Structural Health Monitoring of Vertical Lift Structures Operating in an Urban Environment

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Background

- Fast-developing Urban Air Mobility (UAM) market is likely to lead to operators and innovators to-conceive varied airframes as they seek to improve performance margins and gain a competitive edge.
- These airframes, which include some complex configurations, may not benefit completely from the legacy data sets that have been established for the performance of commercial transport scale, traditional tube & wing or rotary wing designs.
- Assurance of safe flight for passengers, crew, and general public will be critical to the acceptance of UAM.
- The integration of a sensor suite to monitor the structural health of the aircraft during flight is proposed to meet safety requirements for this diverse fleet of newly designed airframes.
- Real time structural health monitoring sensors are seen as a critical part of a technology to:
  - Detect and report structural damage.
  - Transmit the information to a flight management system that is capable of processing information on the structural state relative to the design envelope of the vehicle.
  - Execute a flight maneuver that permits safe flight depending on how the detected damage might influence structural performance.

Preliminary Sensor Survey

Sensor Type	**Measurement Type**	**Coverage**	**Sensitivity**	**DAQ Rate**	**Test Matrix**				
					Tensile Strain	Bend Strain	Impact	Crack Detection	Drop Test
Foil Strain Gauge	Strain	Point			X	X			Debonds
Fiber Optic	Strain	Linear			X	X	X		
Eddy Current	Crack Detection	Point					X	X	
Plate Wave	Defect Detection	Area						X	
Surface Acoustic Wave	Strain (Wireless)	Area				X	X		
Stitched CNT/Electrical Impedance Tomography	Strain/Impact	Area				X	X		
Direct Print Graphene	Strain	Point			X	X			
Wireless Sensors									
Acoustic Emission/Ultrasonic	Impact & Crack Growth	Area					X		
Photogrammetry	Structural Deformation	Area			X	X	X		X

Sensor Types to be Discussed in More Detail

- Active and passive Ultrasonic Structural Health Monitoring techniques
- Embedded and surface bonded Eddy Current sensors
- Surface Acoustic Wave sensors
- Fiber optics
- Electrical Impedance Tomography
- Stitched Carbon Nanotube sensors

Ultrasonic Structural Health Monitoring: a Well-Established Field Supporting Numerous Journals:

- Structural Health Monitoring
- Journal of Civil Structural Health Monitoring
- International Society for Structural Health
- Structural Durability and Health Monitoring
- Structural Control and Health Monitoring
- Structural Monitoring and Maintenance
- Structural Durability and Health Monitoring
- The International Journal on Smart Sensing and Intelligent Systems
- International Journal of Smart Sensor Technologies and Applications

NASA SHM Applications*

- Shuttle: Wing Leading Edge Impact Detection System (WLEIDS)—Post-Columbia Accident development to monitor the Shuttle's wing leading edge for impacts such as foam shedding from the External Tank (Accelerometer based).
- ISS: Ultrasonic Background Noise Test (UBNT). Provided information on the high frequency background noises in the ISS structures. A precursor to developing a leak location system for the ISS. Used the Distributed Impact Detection System (DIDS ultrasonic frequency version).
- ISS: Bigelow Experimental Activities Module (BEAM) impact detection system. Monitors the internal structural walls for detecting external hypervelocity impacts. Uses Distributed Impact Detection System (DIDS low frequency accelerometer version--Still Active).

* Note all these systems were developed under NASA's SBIR programs and later applied to NASA space programs.

Wing Leading Edge Impact Detection System

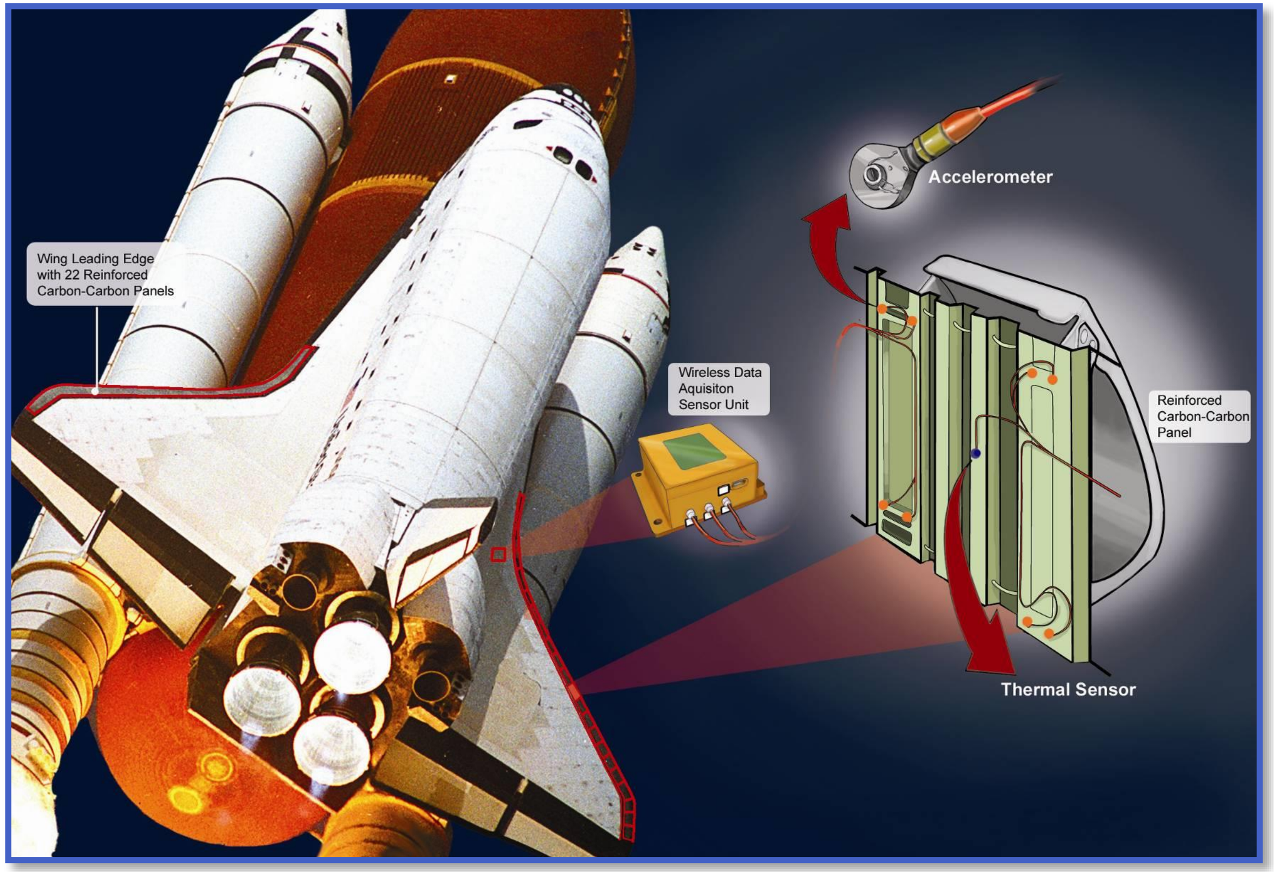
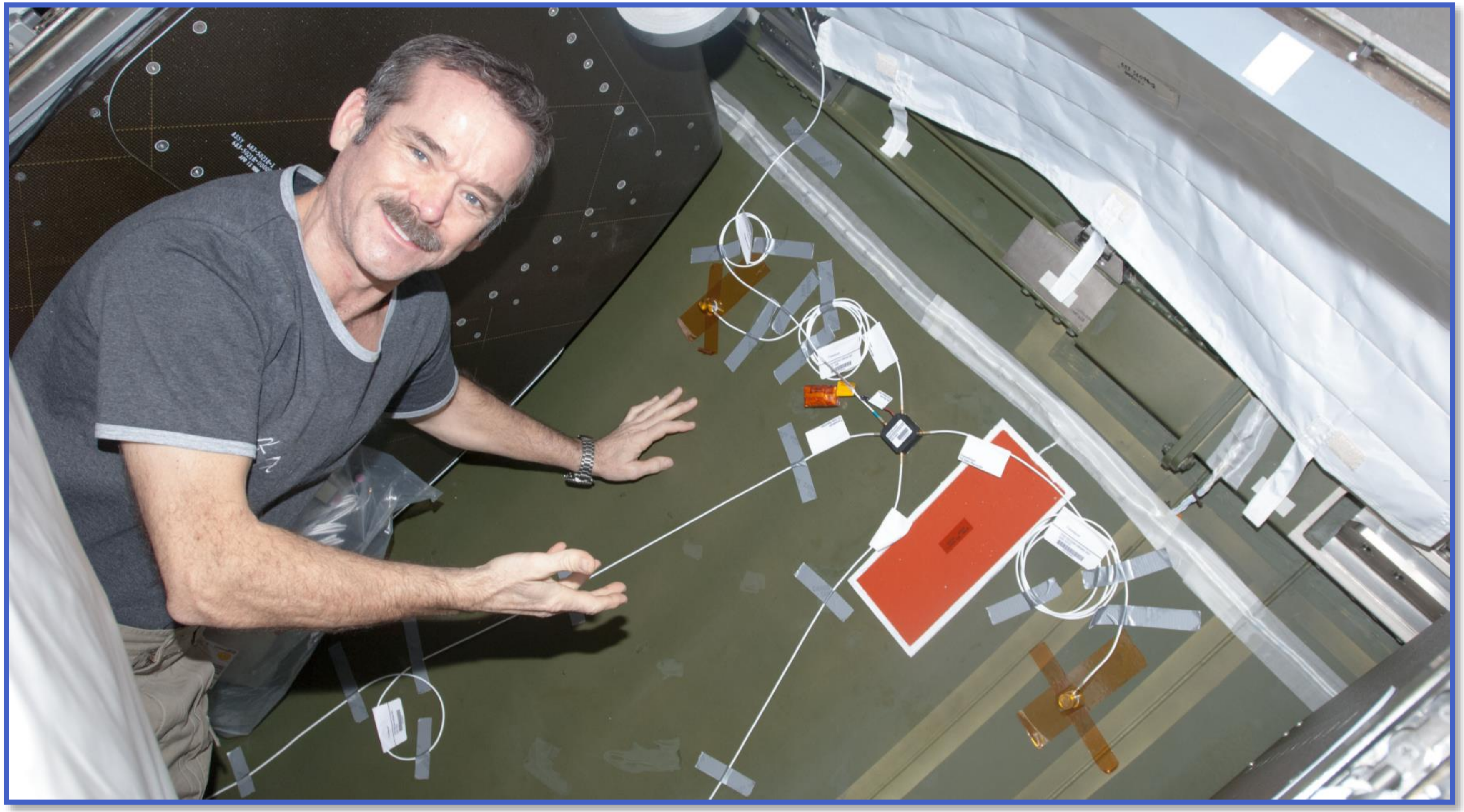


Photo of Chris Hatfield Installing the UBNT (Ultrasonic Background Noise Test) in the US Lab Behind O5 Rack



Astronaut Kate Rubins installing instrumentation into BEAM

Accelerometer Sensor

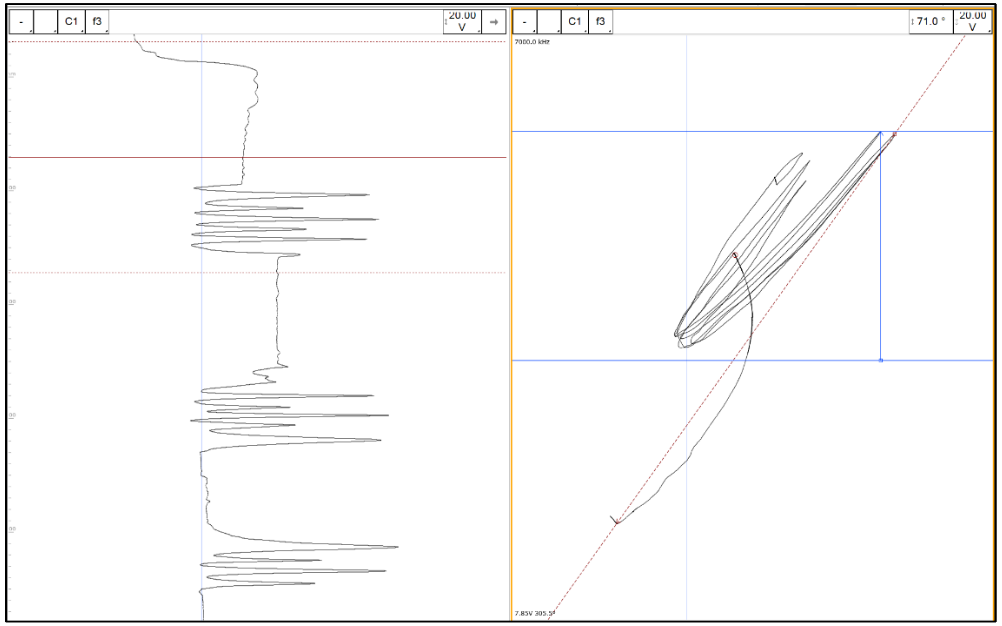
DIDS Unit

Ultrasonic SHM plans for RVLT Testing

- NASA has acquired hardware from Acellent Corp. and plans to install the SHM hardware on some laboratory sized samples to test that hardware on load frame sized panels to assess the hardware's applicability to our material/structures.
    - Flat carbon fiber epoxy composite panels
    - Carbon fiber/Kevlar corrugated tubes
    - Wind tunnel testing on composite control surfaces (sensors installed on the inner mold line outside of the flow)
- NASA also has SHM hardware made by Metis Design Corp.
- NASA also has a new type of fiber optic sensor and instrumentation for AE (Optics11) we plan to study in the same tests.

Eddy Current Techniques for SHM of Vertical Lift Structures

- Eddy Current sensors can effectively be used to detect damage at critical joints in metallic.
- Directional eddy current coils can effectively monitor carbon fiber orientation and breakage in composite components.
- Embedded or surface mounted coils are proposed to monitor the structure during flight.

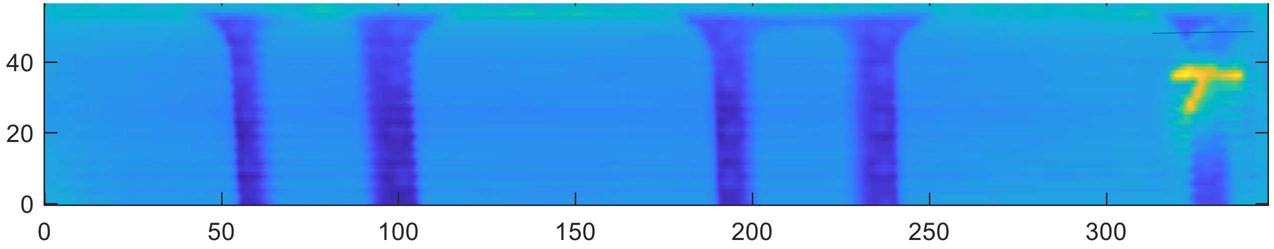


Response of direction eddy current coil to changes in the orientation of carbon fibers in carbon/Kevlar composite.

Examples of Eddy Current Inspection Coils for SHM Applications

NASA Owned Eddy Current Array and Probe

Detection of Cracking in Airframe Aileron Using Array Probe

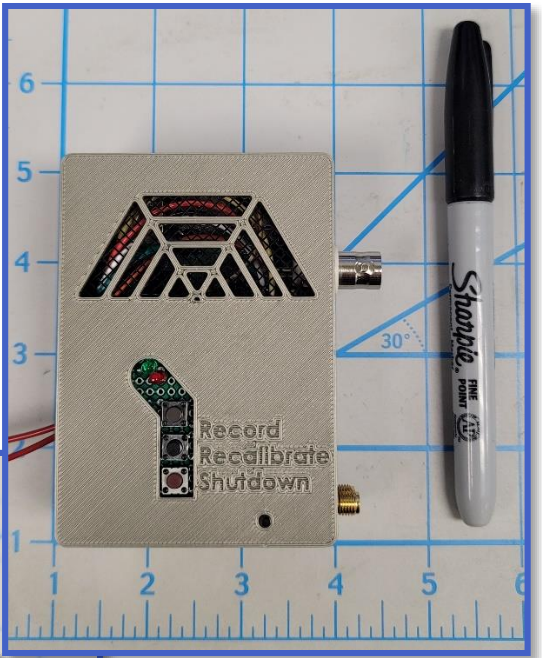


Dimensions in mm

Custom Eddy Current Coil conforming to corrugated tube.

Eddy Current System based upon AD5933 Impedance Analyzer Chip

- Low-cost light-weight Eddy Current inspection system being developed for efficient eddy current sensorization of RVLT platforms.
- Raspberry Pi system has WIFI along with on-board and USB storage for acquired data.
- An AD5933 impedance analyzer chip provides real and imaginary components at ~200Hz.
- Can be Interfaced virtually with VNC/SSH over WIFI/ethernet, or physically via 3 button/2 LED interface.



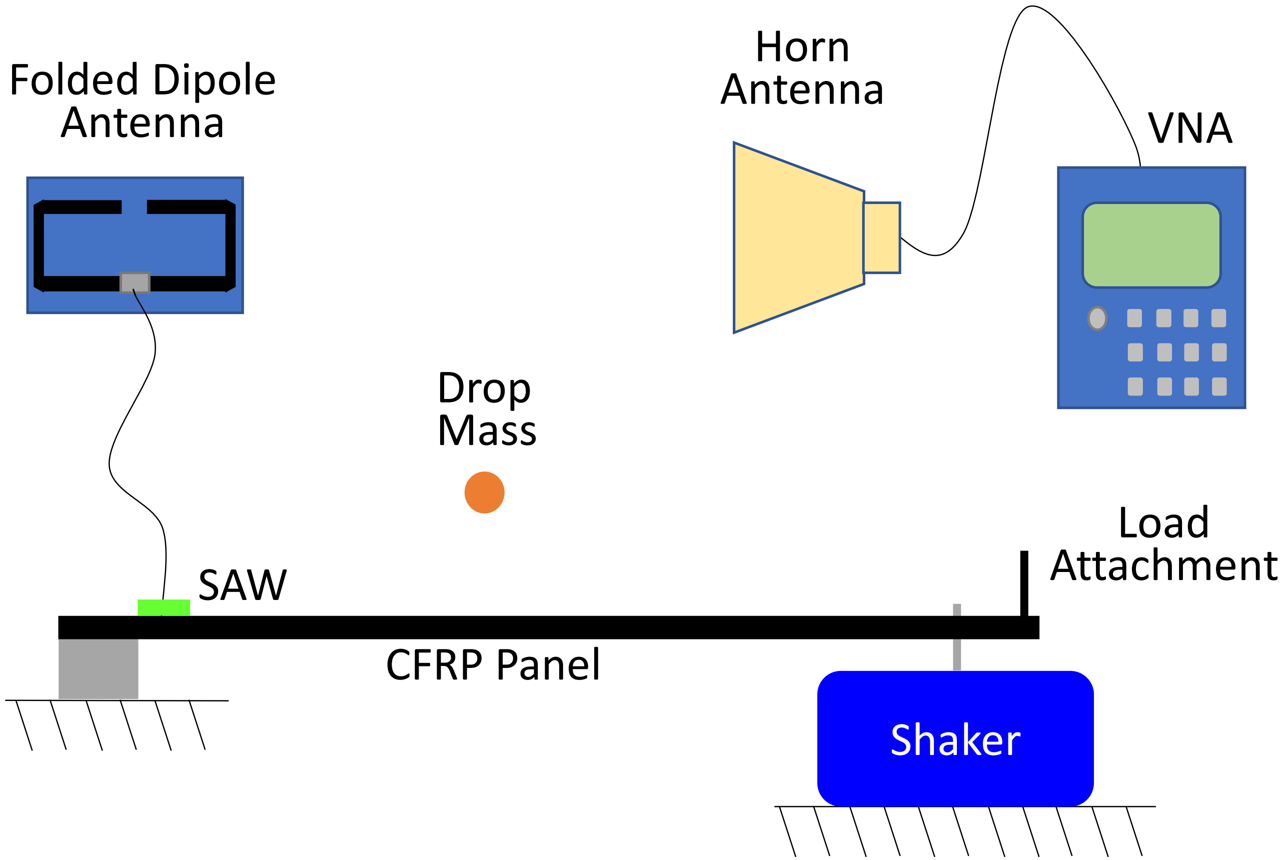
Multifunctional Surface Acoustic Wave (SAW) Sensors for SHM

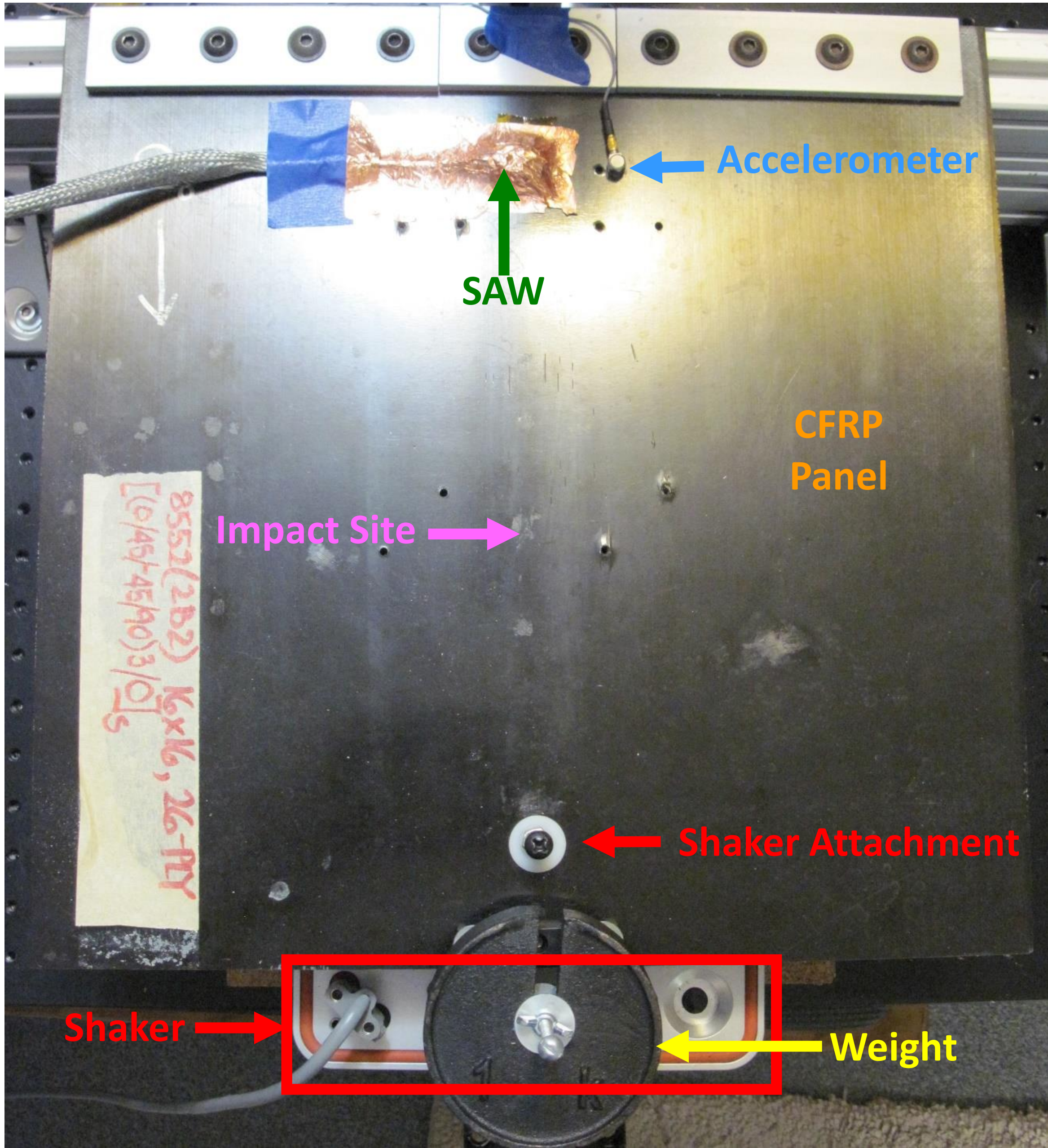
Investigating a passive wireless SAW sensor that simultaneously

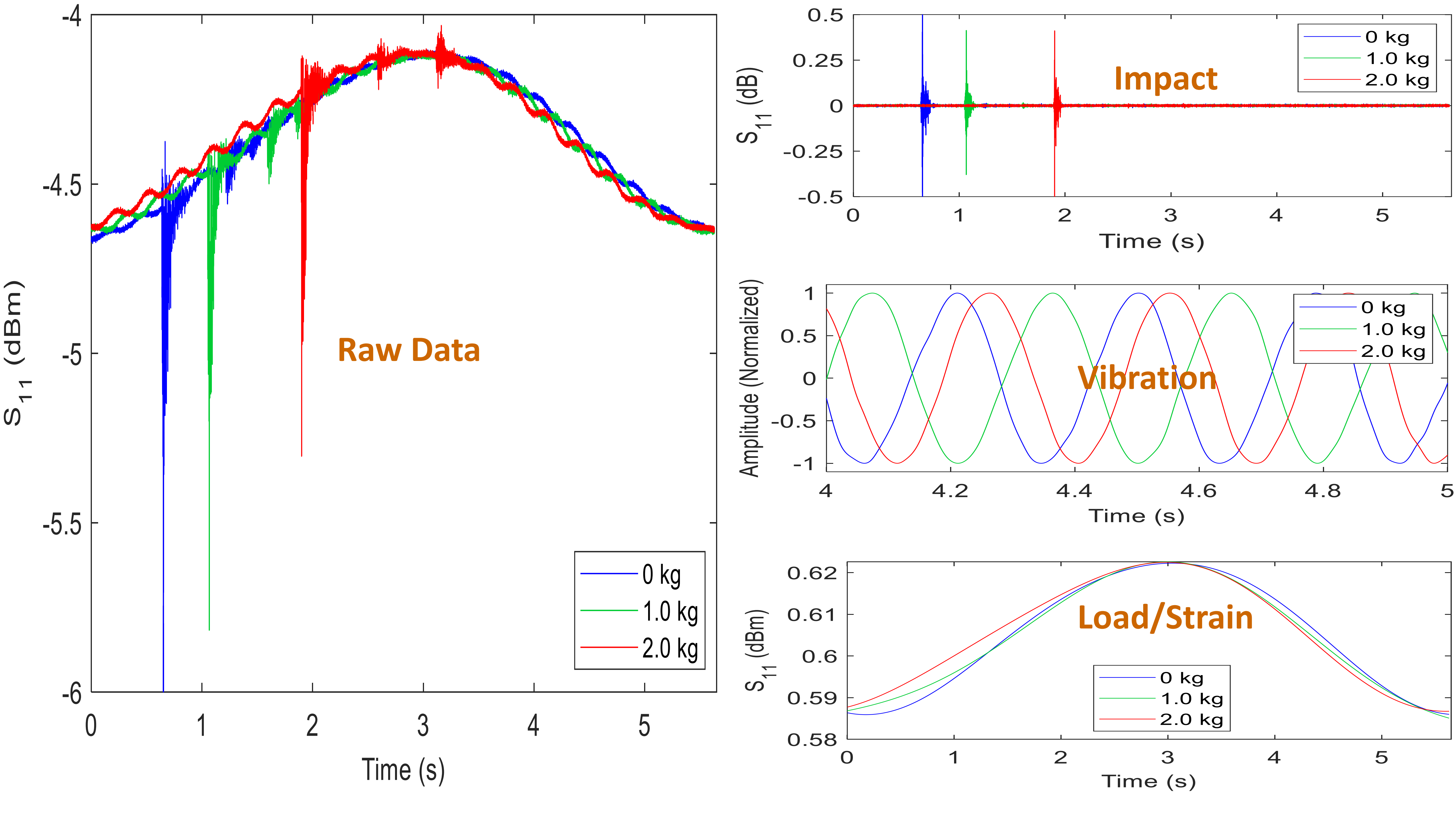
- Measures strain
- Measures vibration
- Detects Impacts

Target Application is composite structures

Multifunctional SAW Test Setup

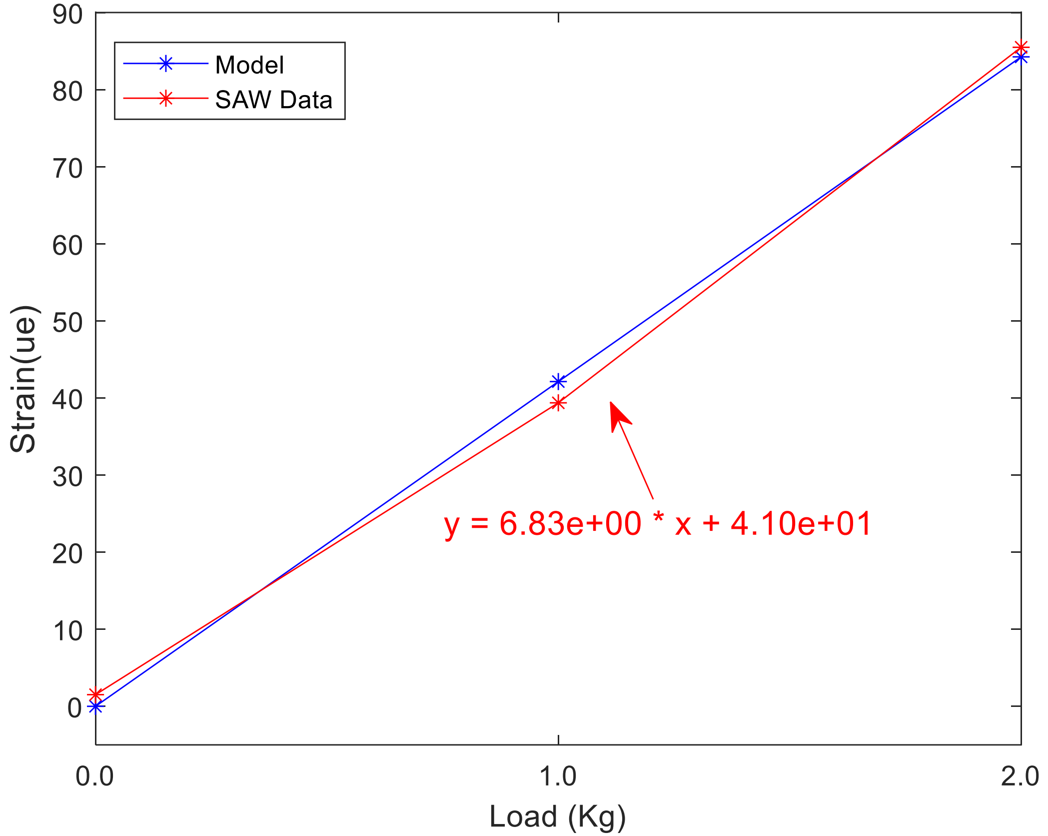




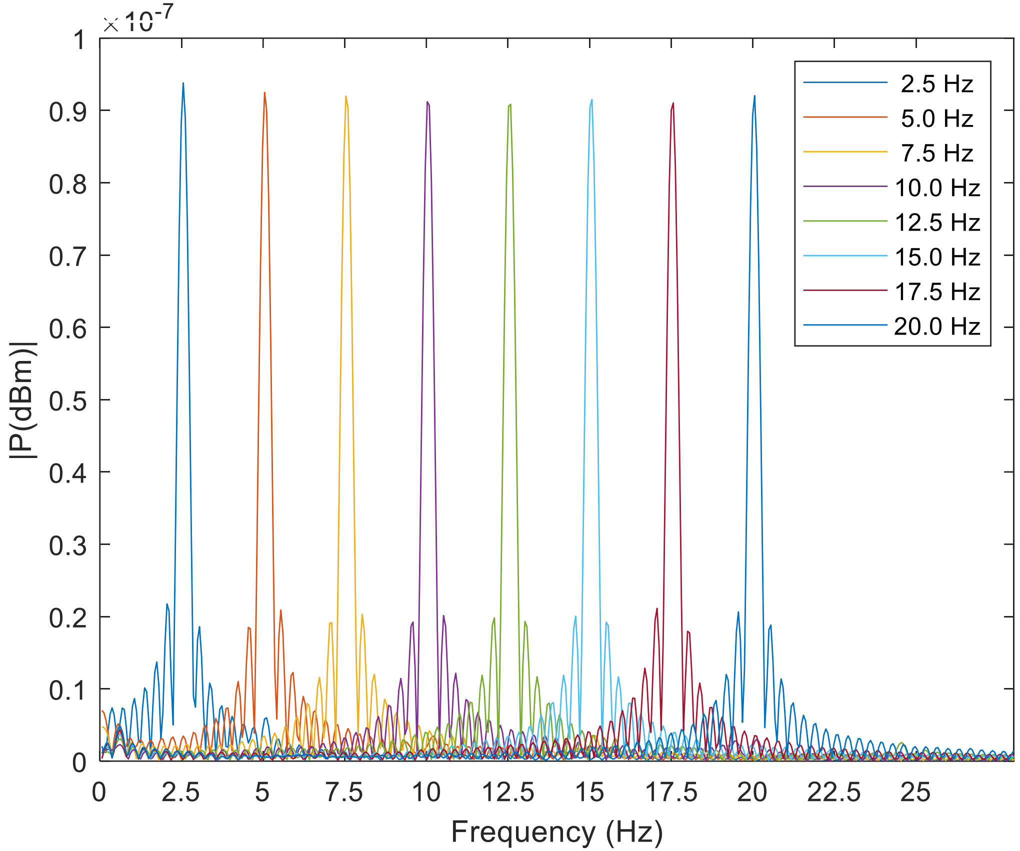


Raw Data
S11 (dBm)
Time (s)
0 kg
1.0 kg
2.0 kg
Impact
S11 (dB)
Time (s)
Vibration
Amplitude (Normalized)
Time (s)
Load/Strain
S11 (dBm)
Time (s)

Multifunctional SAW Strain, Vibration, and Impact Sensor for Composite Aircraft Applications



Strain from the frequency shift data plot (b) on previous slide

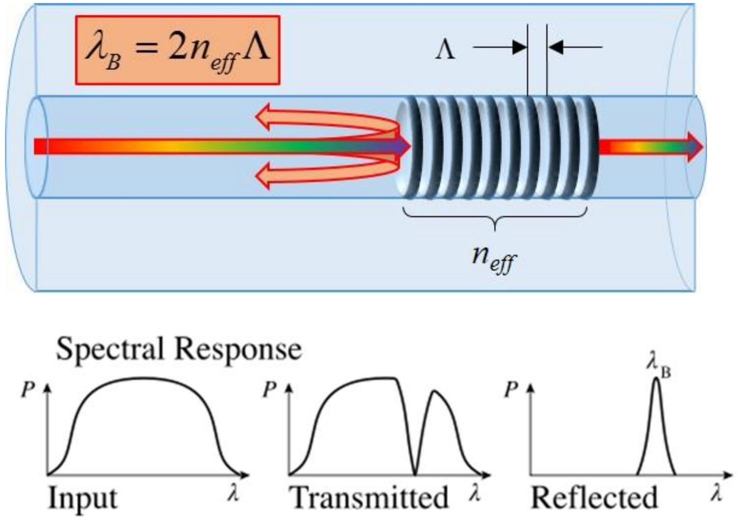


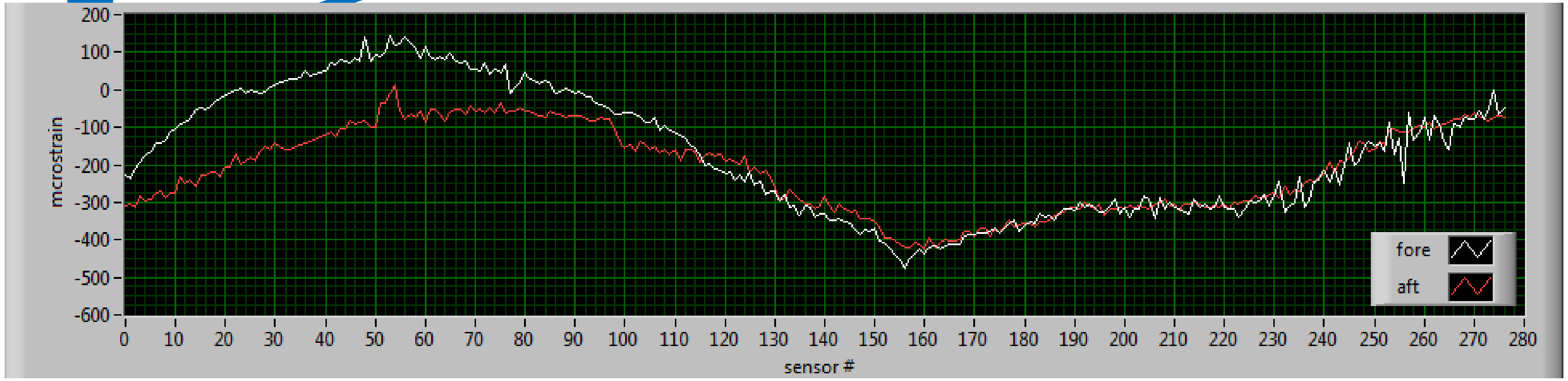
FFT of vibrations using SAW device from 2.5 to 20 Hz.

The frequency shifts from plot on the right can be scaled to match strain.
SAW response to sine wave vibrations (2.5~20 Hz) have been investigated using FFT.

Fiber Optic Sensing

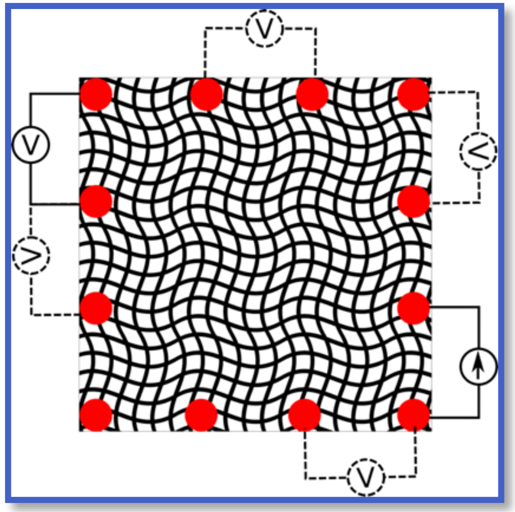
- Fiber optic sensors: lightweight, small form factor (~160 µm diameter), immune to EMI.
- Optical Frequency Domain Reflectometer (OFDR): one sensing cable > 10 m making strain measurements along the fiber at 1 cm sensor spacing.
- Fiber Bragg Gratings (FBG) densely distributed throughout the sensing fiber; direct measurement of fiber “stretch” can measure strain or temperature.





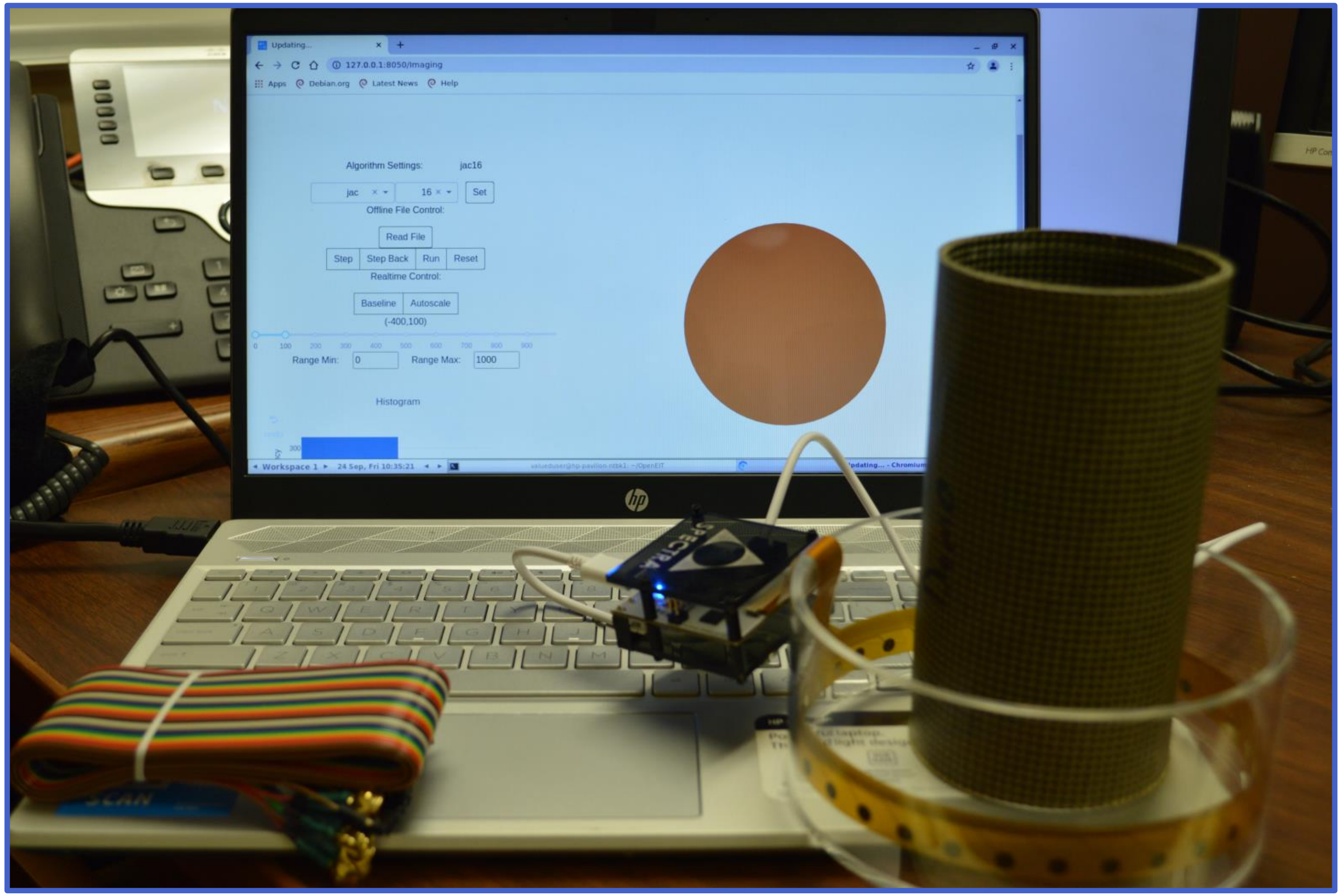
Electrical Impedance Tomography

- A low cost and portable Electrical Impedance Tomography (EIT) device used in biomedical imaging is being evaluated for use in composite damage detection.
- The EIT Kit test device is battery operated with USB and Bluetooth connectivity.
- EIT uses multiple electrodes to map the electrical impedance across a test specimen.
- For composites, these impedance maps may be converted to damage and/or strain distributions.
- PROS: The electrodes can be on the perimeter of a component simplifying the connections while covering a large area than conventional resistive gauges which are spot sensors.
- EIT can potentially accommodate complex sample geometries.
- CHALLENGES: Reconstruction/Interpretation of the electrical response of the materials, including the computational resources and any Finite Element Analysis that may be required in that interpretation.



EIT may enable sensing using component attachment points as the electrodes

EIT Test Set Up



Open-source Python based test software

The Spectra EIT Kit from MindsEye Biomedical that is being considered for testing with composite samples. The system can be battery operated and can support up to 32 sensing channels and can measure up to 160,000 samples per second.

Stitched/Woven Carbon Nanotube Sensors

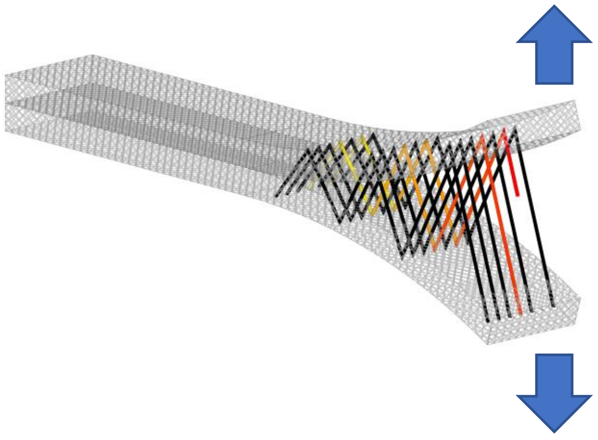
- Carbon-nanotube yarn-based sensors woven or stitched into composite components are also being evaluated.

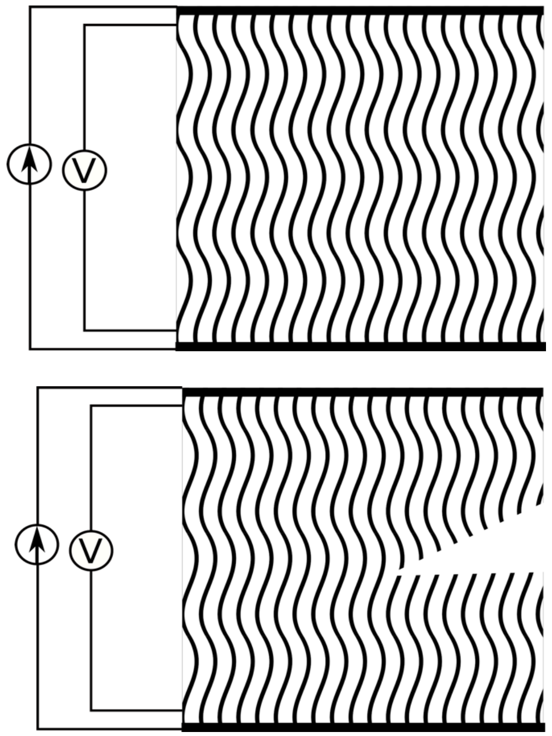
- Carbon nanotube yarns are a lightweight and highly conformable material that can be integrated into the component during the composite fabrication process. Stitching/weaving of the sensors may enable minimal disruption to the structure as well as the manufacturing process.

- Sensing will be through internal deformation and changes in the resistance of the CNT material or network of material or the progressive breakage of selectively pre-tensioned fibers under load (“fuse–style”).

- Sensing through intrinsic changes in the material or stitched/woven network may offer continuous measurements over the load range and lifespan of the component but signals may be difficult to interpret.

- “Fuse-style” sensing offers a complementary approach to un-ambiguously determining damage progression but one that is limited in the number of cycles.





Summary

- Growth of Urban Air Mobility market is anticipated to introduce aircraft of complex and diverse architectures into a crowded environment.
- Acceptance of UAM by the general public will require assurance of safe operations for passengers, crew, pedestrians and urban infrastructure.
- Integration of a sensor suite monitoring the structural health of the aircraft during flight has been proposed to:
  - Detect and report structural damage to crew and maintenance personnel.
  - Transmit the sensor data to a flight management system that is capable of processing information of the structural state relative to the design envelope of the vehicle.
  - Execute a flight maneuver that permits safe flight depending on how the detected damage might influence structural performance.
- The use of multiple sensor types is proposed to provide detection of impact, fatigue, and over-strain events at critical location as well as globally over the aircraft structure.
  - Ultrasound
  - Eddy Current
  - Fiber Optics
  - Electrical Impedance Spectroscopy
  - Integral Carbon Nanotube Sensors