JAMS

JOINT ADVANCED MATERIALS & STRUCTURES
CENTER OF EXCELLENCE

Non-Destructive Evaluation Methods for Detecting Major Damage in Internal Composite Structural Components

Hyonny Kim,
Professor, Dept. Structural Engineering
University of California San Diego

JAMS 2015 Technical Review
March 31 – April 1, 2015

Aircraft Airworthiness & Sustainment Conference 2015
Baltimore Marriott Waterfront, Baltimore MD

Non-Destructive Evaluation Methods for Detecting Major Damage in Internal Composite Structural Components

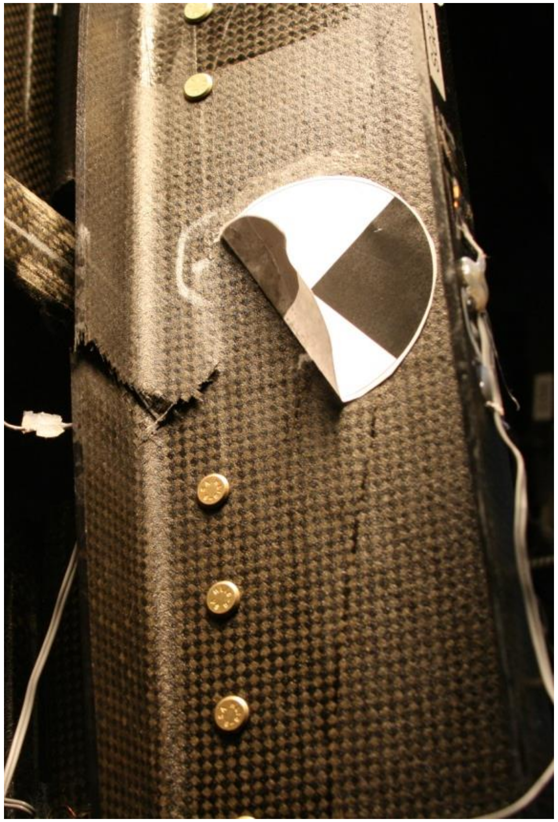
- **Principal Investigators & Researchers**
  - Co-PIs: Professors Hyonny Kim and Francesco Lanza di Scalea
  - Graduate Students
    - PhD: Eric Hyungsuk Kim, Margherita Capriotti, Thompson Nguyen
    - MS: n/a
- **FAA Program Monitor**
  - David Westlund
- **Other FAA Personnel Involved**
  - Rusty Jones
  - Larry Ilcewicz
- **Industry Participation**
  - Boeing, United Airlines, Delta Airlines

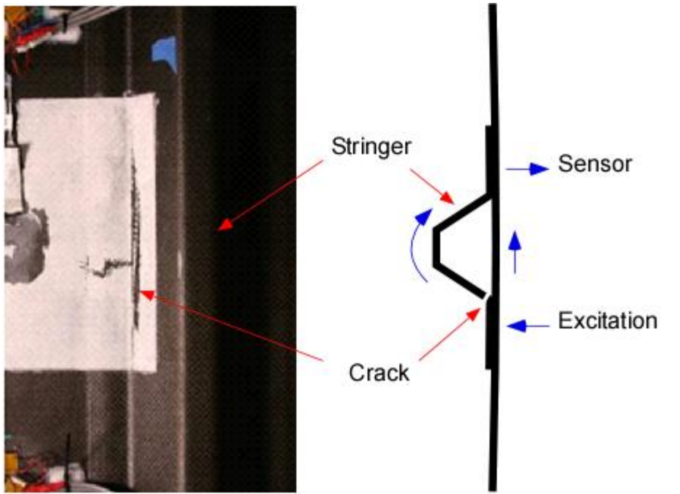
Motivation

- damage from ground service equipment (GSE) can be difficult to visually detect
    - blunt impact damage problem
- key interest: presence of **major damage to internal structure** (frame, shear tie, stringer)
    - cracks usually not detectable by typical one-sided NDE from external skin
- need quick NDE tool to decide if further inspection/action needed

Objectives

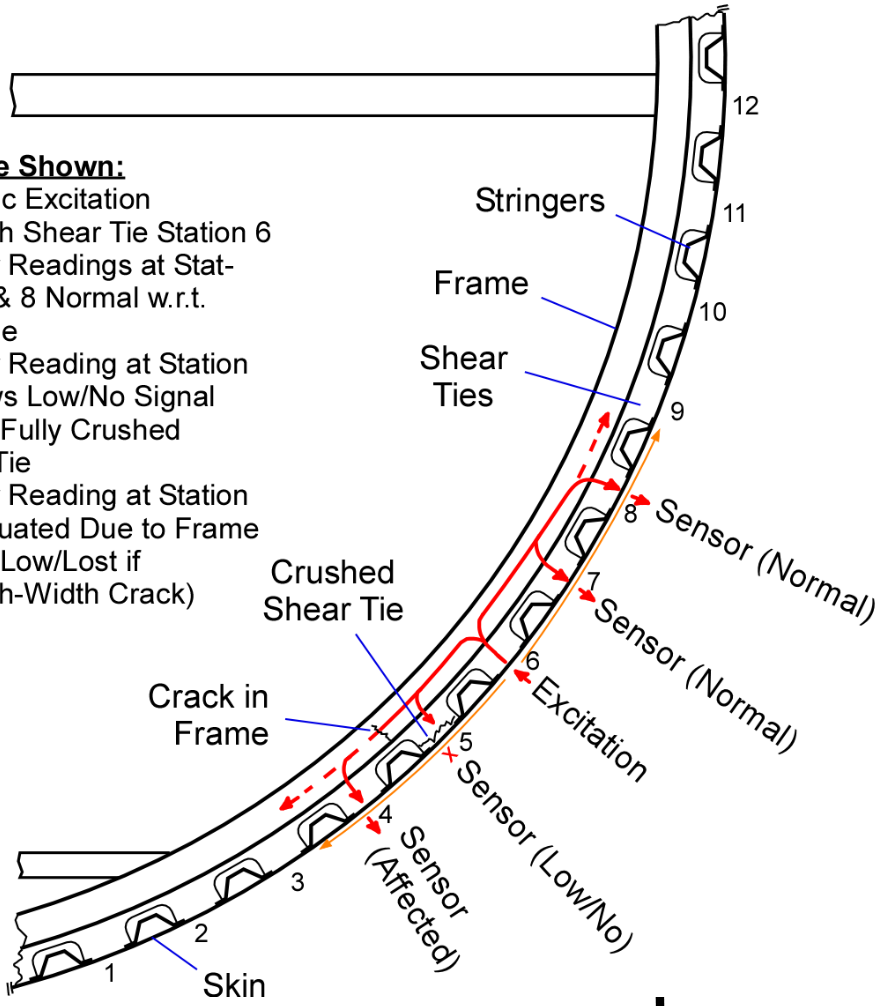
- establish detection method for finding major damage to internal structure:
    - severely cracked frames
    - damaged shear ties
    - stringer heel crack
- detection performed only from exterior skin-side
- system must be "ramp friendly"
- longer-term: relate NDE-measurements with damage location, mode, and size/severity



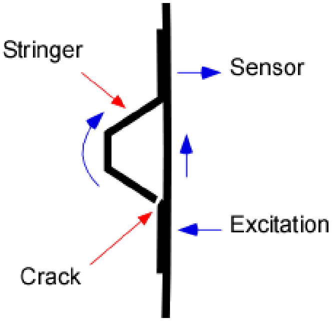


Approach

- pitch-catch guided wave approach
- structures of interest form waveguide paths
- C-frame is like 1D waveguide – wave transmission along length affected by damage
  - excitation → through skin → in through shear tie → travel along frame → out through various shear ties → through skin → sensor
  - broken shear tie and frame will attenuate/modify signal
- key issues:
  - dominant frequencies associated with waves/modes sensitive to damage
  - complex geometry, many interfaces
- stringer heel crack – wave propagation through skin and stringer paths



Example Shown:
- Acoustic Excitation Through Shear Tie Station 6
- Sensor Readings at Stations 7 & 8 Normal w.r.t. Baseline
- Sensor Reading at Station 5 Shows Low/No Signal Due to Fully Crushed Shear Tie
- Sensor Reading at Station 4 Attenuated Due to Frame Crack (Low/Lost if Through-Width Crack)



Summary of Activity

Since project start in June 2014:

- survey of damage to previously-tested specimens
- guided wave tests on damaged C-frames
- C-frame specimens – new fabrication
- wave transmission measurement methodology – excitation, sensors, dispersion curve
- FE wave propagation simulation development

Outline

- Composite Panel and Frame GUW Inspections
- Wave Propagation Methodology Development
- Conclusions, Benefits to Aviation, and Future Work

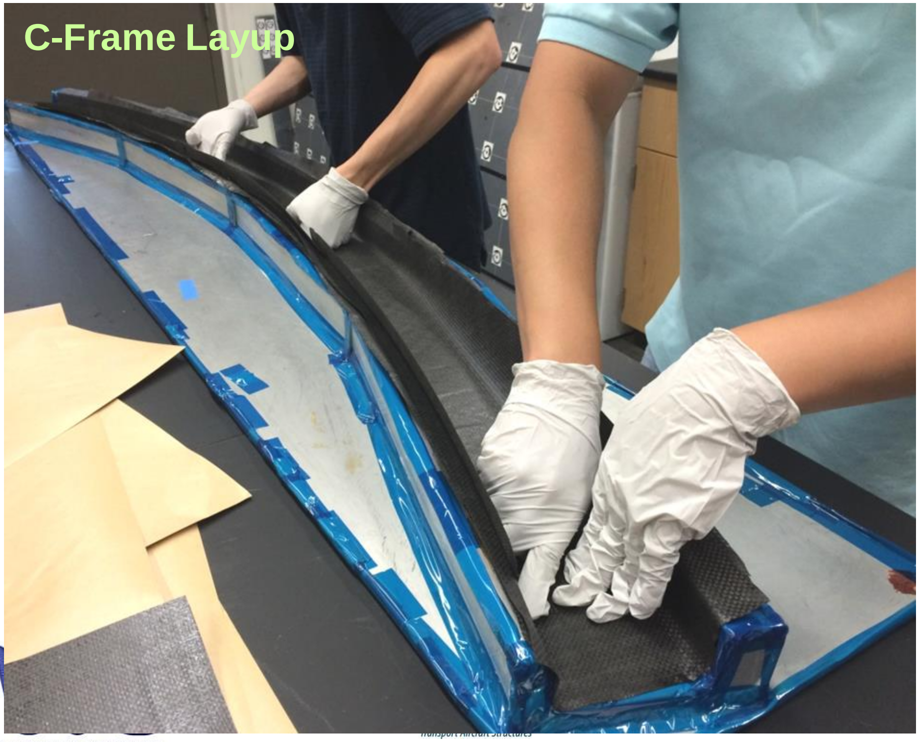
Test Specimens

Use Existing Damaged Specimens

- previously-tested specimens from FAA project “Impact Damage Formation on Composite Aircraft Structures”
- FrameXX panel series
  - C-frame crack
  - shear ties crushed
- StringerXX panel series (stringer-only panels)
  - stringer-skin disbonding
  - stringer heel crack
  - shear ties crushed

New Specimens

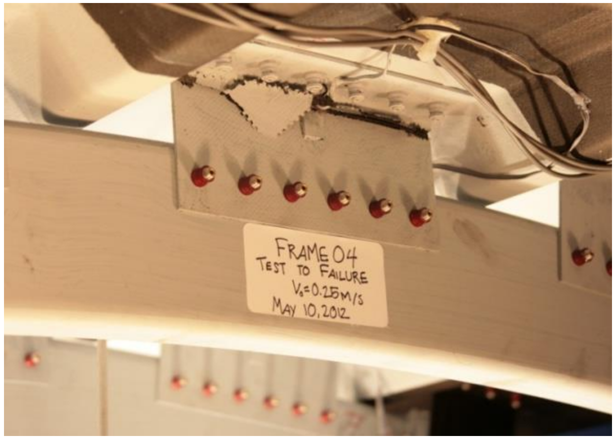
- C-frames – pristine stand-alone frames
  - 3 new frames fabricated
  - 1 previously-fabricated “spare”
- shear ties – qnty ~16 available “new” untested



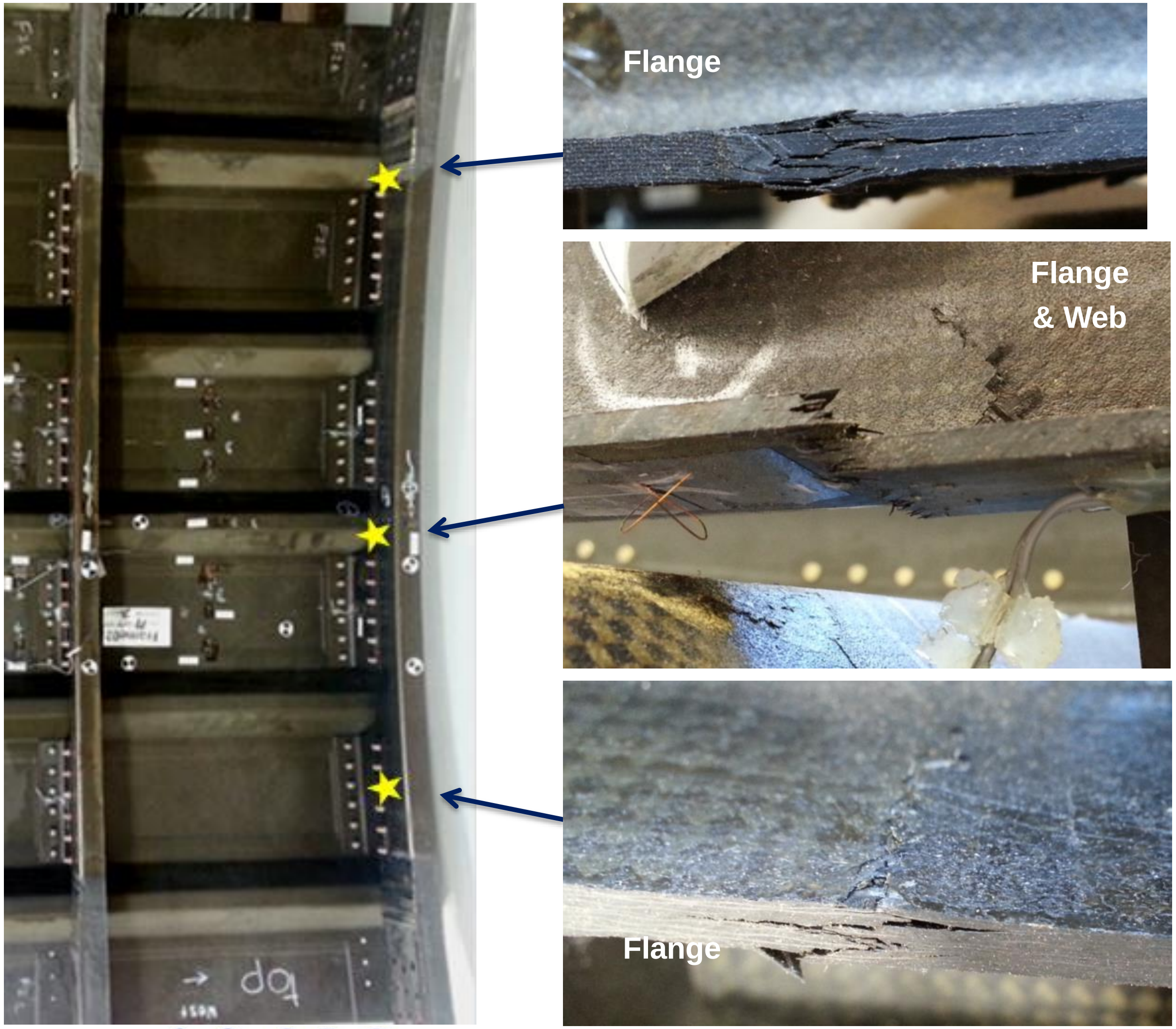
Existing Specimens – Damage Survey

Blunt Impact Damage in Existing Specimens – use for NDE Tests

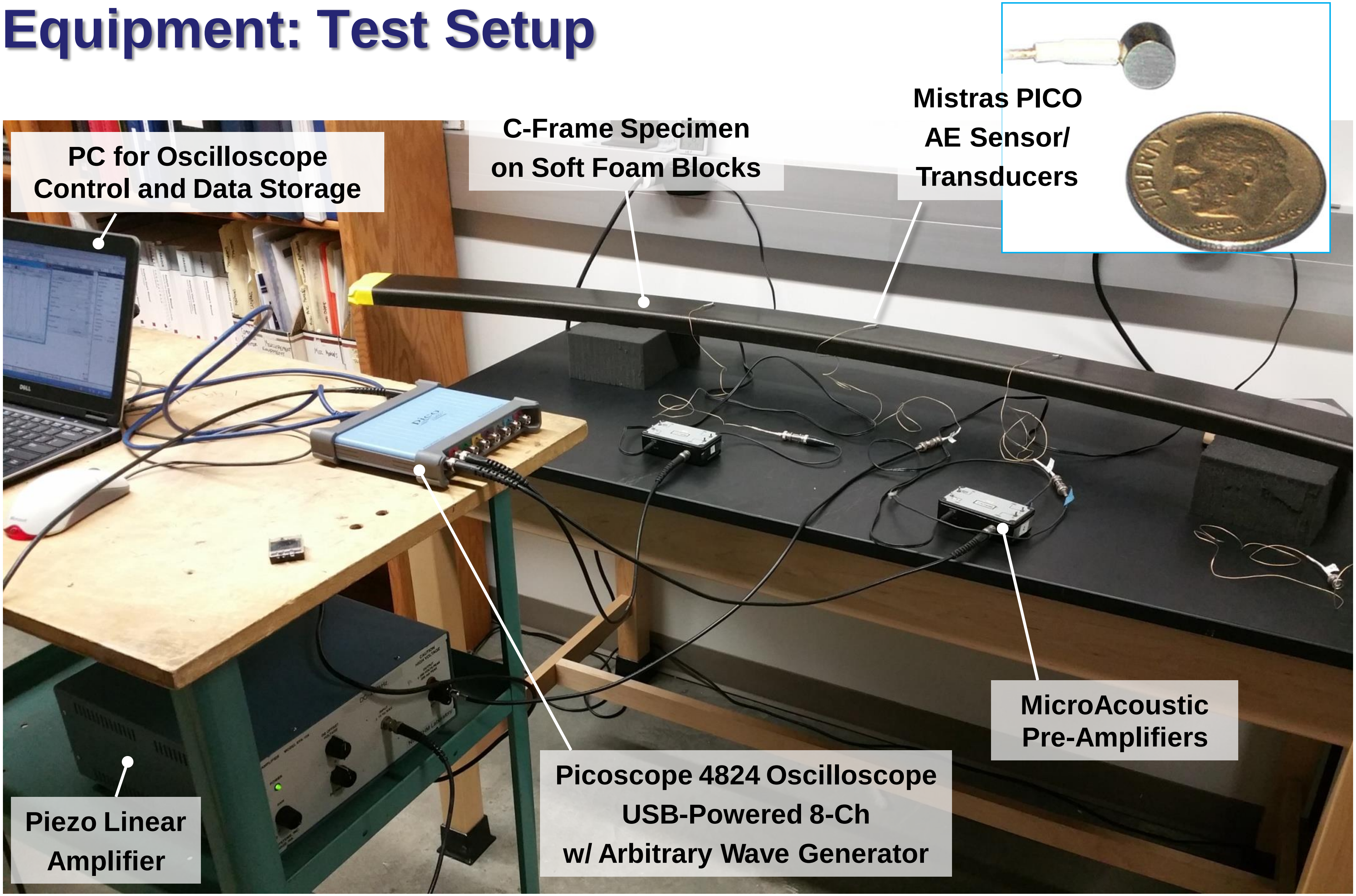
- **partially-cracked frame** available in panel Frame02
- **cracked/crushed shear ties** in all specimens (Frame01 to Frame04)
- **stringer disbonds** in panel Stringer02
- **stringer heel crack** in panel Stringer05



Partially-cracked frames – from specimen Frame02



Equipment: Test Setup



PC for Oscilloscope Control and Data Storage

C-Frame Specimen on Soft Foam Blocks

Mistras PICO AE Sensor/ Transducers

MicroAcoustic Pre-Amplifiers

Picoscope 4824 Oscilloscope USB-Powered 8-Ch w/ Arbitrary Wave Generator

Piezo Linear Amplifier

Seeking equipment allowing assembly of “ramp-friendly” portable system.

Equipment: Signal Measurement Comparison

Part of project effort is to be sure methodology is compatible with “ramp-friendly” operations.

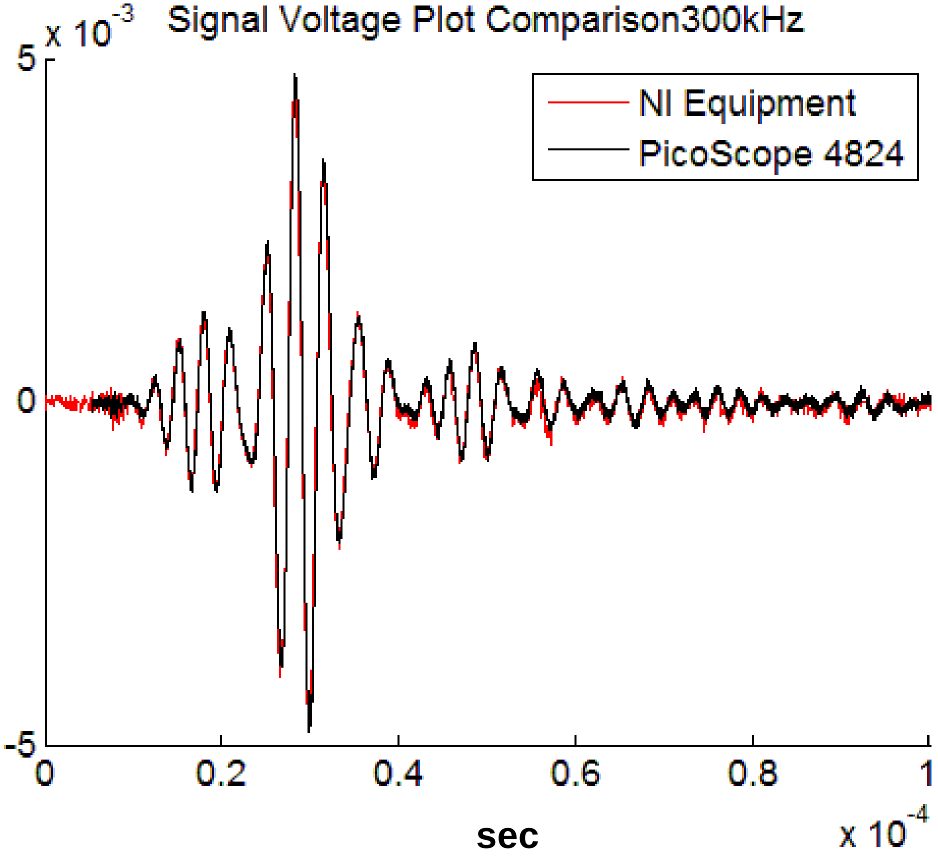
→ seeking field-portable portable set of equipment

Easily portable Picoscope 4824 oscilloscope

Comparison of dynamic signals measured by:

- National Instruments PXI 5122 Digitizer*
- Picoscope 4824

** NI PXI system large and costly bench/cart based system requiring 120 VAC power and powerful computer able to run Labview software.*



Both measured signals identical → all dynamic measurements made by Picoscope oscilloscope.

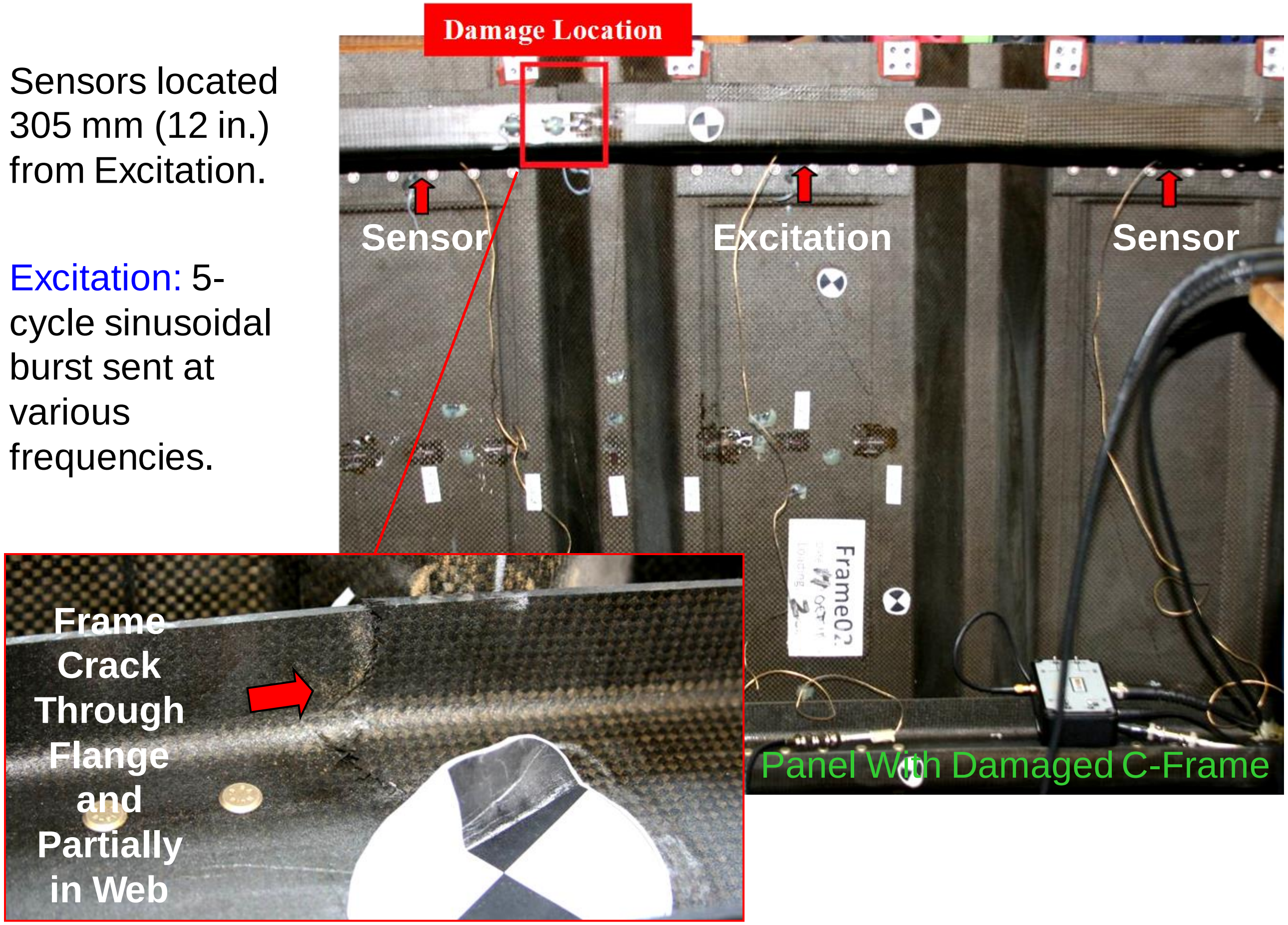
Panel and Frame Initial GUW Tests

Guided ultrasonic wave (GUW) measurement through:

- pristine stand-alone C-frame
  - no damage or holes/geometric effects → get baseline
- damaged C-frame (installed in panel ID: Frame02)
  - cracks, fasteners, contact/connection to other members

Sensors located 305 mm (12 in.) from Excitation.

Excitation: 5-cycle sinusoidal burst sent at various frequencies.



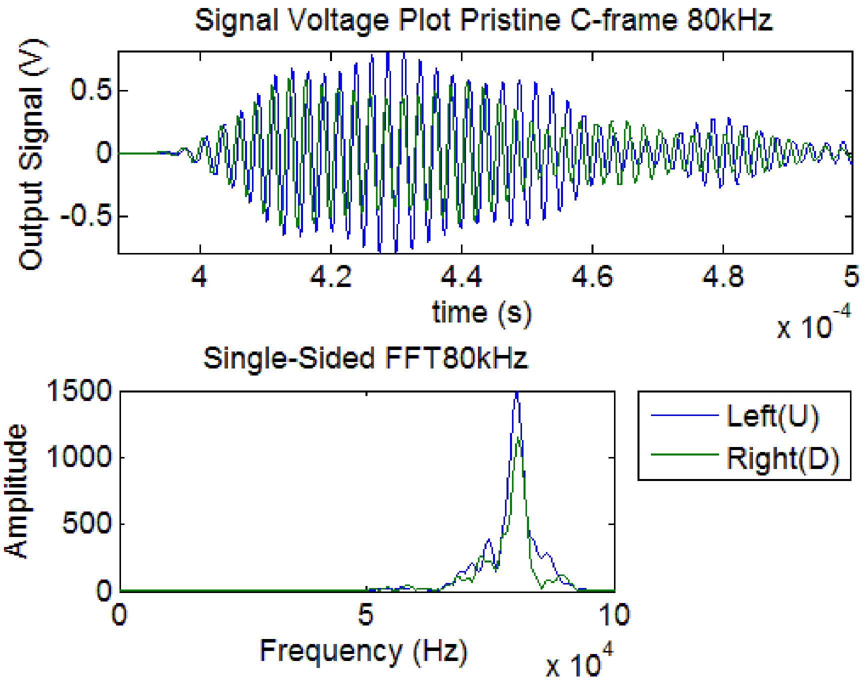
Results: Panel and Frame Initial GUW Tests

Frequency sweep conducted to find dominant frequencies (80 kHz shown below).

Expect: presence of damage → attenuation of signal.

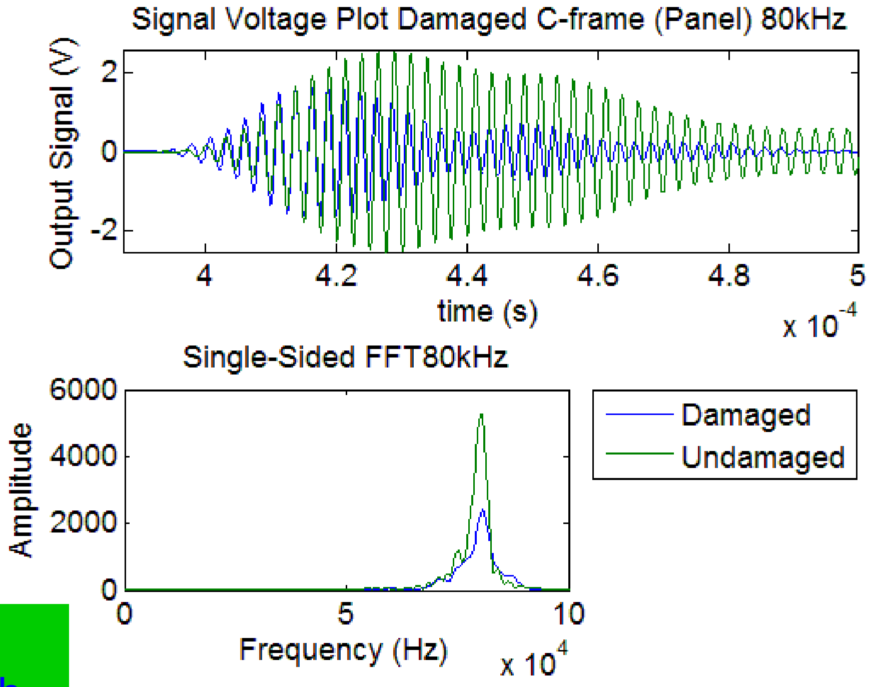
Pristine stand-alone C-frame:

- small difference measured for left vs. right sensor – due to internal layup/splice effects (needs further investigation)



Damaged C-frame installed in panel:

- significant attenuation (55%) through damaged path
- ***cracked C-frame flange detectable*** for sensors directly mounted to frame – need to test sensing through skin



Next Steps: (i) fundamental studies to estimate damage info (mode, size), (ii) excite/sense through skin - account for complex geometry, fasteners.

AMTAS Advanced Materials in Transport Aircraft Structures

Outline

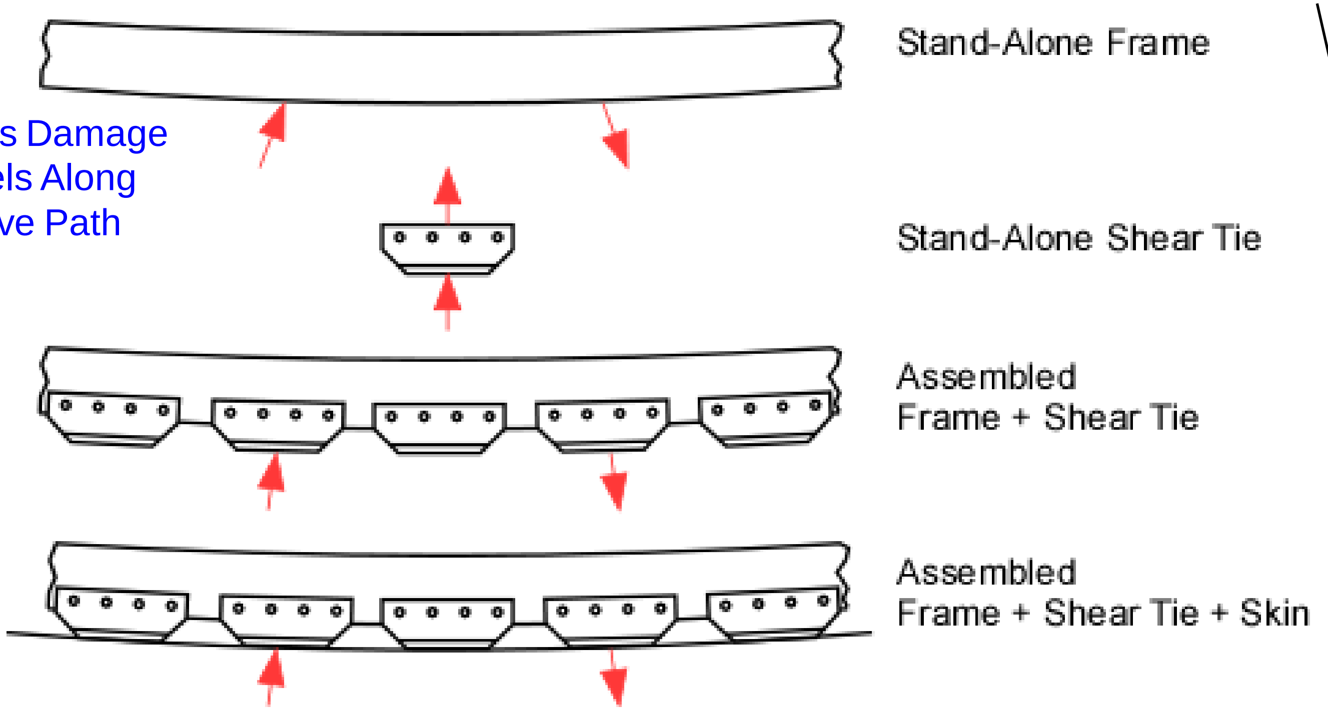
- Composite Panel and Frame GUW Inspections
- Wave Propagation Methodology Development
- Conclusions, Benefits to Aviation, and Future Work

Wave Propagation Measurement Methodology

- successful damage detection by GUW influenced by:
    - equipment choice; sensor deployment/positioning details
    - dominant wave modes in structure and accompanying frequencies
    - method of excitation – defines frequency content
    - signal processing algorithms

Address for each stage of increasing complexity

- systematic build-up of complexity



Various Damage Levels Along Wave Path

Stand-Alone Frame

Stand-Alone Shear Tie

Assembled Frame + Shear Tie

Assembled Frame + Shear Tie + Skin

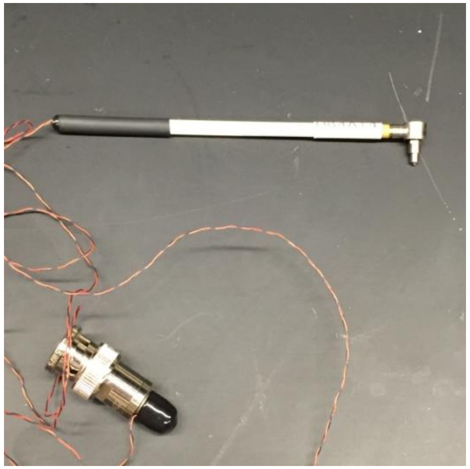
<u>Need stable methodology</u>: develop on simple well-known structural platform (aluminum plate)

Wave Propagation Measurement Methodology

Aluminum Plate Baseline

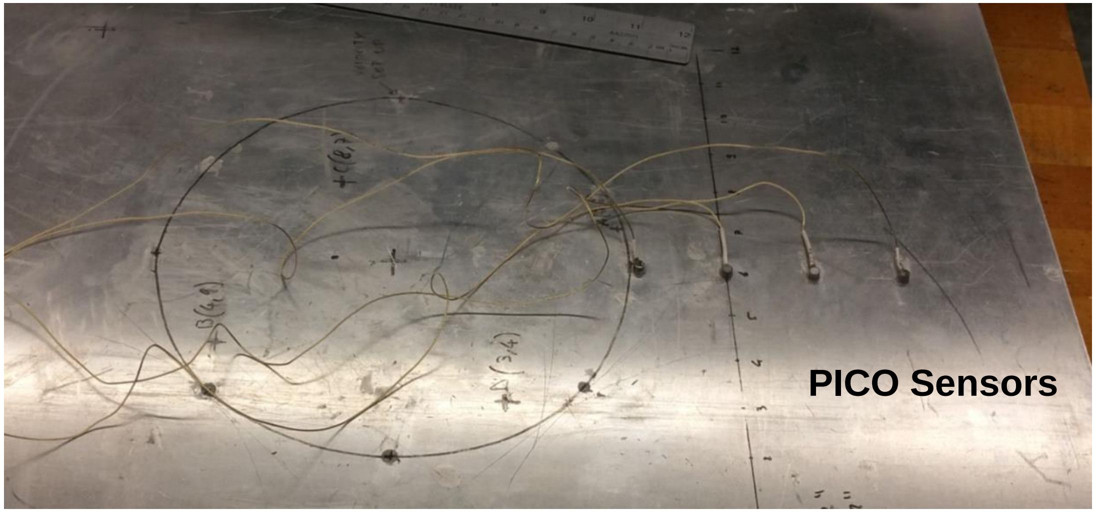
- Establish methods using well-known simple baseline structure → then apply methods to complex composite C-frame components and assemblies.

- Excitation type
  - miniature impulse hammer (Piezotronics)
  - pencil lead break
- Sensors
  - PICO sensors (Mistras)
  - air-coupled sensors (MicroAcoustics) – non-contact



Miniature Impulse Hammer

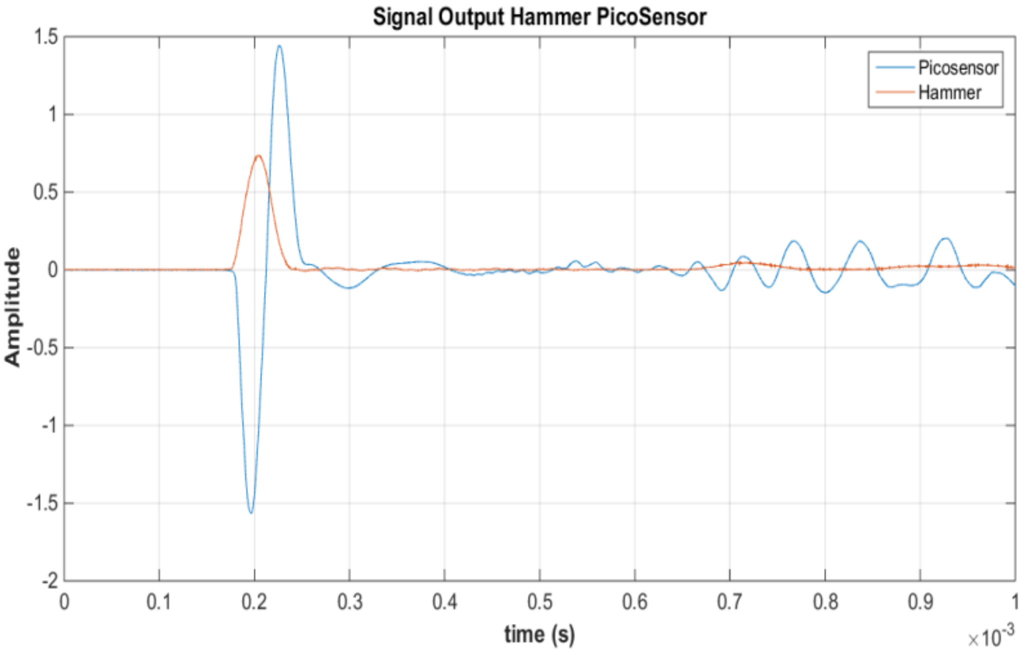
Test out combinations of excitation and sensors

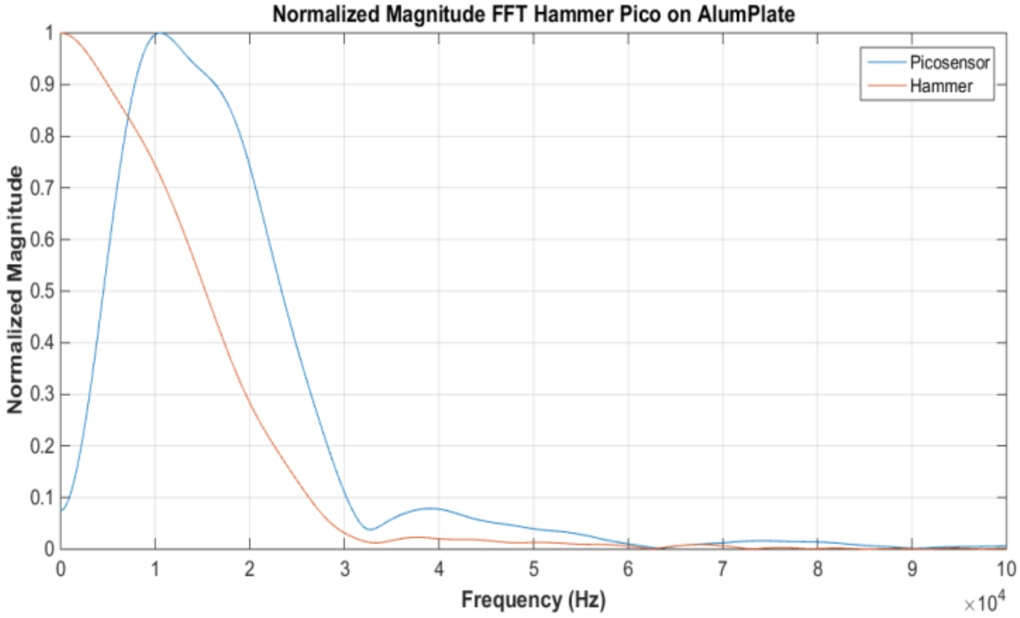


PICO Sensors

Excitation - Impulse Hammer

- excitation: PCB Piezotronics Miniature Impulse Hammer
    - 4.8 g mass
    - measures force vs. time pulse
- wave-measurement sensors:
    - PICO
    - air-coupled
- impact force vs. time pulse defines frequency content of excitation
    - affected by both hammer and target dynamics
    - more compliant target → longer-duration pulse (lower frequency content)
- **summary:**
    - excitation up to 20 kHz (for aluminum panel impact)
    - air-coupled measurement attenuated above 10 kHz
    - use direct-contact sensors

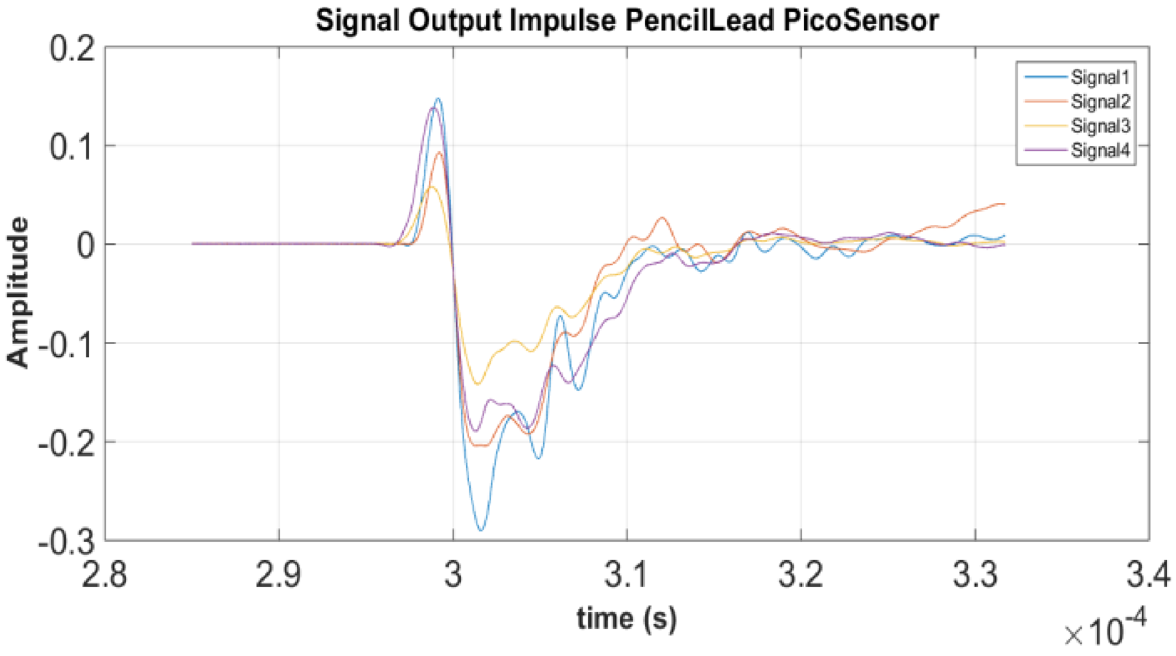


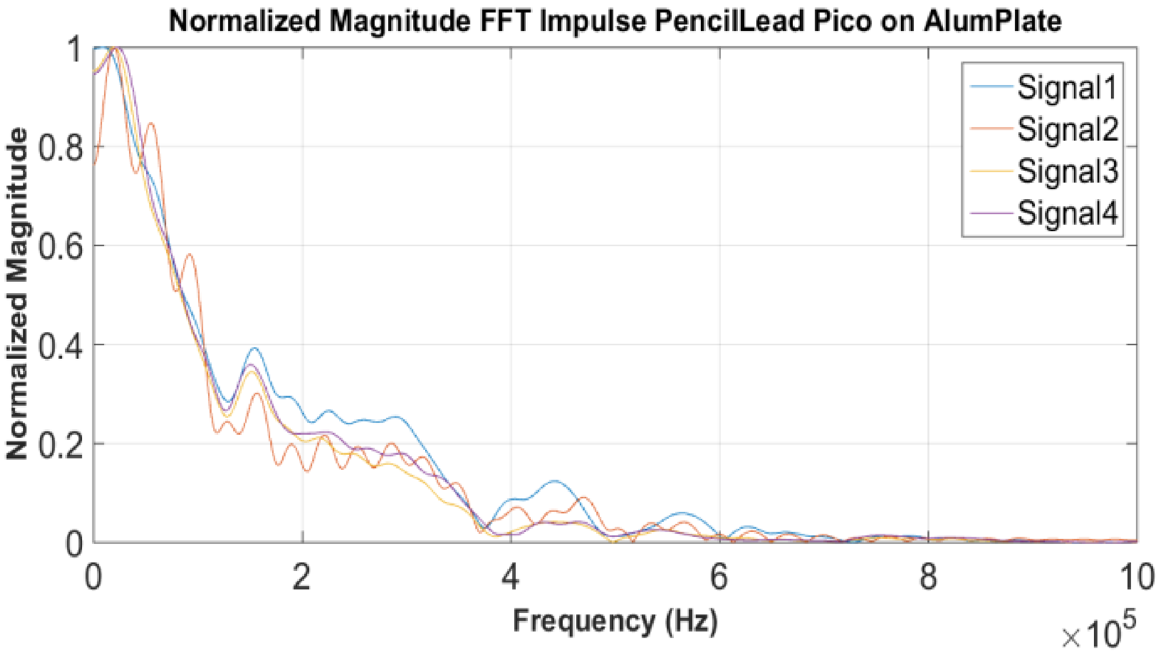


Excitation

Pencil Lead Break

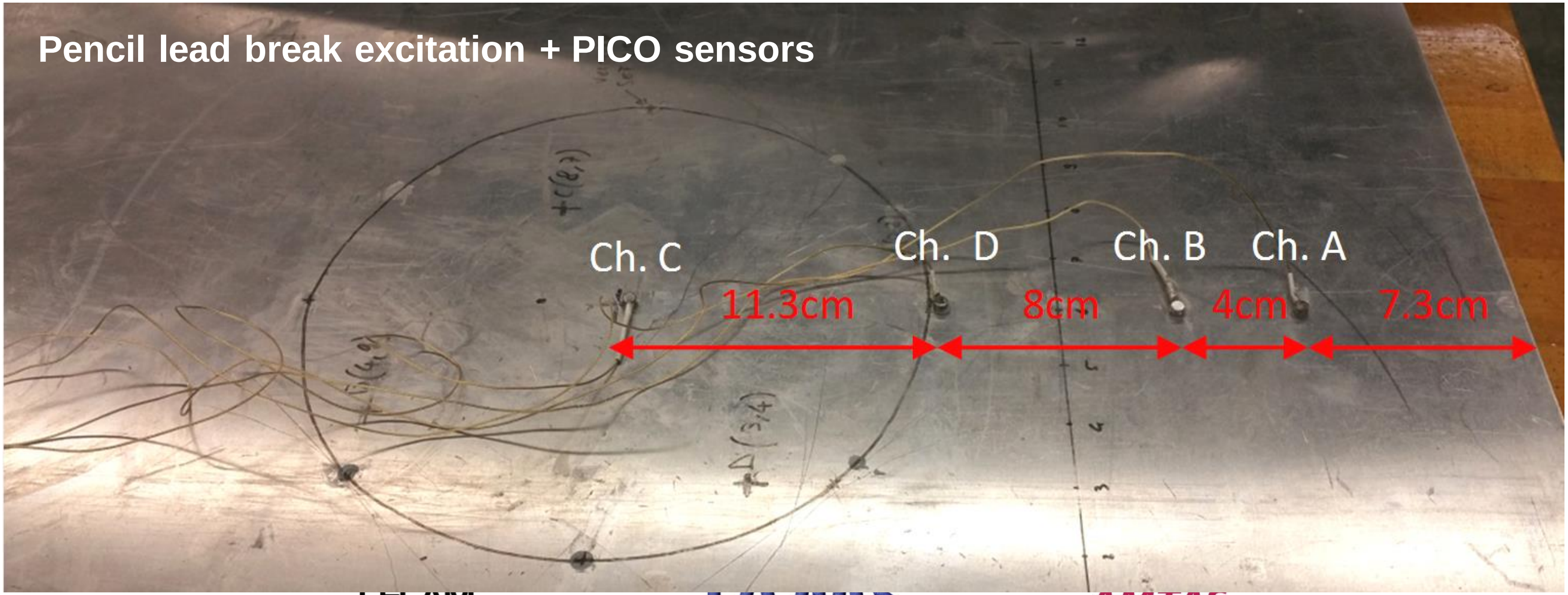
- excitation: mechanical pencil lead: 0.3 and 0.5 mm HB hardness
- wave-measurement sensors:
  - PICO
  - air-coupled
- breaking lead onto structure imparts broadband excitation
- **summary:**
  - excitation - broadband up to 300 kHz
  - issue: low intensity
    - limits distance of wave travel
    - too low for air-coupled sensors





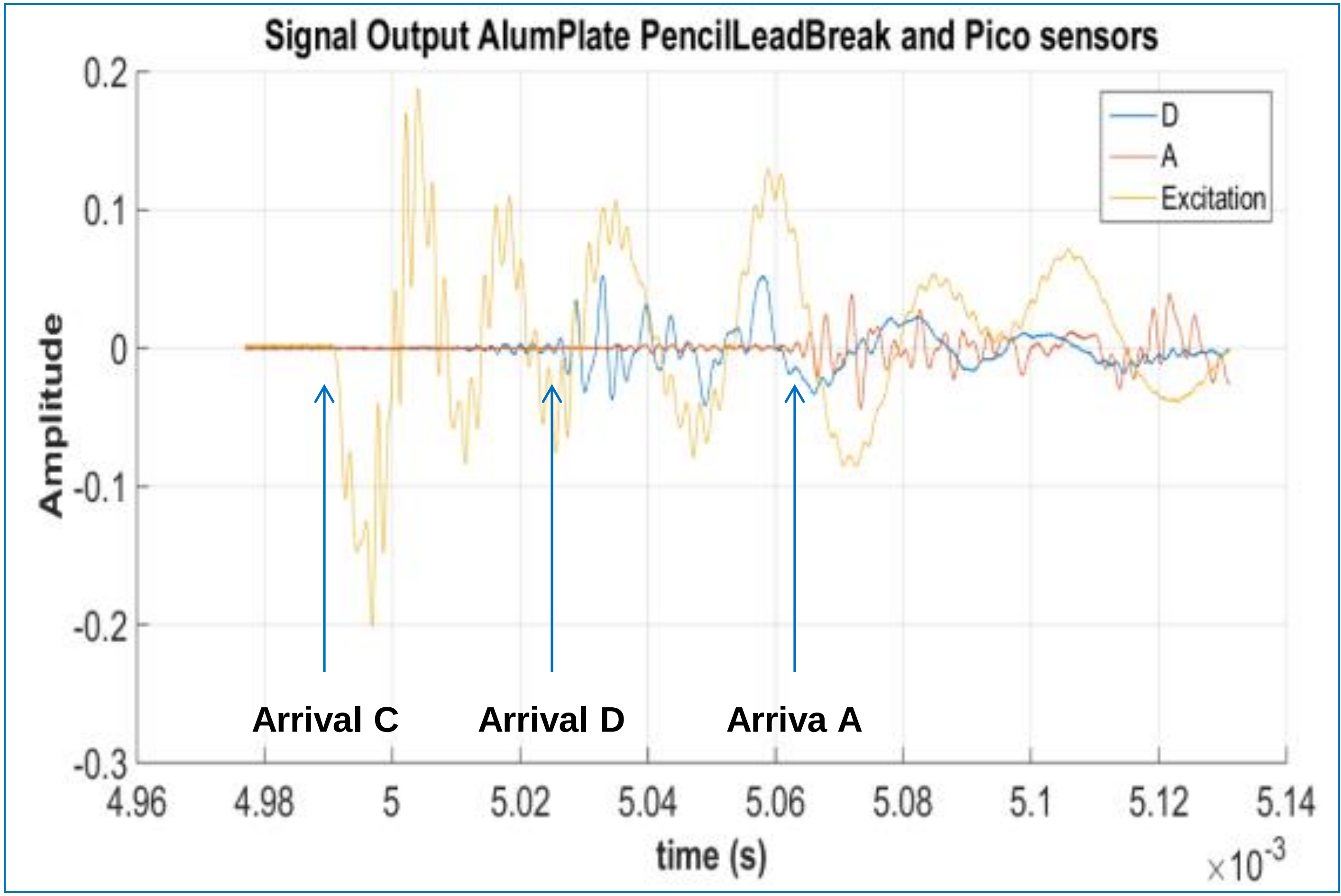
Dispersion Curve Measurement I

- seeking to experimentally measure dispersion curves
  - describes fundamental guided wave behavior through structure
    - propagating modes
    - frequencies
    - attenuations
- 1st establish best practice/technique with well-known simple structure (aluminum plate)


Pencil lead break excitation + PICO sensors

Dispersion Curve Measurement II

Time domain measurement from PICO sensors (wave transit time visible).



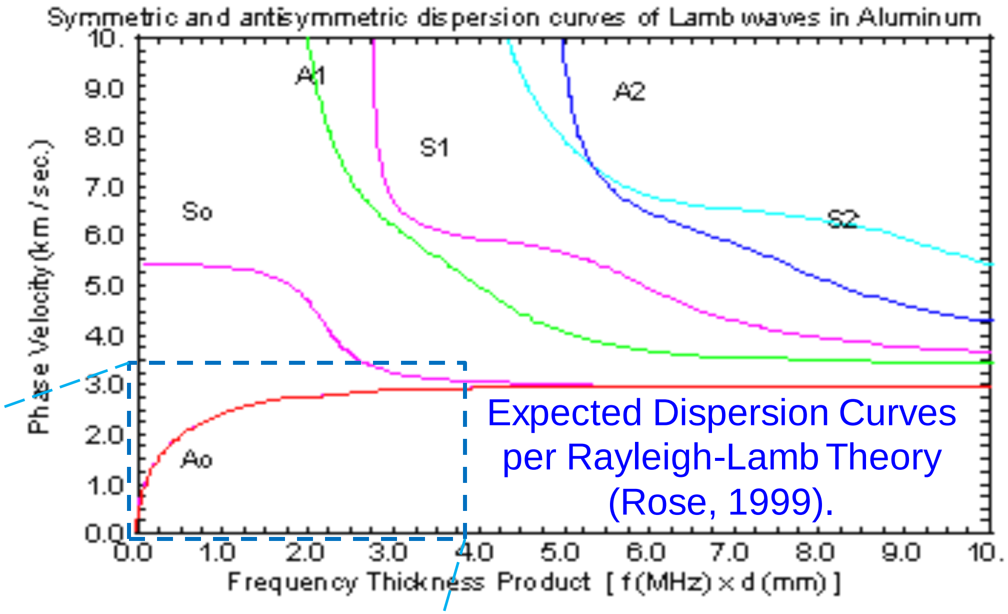
Calculate:

- FFT Amplitude Plot
- Phase Spectra Plot

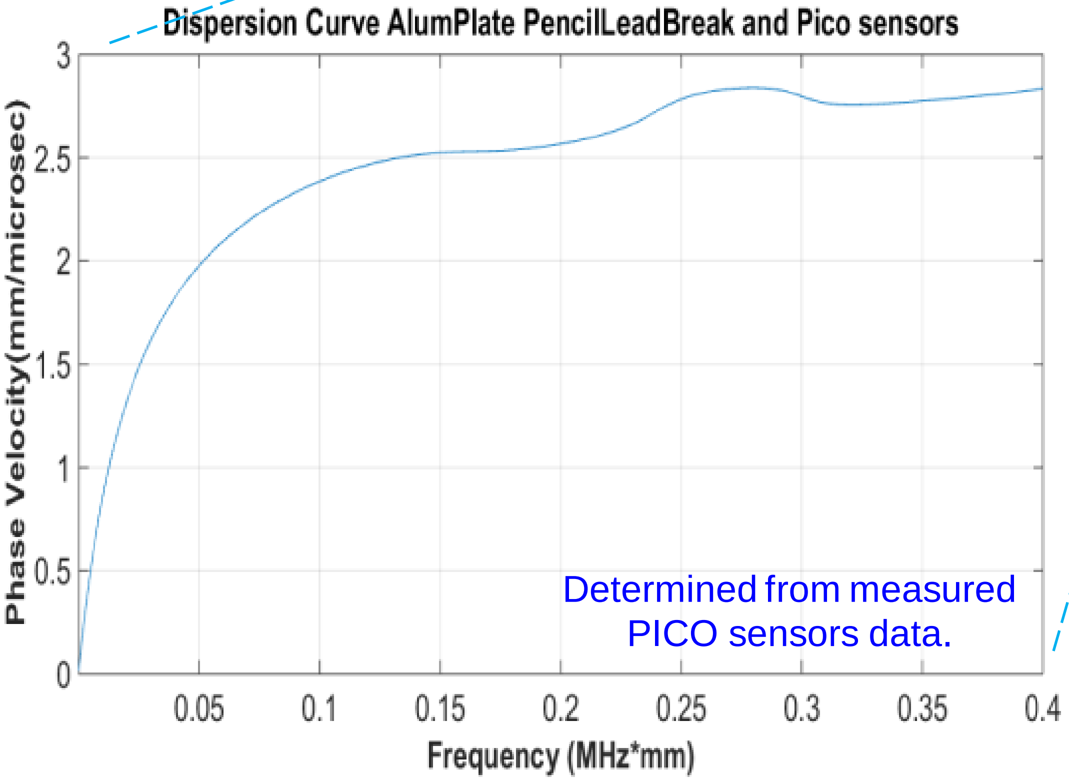
Dispersion Curve Plot

Dispersion Curve Measurement Results

Fundamental flexural mode Ao – extracted by phase-difference method.



Expected Dispersion Curves per Rayleigh-Lamb Theory (Rose, 1999).

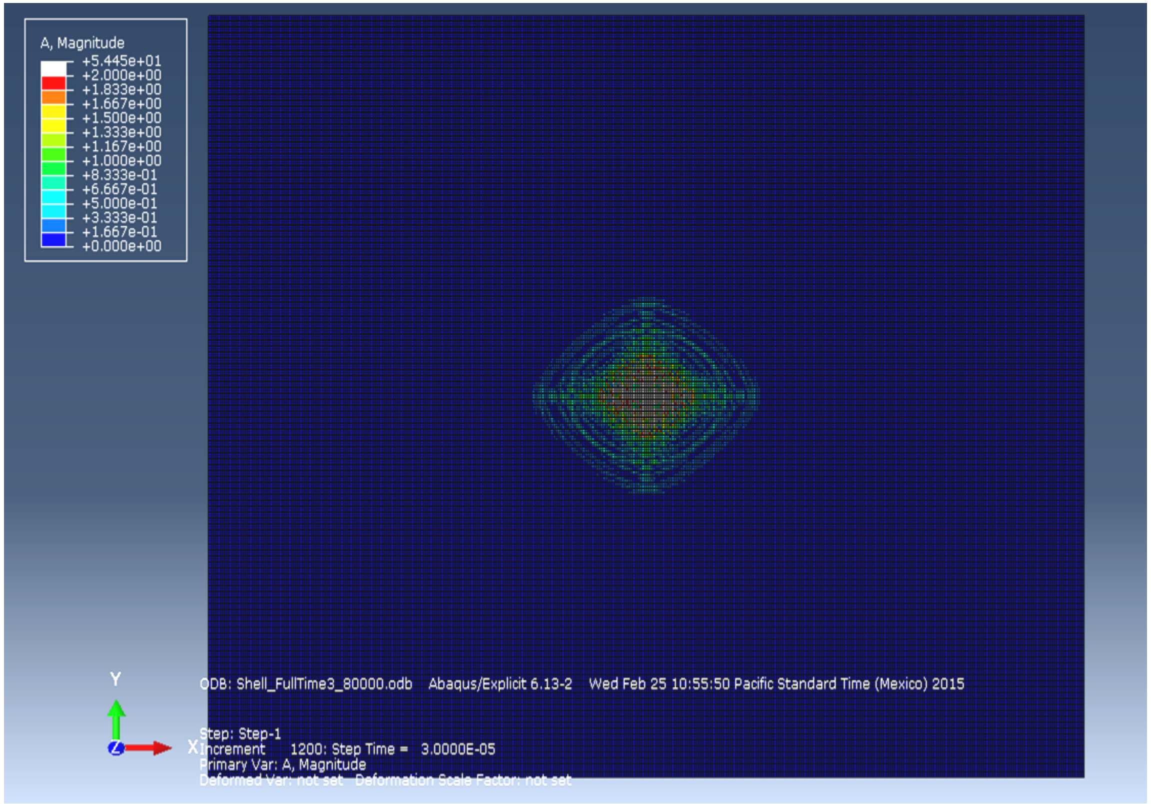


Determined from measured PICO sensors data.

Next: apply methodology to composite C-frame.

Finite Element Simulation of Wave Propagation I

- seeking to establish FE based simulation to:
    - study wave propagation through complex geometry
    - find dominant frequencies and associated modes (to select for best sensitivity to damage location)
    - attenuation of wave due to damage
- 1st set up model of well-known simple structure (aluminum plate) → apply to composite C-frame & assembled panel



ODB: Shell_FullTime3_80000.odb   Abaqus/Explicit 6.13-2   Wed Feb 25 10:55:50 Pacific Standard Time (Mexico) 2015

Step: Step-1
Increment   1200: Step Time =   3.0000E-05
Primary Var: A, Magnitude
Deformed Var: not set   Deformation Scale Factor: not set

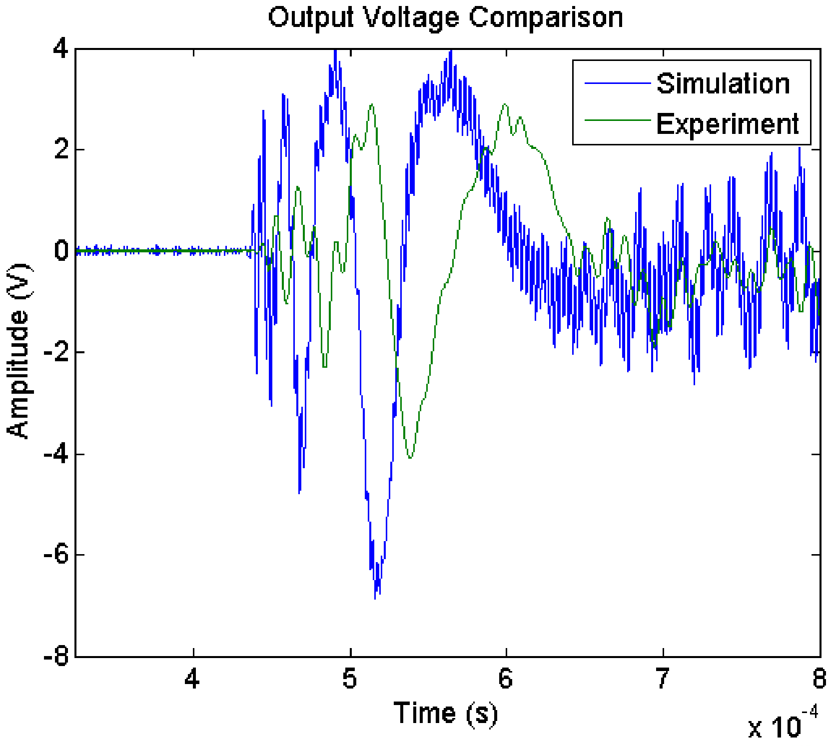
Model Details:

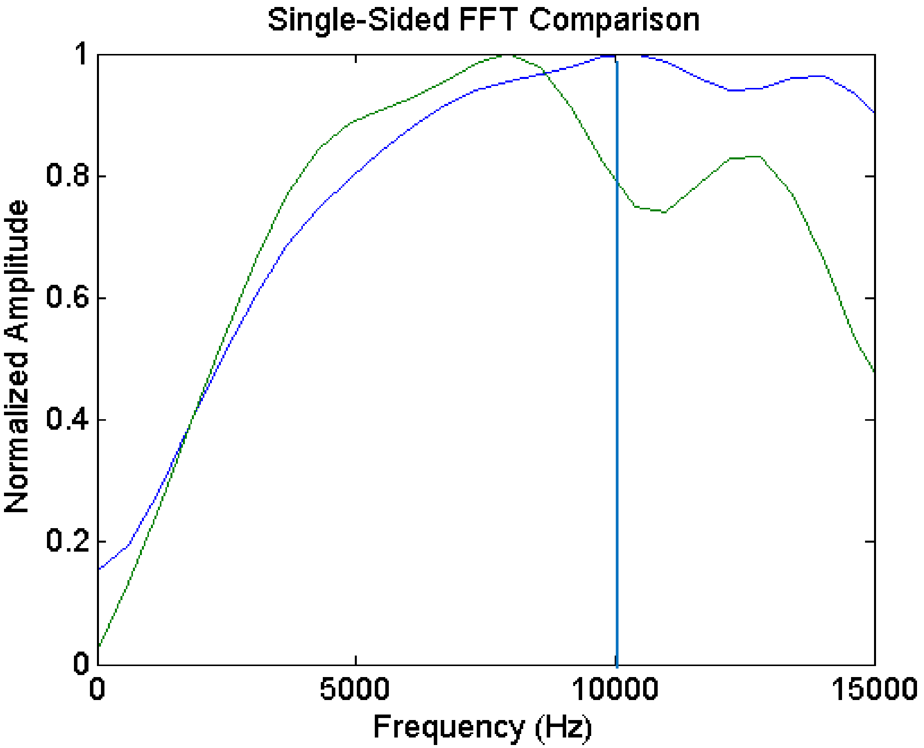
- Abaqus/Explicit dynamic simulation

- S4R thin shell with 1.59 mm element size for 610 x 610 mm overall plate dimensions

Finite Element Simulation of Wave Propagation II

- compare acceleration data from model vs. experiment
  - magnitude and general trend matches
  - improvement needed: model details of hammer impact
- FFT comparison: matches up to ~10 kHz
  - accelerometer limited to 10 kHz max frequency


Output Voltage Comparison


Single-Sided FFT Comparison

Outline

- Composite Panel and Frame GUW Inspections
- Wave Propagation Methodology Development
- Conclusions, Benefits to Aviation, and Future Work

Conclusions

- Proposed methodology found capable of detecting major damage in frame
  - guided wave tests showed significant acoustic wave attenuation (55%) for cracked C-frame structure
  - need to build stronger foundational understanding of response – especially in order to relate measurements with damage information (damage mode, size estimate)
- Guided wave testing methodology established using aluminum plate as well-known simple baseline → to be applied for complex composite structures
  - excitation and sensing methods testing
  - setup and procedures validated
- Experimentally-determined dispersion curves for Ao (asymmetric flexural) mode matches with theoretical expectations
  - methods for higher-order modes detection to be established – these can play role at higher frequencies in complex structural assemblies
- FE model correlates with experiments for frequency up to 10 kHz
  - more improvement needed
  - next apply modeling procedures to more complex structures

Benefits to Aviation

- A method for detecting damage to internal structures is needed since typical ultrasonic one-sided inspection can't detect these damage modes.
- Relatively quick and non-invasive detection method can be applied following event involving contact with GSE.
  - is there significant damage present?
  - does additional (more invasive) inspection need to be performed?
  - can aircraft remain in operation until next service check involving removal of aircraft interior?
- Inspection method can prospectively provide enhanced detection capability: find smaller-sized damage, weakening of structure (degradation affecting stiffness, continuity)
  - possibly can be supplement to visual inspection (cracks difficult to see on black carbon/epoxy)
  - could be incorporated into scheduled inspection procedures

Looking Forward

- Near-term:
  - Identify significant frequencies sensitive to detecting C-frame cracks.
  - Achieve improved simulation capability and apply to modeling stand-alone C-frame and assembled complex panel structure.
  - Differentiate wave attenuation behavior caused by holes, stringers, fasteners, cracks, etc. This is needed since all of these geometric features are present in the panel.
  - Establish improved dispersion curves extraction methods (e.g., using different theoretical methods, gating intervals).
  - Extract So mode dispersion curve and Attenuation and Group Velocity curves.
- Long-term:
  - Identify wave behavior changes from various types of damage modes (e.g., fiber discontinuity, small to large cracks, and more).
  - Compose methodology for combining the response of individual components subjected to guided ultrasonic wave testing into an assembly of components, i.e., complex structure.
  - Determining suitable “ramp-friendly” equipment to be used for exciting and sensing acoustic signals. Challenge: defining portable broadband excitation source providing high enough amplitude and desired frequency range.
  - Relate measurements to additional information about the damage, namely: damage mode, location, and an estimate of size/severity.

CECAM
center of excellence for composites and advanced materials

JAMS
JOINT ADVANCED MATERIALS & STRUCTURES
CENTER OF EXCELLENCE

A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures