

Low Velocity PDV Measurements for Resonance Testing of Monolithic and Laminated Aluminum Components

Daniel Foster

Foster.373@osu.edu

Welding Engineering Program

Geoff Taber

Taber.17@osu.edu

Materials Science and Engineering Department

The Ohio State University

Advisor: Prof. Sudarsanam Suresh Babu

Collaborator: Prof. Glenn Daehn

Outline



- Resonance Testing
 - How
 - Why
- Ultrasonic Additive Manufacturing (UAM)
 - Background
 - Application
- Proof of concept resonance testing with PDV on monolithic Al 3003
- Resonance testing with PDV on Al-3003 Ultrasonic Additive Manufactured samples
- Conclusions
- Future work

- Apply impulse to a structure to induce vibrations
- Monitor displacement/velocity/accleration with a sensor
 - Contact probe
 - Microphone
 - Laser beam
- Analyze waveform to obtain resonant frequency

Resonance Testing

- Resonant frequency of a mechanical structure is dependent on geometry, material properties, boundary conditions and vibrational mode
- Defects such as cracks, inclusions, porosity, etc change effective material properties (stiffness (E and G) and density (ρ)) of the structure
- The change in material properties due to defects will manifest as a change in resonant frequency
- Therefore measuring resonant frequency can be directly related to defects in a structure

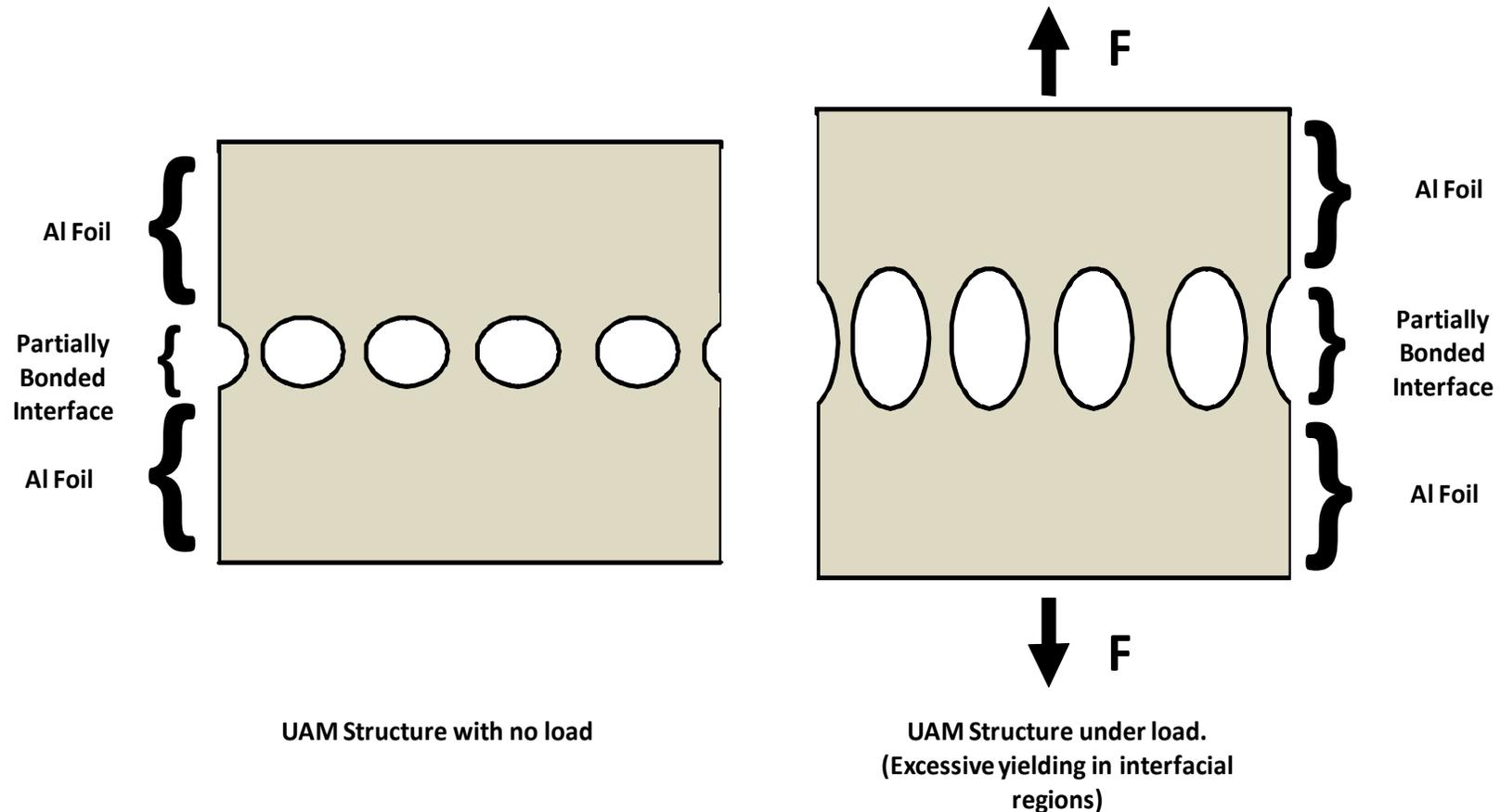
Bending vibration of slender rectangular bar (Continuous Vibration exact solution)

$$\omega_n = (\beta_n l)^2 \cdot \left(\frac{E \cdot I}{\rho \cdot A \cdot L^4} \right)^{\frac{1}{2}}$$

Torsional vibration of slender rectangular bar (Empirically determined ASTM C1259)

$$\omega = \sqrt{\frac{G \cdot b \cdot t \cdot (1 + A)}{4 \cdot L \cdot m \cdot B}}$$

Effect of Voids on Stiffness



- When the material is stressed the voids in the material allow for greater elastic deformation
- Effective material stiffness is reduced

$$\sigma = \frac{F}{A} \quad E = \frac{\sigma}{\epsilon}$$

Example Resonance Testing Use

- Steel Castings with porosity and inclusions

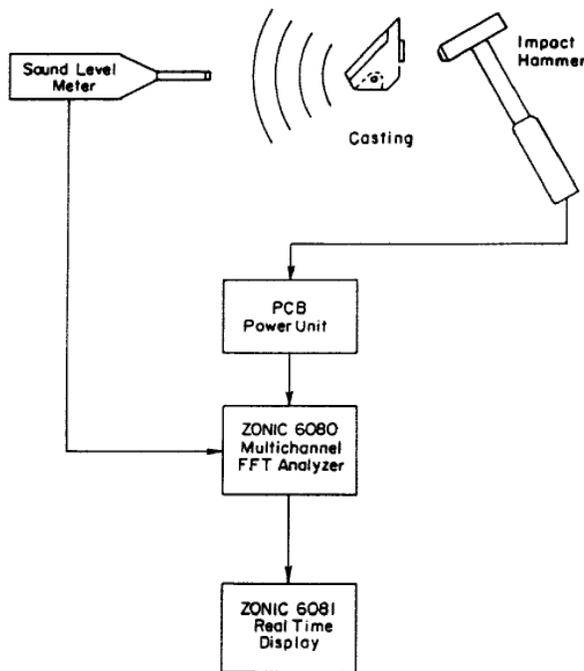
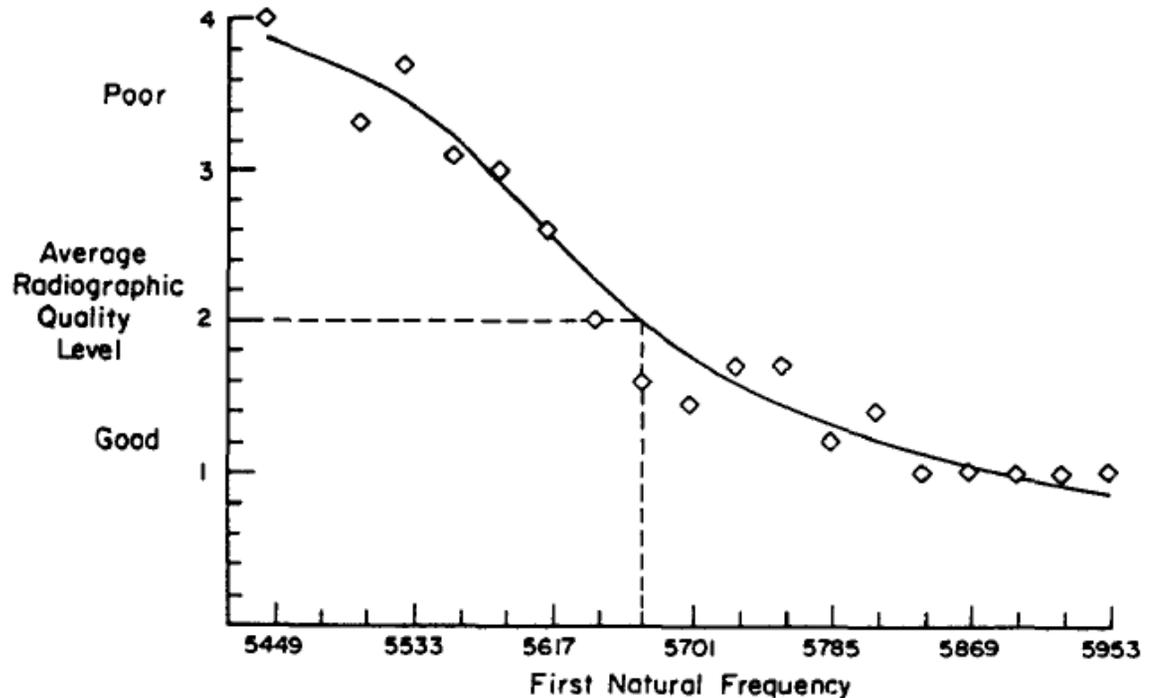


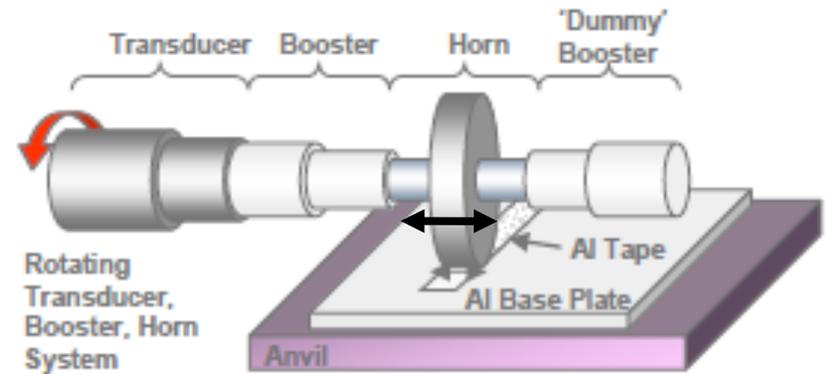
Fig. 3. Frequency-analysis-test set-up.



5. Relationship of the first natural frequency of the castings with the radiographic quality level.

Ultrasonic Additive Manufacturing (UAM)

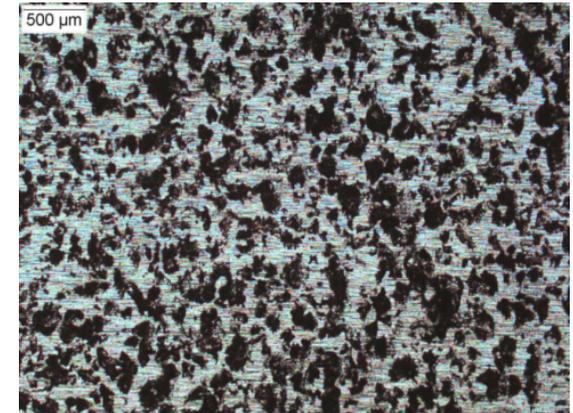
- Ultrasonic Energy applied through a rolling sonotrode to metal foil
- Controllable parameters
 - Normal Force (0-10000lbf)
 - Vibrational Amplitude (0-56 μ m)
 - Welding Speed
- Tangential ultrasonic vibration between foil and substrate remove oxides and create plastic deformation and recrystallization
- Continuous layered manufacturing process
- 3D Metal Printer



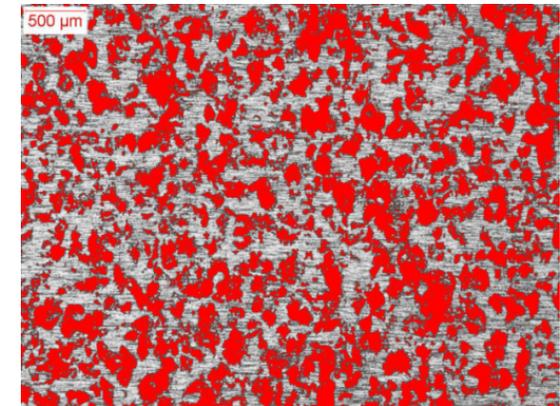
Courtesy of Solidica

Bonding Measurements

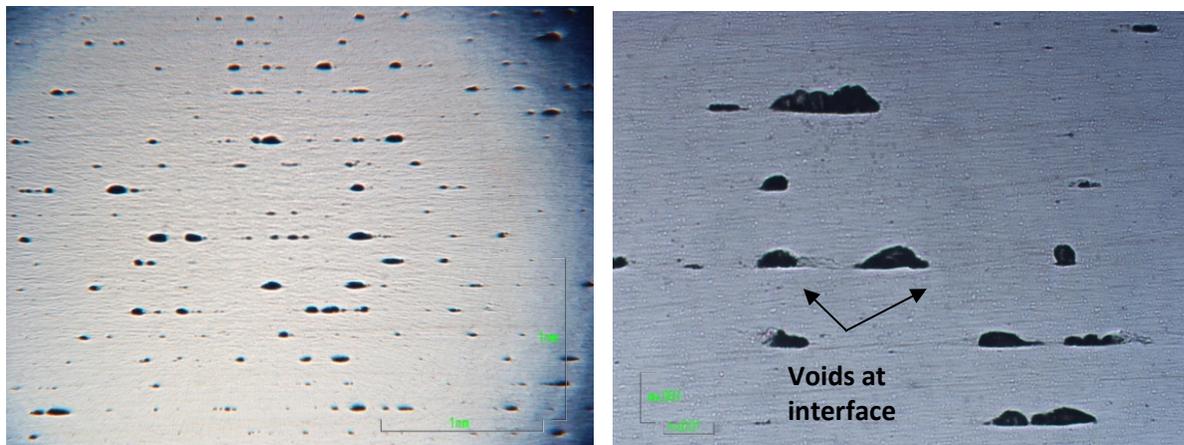
- Incomplete bonding at interfaces
 - Bonded Area/Linear weld density can range from 35%-100%
- Percentage of Bonded Area
 - Fracture surface
 - Use imaging software to differentiate between bonded and unbonded areas
- Voids are analogous to Porosity in casting
 - Can affect material properties



Fracture Surface



Fracture Surface
“Percent Bonded Area
Measurement”

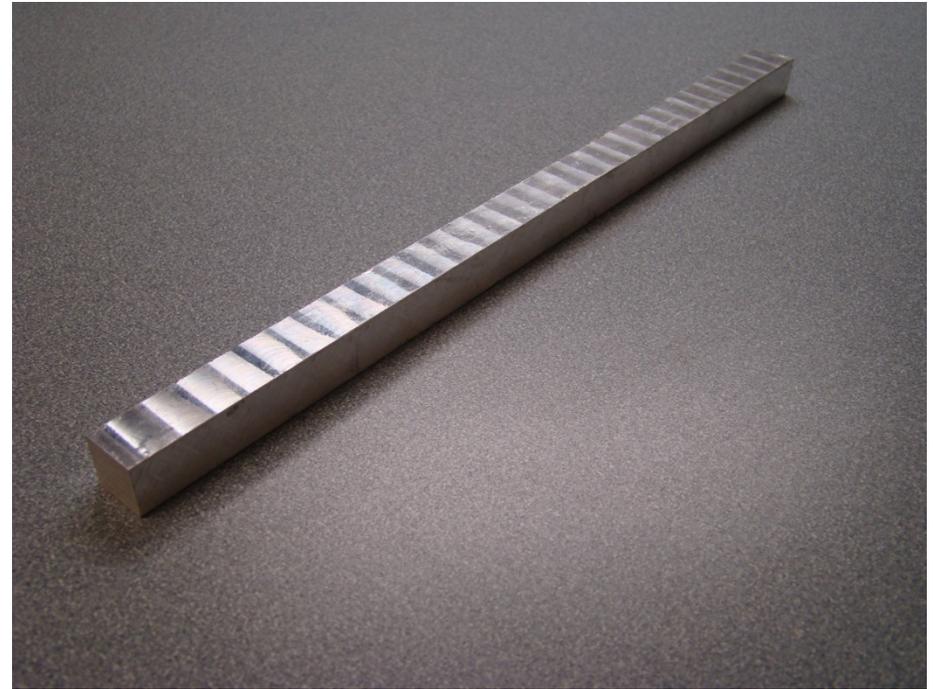


Cross-section (Linear Weld Density)

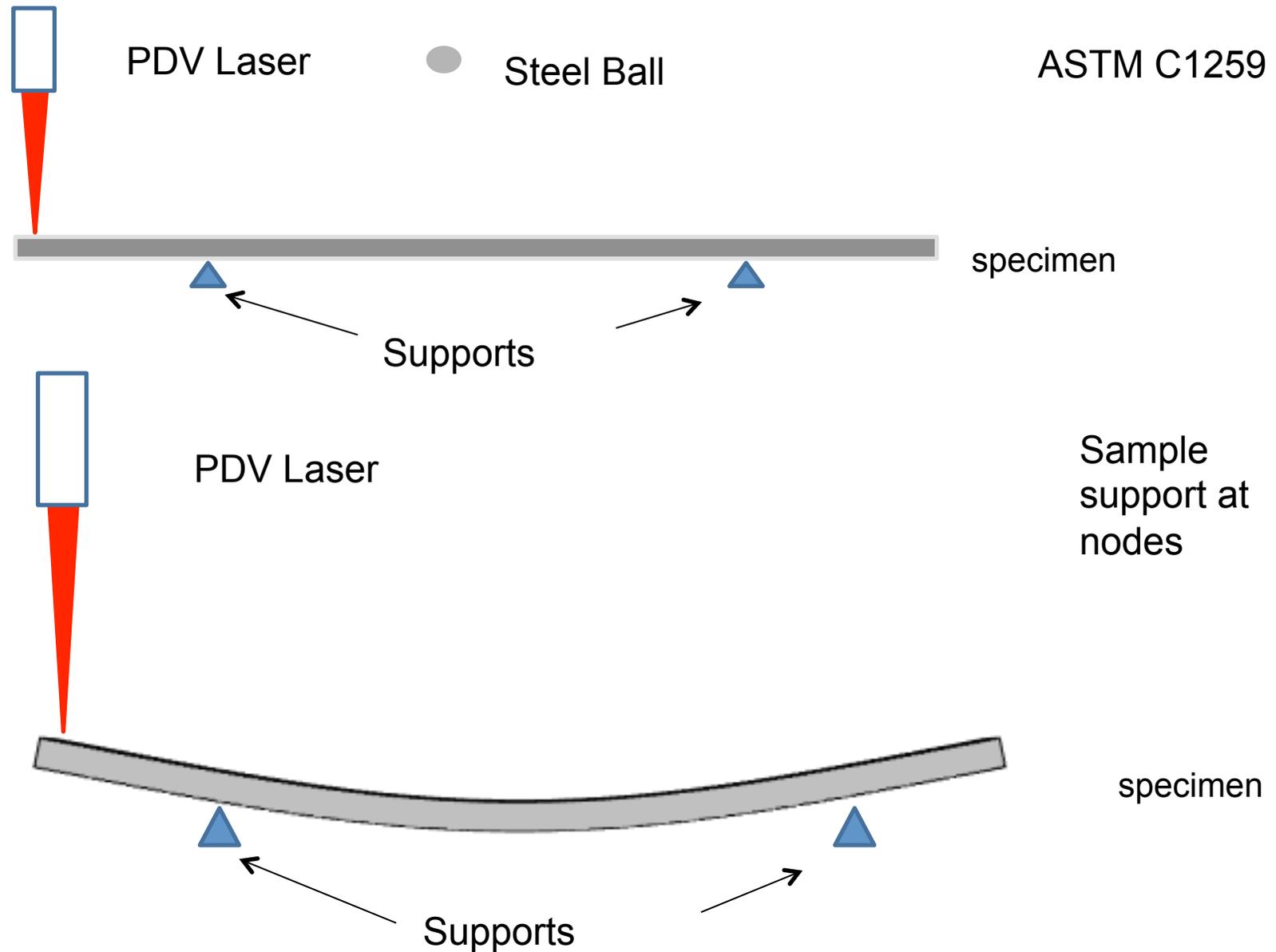
- Need to non-destructively determine bonded area
 - Directly related to mechanical properties (strength, stiffness, and Poisson's ratio)
- Resonance testing could be used to relate bonded area to resonance frequency
- No access to laser vibrometer
- PDV could be used to measure velocity and determine mechanical frequency of vibration
- Photonic Doppler Vibrometry?
- Potential Application
 - PDV could be used in a system for in process monitoring during UAM

Proof of Concept

- To test the effectiveness of PDV as a low velocity vibration sensor a proof of concept study was performed
- 10in X 0.5in X 0.5in monolithic Al 3003-H14 rectangular bar

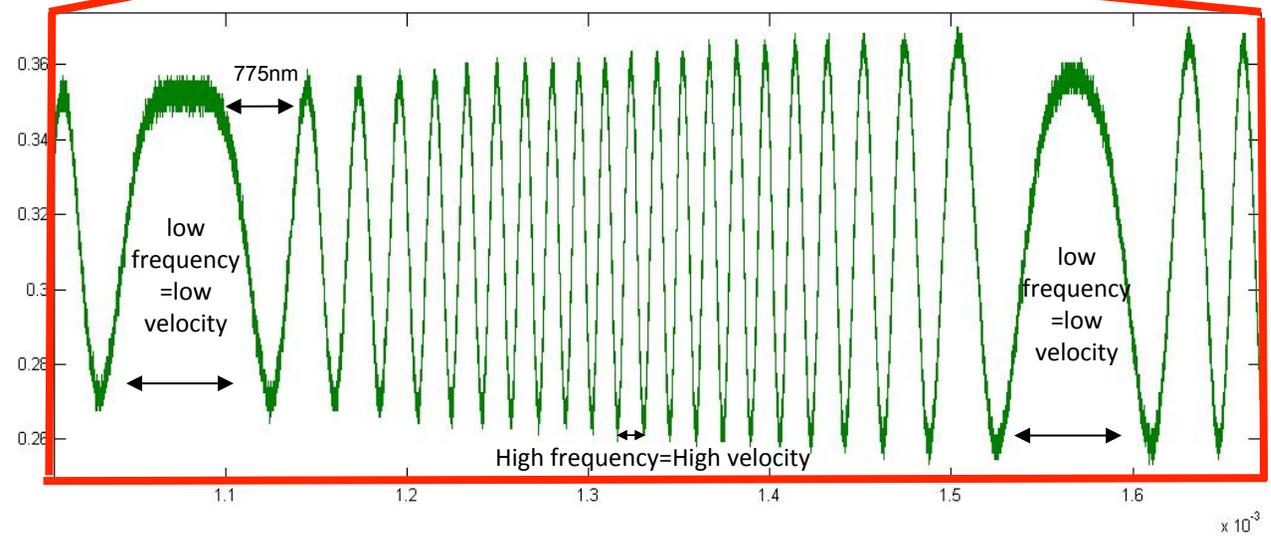
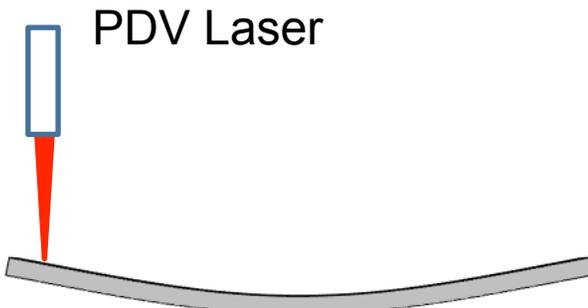
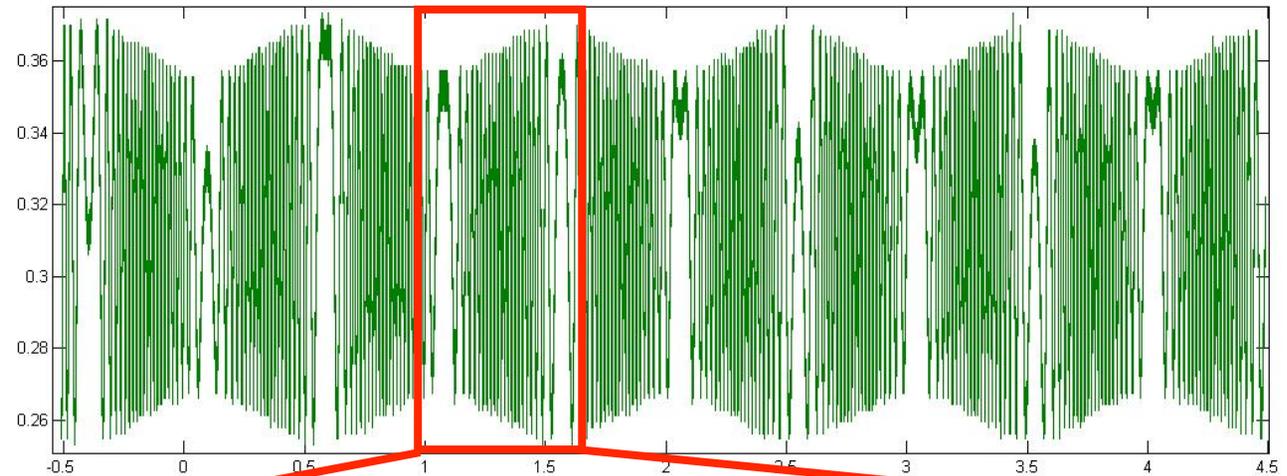


Impulse Excitation Resonance Testing (Free-Free Bending Vibration)



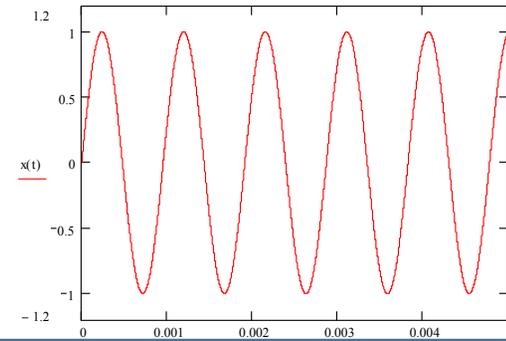
Raw PDV vibration data on Proof of Concept Sample

- Low frequency regions are when the bar's velocity slows down to zero and then reverses direction

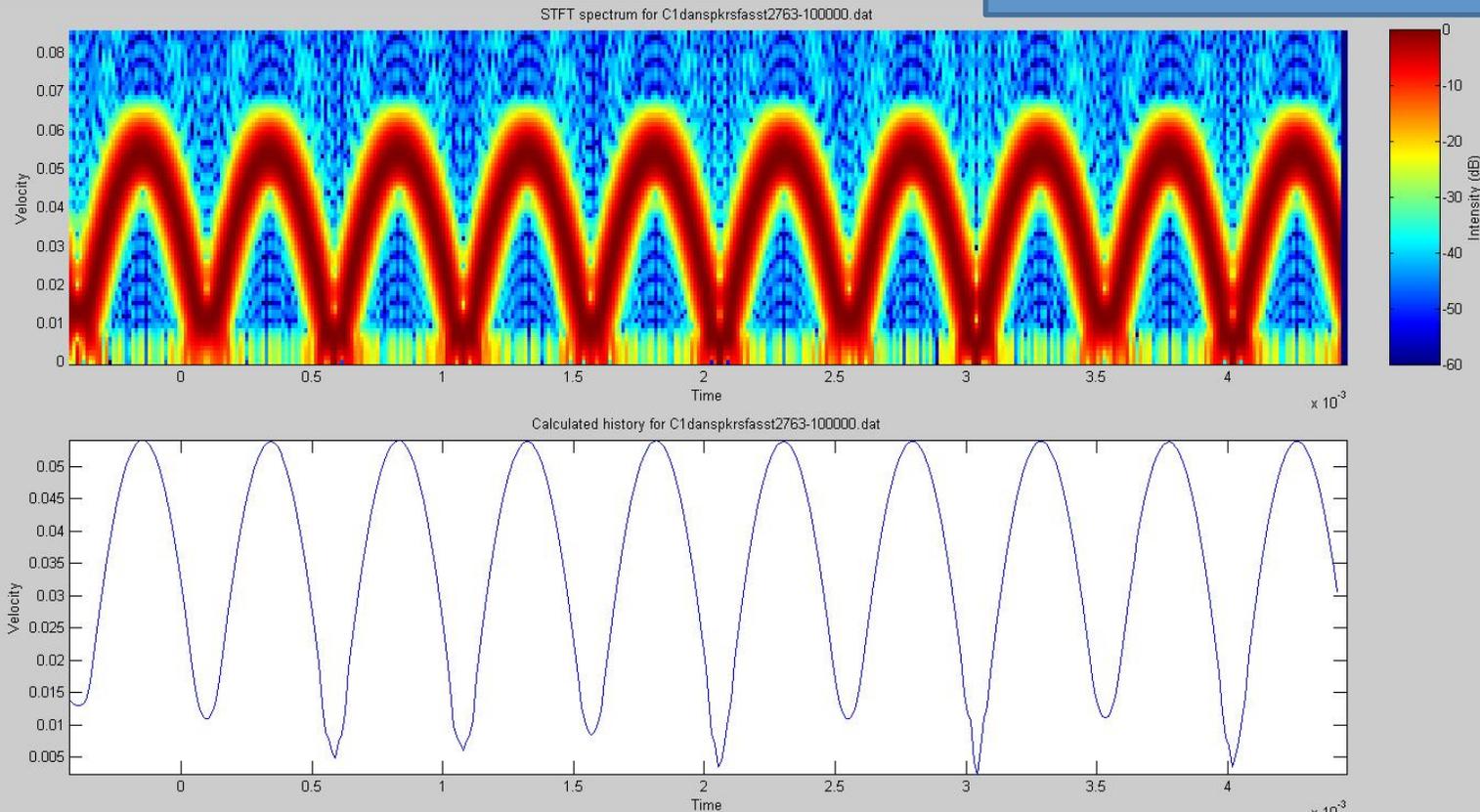


Proof of Concept

- Short-time Fourier transform of Raw PDV data
- Accuracy problem near zero velocity
- OSU's DC PDV system cannot distinguish between negative and positive velocity
- Mechanical vibrational frequency can be determined by inverting the different between the time for every other peak

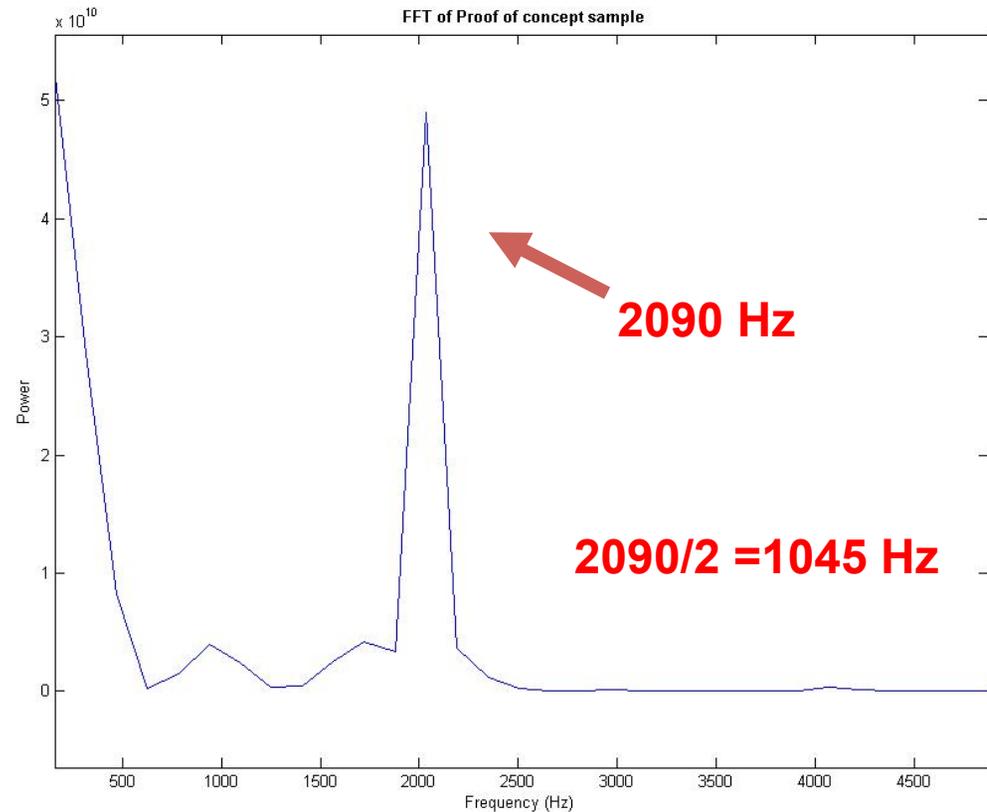


Example Waveform of mechanical vibration

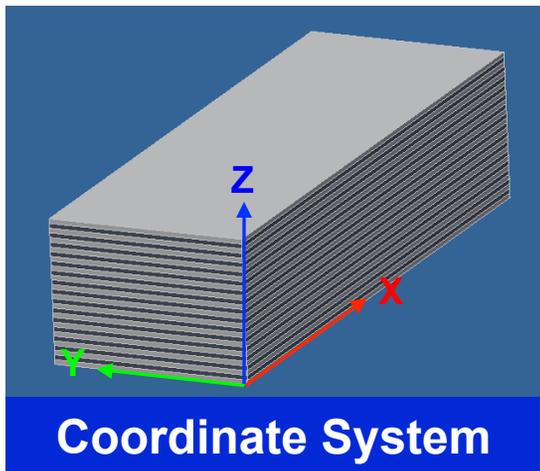


Proof of Concept

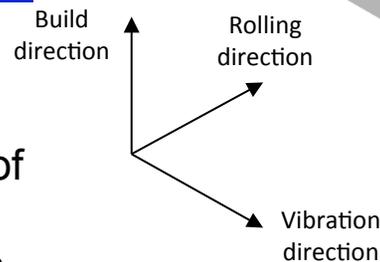
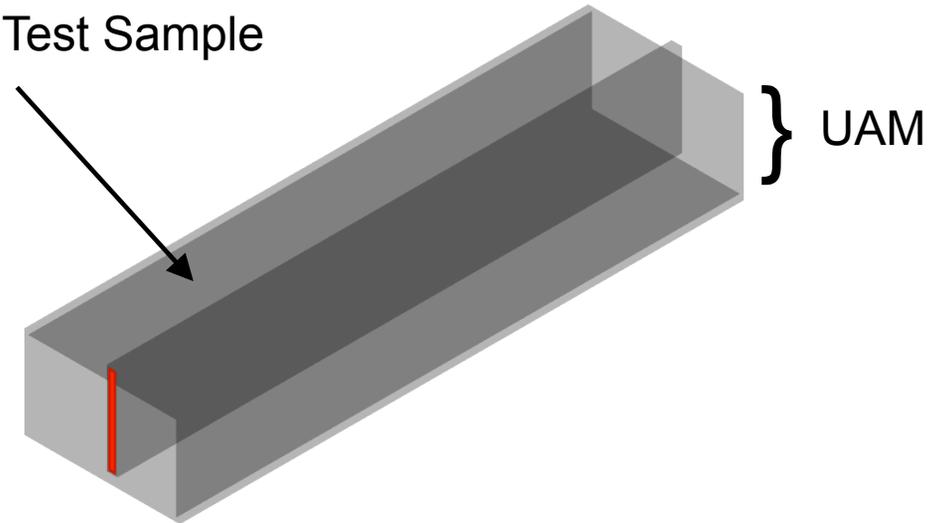
- Extracted velocity profile is put into a Fast Fourier transform
- Resulting frequency of the FFT is twice the actual resonance frequency
- Predicted value 1030Hz
- Measured value using PDV 1045 Hz
- Measured value is similar to predicted value



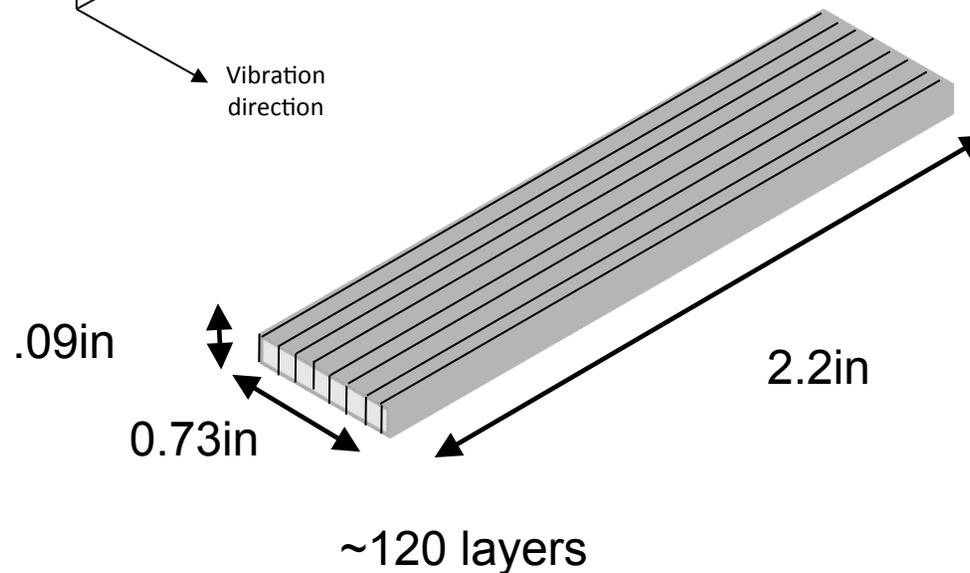
Resonance Testing on Al 3003-H18 UAM Components



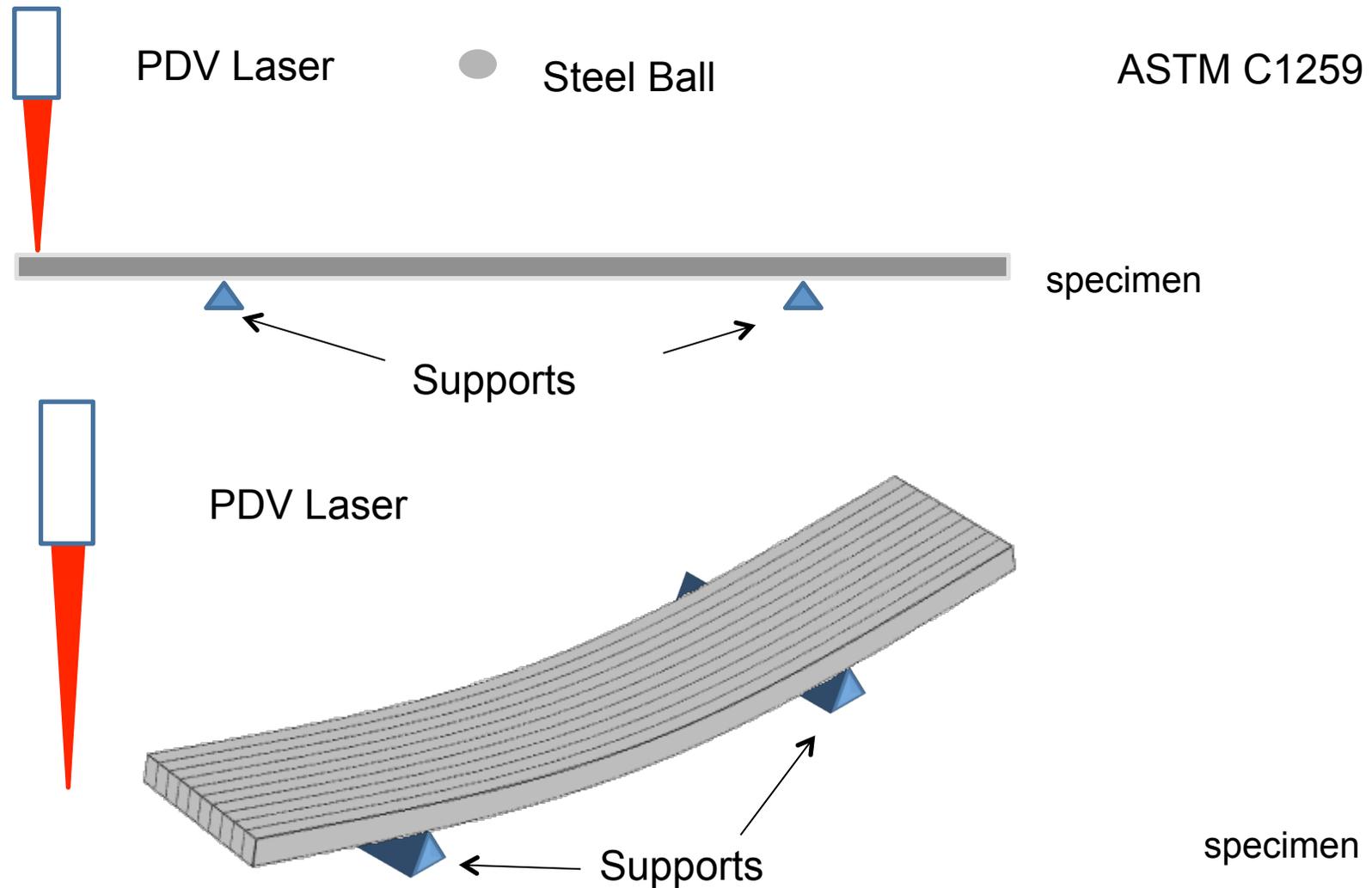
Vibration Test Sample



- UAM test samples are much smaller than Proof of concept sample due to geometric build limitations
- Beams cut from UAM samples with different amounts of bonded area
- Beam geometry chosen so torsional and Bending modes can be tested
- A control sample of the same geometry was also tested for comparison



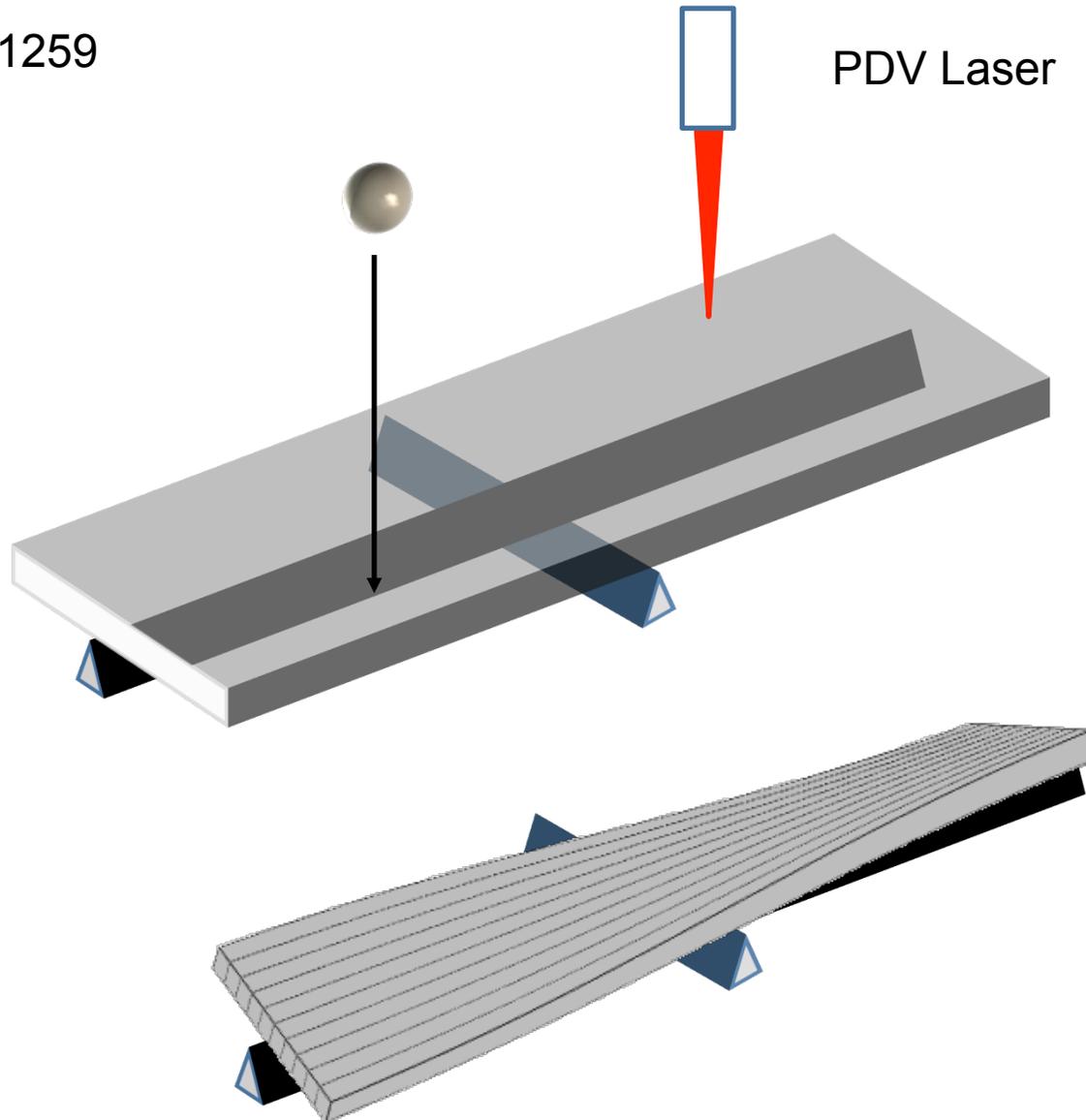
Impulse Excitation Resonance Testing (Free-Free Bending Vibration)



Free-Free Torsional Vibration

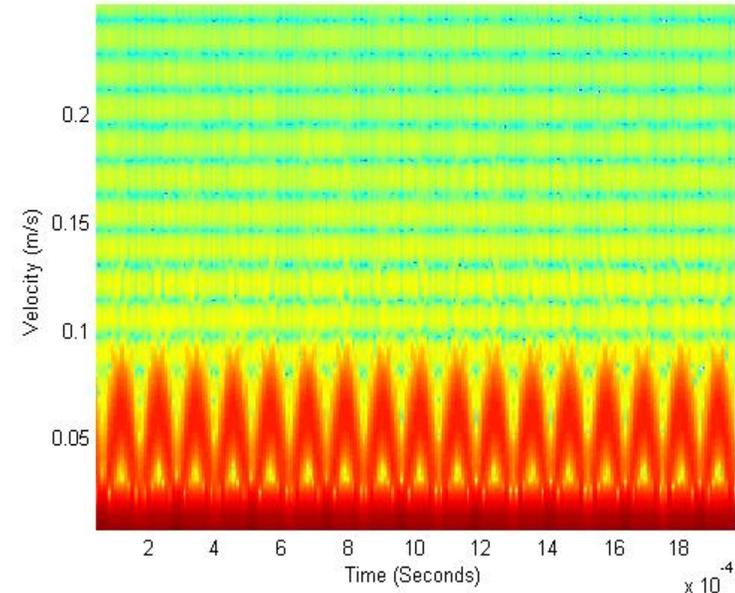
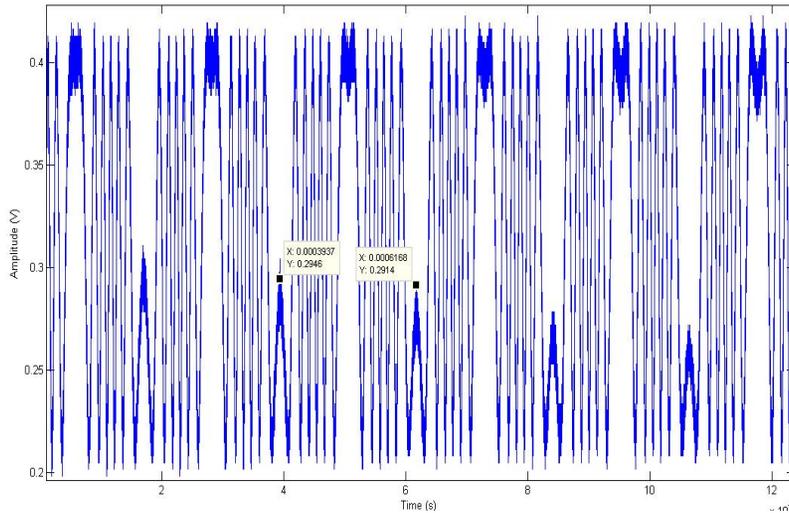
ASTM C1259

PDV Laser

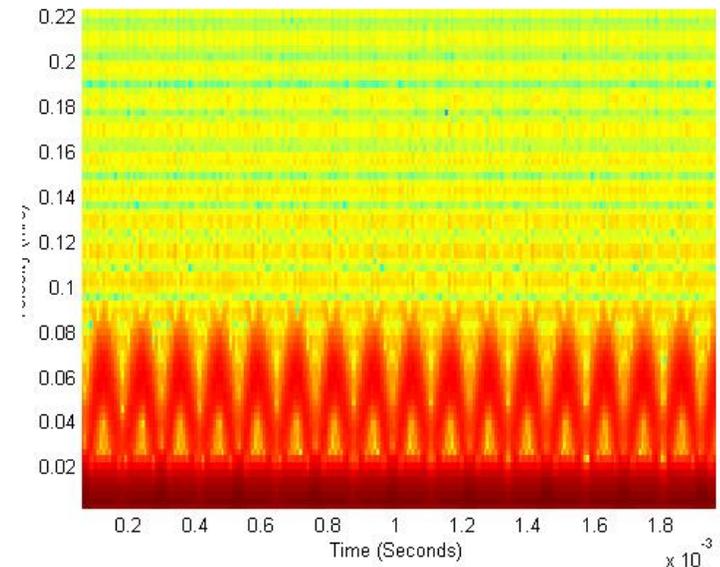
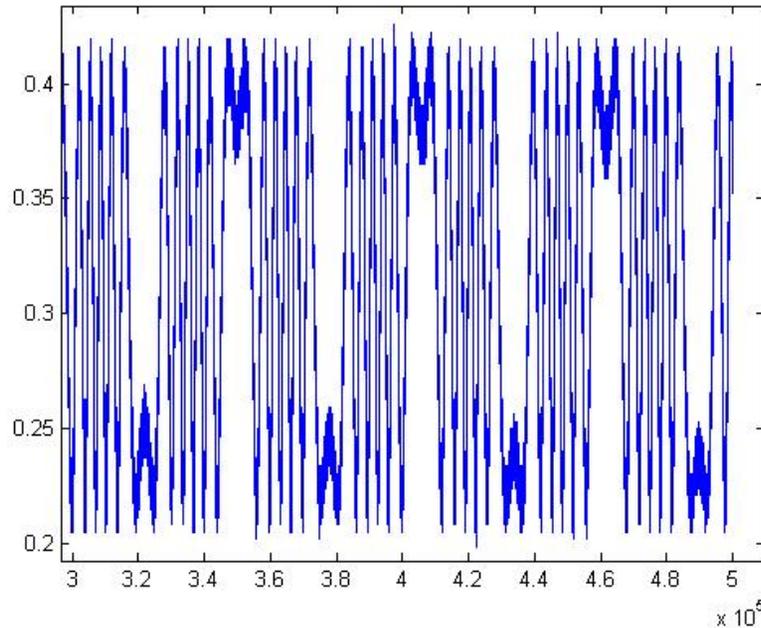


Results of Bending Mode Tests

Control
Sample



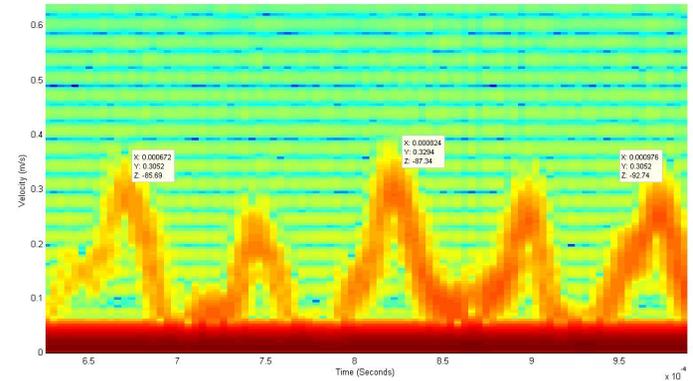
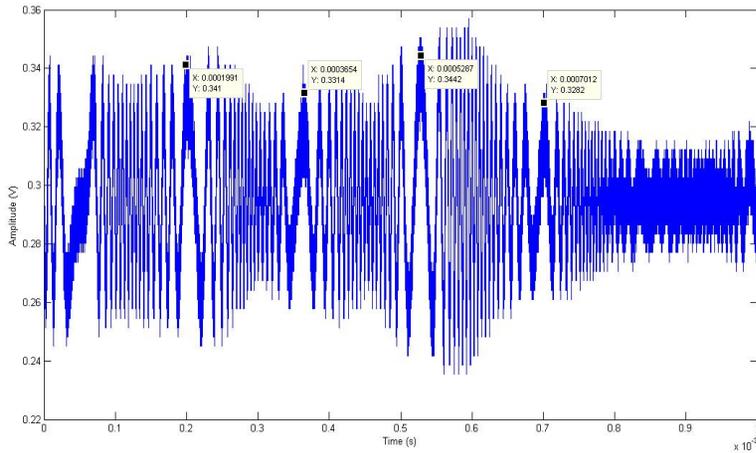
UAM
Sample



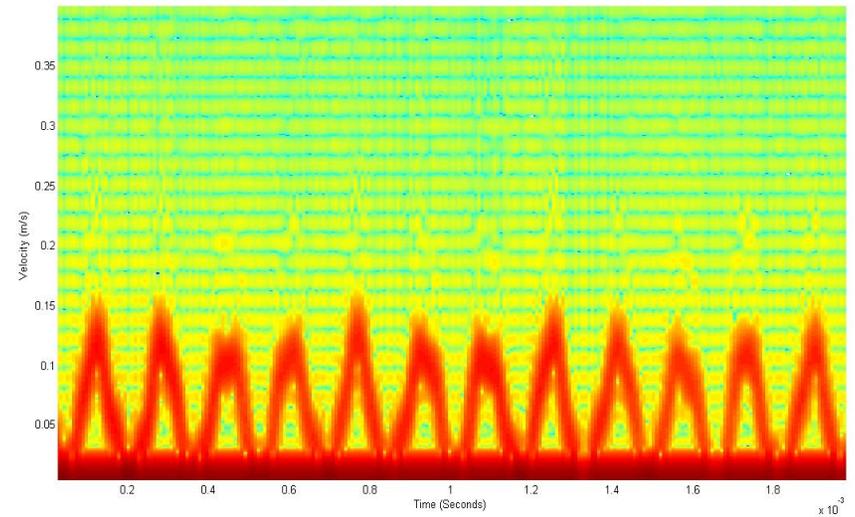
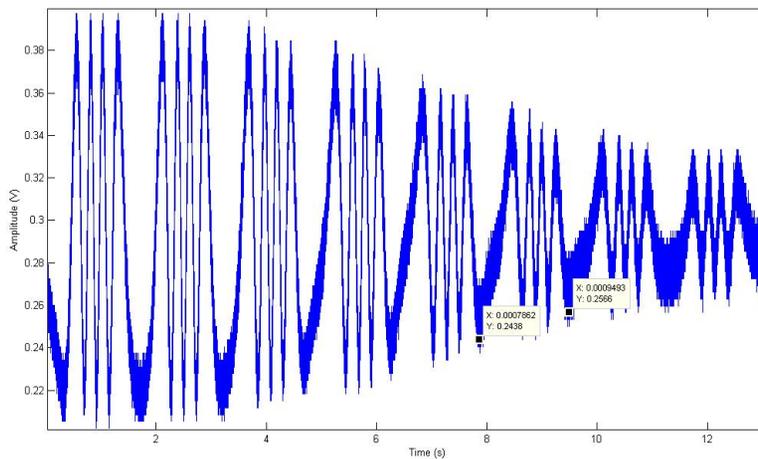
Results of Torsional Mode Tests



Control Sample

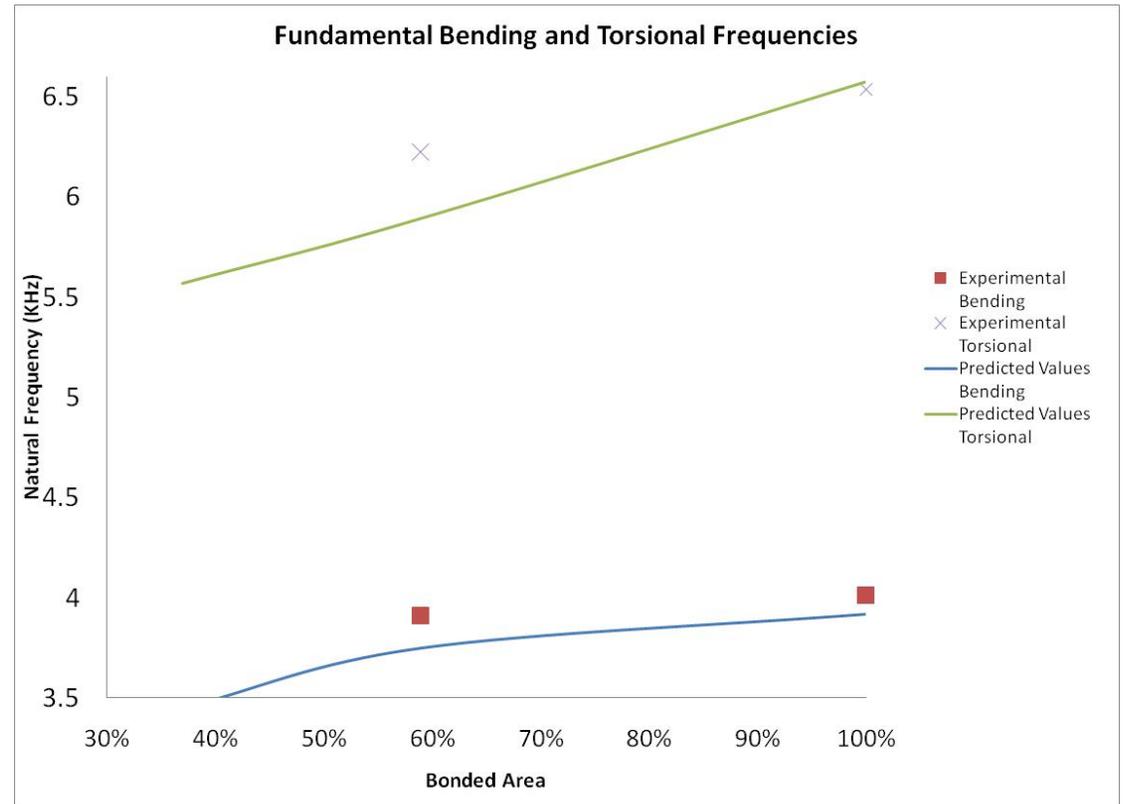


UAM Sample



Results

- Predictive values are from previous research
- Decrease in Resonant Frequency with decrease in bonded area for samples tested
- Preliminary results are promising
- More samples are needed to fully describe relationship between natural frequency and bonded area



	Monolithic (Hz)	UAM (Hz)	Difference (Hz)	Difference (%)
Bending mode	4010	3906	104	2.594%
Torsional mode	6491	6234	257	3.959%

PDV Results Validation

- To test the accuracy of PDV test results the samples were also tested with a known vibrational system(Grind-o-sonic MK4X)
- Used Non-contact microphone to detect vibrational frequency
- Results are very close to PDV measurements

	Resonant frequency (Hz)		
	PDV	Grind-o-sonic	Difference
Monolithic Bending	4010	4035	0.620%
UAM Bending	3906	3892	0.360%
Monolithic Torsional	6491	6518	0.414%
UAM Torsional	6234	6237	0.048%

Conclusions



- PDV can be used for low velocity vibration measurement
- Preliminary results showed a decrease in resonant frequency in UAM samples vs. monolithic samples
 - The reduction was more severe in torsional vibration compared to bending vibration due to orientation of the consolidated layers

Future Work



- Test additional UAM samples with different amount of bonded areas
 - Fully develop Resonance vs. Bonded area relationship
- Test samples using frequency conversion PDV
 - Eliminate inaccuracies near zero velocity