SELECTION OF MATERIALS AND SENSORS FOR HEALTH MONITORING OF COMPOSITE STRUCTURES

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OUTLINE

- Background and motivation
- Selection
  - SHM system
  - Sensor/actuator approach
  - Materials
- Results for Lamb wave sensors applied to composite structures

SHM MOTIVATION

- Structural Health Monitoring (SHM) denotes a system with the ability to detect and interpret adverse “changes” in a structure in order to reduce life-cycle costs and improve reliability
- Inspection and maintenance expenses could be reduced by SHM
  - currently, about 25% of aircraft life cycle cost is spent in inspections
  - commercial airlines spend a combined $10 bn/year on maintenance
  - condition based maintenance could reduce costs by 33%
- Particular concern for composite structures
  - Critical damage often not visible
  - Integrated manufacturing methods prevent tear down inspections

SHM SYSTEM COMPONENTS/ISSUES

- Architecture - this is a system problem
- Damage characterization - what are we looking for?
- Sensors - can it detect critical damage
- Communication - triggering, information to user
- Computation - large amounts of data can be generated
- Algorithms - intepretation of signals
- Power - powering of distributed systems a key issue
- Intervention/action - how to respond to damage detection
- System reliability
  - Reliable detection of damage, false positives, undetected critical damage
  - Introduction of sensors does not require more maintenance than without

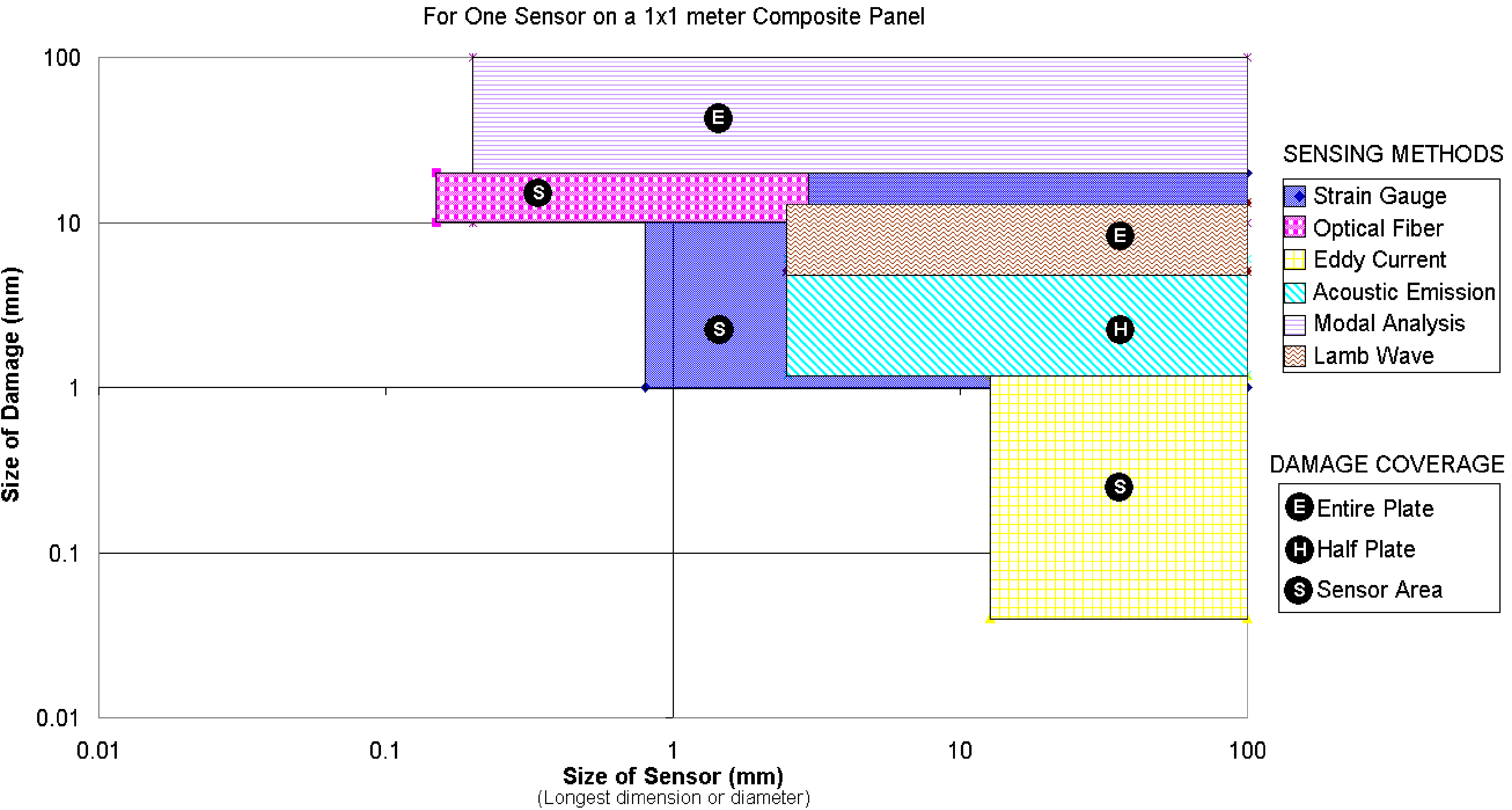
Only going to look at sensors here - but the other components are also key

NEED TO SELECT SHM SYSTEM COMPONENTS ON RATIONAL BASIS

- There are functional requirements and performance metrics by which to compare SHM systems
- Key choice is damage detection method
- Requirements
  - Capability for detecting size of damage that is critical for structure
- Performance metrics
  - Size of sensor
  - Power requirements for sensor
  - Density of sensors on structure
  - Lifecycle cost (the key one - but difficult to estimate/obtain data)
- Can map out SHM approaches on this basis - provide basis for selection

More data is required, but basic concept is valid, order of magnitude estimates quite acceptable

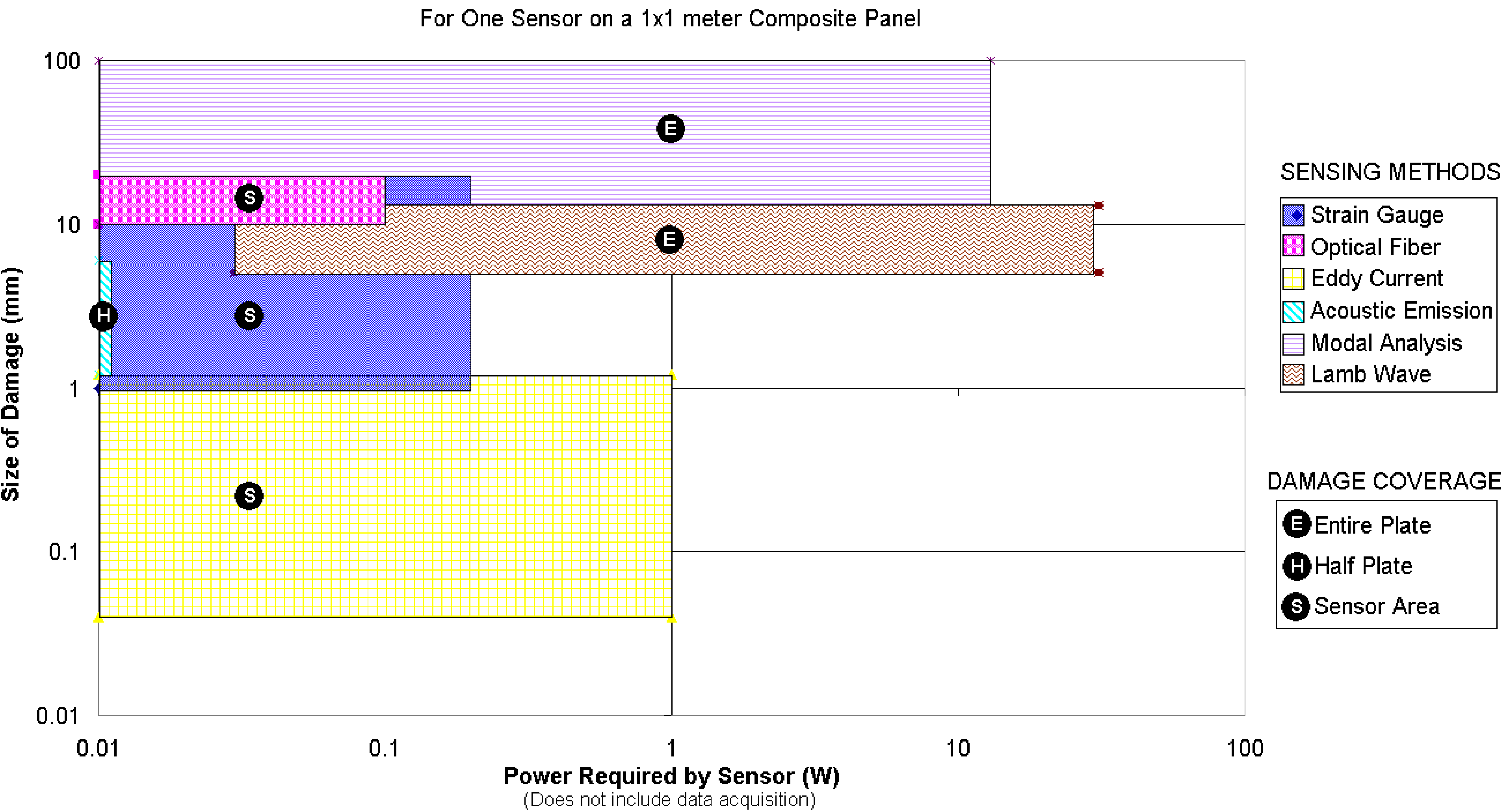
SIZE OF DETECTABLE DAMAGE Vs. SENSOR SIZE



Trade off between damage detection size and coverage

For composite structures 5mm damage detection adequate

RESOLUTION Vs. POWER



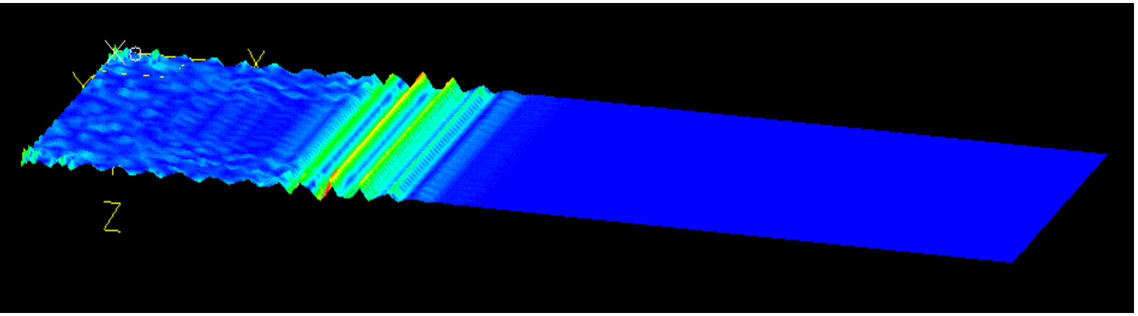
Methods with lowest power requirement typically have lowest coverage; Lamb wave and FR: sensitivity scales with power level

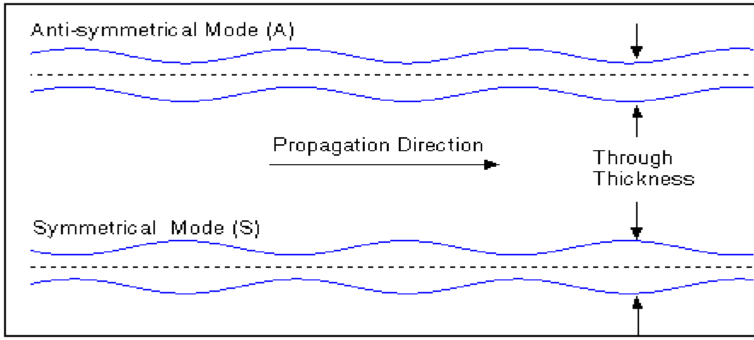
CHOICE OF LAMB WAVE APPROACH

- Good coverage
- 5mm damage detection capability
- Acceptable power draw and sensor size
- Well suited for composite skin structures
- In addition can use basic sensors for acoustic emission, local strain and frequency response

LAMB WAVES

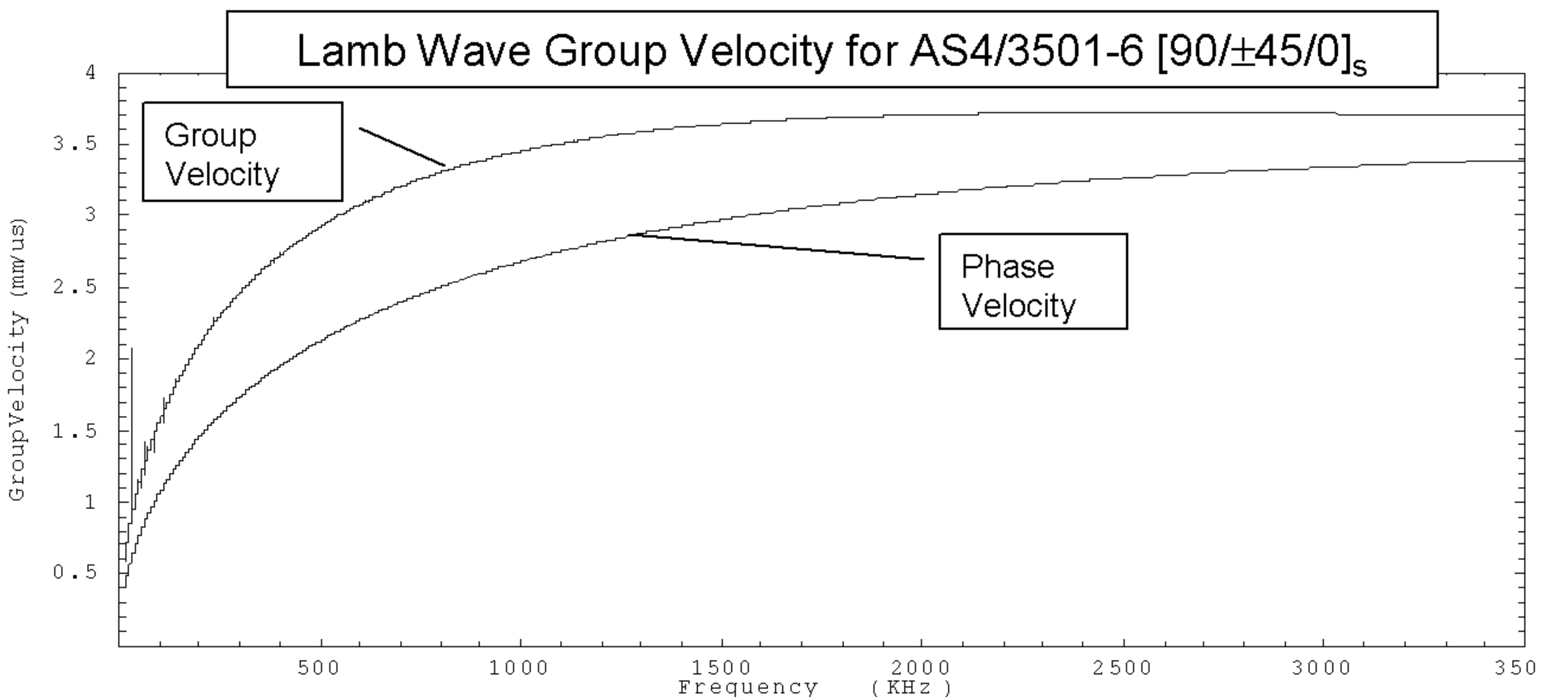
- Form of elastic perturbation in finite thickness structures
  - function of elastic constants and density
  - symmetric and anti-symmetric waves possible
- Background work from literature
  - Described by Horace Lamb (1917), developed by GE for NDE in 1960
  - Previous work on metals e.g. Cawley (2000), detecting damage in complex metallic structures
  - Soutis (2000) demonstrated relationship between delamination area and time of flight shifts in a composites





LAMB WAVE DAMAGE DETECTION

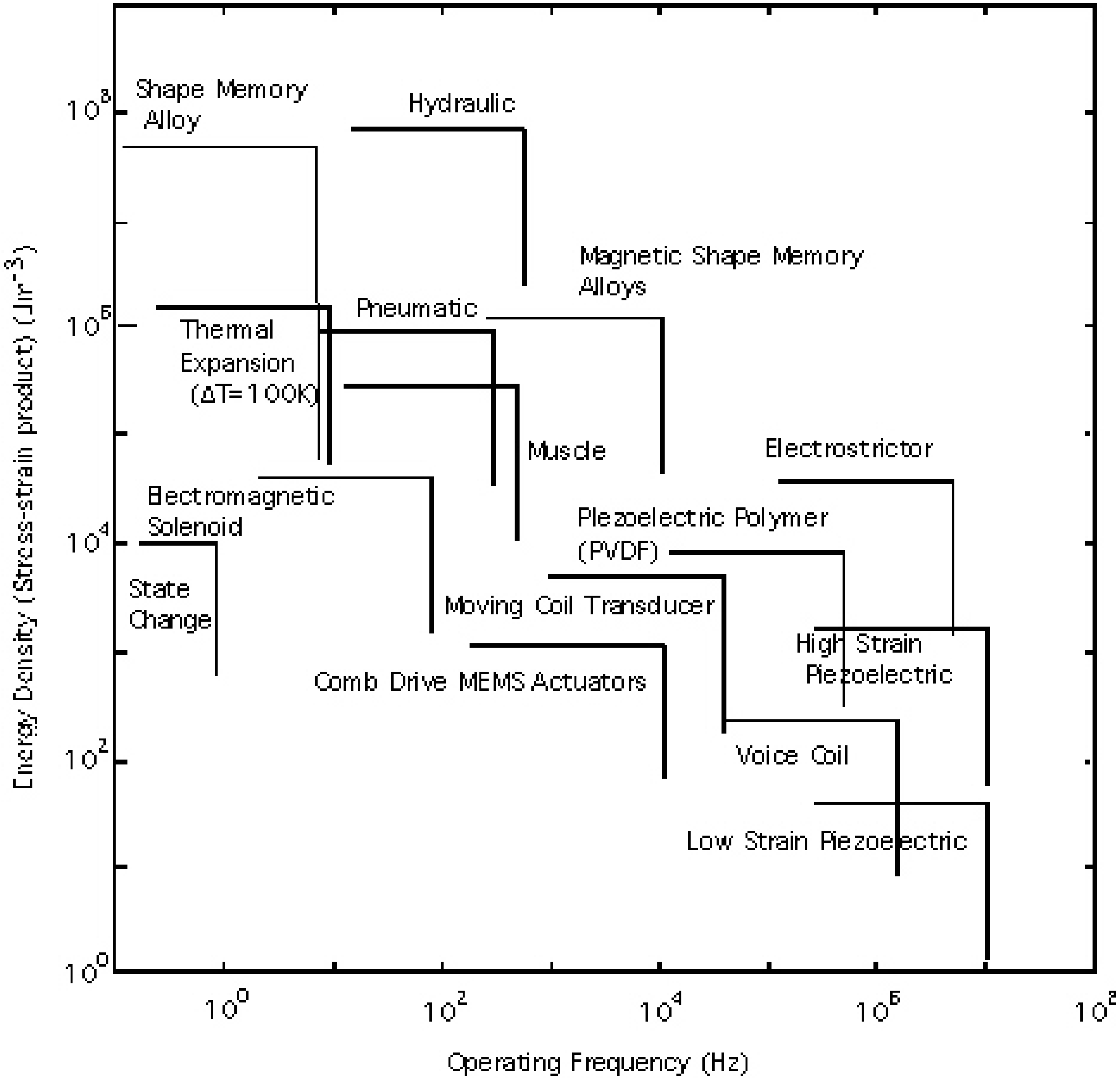
- Dispersion curves characterize Lamb waves
  - phase or group velocity versus frequency thickness product
  - use to select actuating frequency and predict attenuation
- Damage can be identified in two ways
  - group velocity approximately $\propto (E/\rho)^{1/2}$ - damage reduces E
  - reflected waves can be used to determine location



LAMB WAVE TRANSDUCER SELECTION

- “Sensor” consists of actuator - to generate Lamb waves and sensor to receive reflected and transmitted waves
- Again, approach to select actuator and sensors should be conducted on rational basis
- Actuator: achieve high strain energy density at useful operating frequencies - 10-100 kHz
- Sensor: Sensing small forces (accelerations) at 10-100 kHz
- Can plot capabilities of sensor and actuators on selection charts

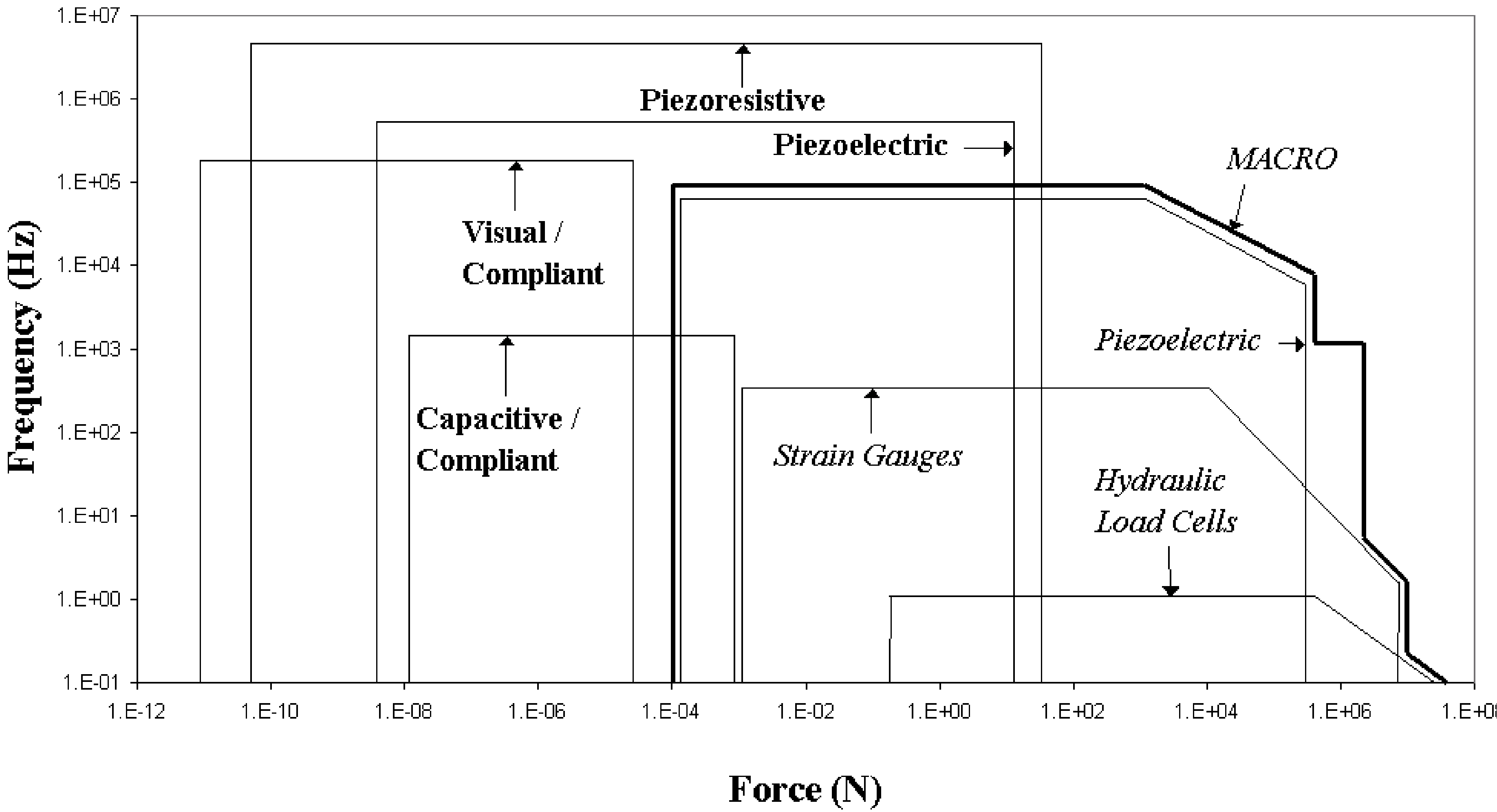
ACTUATOR SELECTION



After Huber, Fleck and Ashby, Proc. Roy. Soc. 1997

Electrostrictors and piezo-ceramic materials have best combination of frequency and energy capability

SENSOR SELECTION



Bell, Lu, Fleck and Spearing, Submitted to JMEMS 2003

Piezo-resistors and piezo-ceramic materials have best capabilities, piezoceramics best for actuator/sensor pair

DETAILED MATERIAL SELECTION

- Actuator: Maximise e_{31}^{p} piezo-stress coefficient
- Sensor: use 3-1 piezoelectric coupling properties to output an open circuit voltage in response to Lamb wave
  - 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
  - length of (1 + *n / 2)**λ 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

SELECTION OF SENSOR PIEZO-

Material	k_{31} (-)	d_{31} (p m / V)	g_{31} (mV m / N)	$Y_{11}{}^{D}$ (GPa)	$\lvert (k_{31})^2/(d_{31}(1-(k_{31})^2)) \rvert$ 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

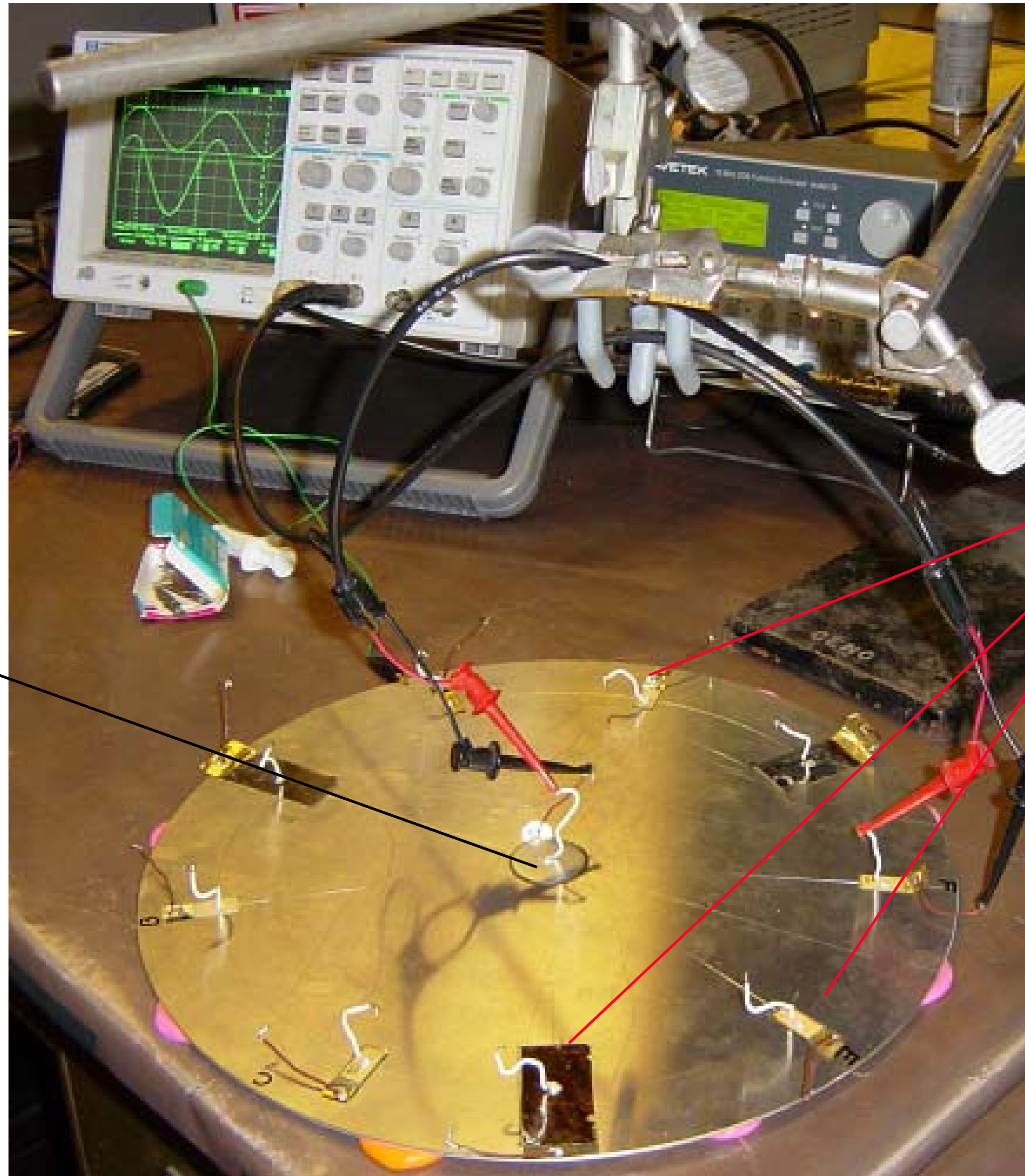
SELECTION OF ACTUATOR PIEZO-

Material	k_P (-)	s_{11}^E (p m^2 / N)	s_{12}^E (p m^2 / N)	σ^P (-)	ε_{33}^P (nF/m)	e_{31}^P (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

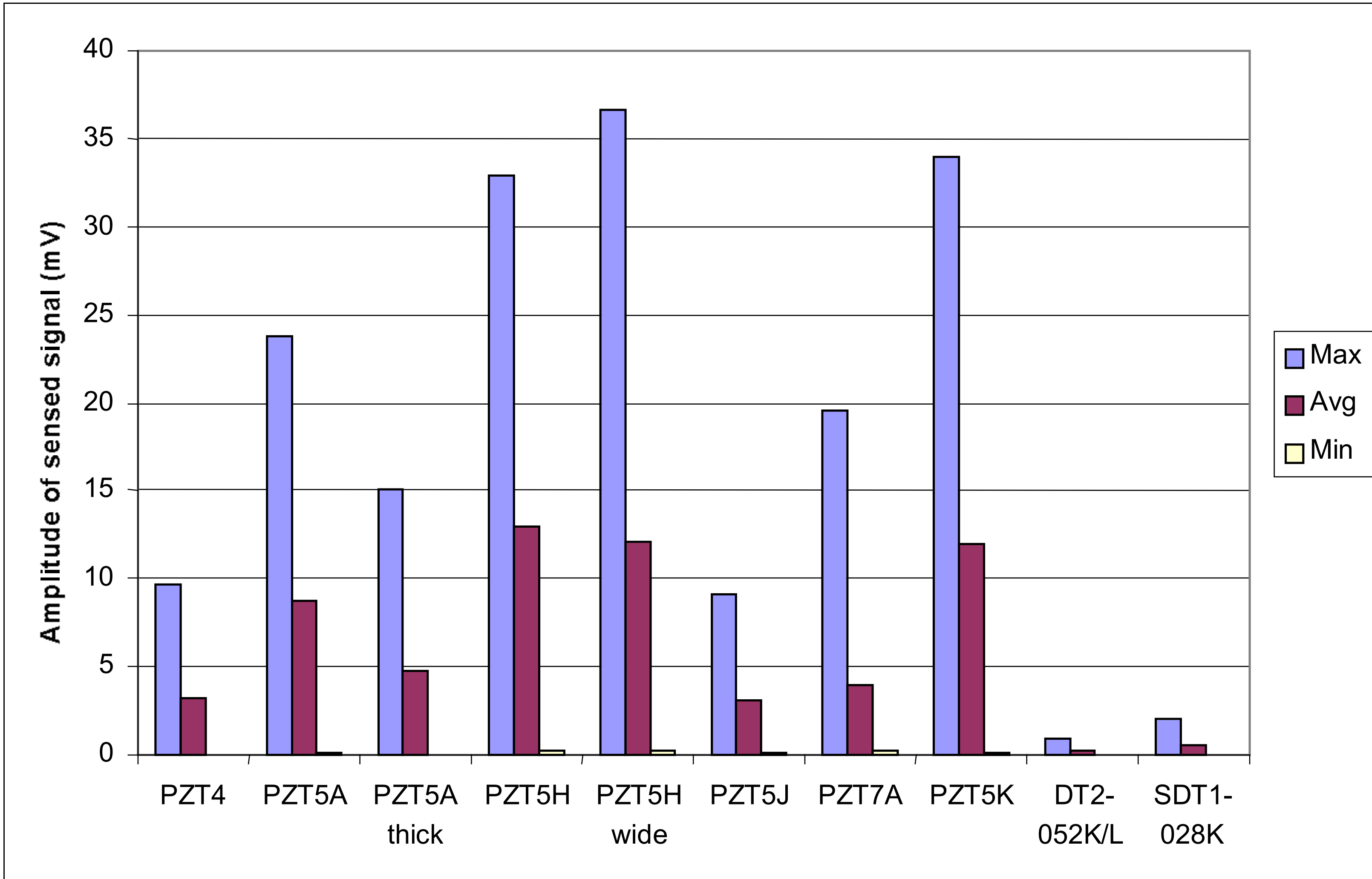
EXPERIMENTAL MATERIAL SELECTION

- Candidate materials fabricated into rectangular pieces 12.5x6.4x0.25mm - 25 x 6.4x0.5 mm
- Attached to composite and aluminum circular plates 2mm thick, 400 mm diameter
- Actuators placed at center of circular plate
- 20 V peak to peak applied, frequency sweep 1-250 kHz
- All combinations of sensor and actuator were tried
- Minimum, maximum and average sensed signal across frequency range was recorded

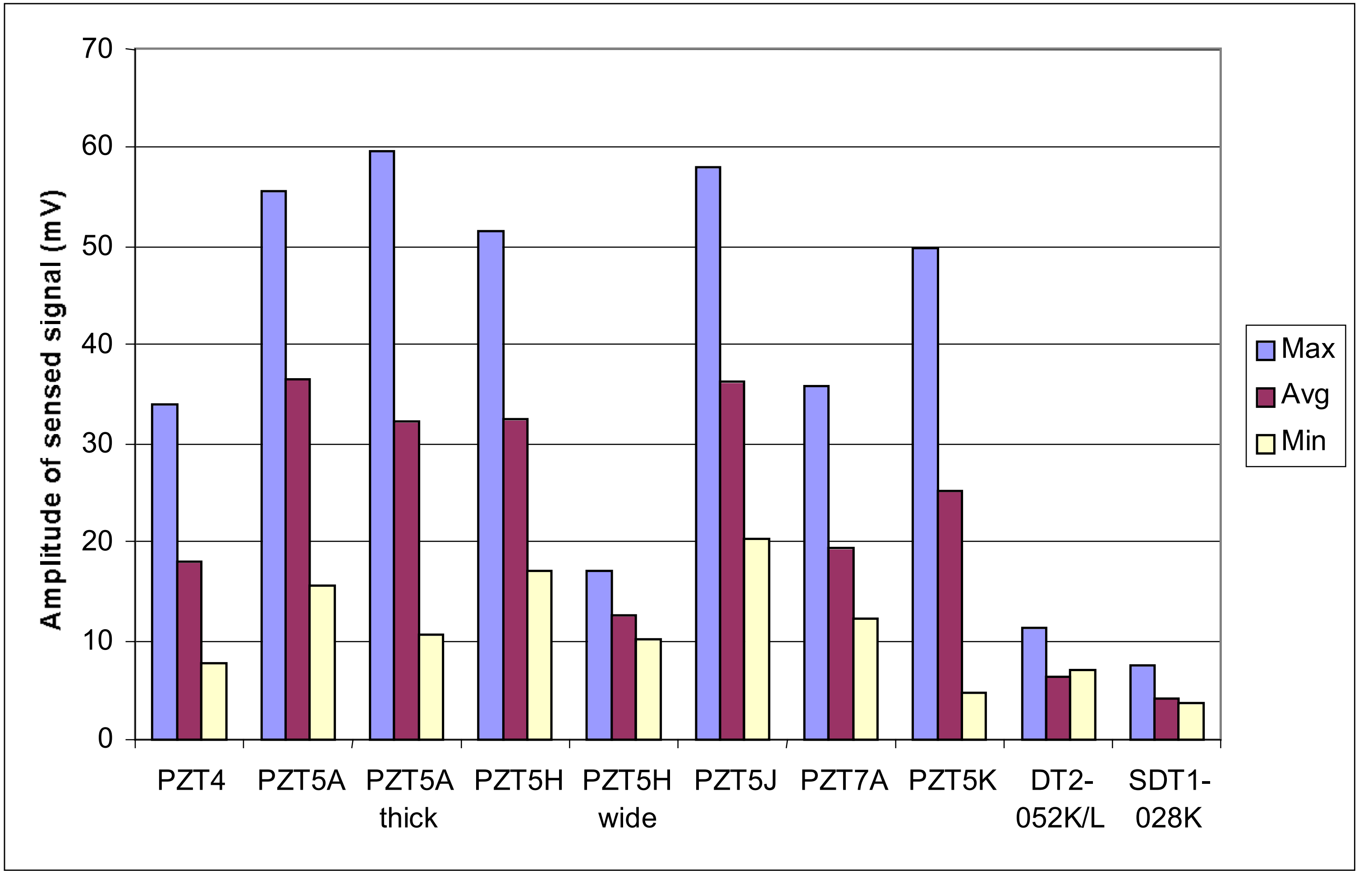
TEST CONFIGURATION



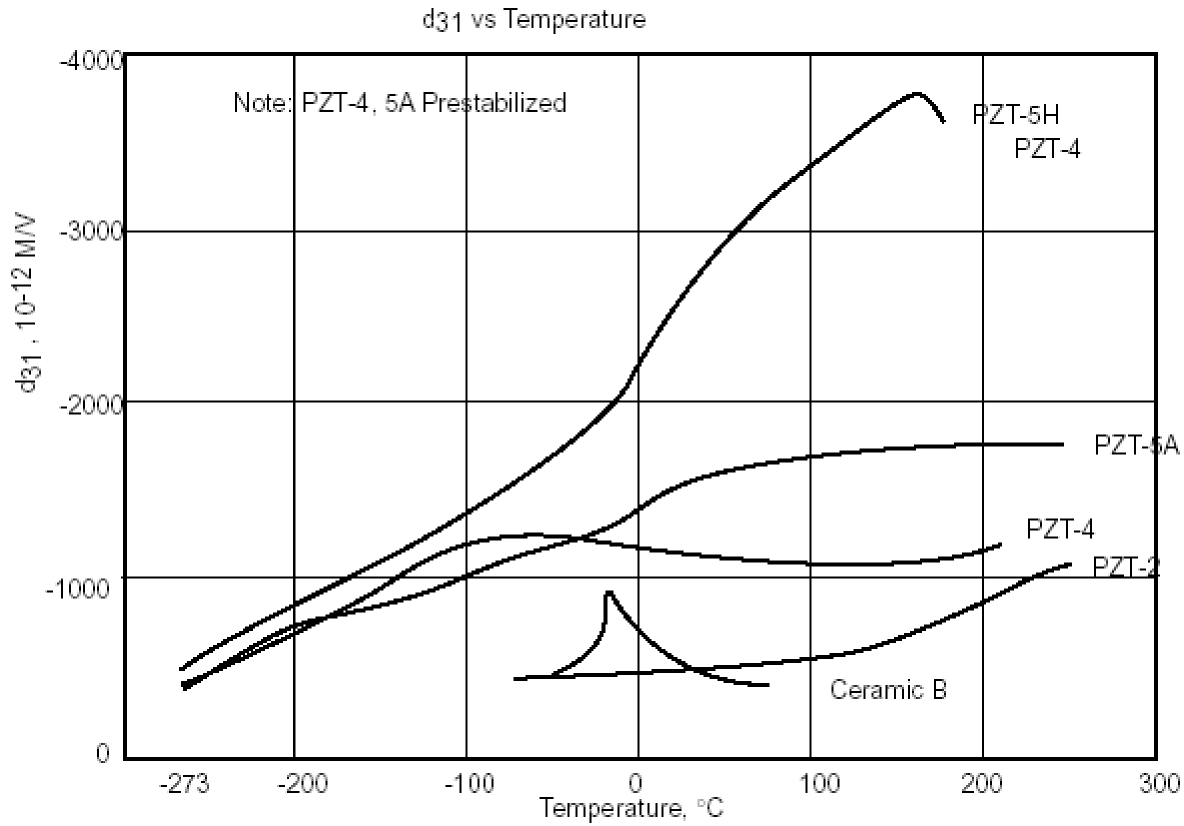
EXPERIMENTAL RESULTS FOR ACTUATOR MATERIALS



EXPERIMENTAL RESULTS FOR SENSOR MATERIALS

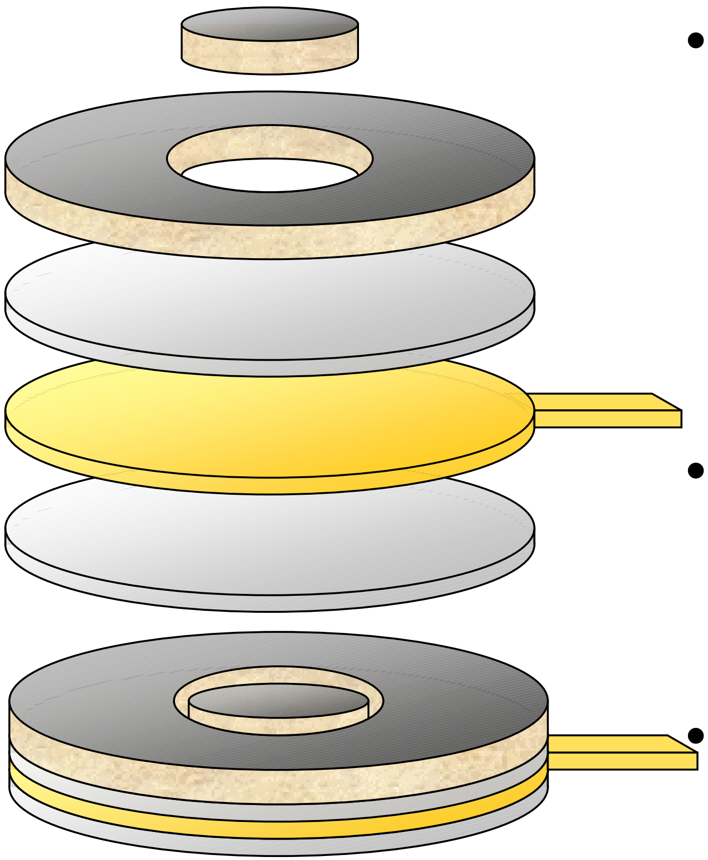


TEMPERATURE STABILITY

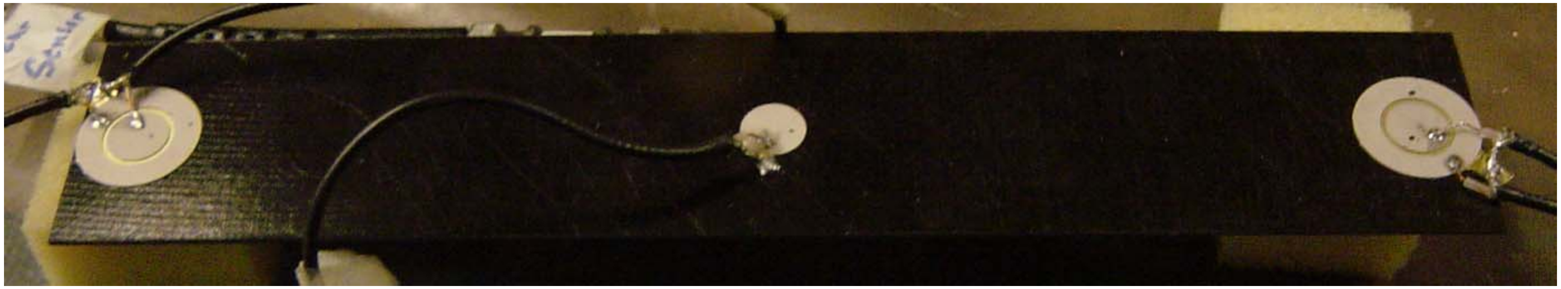


- PZT-5A has the best temperature stability of PZT materials
- PZT-5H has worst stability of PZT materials
- PZT-5K has comparable thermal properties to PZT-5H

ACTUATOR/SENSOR PACKAGE

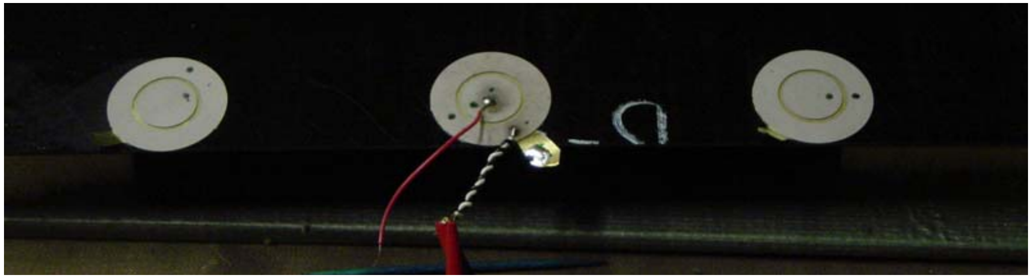


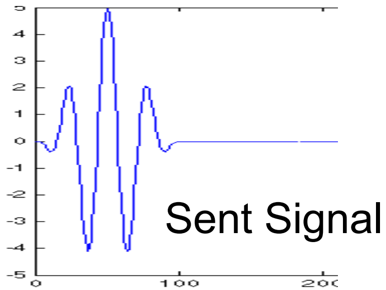
- PZT-5A material selected for actuator and sensor material
  - Highest actuating voltage
  - Temperature stability
  - Bandwidth of peaks
- Electrical & mechanical connections
  - 3M 9703 conductive tape (2 mil)
  - Brass Alloy 260 (1 mil)
- Increased signal strength 4x



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 (will vary with structure, damage)
  - 3.5 sine waves w/Hanning window

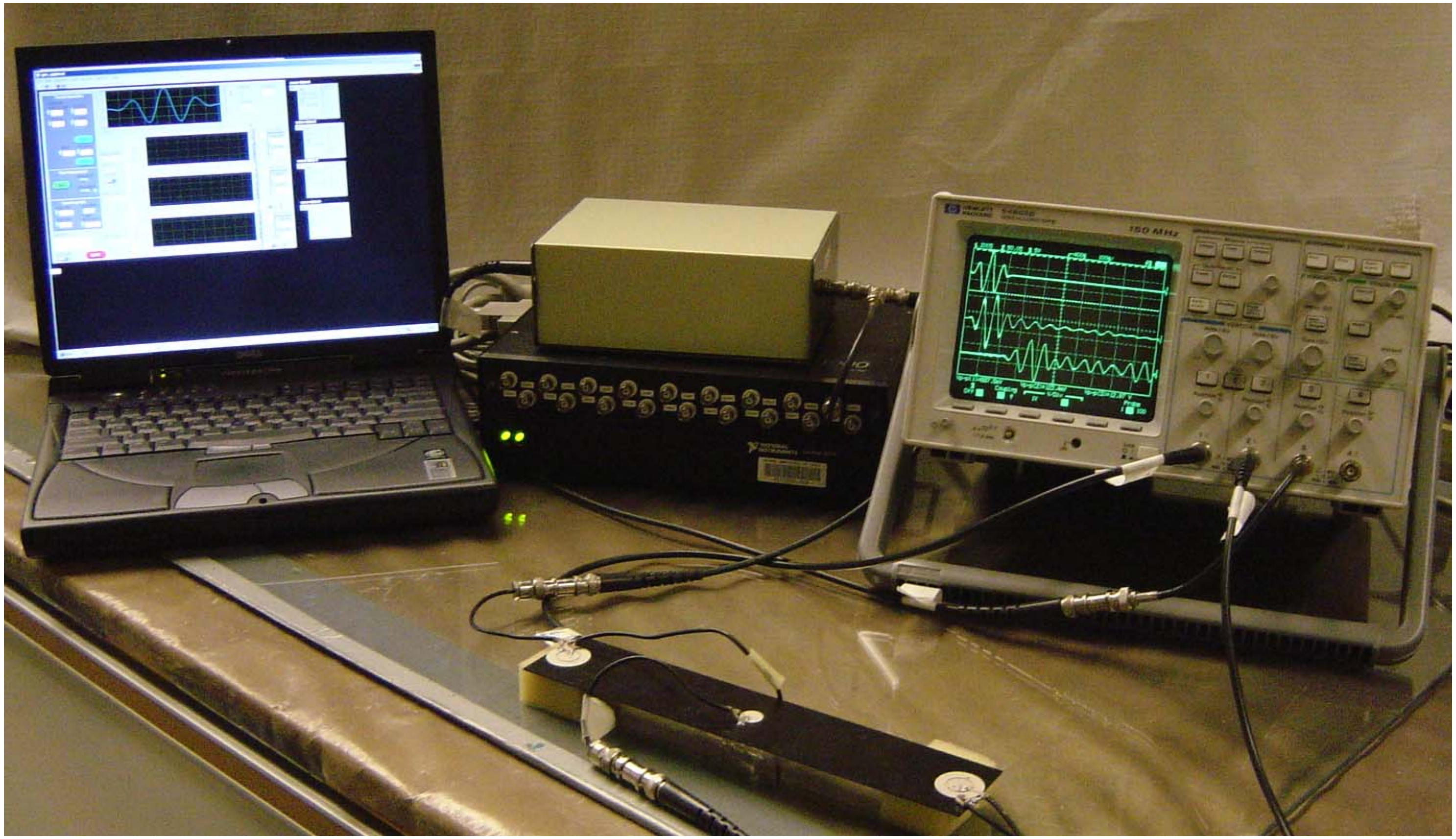




DATA REDUCTION PROCEDURE

- 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 obtain signal energy distribution between 7.5-50 kHz
  - Use *integrated voltage over time* (total received energy) to determine *presence and severity* of damage
  - Use *normalized wavelet energy at driving frequency* of 15 kHz to determine time of arrival thus *damage location*
  - Use *normalized energy received across wavelet spectrum* to determine *type of damage*
  - Need 4 sets of data transmitted & reflected for 2 locations

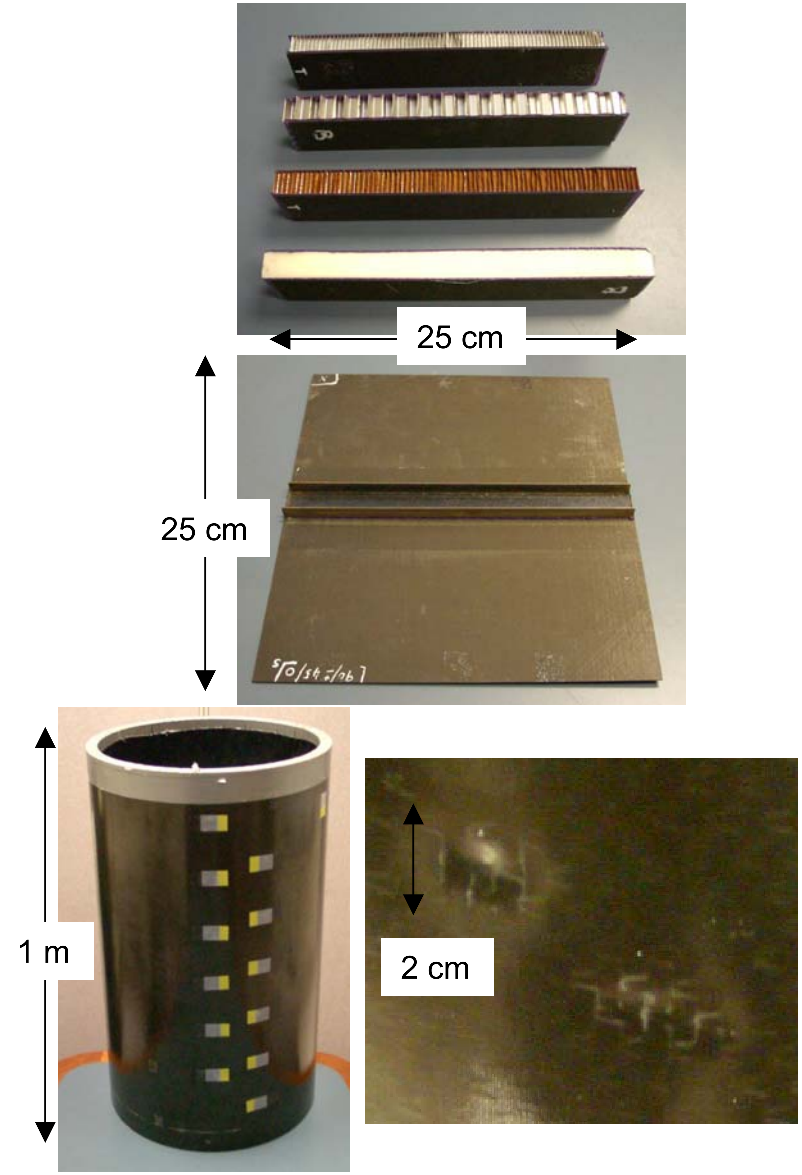
OPERATIONAL SYSTEM



- Tests executed via PC laptop and NI data acquisition board
- Completely portable, simple to use and automated results
- HP oscilloscope and function generator have also been used

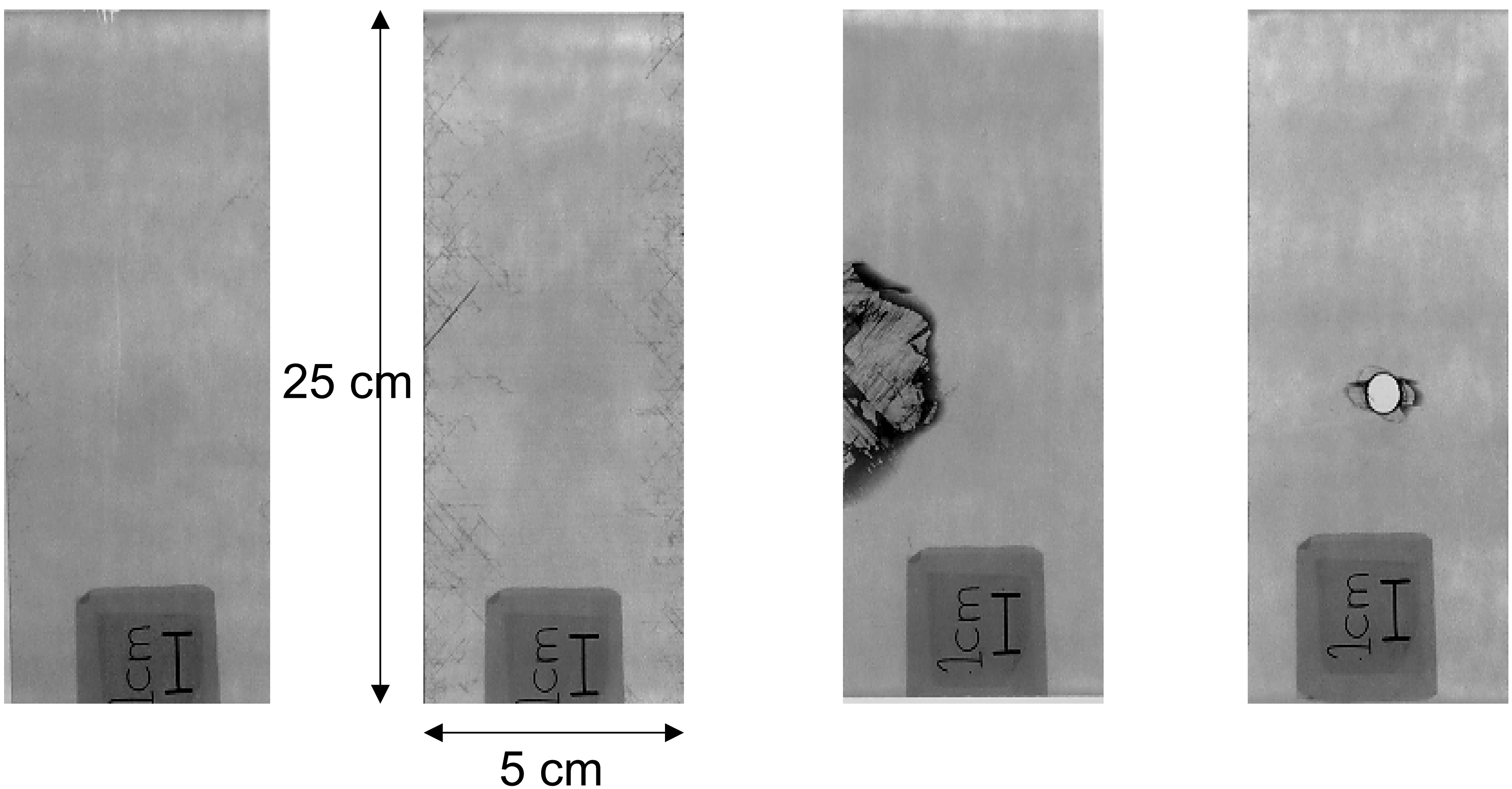
APPLICATION: BUILDING BLOCK APPROACH

- Narrow coupon laminates
  - same specimen used for FRM
  - several types of damage
- Narrow sandwich beams
  - various types of cores tested
  - disbonds between laminate and core
- Stiffened plate
  - various types of bonded ribs
  - disbonds between laminate and rib
- Composite sandwich cylinder
  - 0.4m diameter cylinder with core
  - low velocity impacted region

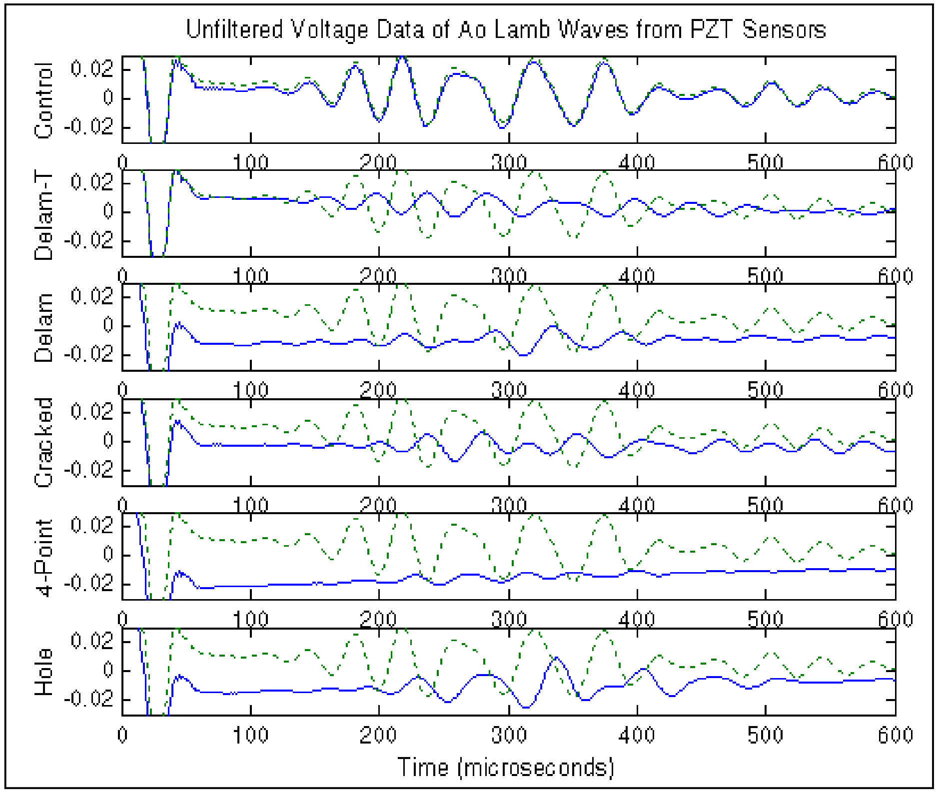


COUPONS WITH REPRESENTATIVE DAMAGE

Control Specimen | Matrix Crack Specimen | Delaminated Specimen | Core Drilled Specimen



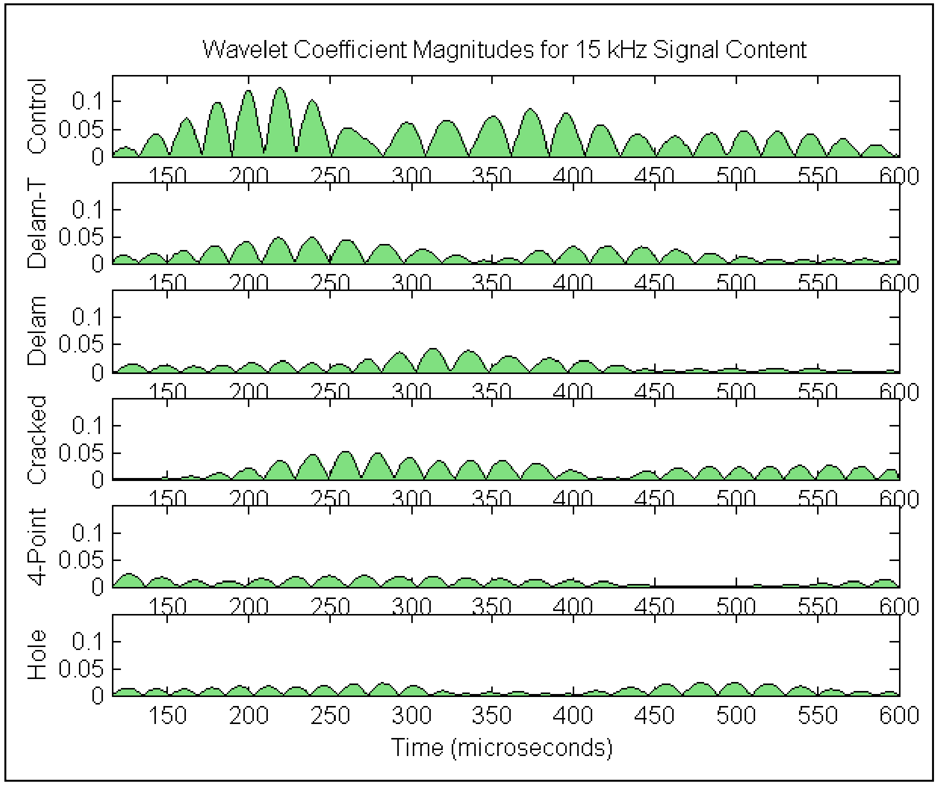
COUPON RESULTS



Specimen labeled on plot
Superimposed control specimen

- Time-trace of voltage signal from PZT sensor 20 cm from actuator driving at 15 kHz
- High degree of consistency between all control traces
- All damaged traces show a delay in time of arrival, and smaller amplitude responses
- Since these are short specimens, many reflections combine quickly
- While TOF is easily reproduced, difficult to measure accurately

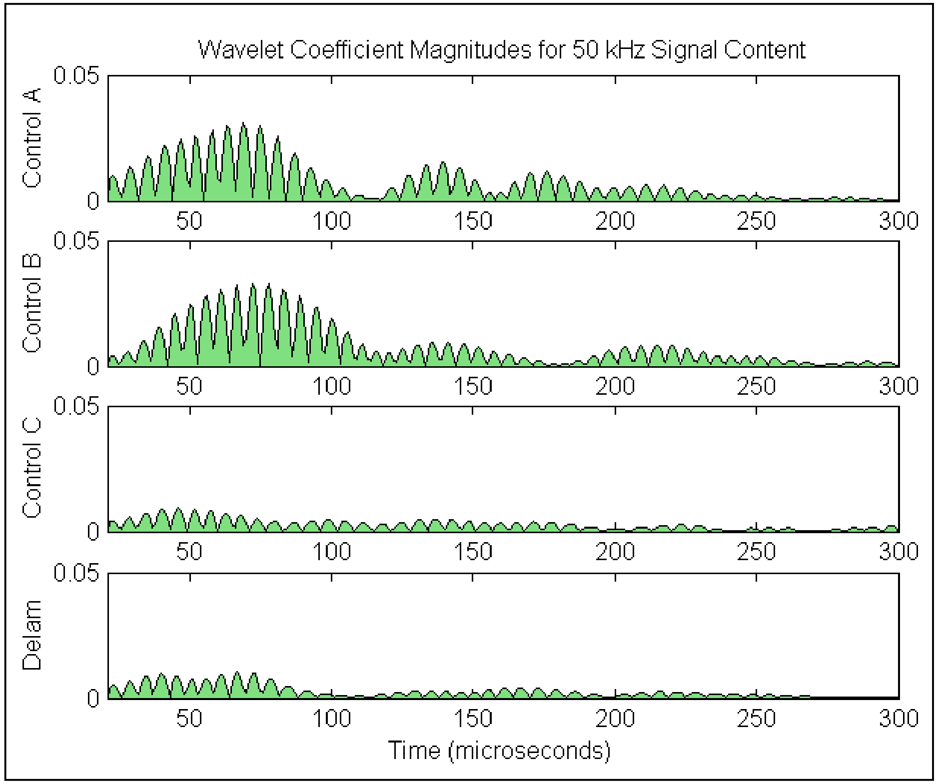
COUPON RESULTS: WAVELET ANALYSIS



- Wavelet decomposition using Morlet signal
- Clear distinction between damage types

Demonstrates ability to detect presence of damage and judge extent

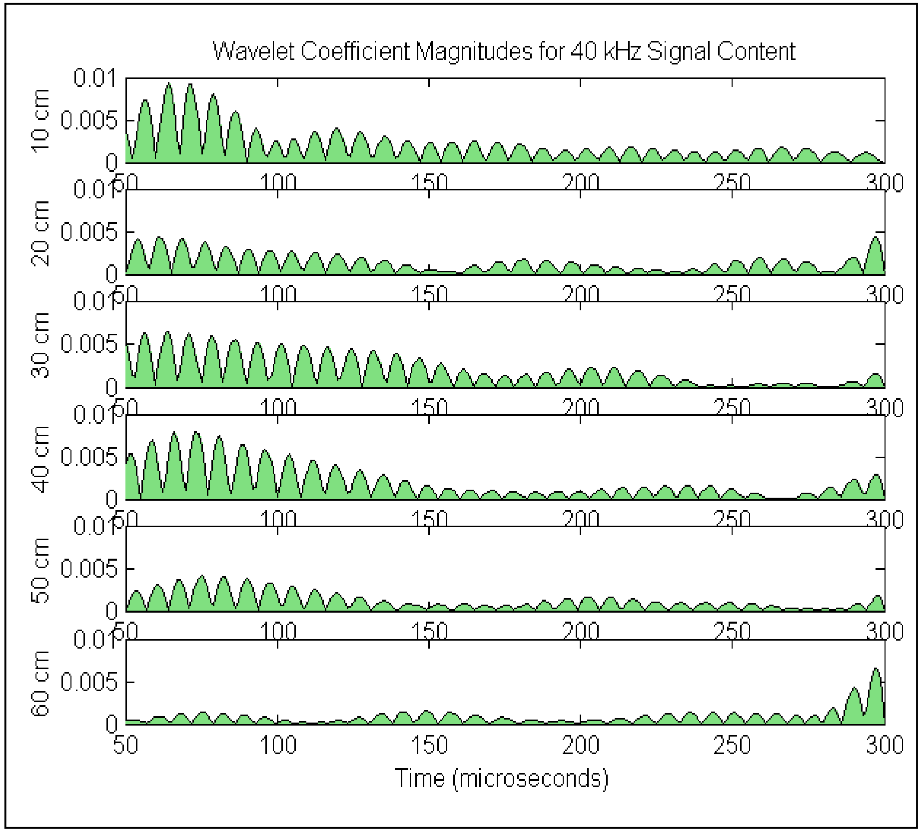
BLIND TEST SANDWICH BEAM



- Wavelet coefficient plot for beam “blind test” compares energy content for 50 kHz
- Three specimens with high density Al core, one has an unknown delamination
- One specimen with known delam
- Damaged beam clearly identified

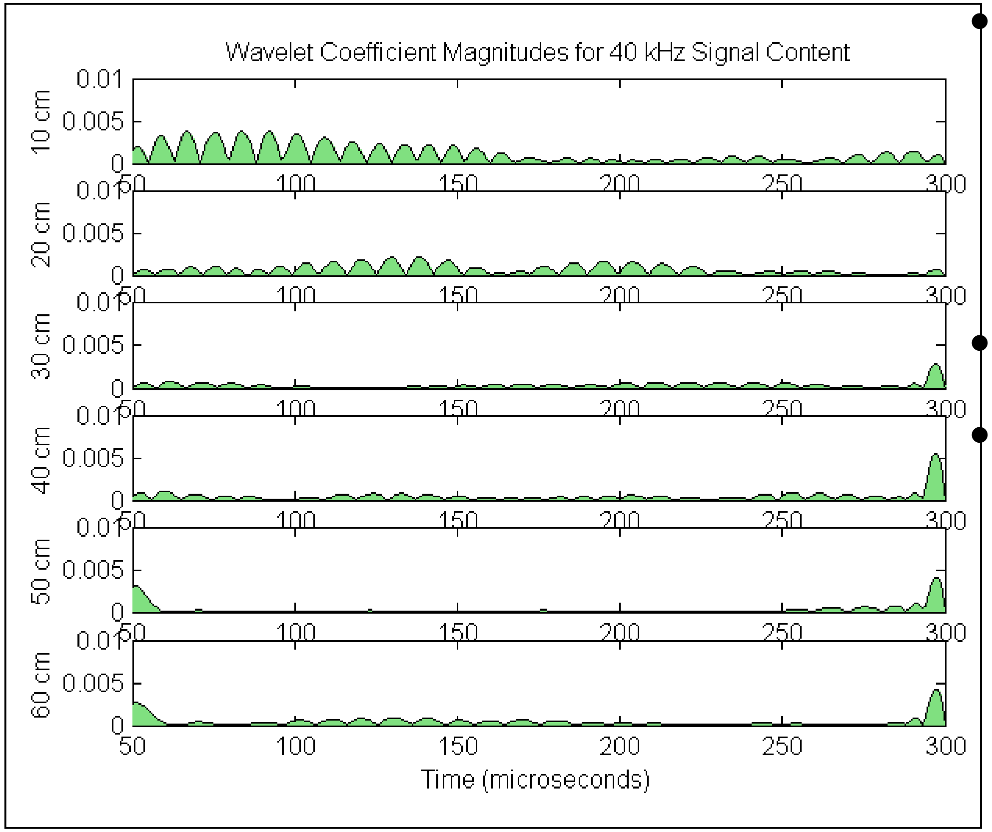
Indicates viability of wavelet method for use in at least simple structures

TESTS ON CYLINDRICAL SANDWICH STRUCTURE - UNDAMAGED



- CFRP tube, 4-plies surrounding low-density anticlastic Al core
- Multiple sensors used
- Axial signal transmission limitation appears to be about 0.5 m
- Circumferential transmission limit of 0.2 m; curvature causes more dispersion in signal (not shown)
- Wavelet coefficient plot for 40 kHz

DAMAGED CYLINDRICAL STRUCTURE



- Known impact damage region in tube of 2.5 cm diameter (damage visible on surface of outer ply)
- Damage clearly detected
- Downstream sensor masked by damage

Demonstrated application on moderately complex structure

SUMMARY

- Rational basis for structural health monitoring system, sensor and material selection
  - Experiments still required
  - More data required to compare approaches
- For composite structures piezo-ceramic Lamb wave sensors appear very promising
- Demonstrated capability to detect characteristic damage in simple and moderately complex structures
- Activities ongoing
  - Developed algorithms to triangulate damage location
  - Developing multi-physics sensors: acoustic emission and frequency response with Lamb waves
  - Developing packaging for sensors