Structural Health Evaluation of Composite Materials using Lamb Wave Methods

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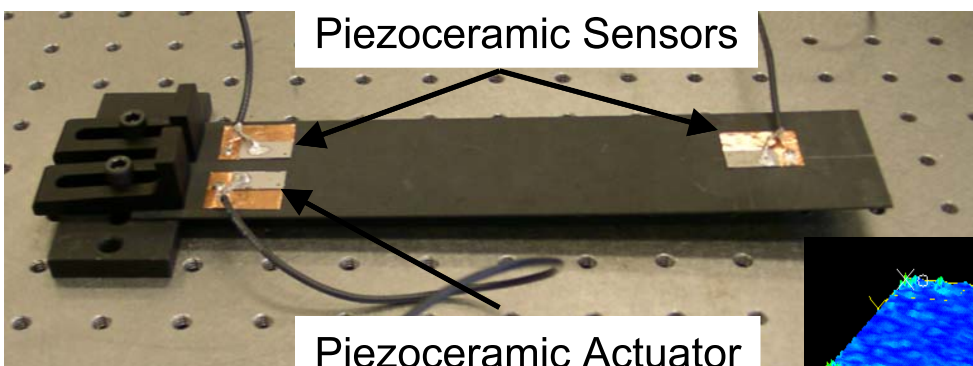
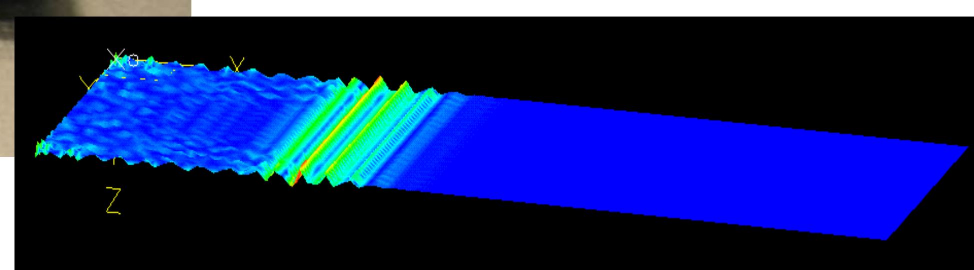
Program Goals

- Motivations for SHM within NRO OSL
  - hidden damage possible during manufacture and handling of spacecraft
  - lack of access to make quantitative measurements
  - detect/map extent of damage before and/or on the launch pad
  - facilitate launch/no-launch decisions
- Sensors/actuator optimization
  - increase reliable, robustness, signal strength of sensor/actuator
  - more efficient sensing schemes (architecture)
  - damage evaluation algorithms in MATLAB
  - large set of simple test results to compare, confirm, and tune
- Sandwich structure testing
  - test sensors/algorithms on more complex geometries
  - observe effects of various core densities and thickness
  - observe effects of disbonds, delams and gaps
  - continue to update algorithms supported by finite element analysis

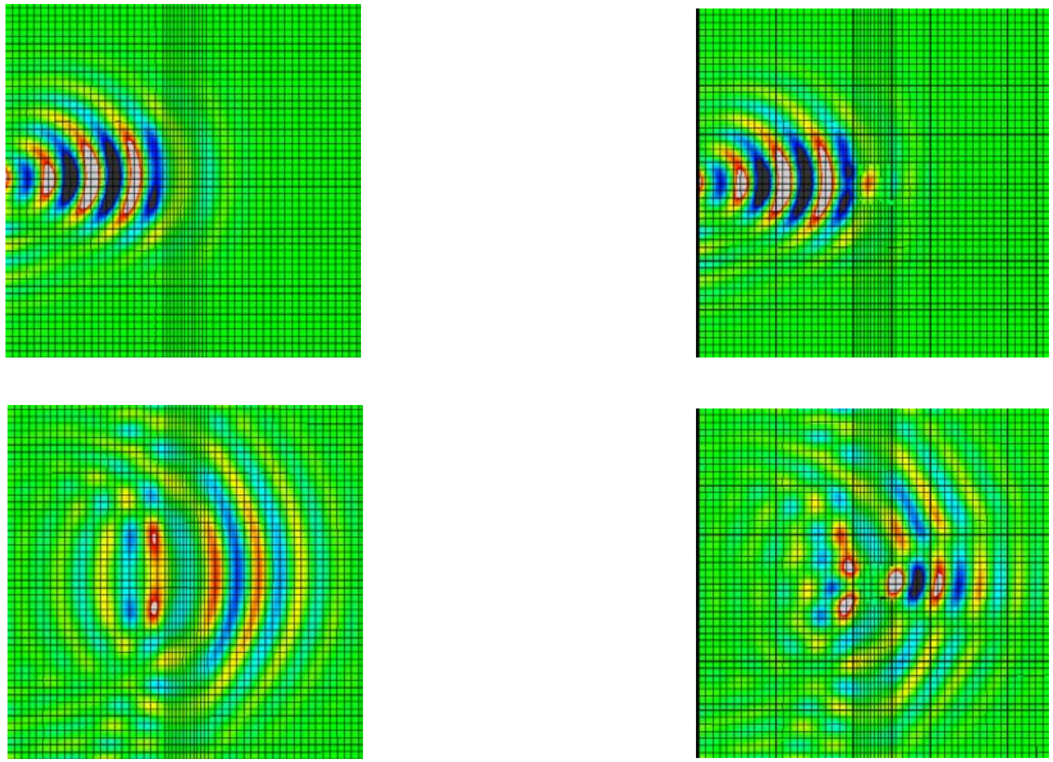
Lamb Wave Methods

- Form of elastic perturbation that propagates in a solid medium
  - actuation parameters determined from governing equations
  - excite A_o wave for long travel distances and to minimize clutter
- Damage can be identified in several ways
  - group velocity approximately $\propto (E/\rho)^{1/2}$, damage slows down waves
  - reflected wave from damage can be used to determine locations
- Research uses piezoelectric actuators/sensors to detect energy present in transmitted and reflected waves, builds off prior research





Effect of Damage on Lamb Waves



- Figure on left shows FEA results for stiffened plate without damage
- Figure on right shows FEA results for rib with 25 mm disbond
- Reduced stiffness in damaged region causes slower propagation
- Disbond yields fringe pattern in both reflected and transmitted wave

Sensors Material Analysis

- Use 3-1 piezoelectric coupling properties to output an open circuit voltage in response to strain wave
- Desirable attributes
  - maximize $\frac{k_{31}^2}{d_{31}\left(1-k_{31}^2\right)}$ where d_{31} is the *3-1* piezoelectric "strain" coefficient and k_{31} is the *3-1* coupling coefficient
  - minimum stiffness to maximize strain of wave passing though it
  - length of $(1 + n / 2)*\lambda$ where λ is the wavelength and n = 0,1,2,3,…
  - capacitance such that 1 MΩ (oscilloscope impedance) appears as an open circuit to the sensor

Sensors Material Comparison

Material	k_{31}	d_{31}	g_{31}	Y_{11}^D		$\lvert (k_{31})^2/(d_{31}(1-(k_{31})^2)) \rvert$
	(-)	(p m / V)	(mV m / N)	(GPa)		V / (mm $\mu\varepsilon$)
PZT-7A	-0.300	-60	-16.2	104		1.65
EBL#5	-0.300	-60	-16	103		1.65
EBL#1	-0.360	-127	-10.7	106		1.17
EBL#7	-0.330	-107	-10.9	104		1.14
EBL#4	-0.310	-95	-10.5	110		1.12
PZT-8	-0.350	-127	-12.2	89		1.10
PZT-4	-0.340	-125	-10.6	91		1.05
EBL#9	-0.340	-135	-10.5	92		0.97
PZT-7D	-0.300	-112	-9.6	94		0.88
PZT-5R	-0.385	-200	-11.5	75		0.87
EBL#2	-0.360	-173	-11.5	76		0.86
PZT-5B	-0.380	-210	-10.1	79		0.80
PZT-5A	-0.343	-177	-11.1	71		0.75
EBL#23	-0.440	-320	-9	79		0.75
PZT-5J	-0.375	-230	-9.8	73		0.71
EBL#3	-0.380	-262	-8.6	75		0.64
PZT-5H	-0.375	-264	-8.9	69		0.62
EBL#6	-0.370	-260	-9.8	57		0.61
PZT-5M	-0.370	-270	-7.6	78		0.59
EBL#25	-0.300	-179	-11	49		0.55
PZT-5K	-0.380	-323	-6.9	73		0.52
PT2/PC6	-0.030	-3	-2.1	135		0.30

- Chart compares figure of merit for available PZT
- Separate analysis performed for PVDF
- Candidate materials which were selected to test broad range
  - EBL#5
  - EBL#1
  - EBL#2
  - EBL#23
  - EBL#3

Actuator Material Analysis

- Uses 3-1 piezoelectric coupling properties to output a strain wave in response to voltage
- Desirable attributes
  - maximize the strain per volt induced in the structure, P=2π*f*CV²
  - maximize $\frac{e_{31}^{P}}{\left(c_{11}^{P}+c_{12}^{P}\right)h_{P}+\left(Q_{11}+Q_{12}\right)h_{s}}$ where e^{P} is the planar piezoelectric “stress” coefficient, h_P and Q are the thickness and stiffness of the actuator, and h_S and c^P are the thickness and stiffness of the structure
  - minimize the power delivered by the function generator by minimzing the admittance $\varepsilon_{33}^{P}\left(\frac{1}{h_{P}}+\frac{2\,c_{11}^{P}\left(k^{P}\right)^{2}}{\left(c_{11}^{P}+c_{12}^{P}\right)h_{P}+\left(Q_{11}+Q_{12}\right)h_{S}}\right)$

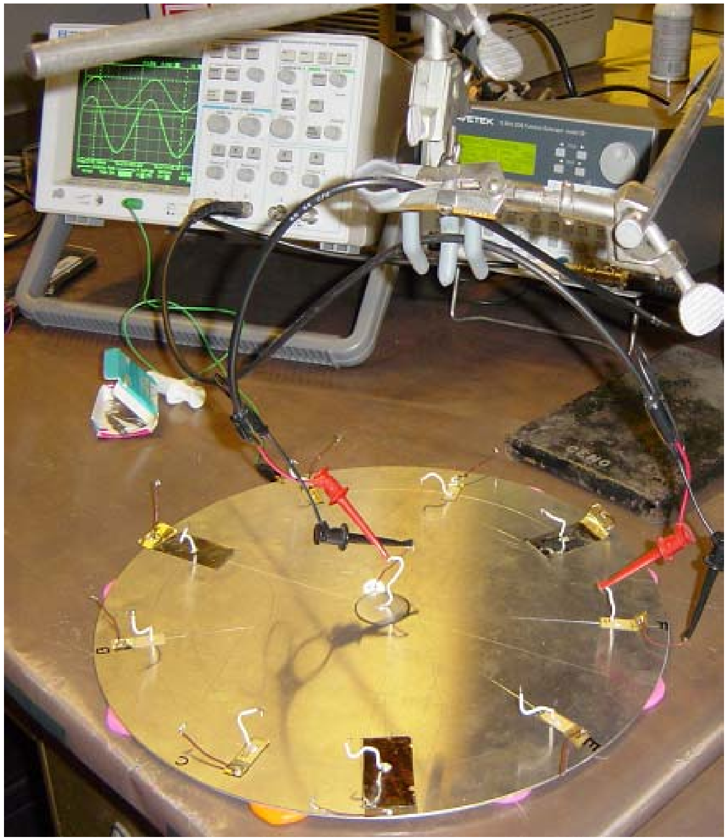
    where k^P is the planar coupling coefficient and ε^P the planar permittivity
  - resonant actuators also considered, but low frequencies required large dimensions (3-4” for 25 kHz) and had narrow range (250 Hz PZT-5A)

Actuator Material Comparison

Material	k_P	s_{11}^E	s_{12}^E	σ^P	ε_{33}^P	e_{31}^P
	(-)	(p m^2 / N)	(p m^2 / N)	(-)	(nF/m)	(N / m V)
EBL#23	0.750	15.7	-4.9	0.31	14.7	-29.6
PZT-5K	0.650	16.0	-5.1	0.32	29.6	-29.5
PZT-5M	0.630	15.0	-4.7	0.31	21.5	-26.1
EBL#3	0.640	15.6	-4.6	0.29	18.0	-23.9
PZT-5H	0.635	16.9	-5.1	0.30	17.4	-22.4
PZT-5J	0.630	16.0	-4.7	0.29	14.1	-20.3
PZT-5B	0.640	14.7	-4.3	0.29	12.3	-20.3
EBL#6	0.630	20.3	-6.3	0.31	14.7	-18.6
EBL#25	0.630	22.3	-12.2	0.55	9.6	-17.7
EBL#9	0.600	12.3	-4.4	0.36	8.2	-17.1
PZT-5R	0.630	15.7	-4.0	0.25	10.9	-17.1
EBL#2	0.620	15.1	-4.9	0.33	9.4	-17.0
PZT-5A	0.600	16.1	-5.6	0.35	9.7	-16.8
EBL#1	0.600	10.8	-3.0	0.28	7.4	-16.3
PZT-4	0.580	12.4	-3.9	0.31	7.6	-14.7
EBL#7	0.560	10.8	-3.3	0.31	6.7	-14.3
PZT-7D	0.510	11.8	-3.6	0.31	8.4	-13.7
EBL#4	0.520	10.1	-2.9	0.29	6.8	-13.2
PZT-8	0.520	12.8	-1.2	0.09	6.8	-11.0
EBL#5	0.520	10.6	-3.6	0.33	2.7	-8.5
PZT-7A	0.510	10.6	-3.3	0.31	2.6	-8.2
BT	0.260	7.8	-2.6	0.33	9.1	-8.1

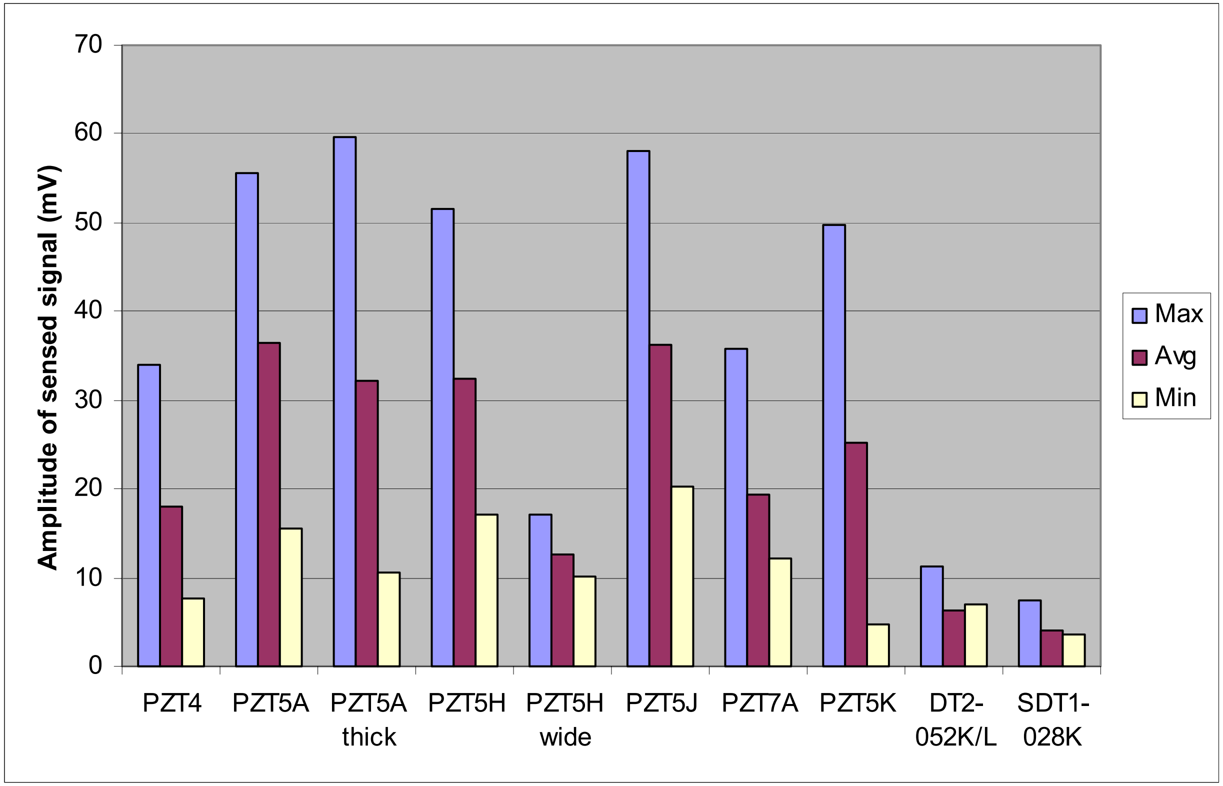
- Chart compares figure of merit for available PZT
- Separate analysis performed for resonant actuators
- Candidate materials which were selected to test broad range
  - EBL#23 (disk)
  - EBL#3
  - EBL#2
  - EBL#1 (disk)
  - EBL#5

Sensors/Actuator Material Testing



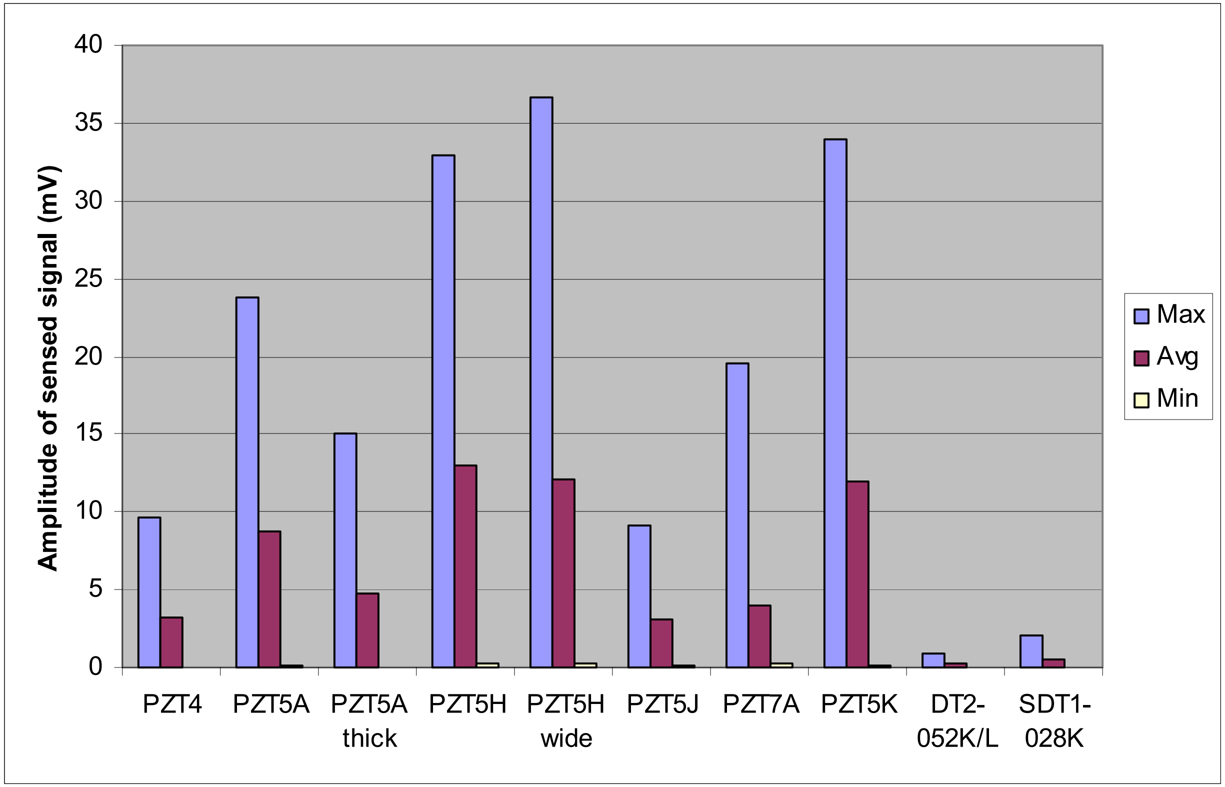
- Sensors bonded to circular Al plate
  - EBL#5 (PZT-7A) - 0.5x0.25x.01", 1.0x0.25x.01"
  - EBL#23 (PZT-5K) - 0.5x0.25x.01"
  - EBL#3 (PZT-5H) - 0.5x0.25x.01", 0.5x0.5x.01"
  - EBL#2 (PZT-5A) - 0.5x0.25x.01", 0.5x0.25x.02"
  - EBL#1 (PZT-4) - 0.5x0.25x.01“
  - DT2-052K/L PVDF
  - SDT1-028K PVDF
- Actuator disk in center
  - EBL#23 (PZT-5K) 0.5"(diameter)x0.01"
  - EBL#1 (PZT-4) 0.5"(diameter)x0.01"
- Tests performed
  - actuated from 1 kHz to 250 kHz
  - 20 V peak to peak
  - duplicates tested for each on separate plates
  - tests also performed in reverse

Sensors Material Results



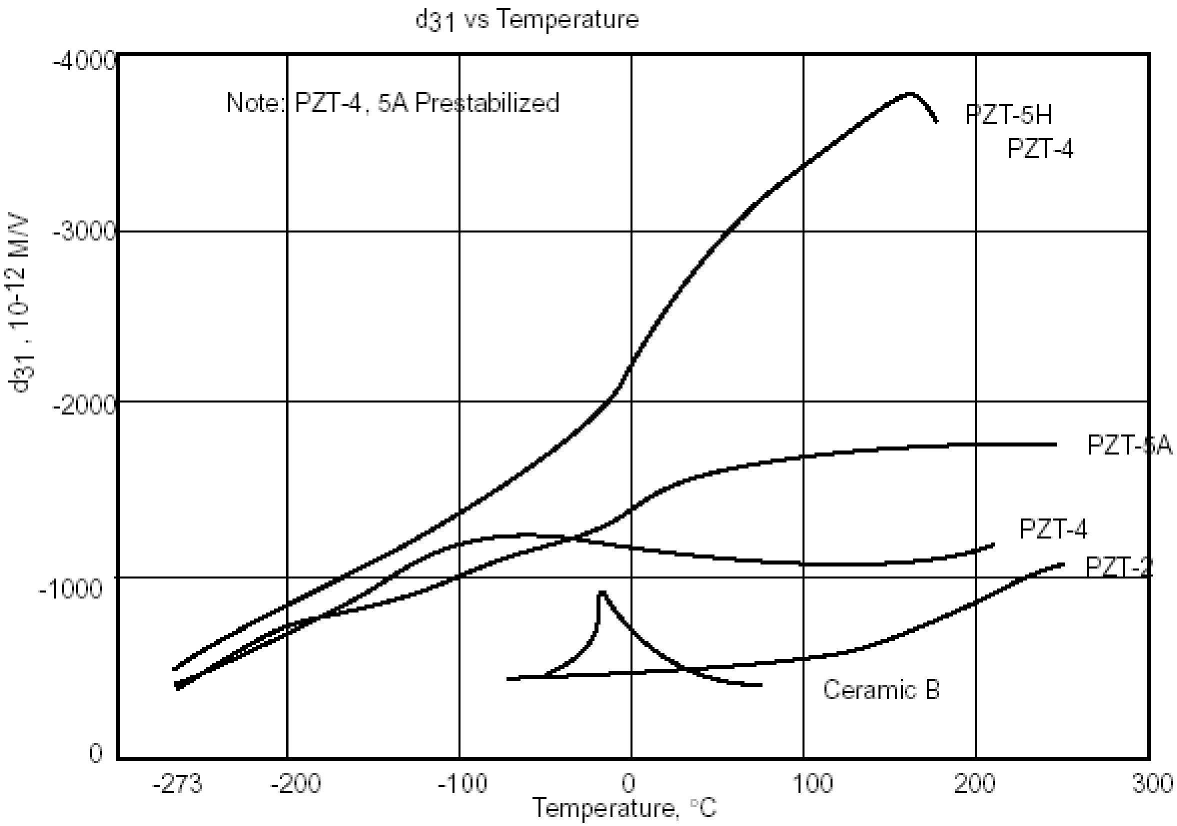
- PZT-5A, PZT-5H, PZT-5J, PZT-5K all comparable maximums
- PZT-5A and PZT-5J have highest means and minimums
- PZT-5A selected because of bandwidths of maximum peaks

Actuator Material Results



- PZT-5H and PZT-5K have highest amplitudes, PZT-5A close
- Overall averages were lower due to poor center sensor
- PZT-5A selected due to better actuation temperature stability

Temperature Stability



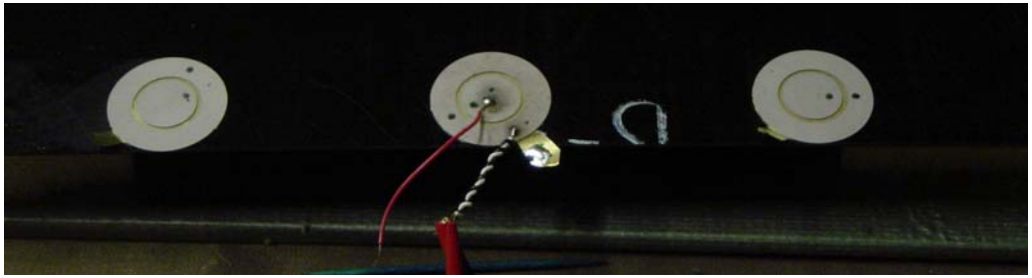
- PZT-5A has the best temperature stability of PZT materials
- PZT-5H has worst stability of PZT materials
- PZT-5K has comparable thermal properties to PZT-5H

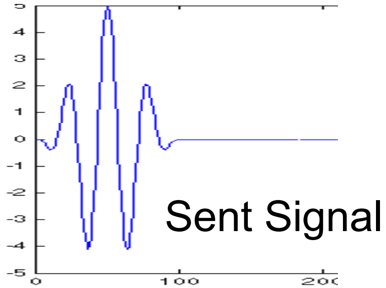
Electrical/Mechanical Connections

- Electrical connections
  - provide an electrical path to the underside of the piezoelectric wafers
  - minimize in-plane stiffness *E*t* to maximize actuation (consider tearing)
  - reasonable through-thickness conductivity (resistance less than 1Ω)
- Mechanical connections
  - adhere piezoelectric wafer assembly to the structure
  - low application temperature, removable without damaging the structure
  - uniform thickness to reduce variability in surface mounting
  - must minimize G/t to maximum actuation
- Brass alloy 260 chosen for bottom electrode
  - 1 mil. thick shim stock used for conductor
  - 81% less stiff than copper shim used previously
- 3M 9703 electrically conductive double-sided tape chosen
  - used to adhere to brass and structure, non-conductive version available
  - 2 mil. thick chosen for adhesive
  - smoother and more repeatable than Ag epoxy

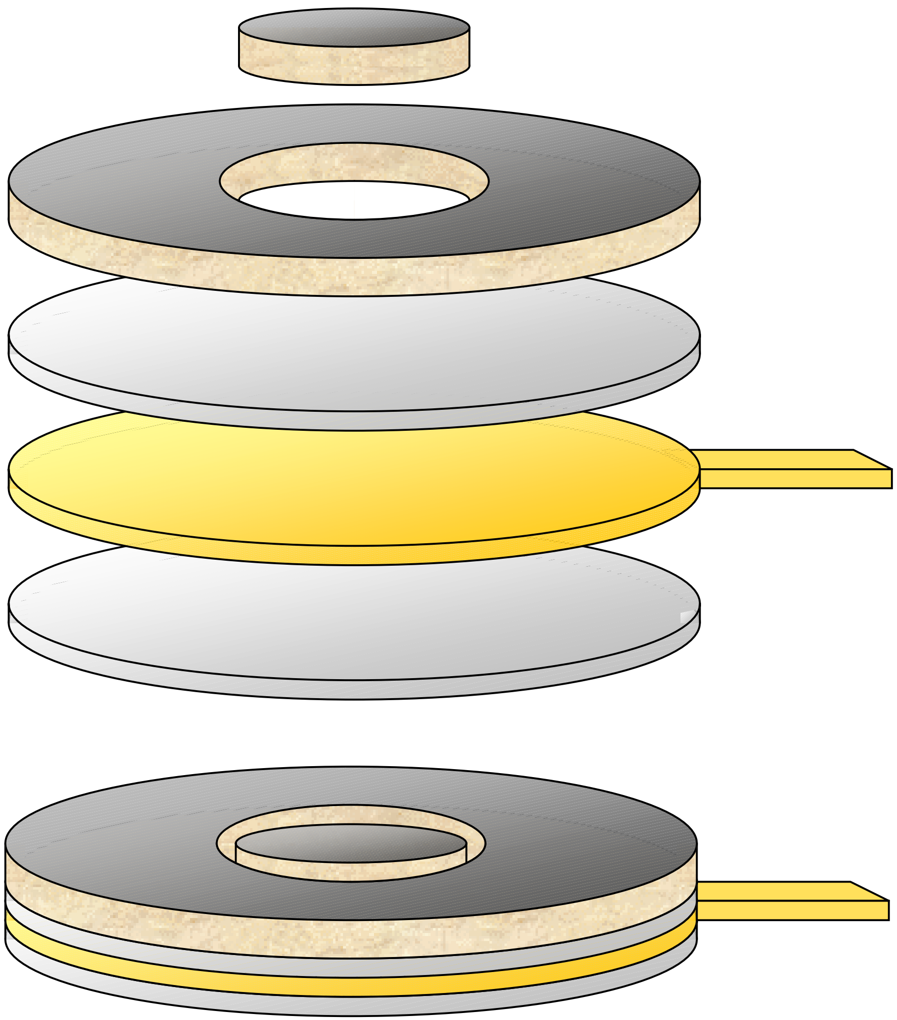
Piezoelectric Wafer Dimensions and Waveforms

- Actuator and sensor lengths
  - chosen to be 0.5” based upon equations for 15 kHz actuation
  - could be either length or diameter
- Actuator and sensor configuration
  - concentric disk/ring chosen for sensor/actuator, common ground
  - experiments demonstrated highest amplitudes with this setup
  - yields less electrical noise than “self-sensing” concepts
- Optimal actuation waveform
  - 15kHz chosen based on previous work
  - 3.5 sine waves w/Hanning window, will also collect data for 5.5 waves





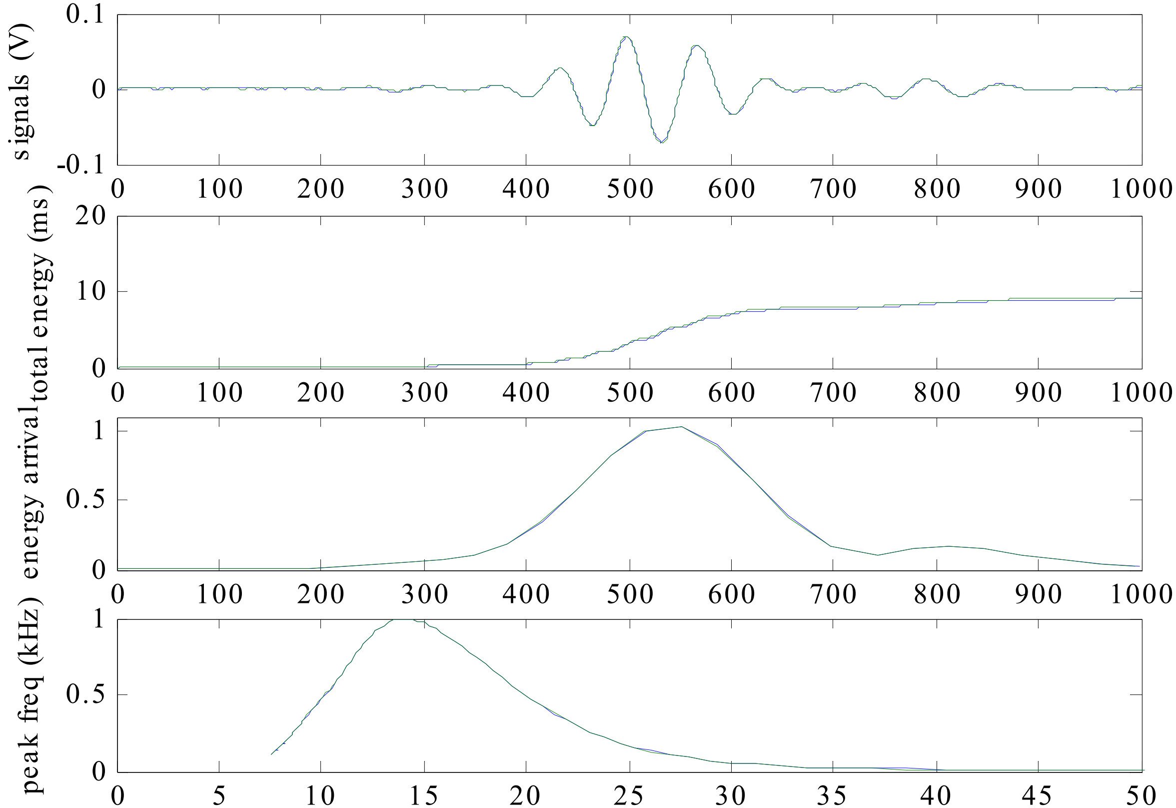
Actuator/Sensor Schematic



Data Reduction Procedure

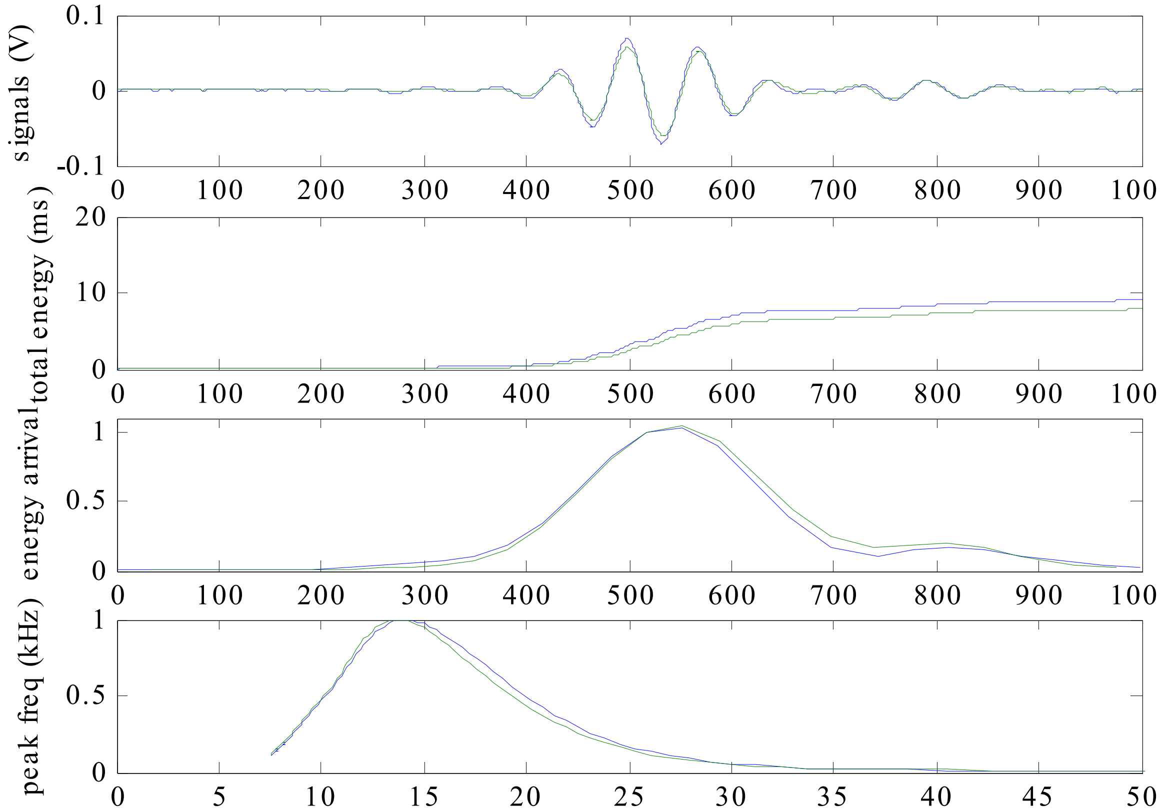
- Procedure developed within Matlab to reduce data
  - bandpass filter designed to remove low frequency drift and high frequency electrical noise without affecting signal shape
  - perform wavelet decomposition using Morlet mother wavelet to breakdown signal energy distribution between 7.5-50 kHz
  - plot *integrated voltage over time* yielding total received energy to determine *presence and severity* of damage
  - plot *normalized wavelet energy at driving frequency* of 15 kHz to determine time of arrival thus *damage location*
  - plot *normalized energy received for across wavelet spectrum* to determine *type of damage*
  - need 4 sets of plots: transmitted & reflected for 2 locations
- Need more consistent signals from new experiments to refine algorithms for automatic determination of damage

Experimental Results – Controls I



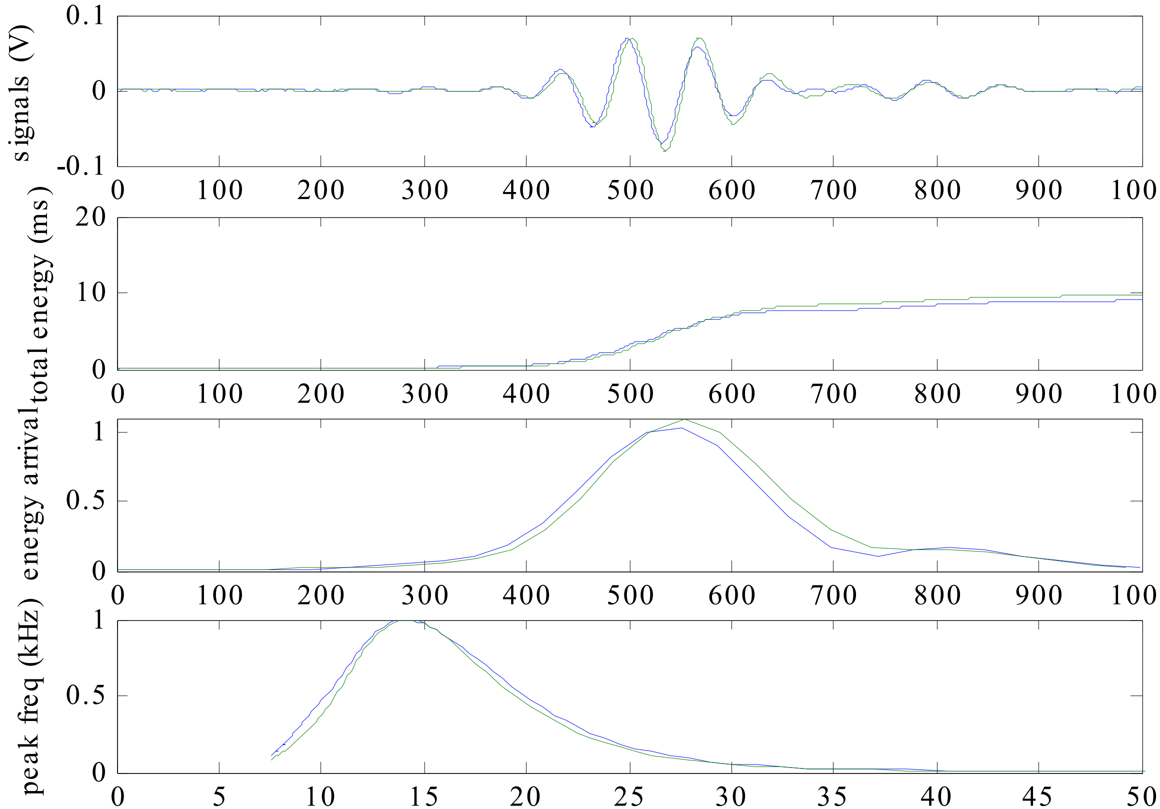
- Highly reproducible signal between same set of actuators and sensors tested several times

Experimental Results – Controls II



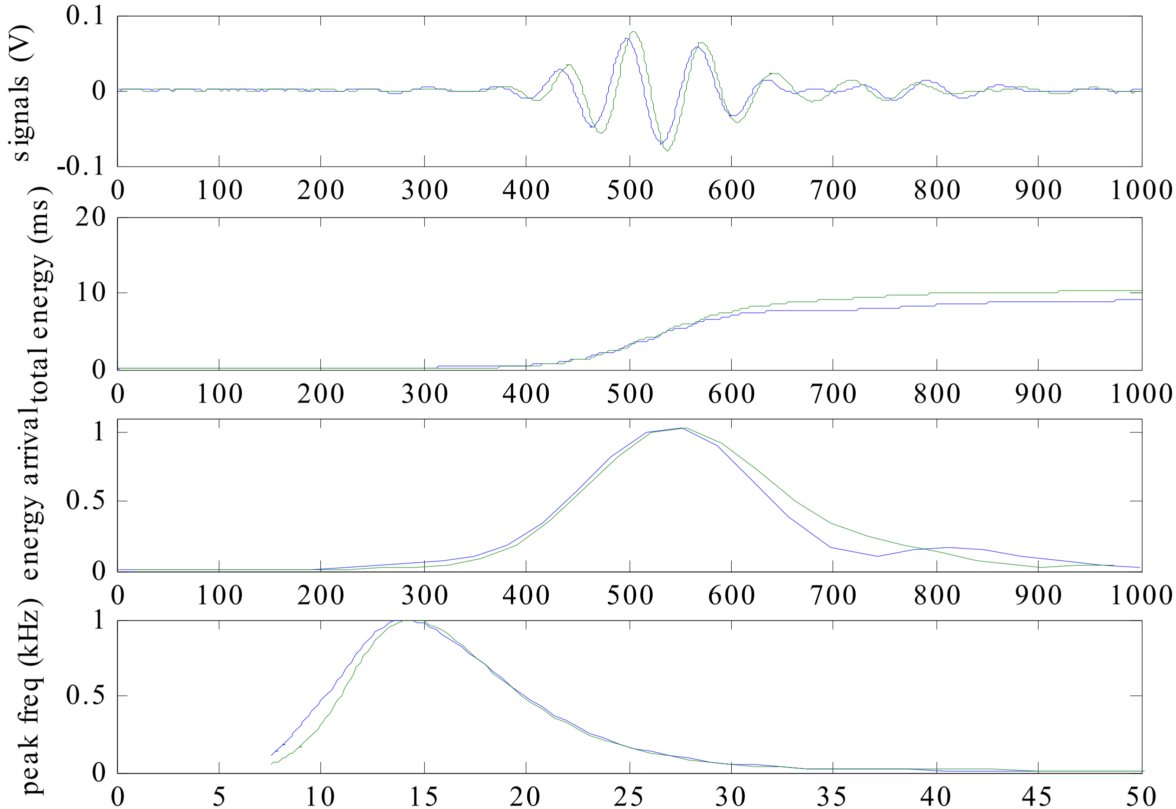
- Signal shape remains unchanged when propagating in reverse direction, other metrics remain similar

Experimental Results – Controls III



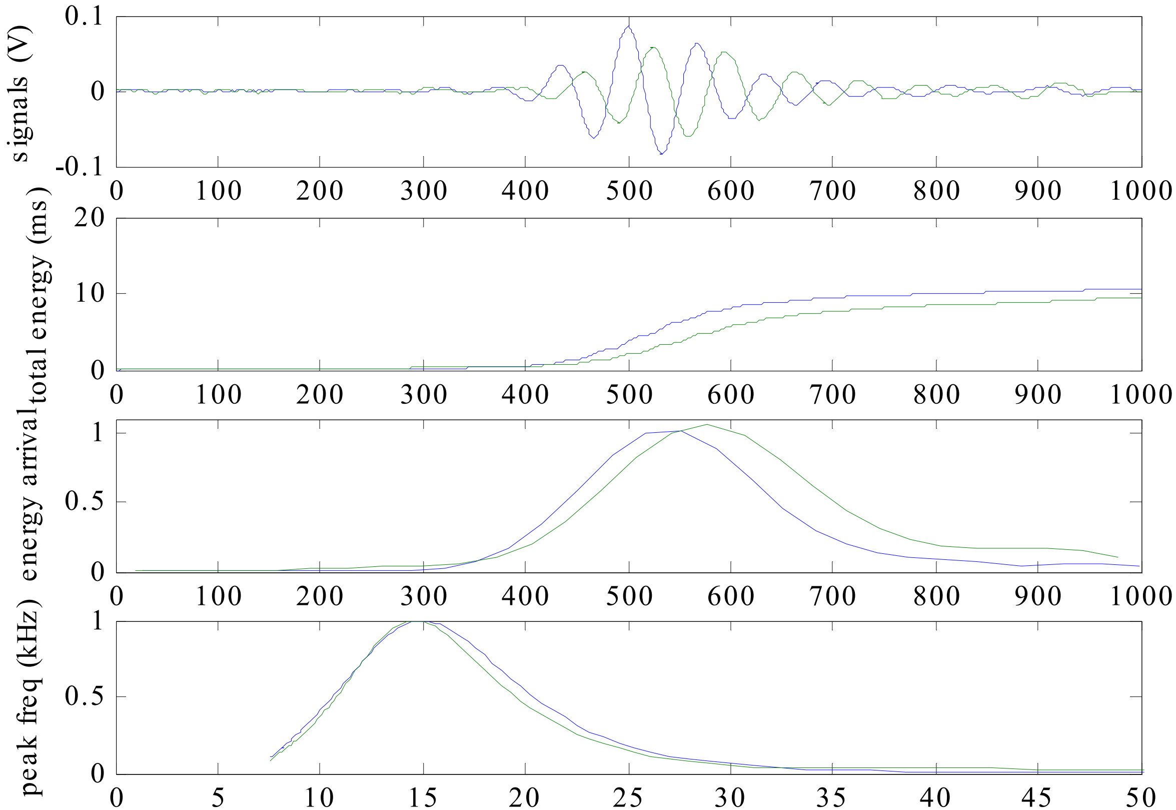
- Similar response across several different pairs of equally spaced actuators/sensors on same plate

Experimental Results – Controls IV



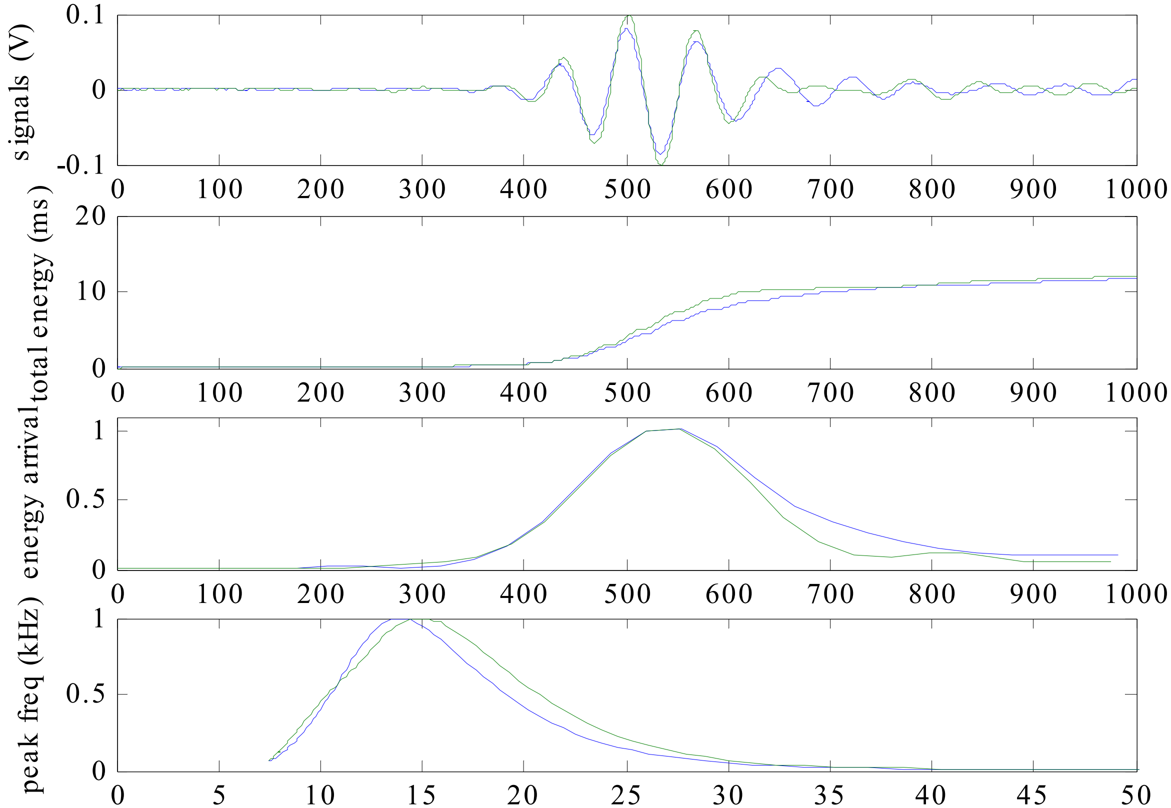
- Similar response between pairs of actuators/sensors located on several undamaged plates

Experimental Results – Delamination



- Delaminated signal is time-lagged, and has slightly lower energy content. Frequency bandwidth remains similar

Experimental Results – Microcracks



- Some matrix cracking caused a slight time delay, less tail energy and a small shift to a higher frequency bandwidth

Conclusions

- Optimized setup has increased signal strength nearly a factor of 4 over the previous research configuration
- New decomposition algorithm appears to work well with new data for transmitted wave, eliminate subjectivity
- Undamaged response is very reliable/reproducible
- Controlled damage does not have significant effect on most parameters, however voltage signal is lagged
- Reflected signal not yielding much information thus far
  - need to perform further analysis, maybe look at other frequencies
  - could affect ability to pinpoint damage location
- Will continue to collect more data to refine algorithm

Future Research

- Collect data on several plate specimens to refine algorithms
- Collect data for beam specimens with various core E and t's
- Continue studies on other potential detection methods
  – acoustic emission
  – eddy current
- Research focusing on other SHM components
  – wireless data acquisition and signal propagation
  – powering devices
- Increase complexity of tests
  – test on built up section
  – test in service environment (natural, mechanical, electrical noise)
  – use multiple sensing methods at once to increase reliability
  – integrate multiple SHM components