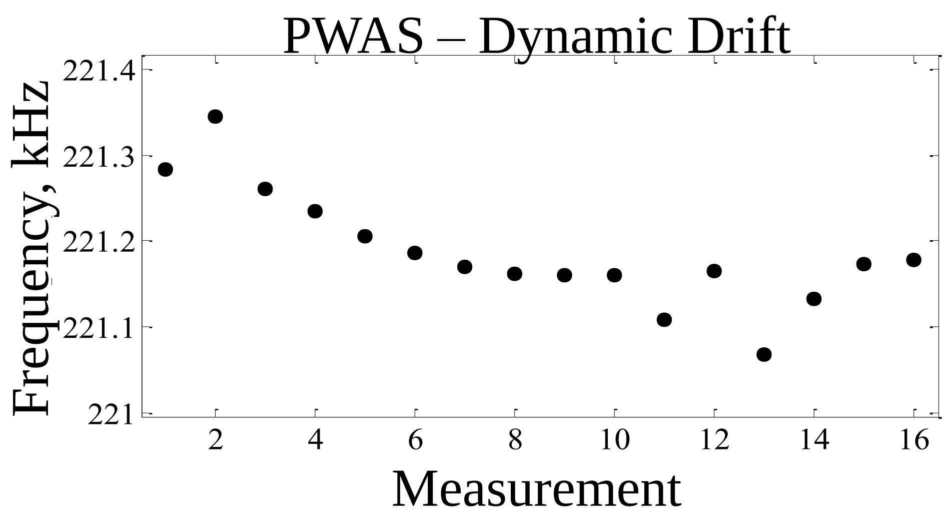






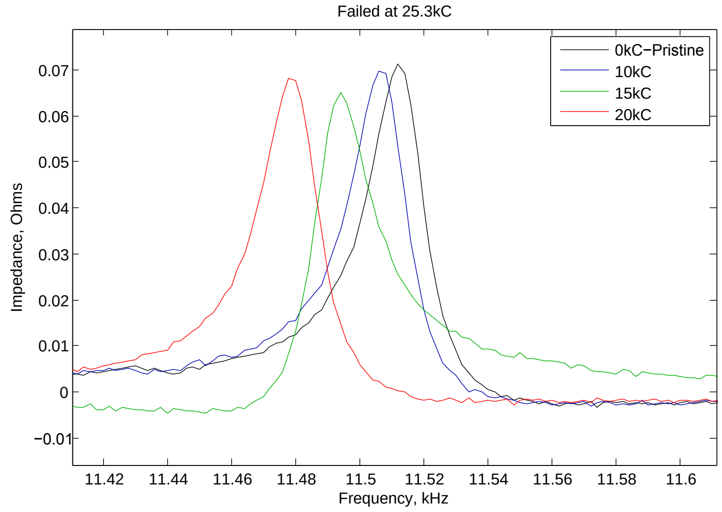
Fatigue Samples Frequency Analysis



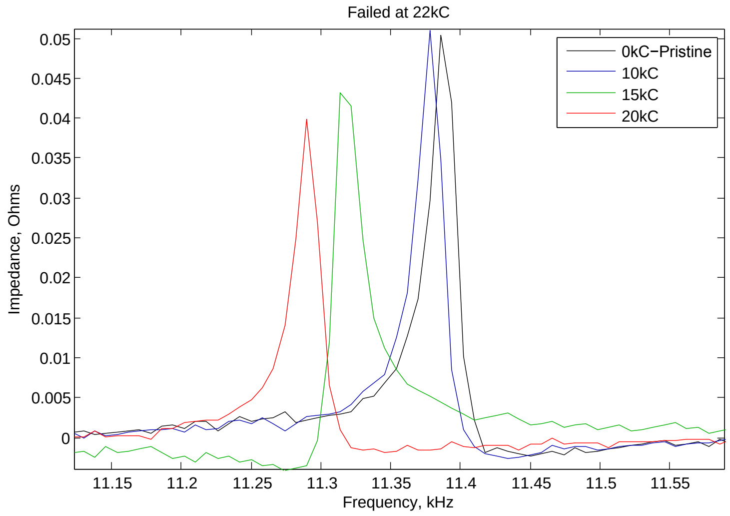


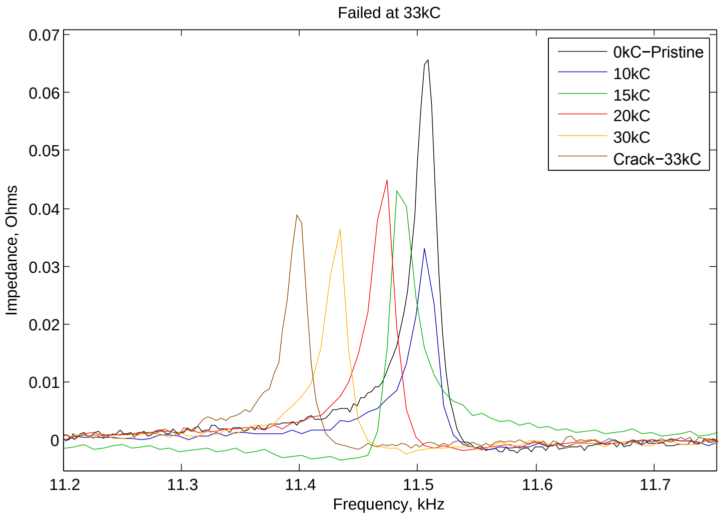
- Measured frequency drift appears consistent with sensor heating.
- Drift is observable in both PWAS and MEAS data indicating independence from equipment.

Fatigue Results for Multiple Specimens

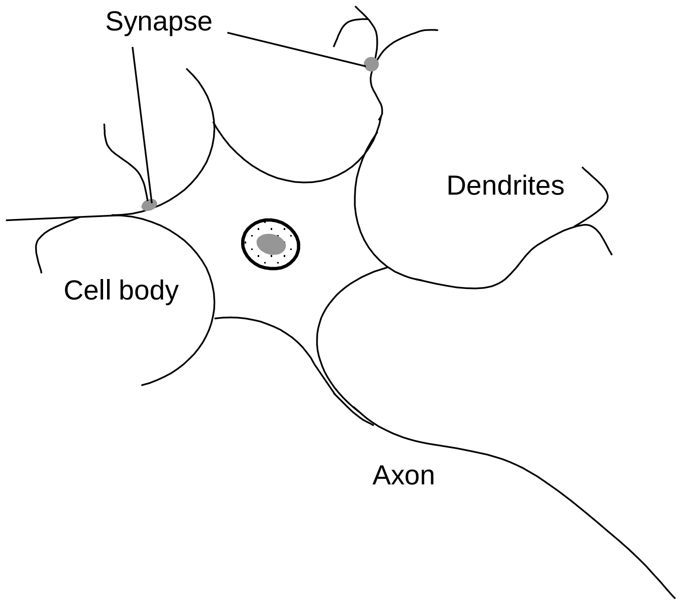


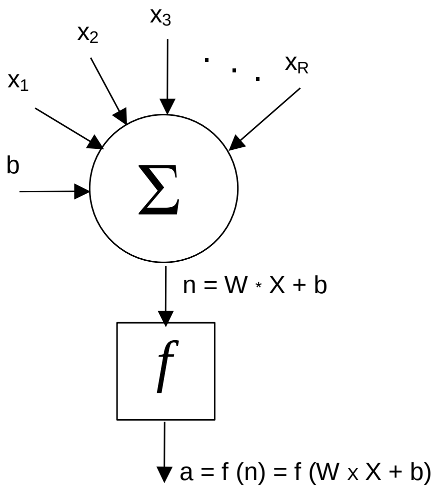
- Detection of fatigue damage was consistent in multiple specimens
- Sensitivity depends on frequency considered
- Magnitude of frequency shift may deviate from sample to sample.

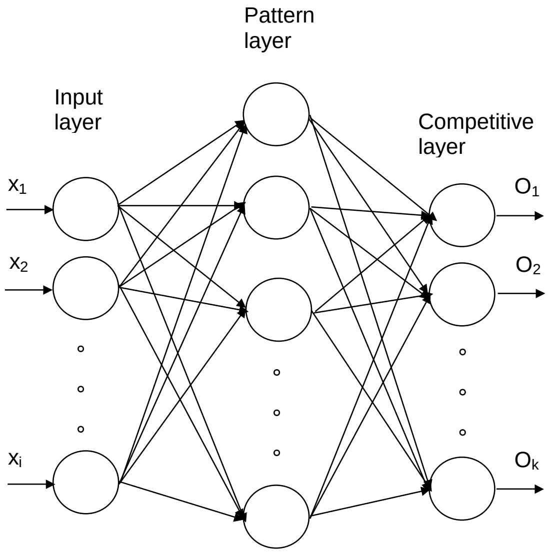




Artificial Intelligence Decision Support







Neural networks (NN) are biologically-inspired artificial intelligence representations that attempt to mimic the functionality of the nervous system

For practical applications, artificial neural networks are organized in layers and are implemented as software algorithms and/or hardwired electronic devices.

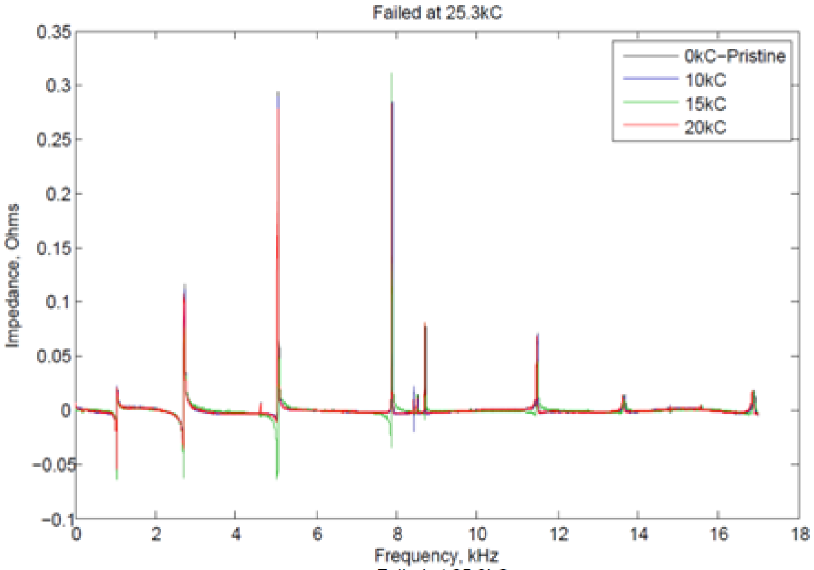
Probabilistic Neural Network

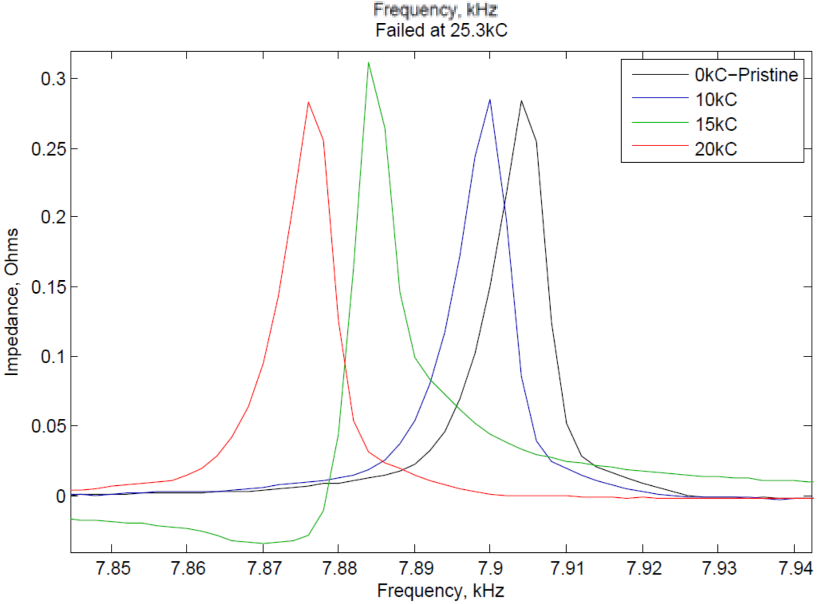
- While a substantial number of NN configurations are available to tackle the classification problem, we employ the probabilistic neural network (PNN).
- The reason for selecting the PNN is that this network reflects an association with classical statistic classification methods as it implements the Bayesian decision analysis with Parzan windows.
- PNN includes input layer, patter layer and competitive layer.

$$p_A(x) = \frac{1}{n \cdot (2\pi)^{d/2} \sigma^d} \sum_{i=1}^{n} \exp\left(- \frac{(x - x_{Ai})^T (x - x_{Ai})}{2\sigma^2} \right)$$

where i is a pattern number, x_{Ai} is i^{th} training pattern from A category, n is total number of training patterns, d is dimensionality of measurement space, and σ is a spread parameter.

PNN Classification of Fatigue Damage





Class	1	2	3	4
Ra, f kHz	7.894	7.89	7.874	7.866
Rb, f kHz	7.81	7.802	7.746	7.73
Rc, f kHz	7.914	7.906	7.898	7.89
Norm freq.				
Ra, f kHz	0	-0.004	-0.02	-0.028
Rb, f kHz	0	-0.008	-0.064	-0.08
Rc, f kHz	0	-0.008	-0.016	-0.024

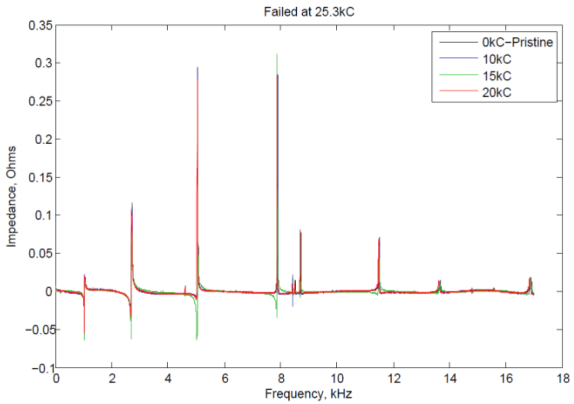
Train

Test

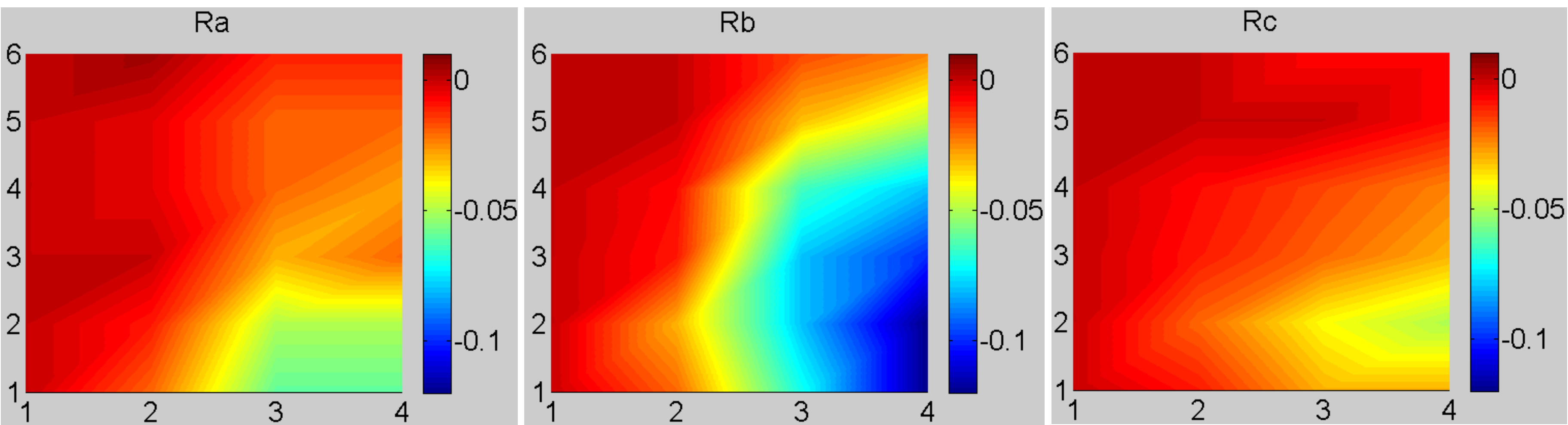
- PNN assigns neuron's weights based on values in the input *Train* vector.
- Spread constant controls distance between classes
- PNN freezes weight and spread constant
- When a *Test* vector is assigned to PNN, it compares *Test* vector values to *Train* vectors values based on neuron function
- Competitive layer outputs resulted classes.

PNN Classification of Fatigue Damage

Six sets of frequencies are considered for classification tests



	Train	Test	Test	Train	Test	Test	Train	Test	Test
Sample	Ra	Rb	Rc	Rb	Ra	Rc	Rc	Ra	Rb
Class **1** 0kc	1	1	1	1	1	1	1	1	1
Class **2** 10kc	2	2	2	2	1	2	2	2	2
Class **3** 15 kc	3	3	3	3	2	2	3	4	4
Class **4** 20 kc	4	3	3	4	2	2	4	4	4



SHM During H-A Balloon and Suborbital Flights

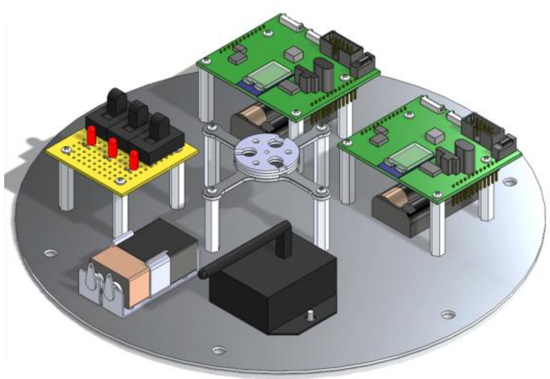
Objectives:

- Test majors concepts of spacecraft SHM systems during high altitude balloon and suborbital flights
- Collect SHM data from an experiment designed, built, and tested by the a student team.

The Spaceloft XL rocket lifting off (left) and a large high altitude balloon (right).

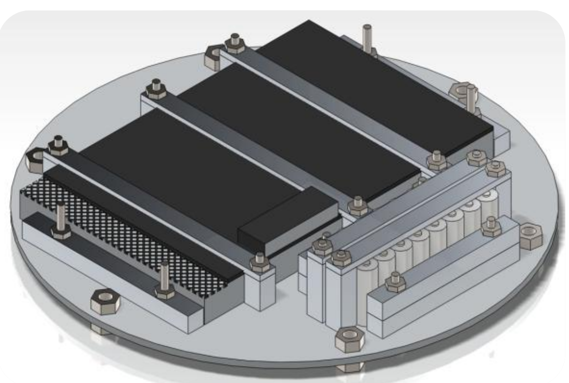
Sponsors: NASA FOP NMT, FAA COE

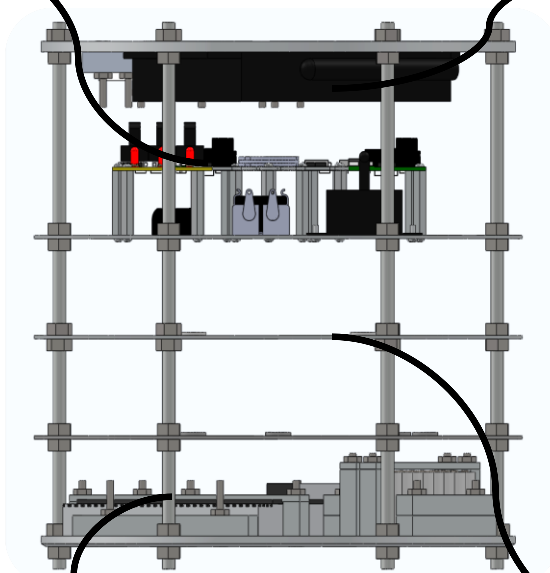
Payload Design

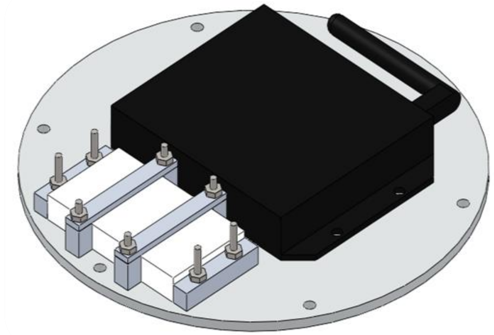


Impedance (LANL-WID3): Frequency response

METIS: Wave propagation

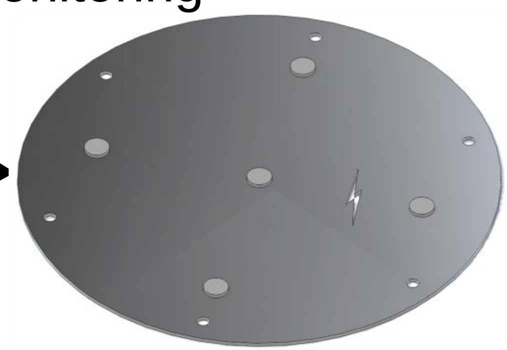






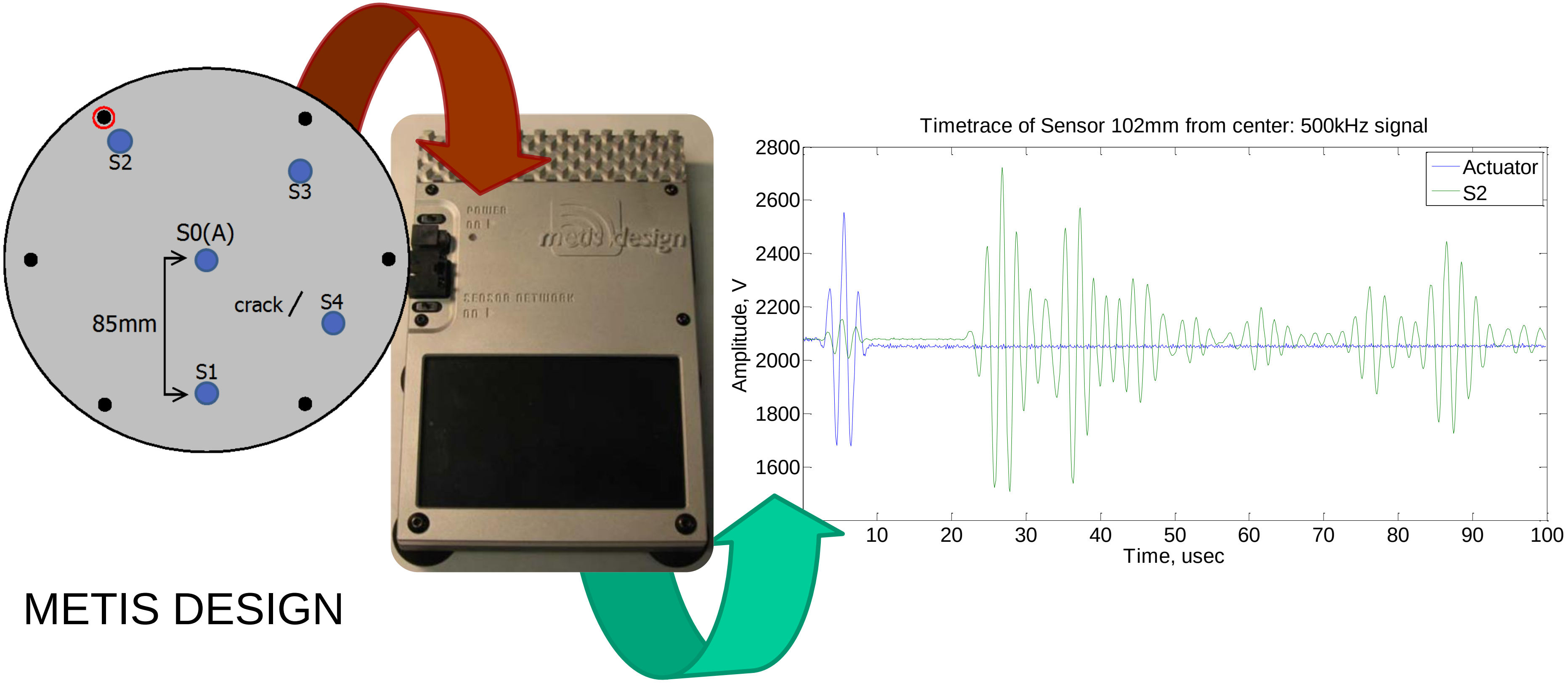
Microstrain: Wireless Strain & Temperature

Structural damage monitoring



Elastic Wave Propagation Experiment

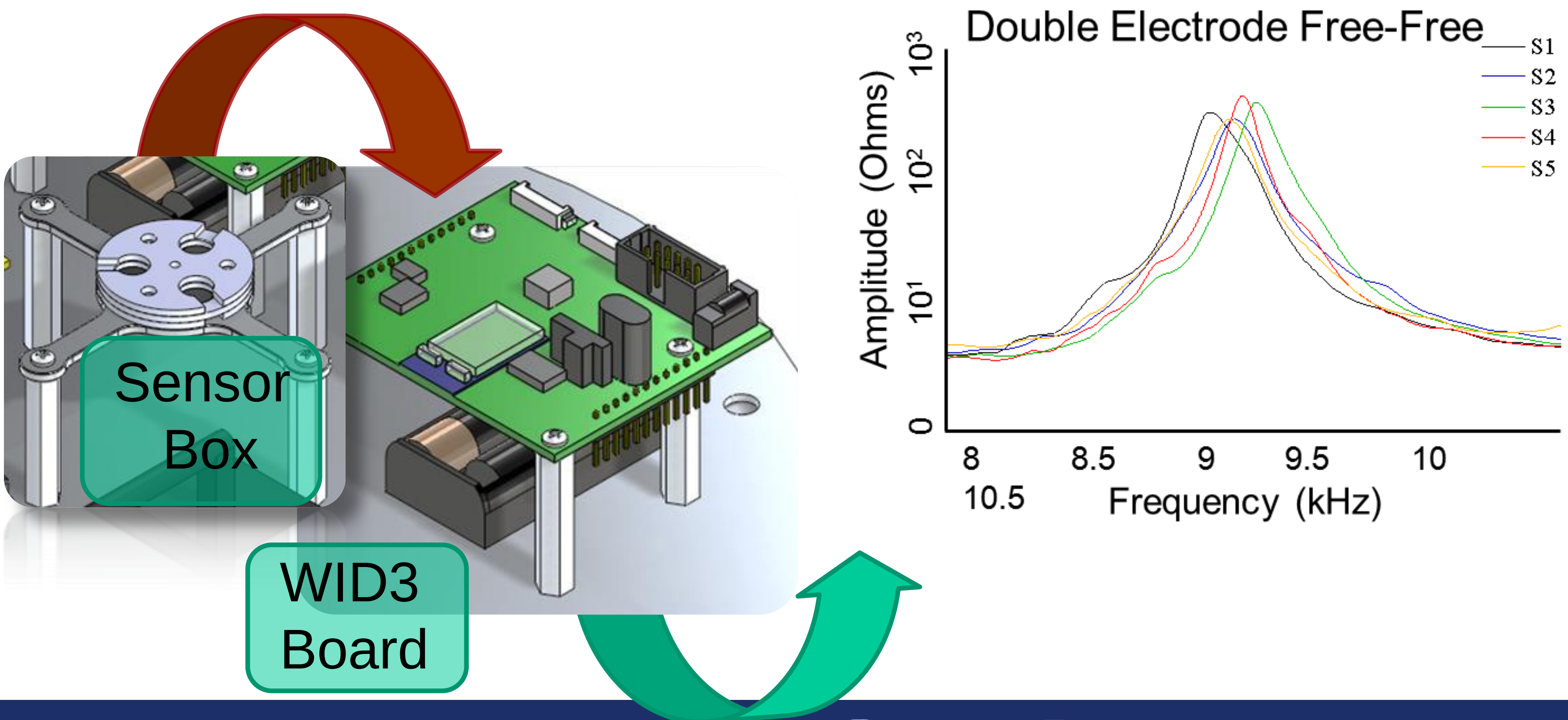
- Structural sound speed measurement
- Active ultrasonic SHM (mode 1)
- Acoustic emission (mode 2)



METIS DESIGN

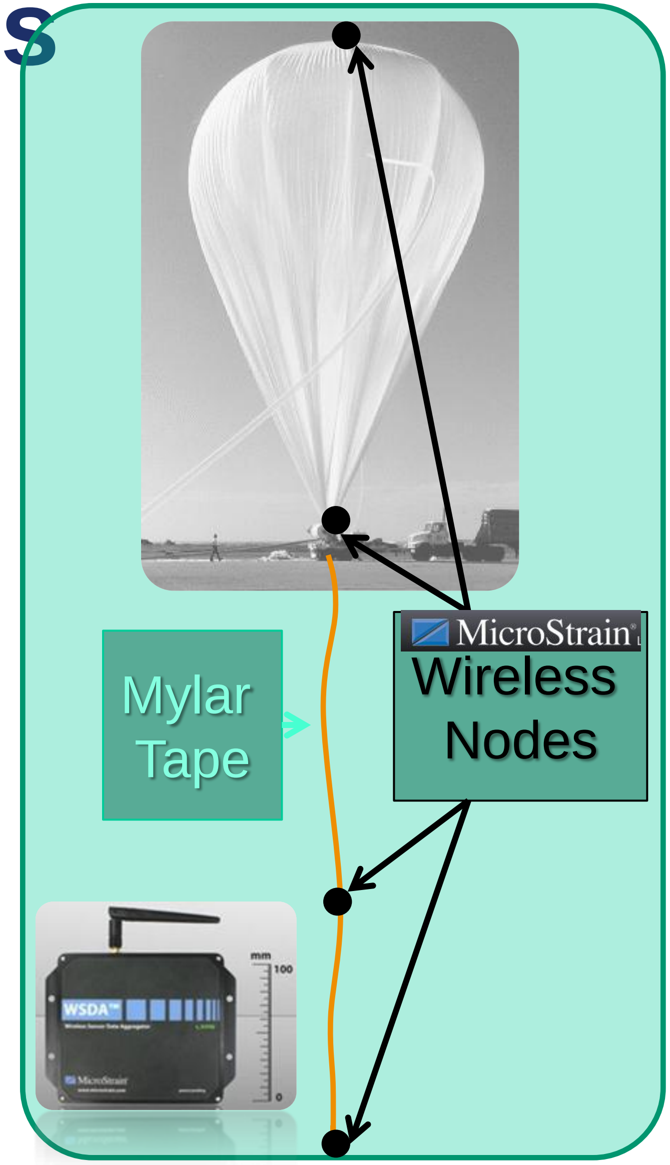
Electro-mechanical Impedance

- Electro-mechanical impedance measurements using LANL WID-3
  - Sensor characterization in high-altitude/space environment
  - Impedance-based SHM



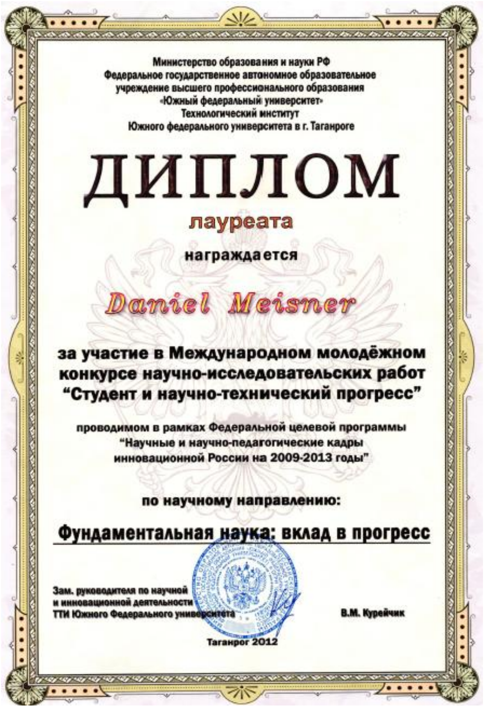
Wireless Measurements

- Experiment Components:
  - Goals is to conduct wireless measurement in space/near-space environment and explore associated technical/regulatory issues with launch providers
  - WSDA-1000 wireless data aggregator
  - Four wireless strain and temperature sensors
  - 8 full-bridge strain gauges and 4 internal temperature sensors
  - Approximately 234 ft span (70 ft balloon and (164 ft – Mylar tape)



Publications/Presentations

- Conrad, D and Zagrai, A, (2011) “Active Detection of Structural Damage in Aluminum Alloy Using Magneto-Elastic Active Sensors (MEAS),” *Proceedings of SMASIS-11, ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, September 18 – 21, 2011, Scottsdale, AZ, paper: SMASIS2011-5219.
- Meisner, D and Zagrai, A (2012) “Magneto-elastic Active Sensors for Detection Of Incipient Fatigue Damage in Aerospace Structures,” International Youth Competition of Scientific Research Works “Student and Science & Technology Progress,” Taganrog, Russia, June 20, 2012.
- Conrad, D., Zagrai, A., Meisner, D, (2012) “Influence of Sensor Statistics on Piezoelectric and Magneto-elastic Damage Detection,” *Proceedings of SMASIS-12, ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, September 19 – 21, 2012, Stone Mountain, GA, paper: SMASIS2012-8255.
- Conrad, D., Zagrai, A., Meisner, D, (2012) “Design, Development, and Assembly of Space Flight Structural Health Monitoring Experiment,” *Presentation at ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, September 19 – 21, 2012, Stone



Contact Information

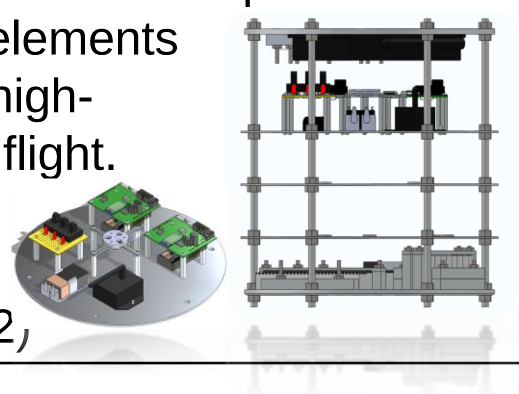
- Andrei Zagrai
- Department of Mechanical Engineering
- New Mexico Institute of Mining and Technology
- 801 Leroy Pl., Weir Hall, Room 124, Socorro, NM
- Ph: 575-835-5636;
- Fax: 575-835-5209;
- E-mail: azagrai@nmt.edu

Task 228: Magneto-Elastic Sensing for Structural Health Monitoring

5 months extension: Acoustic Emission Monitoring for Vehicle Re-entry and Post-Flight Diagnosis

MAJOR MILESTONES - PAST

- Payload design and development for demonstrating elements of SHM during high-altitude balloon flight. (this task was considered early in fall 2012)



MAJOR MILESTONES - FUTURE

- Payload design and development for demonstrating elements of SHM during suborbital flight.
- Correlation between fatigue/thermal damage and acoustic emission activity measured with PWAS and MEAS
- Guidelines for AE sensor installation.

SCHEDULE

Tasks / Milestones	January 1st to May 31st 2013 — Months 1	2	3	4	5	6
1. Acoustic Emission (AE) monitoring of fatigue damage using MEAS and PWAS.	Correlation between fatigue damage and AE activity.					
2. AE monitoring of thermal damage using MEAS & PWAS				Correlation between thermal damage and AE activity		
3. Guidelines for sensor installation and AE measurement procedures						Guidelines for AE SHM and sensor installation.

BUDGET

	FY13	FY14	FY15	FY16	FY17
FAA	$37.5K	$0	$0	$0	$0
Share	$38.4K	$0	$0	$0	$0

- Notes
  - ♦ Elements of SHM will be demonstrated during high-altitude balloon and suborbital flights sponsored by NASA Flight Opportunity Program Nov.2012 and spring 2013.