Structural Health Monitoring of Aerospace Structures with Piezoelectric Wafer Active Sensors

Victor Giurgiutiu
University of South Carolina

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Laboratory for Active Materials and Smart Structures

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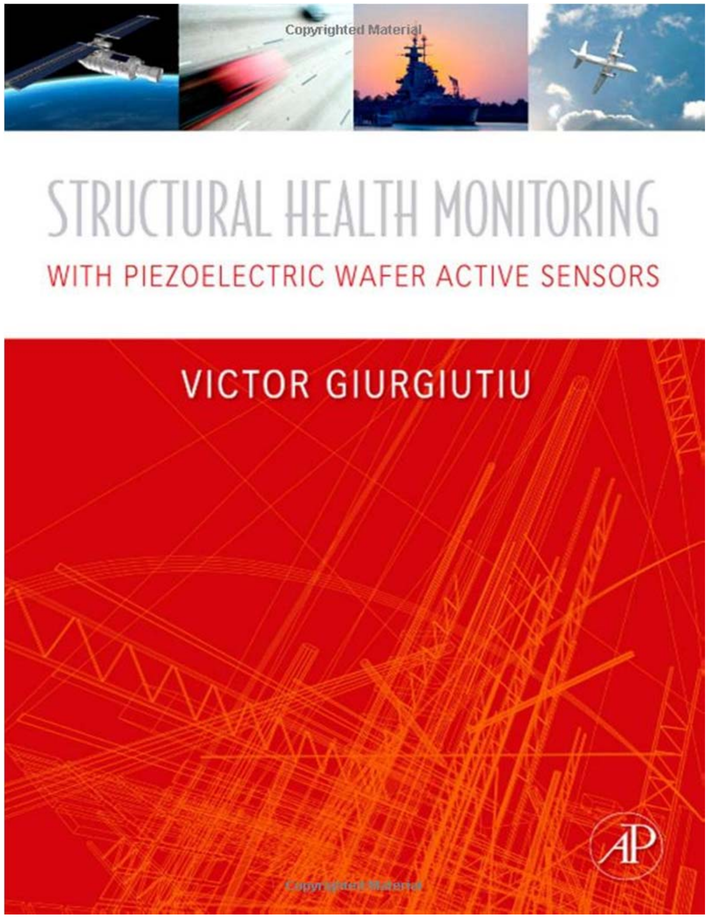
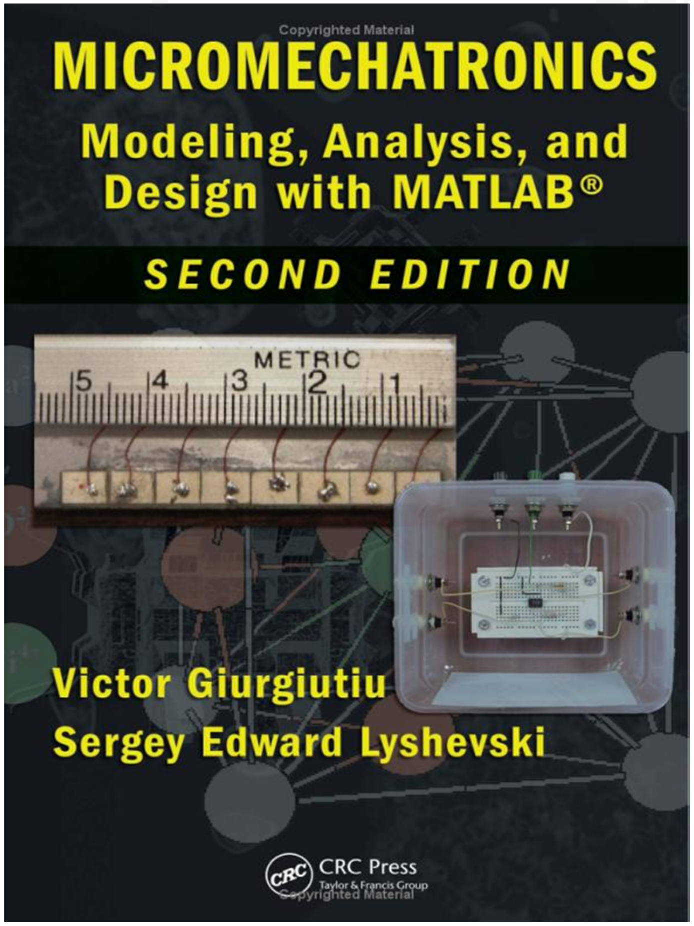
Two recent books on the subject



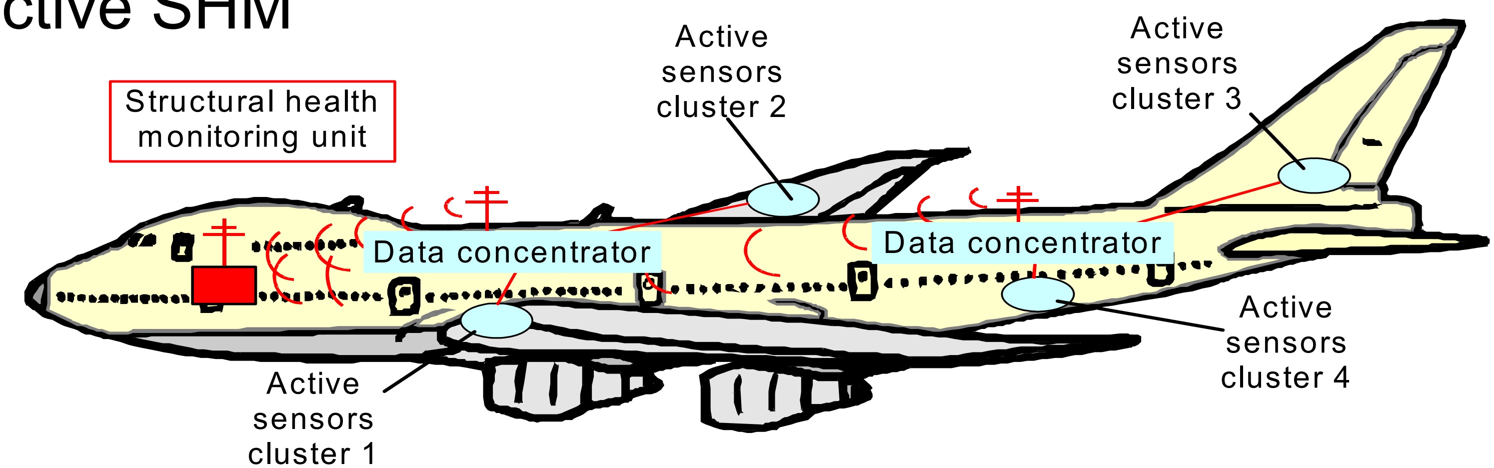


Outline

- PWAS principles
- Theoretical developments
  - Shear lag transfer into multiple guided wave modes
  - Power and energy transduction
- Experimental and data analysis developments
  - Thickness mode PWAS
  - Acoustic emission PWAS
  - Damage imaging with phased arrays and sparse arrays
- Summary and conclusions

Structural Health Monitoring (SHM)

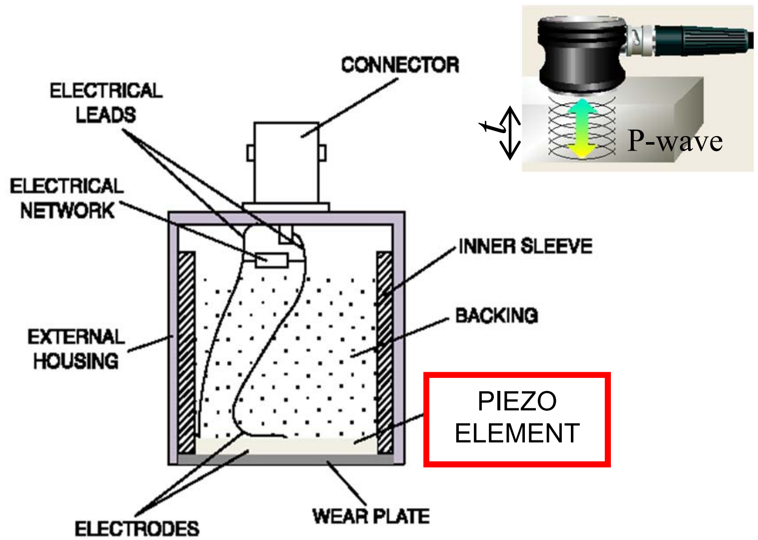
- Passive SHM: **records** flight parameters, loads, strain, environment, vibrations, impacts, acoustic emission from cracks, etc.
- Active SHM: **detects** damage, cracks, disbonds, delaminations, etc. (**embedded ultrasonic NDE**)
- Research Aim: Develop embedded NDE sensors for active SHM



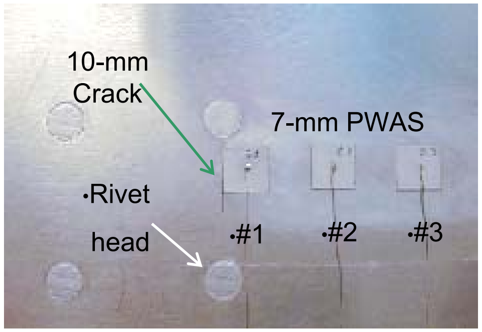
•(Giurgiutiu, V.; Zagrai, A. N.; Bao, J. "Piezoelectric Wafer Embedded Active Sensors for Aging Aircraft Structural Health Monitoring", *Structural Health Monitoring – An International Journal*, Sage Pub., Vol. 1, No. 1, July 2002, pp. 41-61)

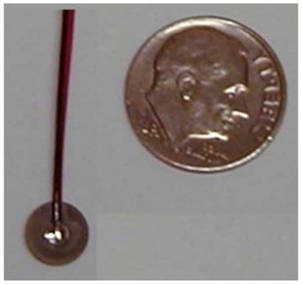
Piezoelectric Wafer Active Sensors for Structural Health Monitoring

Conventional ultrasonic transducers

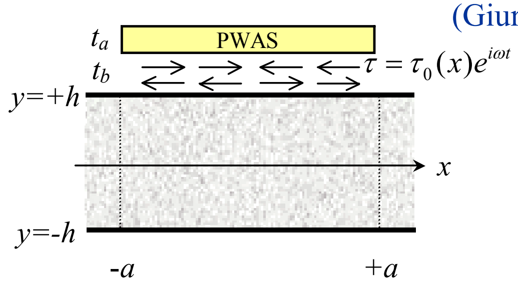


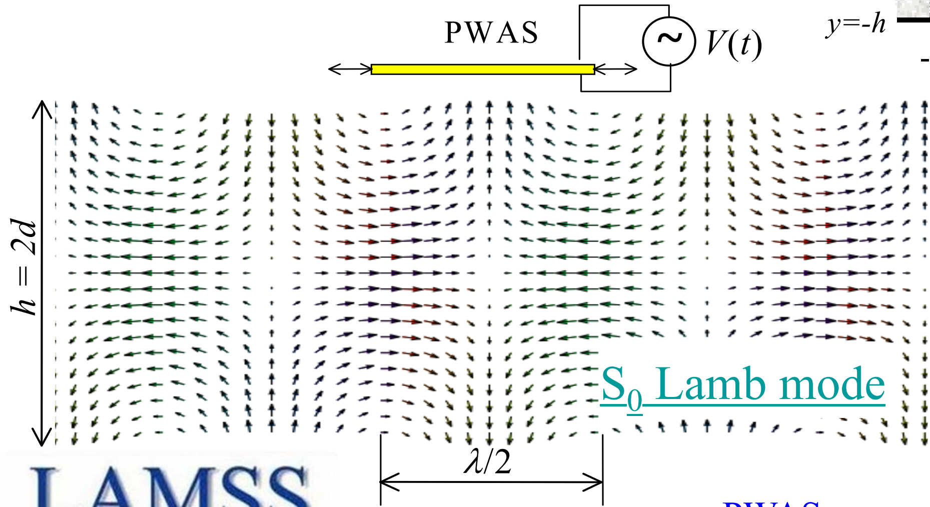
Piezoelectric wafer active sensors (PWAS)

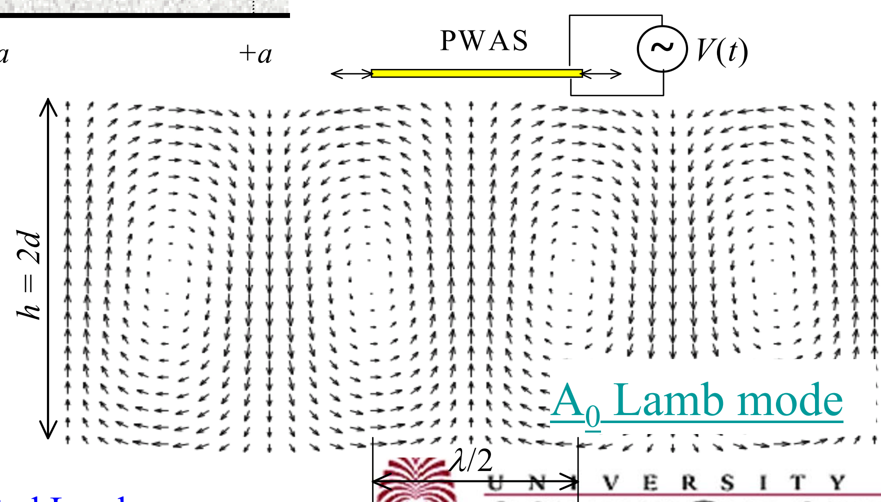




(Giurgiutiu et al., US patent 7,024,315/2006)







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PWAS generated Lamb waves

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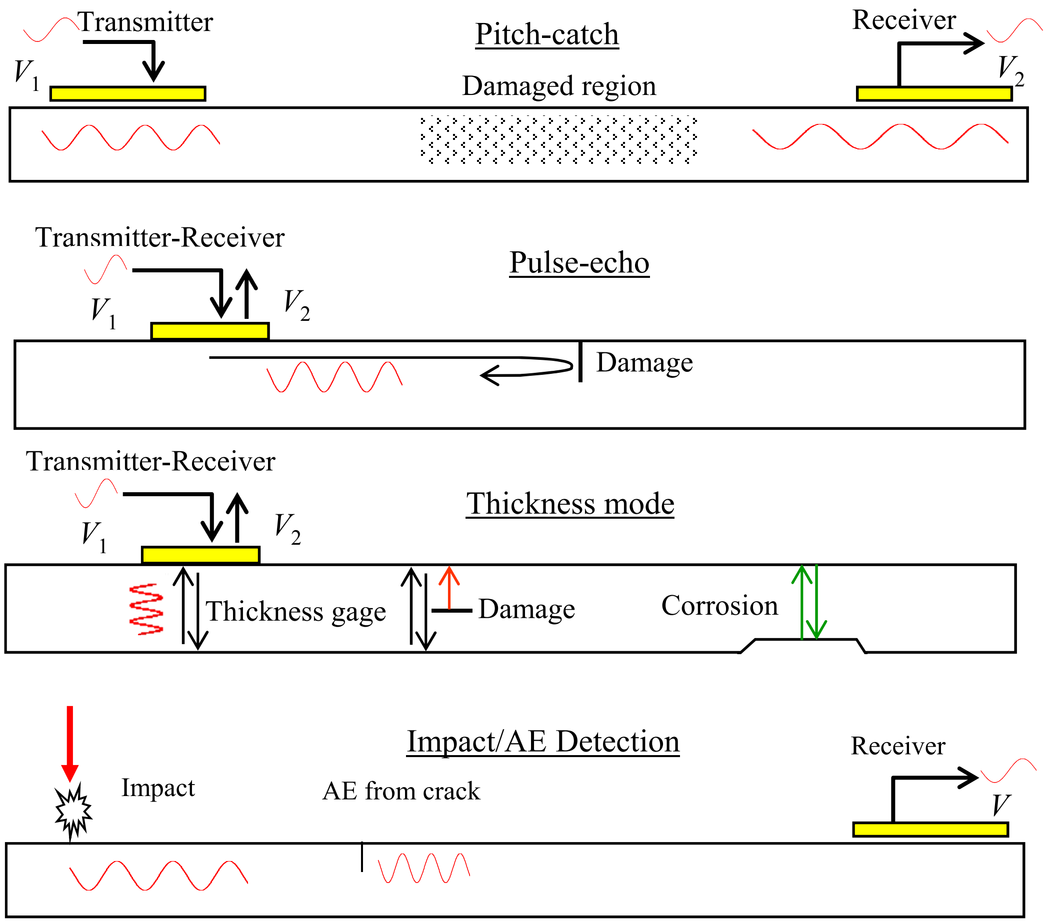
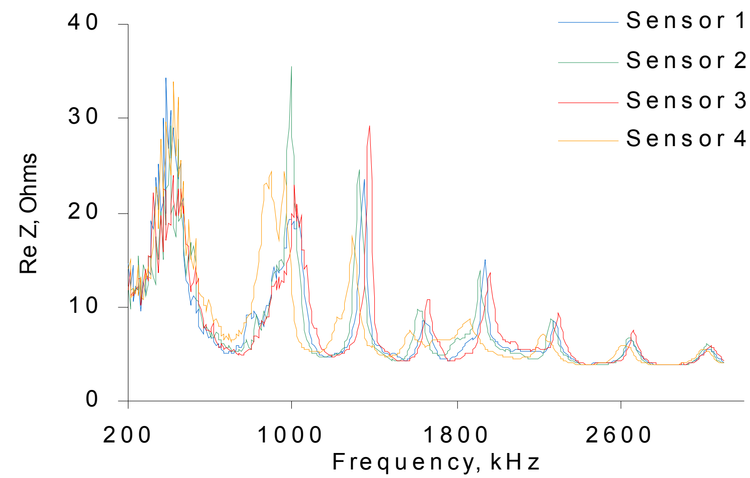
Piezoelectric Wafer Active Sensors (PWAS)

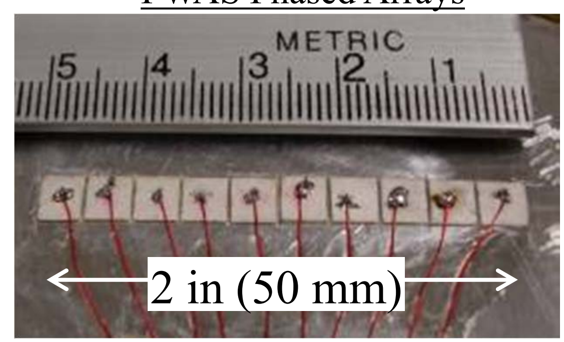
Propagating Lamb waves



Standing Lamb waves (E/M Impedance)



PWAS Phased Arrays



(Giurgiutiu et al., US patents: 7,174,255/2007; 7,024,315/2006; 6,996,480/2006)

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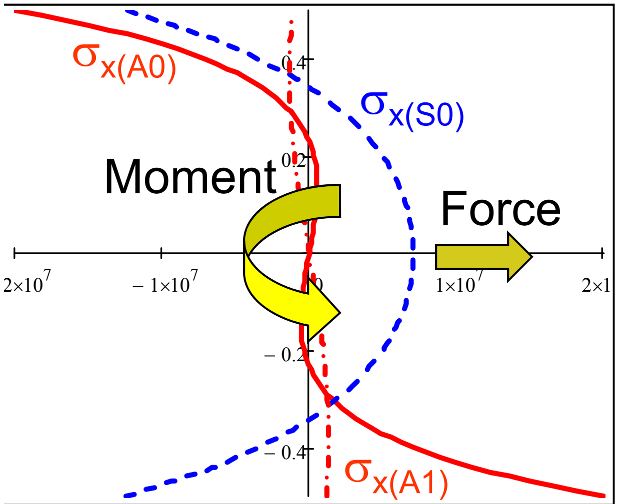
Shear-lag Transfer between PWAS and N Guided Wave Modes



Normal stress according to NME theory

$$\sigma(x,y)=\sum_{n=1}^{N}a_n(x)\sigma_n(y)$$

Acoustic field amplitude from the NME theory

$$a_{\pm n}(x)=\frac{e^{\mp i\xi_n x}}{4P_{nn}}\tilde{\mathbf{v}}_{\pm n}(d)\cdot\int_{-\infty}^{\infty}e^{\pm i\xi_n\eta}\mathbf{t}(\eta)d\eta$$

Integro-Differential Equation

$$\tau''(x)-\Gamma^2\tau(x)-i\sum_{n=1}^{N}\eta_n\left[e^{-i\xi_n x}\int_{-a}^{x}e^{i\xi_n\bar{x}}\tau(\bar{x})d\bar{x}+e^{i\xi_n x}\int_{x}^{a}e^{+i\xi_n\bar{x}}\tau(\bar{x})d\bar{x}\right]=0$$

Shear-lag parameter

$$\Gamma^2=\frac{1}{t_a t_b}\frac{G_b}{E_a}\frac{\alpha+\psi}{\psi}$$

Modal repartition number

$$\alpha=-\sum_{n=1}^{N}\frac{t\tilde{v}_x^n(d)\sigma_n(d)}{2P_{nn}}$$

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(Santoni-Bottai, G.; Giurgiutiu, V. (2010) “Exact Shear-lag Solution for Guided Waves Tuning with Piezoelectric Wafer Active Sensors”, AIAA Journal, manuscript # 2010-05-J050667, under review)

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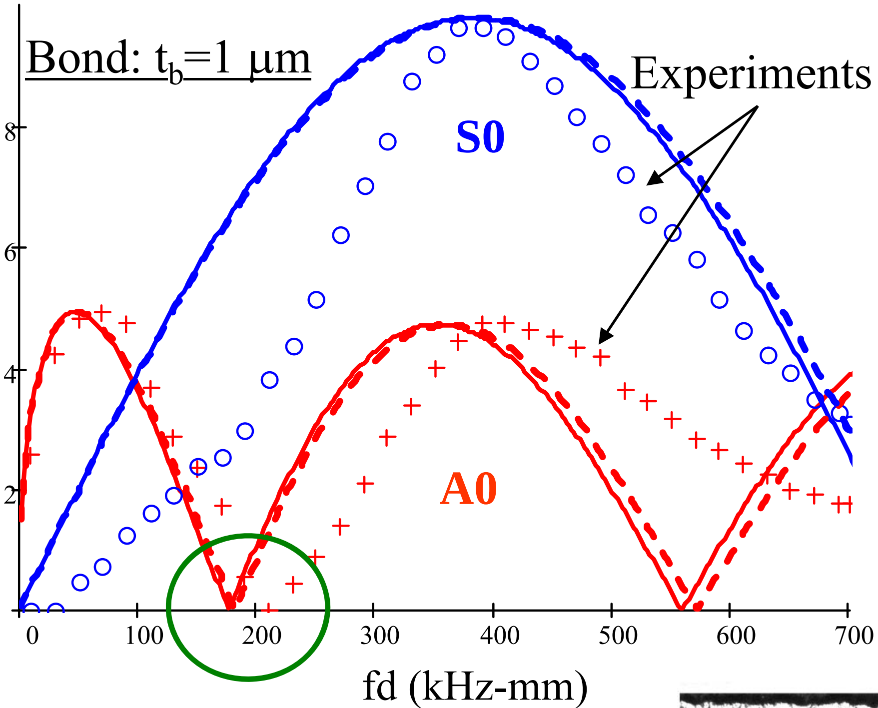
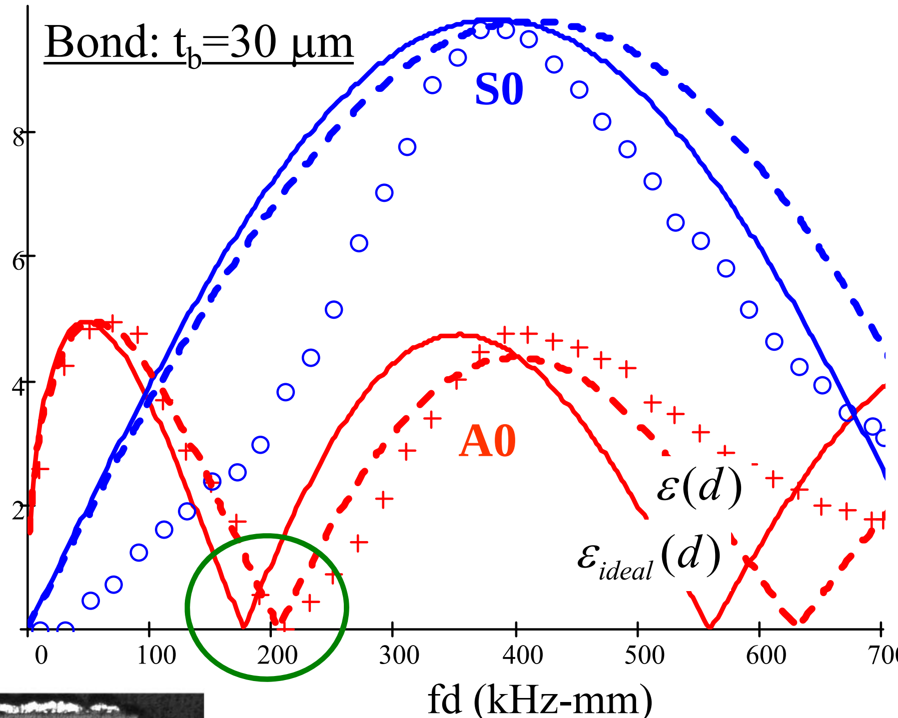
Improved Tuning Curves

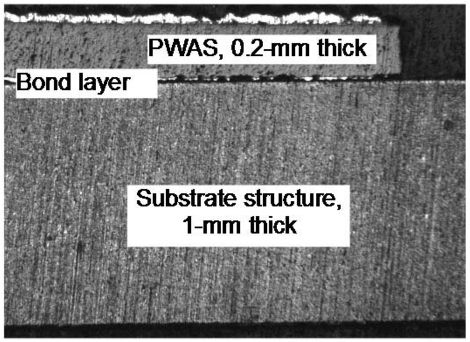
- Comparison between strain derived with ideal bond solution and no assumption on bond
- Effect of bond thickness on the predictions

$$\varepsilon_x(d) = -\frac{a}{\mu}\sum_n \frac{N_n(\xi_n)}{D_n'(\xi_n)} F_a(\xi_n, \Gamma, a, N) e^{i(\tilde{\xi}_n x - \omega t)}$$





Al plate: t=1 mm
PWAS: t_a=0.2 mm
a=3.5mm



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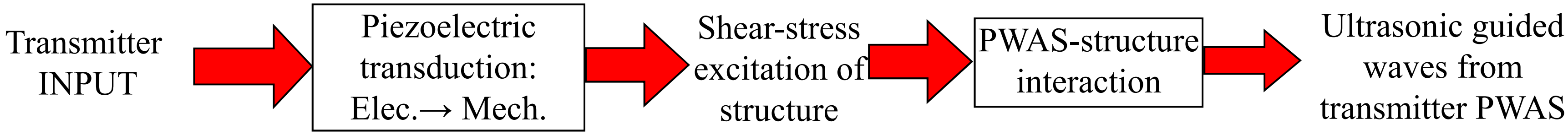
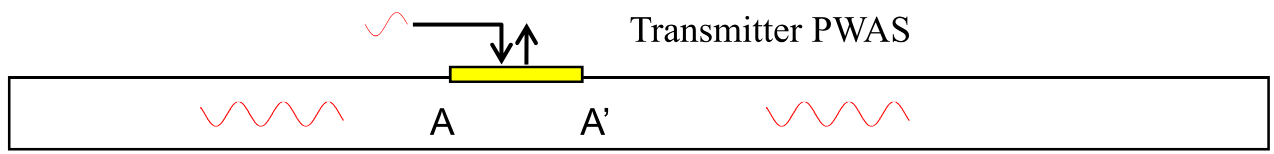
Power and Energy: Transmitter Transduction





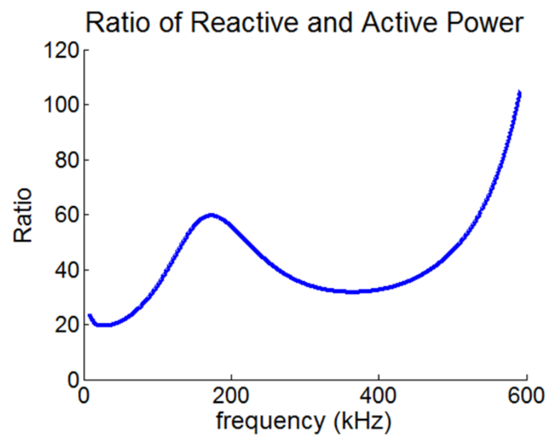
- Electrical response (7-mm PWAS transmitter)
  - Active power

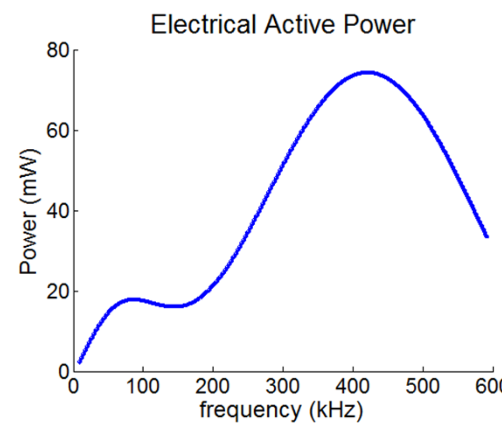
$$P_{active} = \frac{1}{2} Y_R \hat{V}^2$$

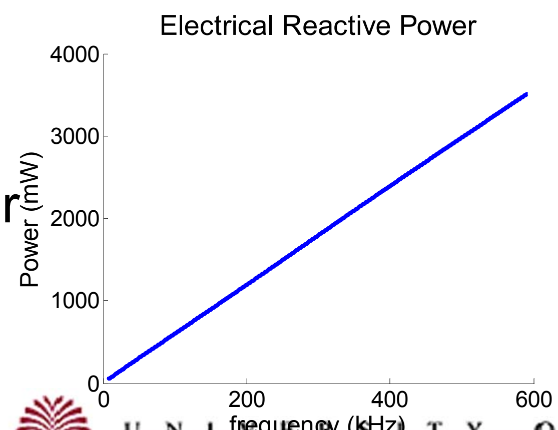
- Reactive power

$$P_{reactive} = \frac{1}{2} Y_I \hat{V}^2$$

  - Reactive power dominates: capacitive behavior







(Lin, B.; Giurgiutiu, V.; “Modeling of Power and Energy Transduction of Embedded Piezoelectric Wafer Active Sensors for Structural Health Monitoring”, *Journal of Nondestructive Evaluation*, in preparation)

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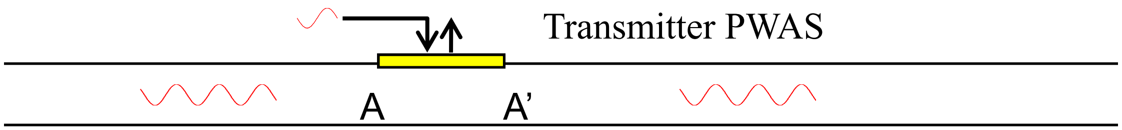
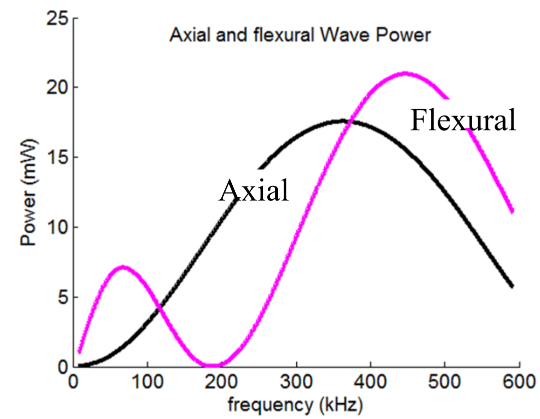
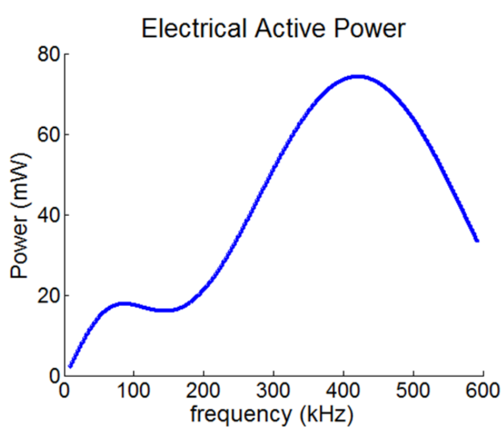
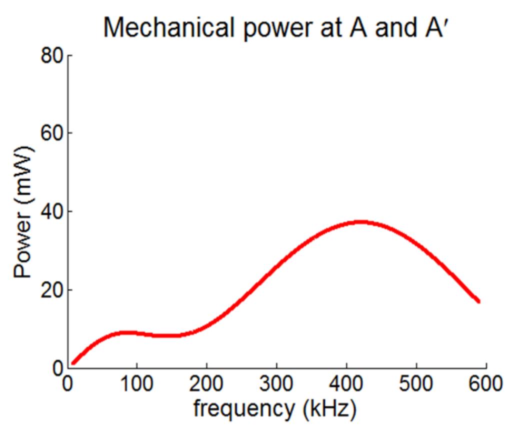
Transmitter Mechanical Response



- Active power converts to mechanical power
- Mechanical power at both ends are equal
- Mechanical power converts to wave power
- Waves contain axial and flexural waves







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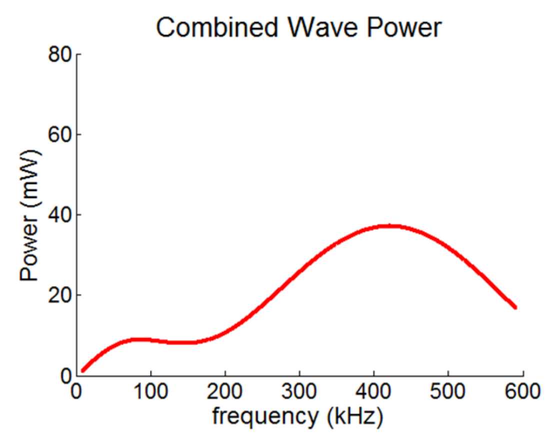

$$P_{active} = \langle P_A \rangle + \langle P_{A'} \rangle \qquad \langle P_A \rangle = \langle P_{A'} \rangle$$

$$\langle P_{A'} \rangle = \langle P_{Wave} \rangle$$

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7-mm Transmitter

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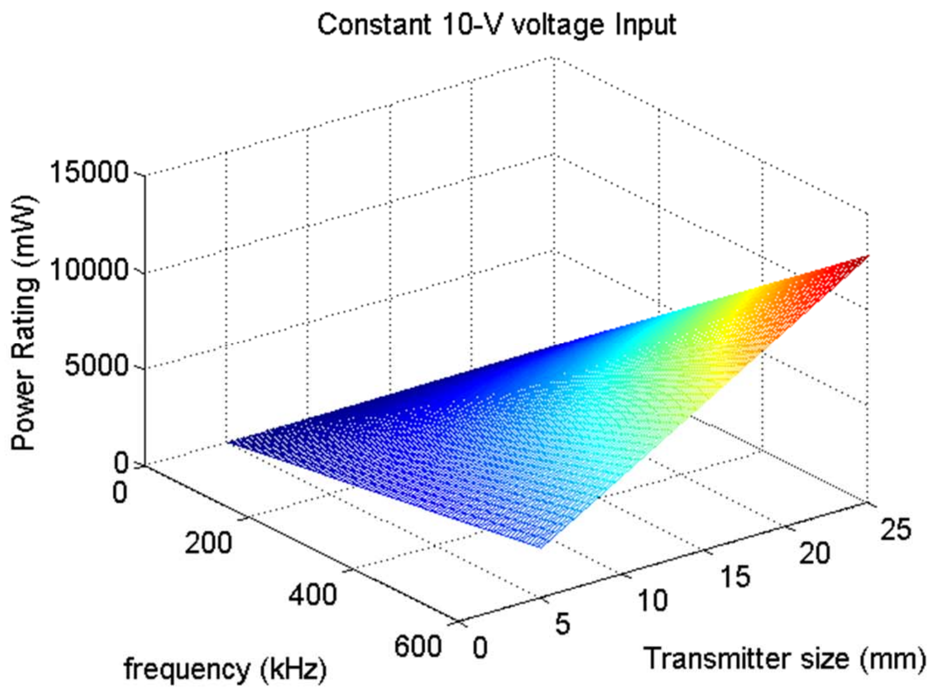
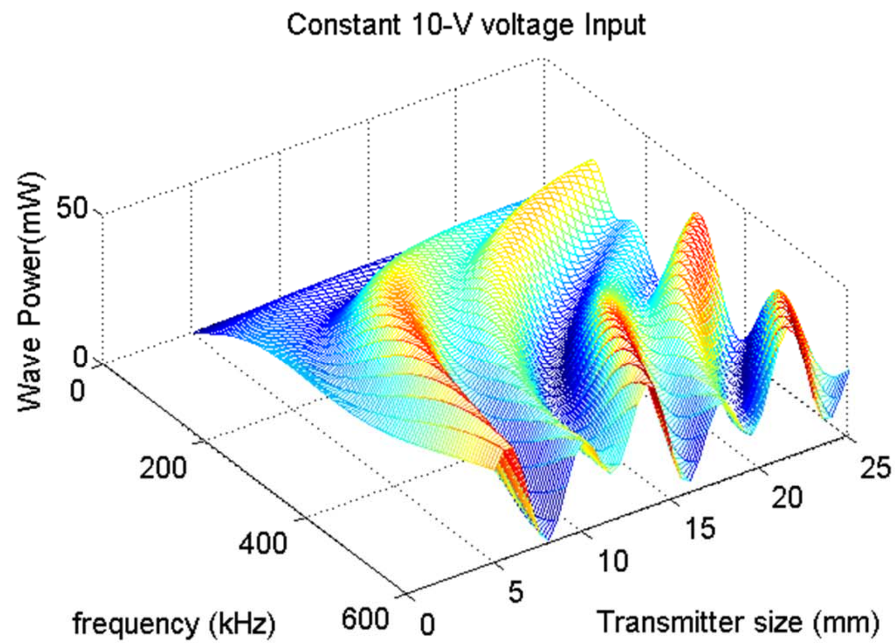
Transmitter Size Effects





- Reactive power is dominant
- Power rating increases when frequency increases
- Power rating increases when transmitter size increases

- Wave power is relatively small
- **Tuning effects**
  – Maximum wave power output depends on both frequency and transmitter size

- Increasing transmitter size and frequency requires more input electrical power
- Increasing transmitter size may NOT increase the wave power

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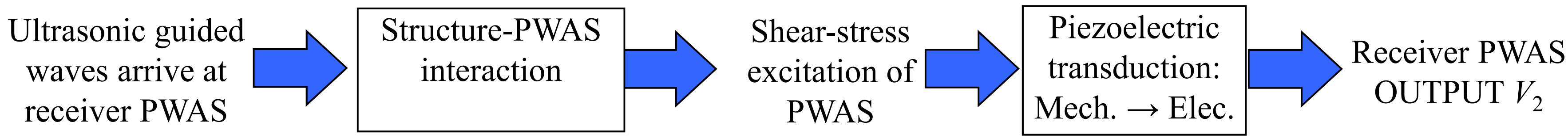
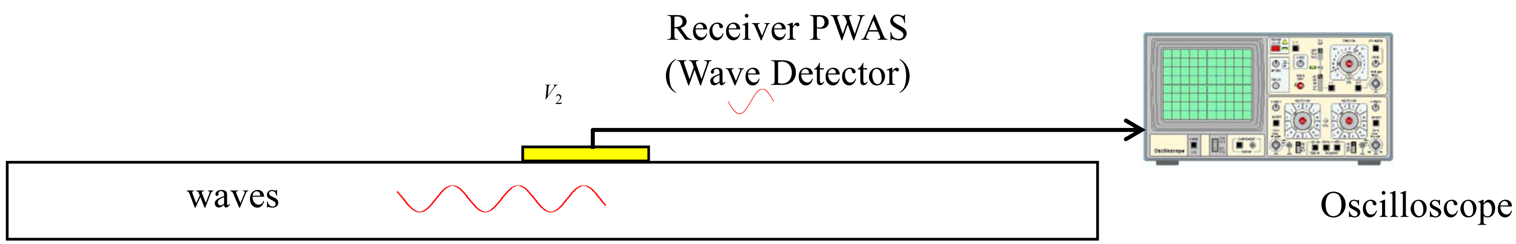
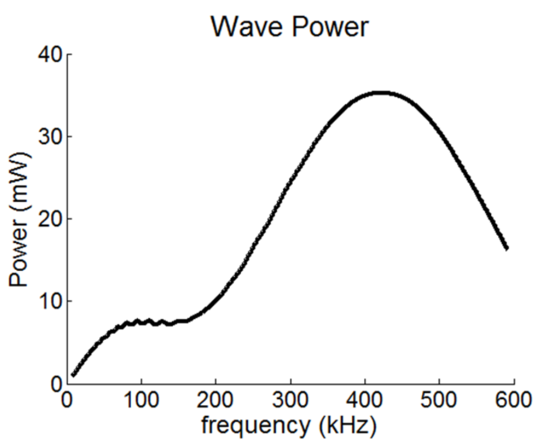
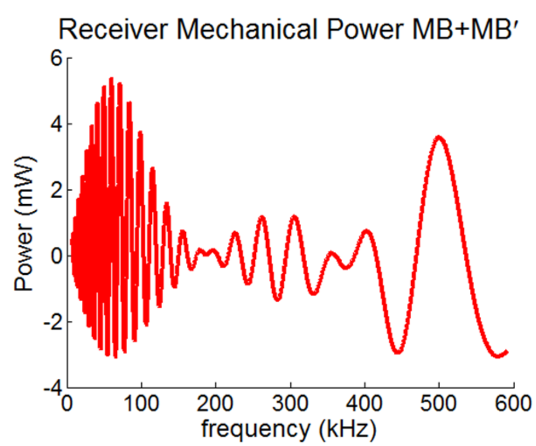
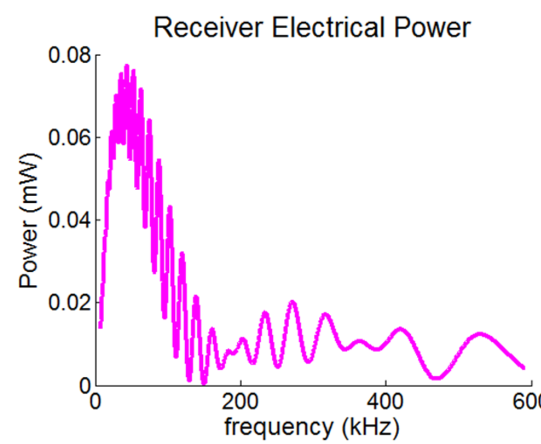
Power and Energy: Receiver Behavior











- Only a small portion of wave power converts to receiver electrical power

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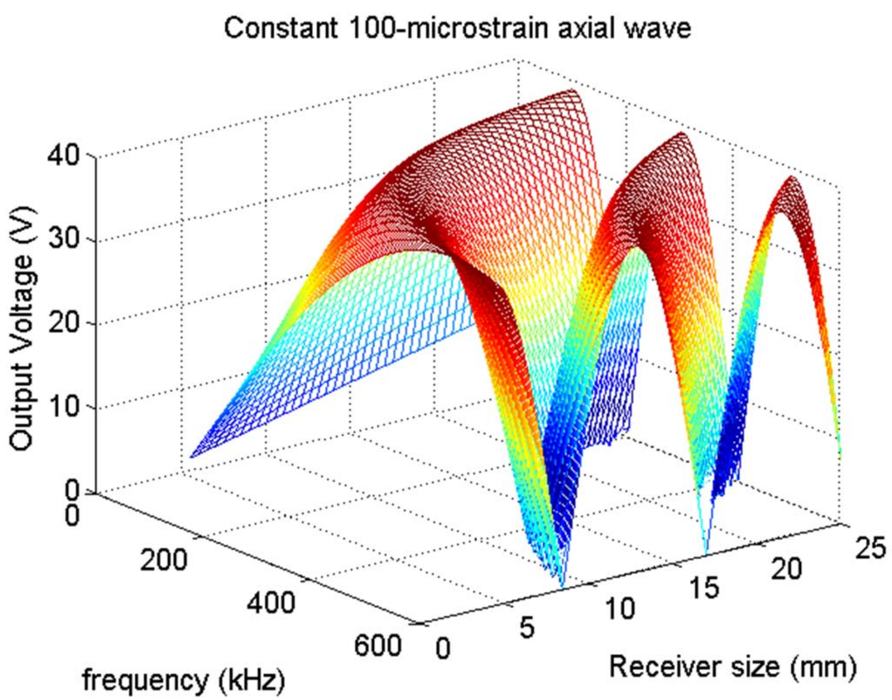
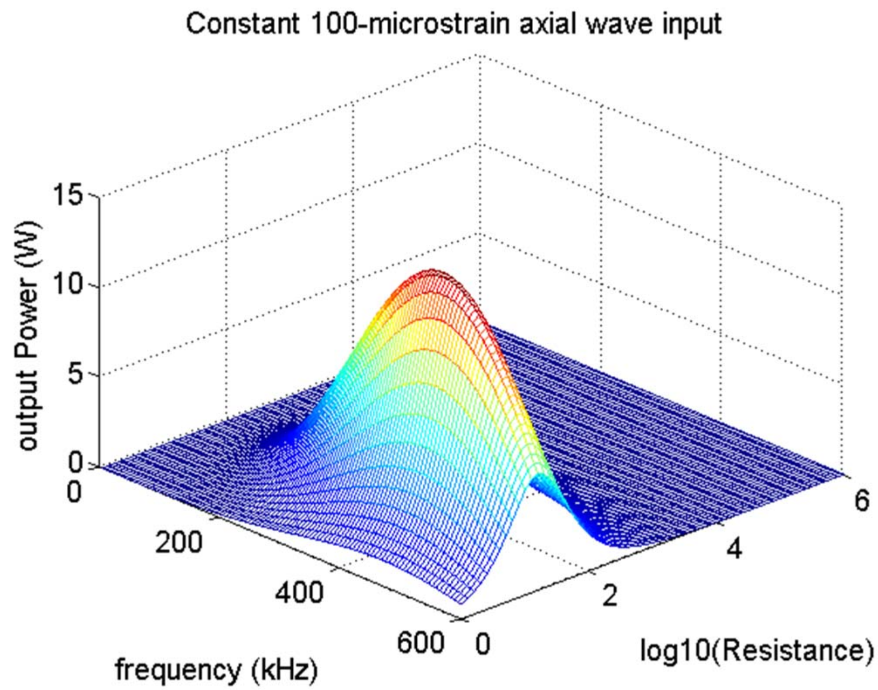
Receiver Effects





- Sensing Voltage
  - High resistive load (High Z)
- Receiver tuning effects
  - Large receiver size may not output high voltage under constant strain axial wave

- Power harvesting
  - 7-mm receiver
- Load impedance match
  - Maximum power output at 400 kHz and 100 Ω

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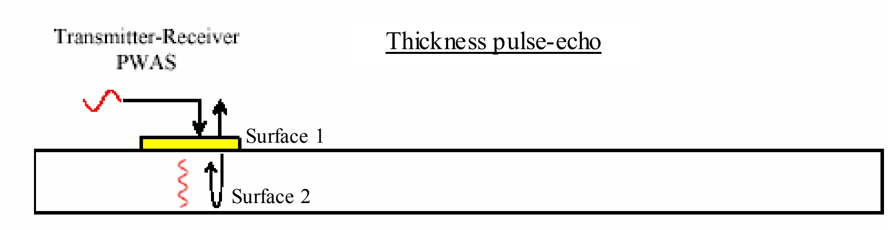
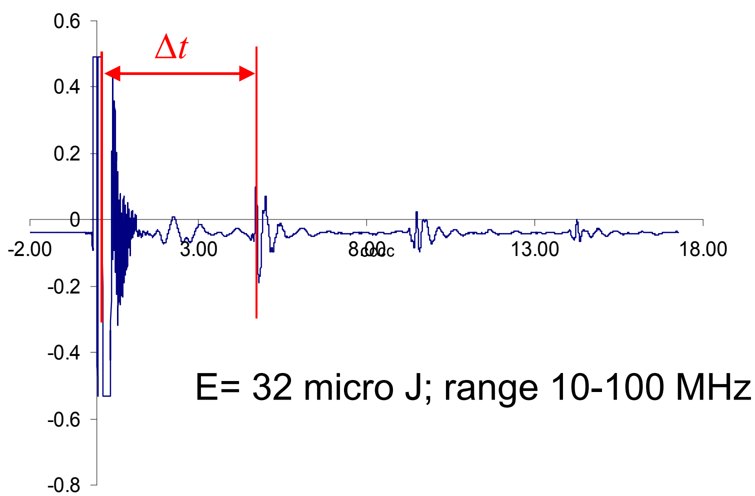
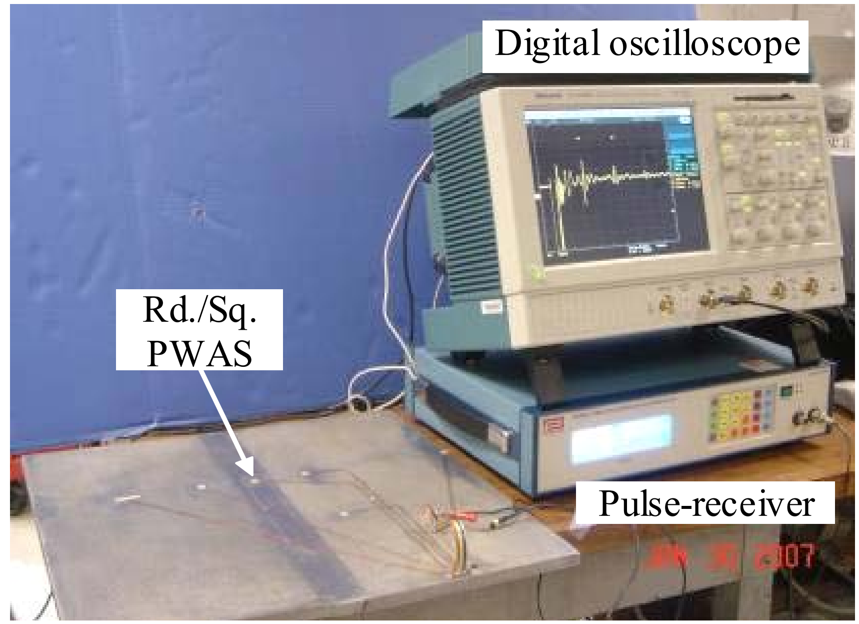
PWAS Thickness Mode





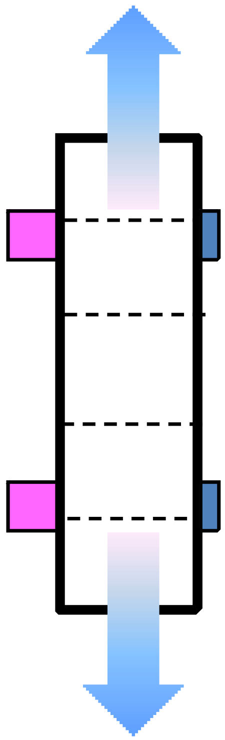
(Yu, L.; Giurgiutiu, V.; Chao, Y.; Pollock, P. (2007) "In-situ Multi-mode Sensing with Embedded Piezoelectric Wafer Active Sensors for Critical Pipeline Health Monitoring", *ASME IMECE*, Nov. 11-15, 2007, Seattle, WA, paper # IMECE2007-43234)



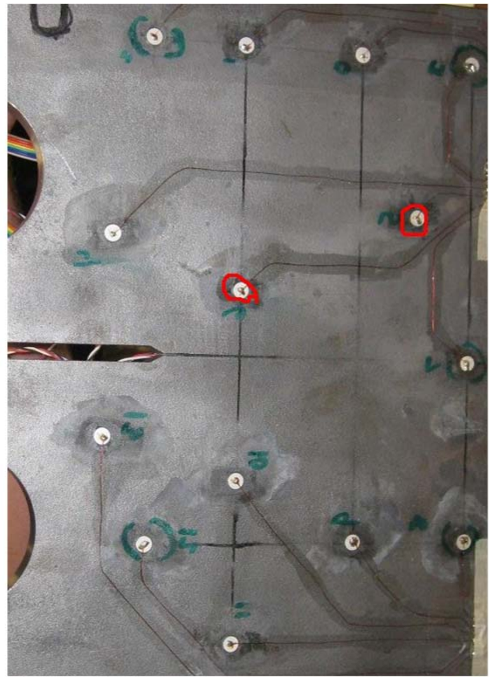
Material	h_0 (mm)	c (mm/μs)	Δt (μs)	h_i (mm)	*Error* (%)
Aluminum 2024 T4	3.3	6.37	0.842	2.68	18.8%
Aluminum 2024 T4	6.4	6.37	2.05	6.529	2.5%
Steel 4340	13.5	5.85	4.59	13.43	0.5%

PWAS as Passive AE Transducers

Conventional AE sensors (R15)



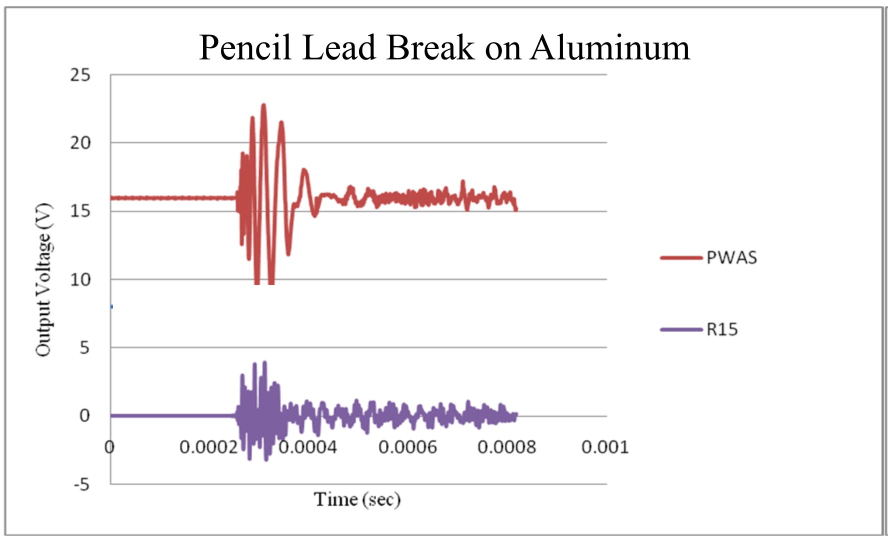
PWAS transducers

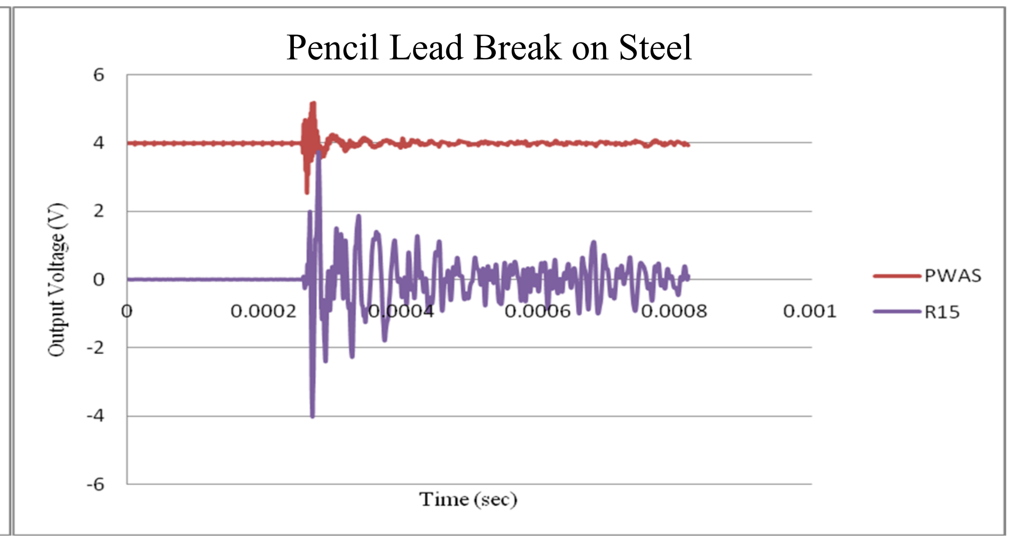


(Ozevin et al., (2009) "Self-Powered Sensor Network for Structural Bridge Health Prognosis: a 5-year Research and Development Project for Infrastructure Sustainability", *7th IWSHM*, Stanford, CA, 2009)

PWAS as Passive AE Transducers (cont.)

- Laboratory tests of AE-PWAS using pencil lead break excitation:
  - On 0.8-mm aluminum plate
  - On 6.35-mm steel plate

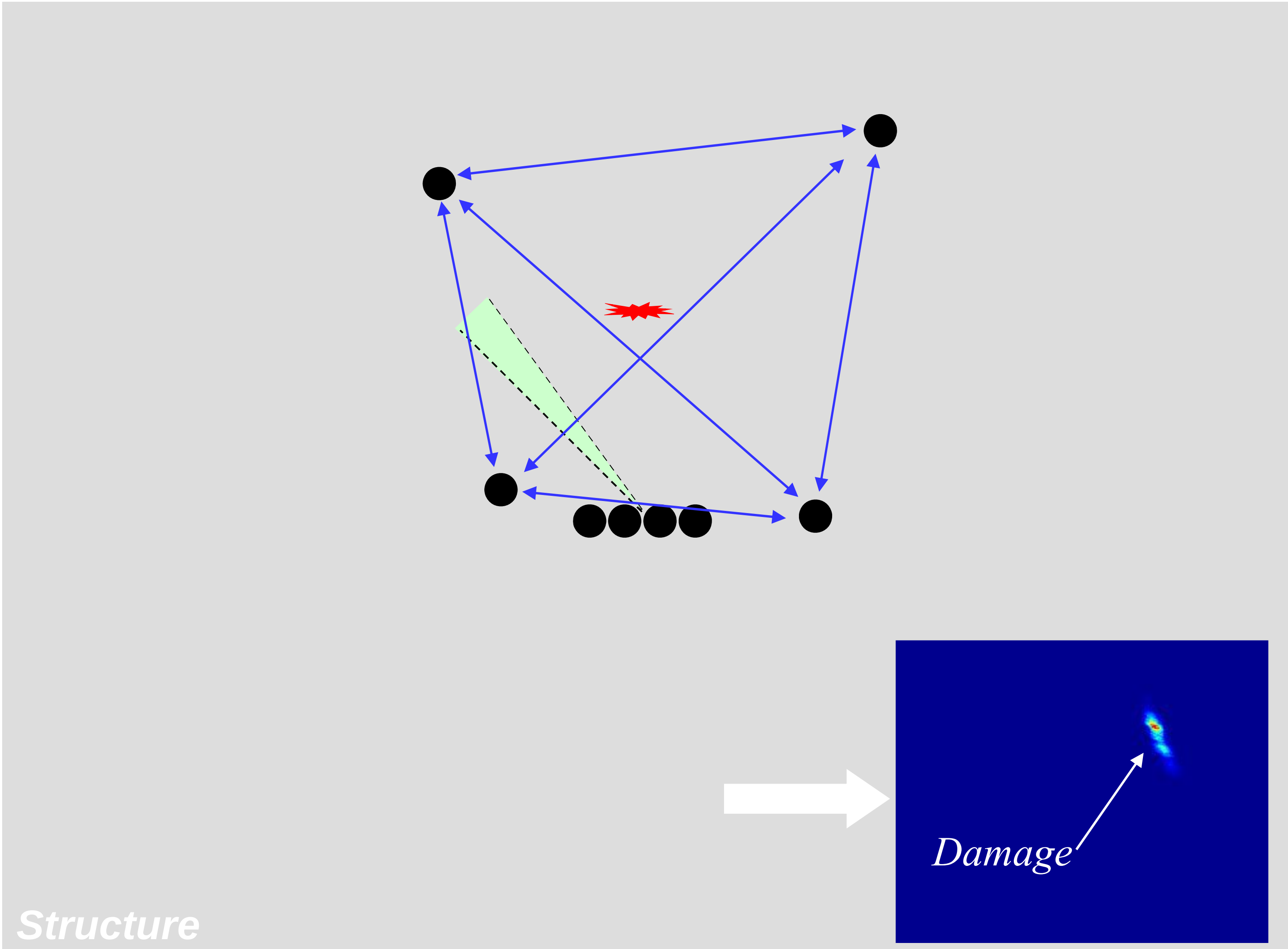




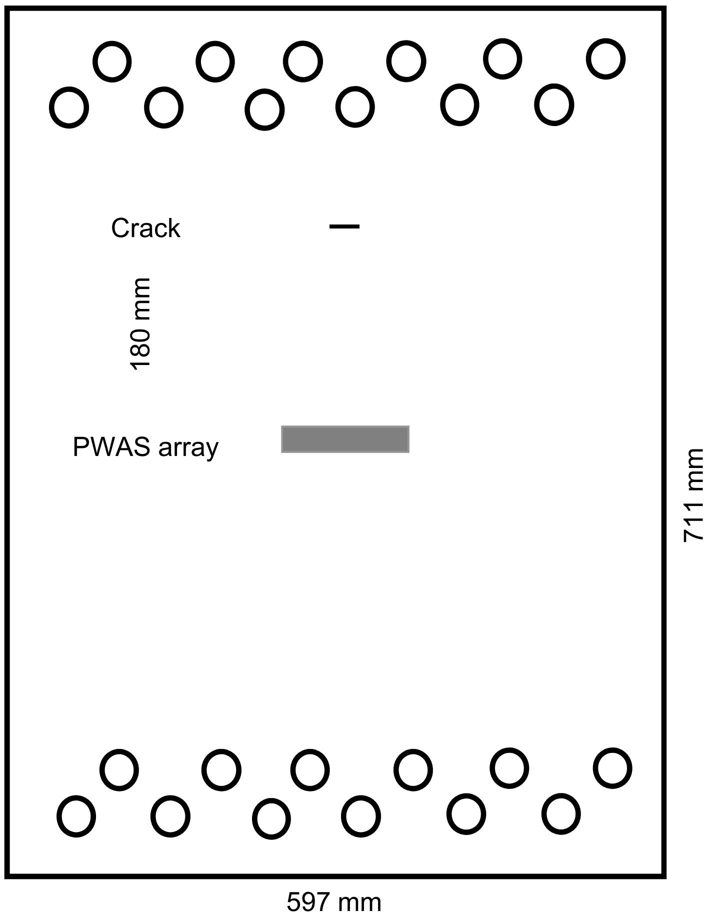
(Giurgiutiu et al., US patent 7,024,315/2006)

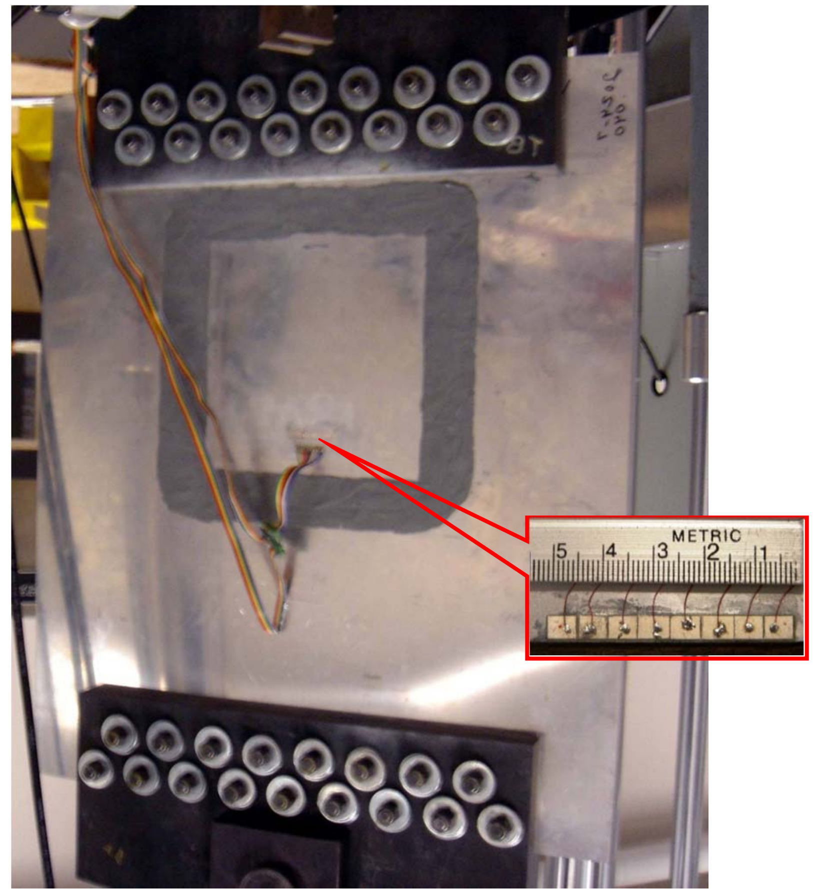
(Ozevin et al., (2009) "Self-Powered Sensor Network for Structural Bridge Health Prognosis: a 5-year Research and Development Project for Infrastructure Sustainability", *7th IWSHM*, Stanford, CA, 2009)

Lamb Wave Array Imaging



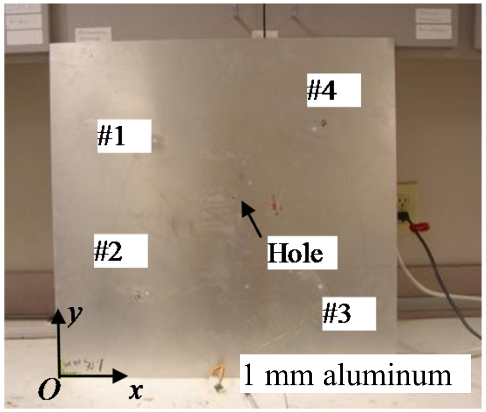
Crack growth monitoring with PWAS phased arrays





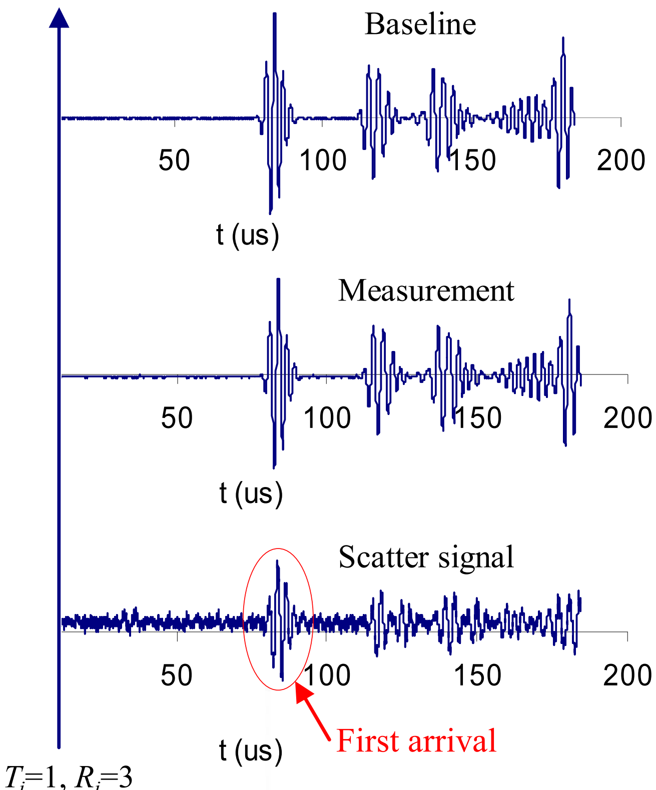
(Giurgiutiu, V.; Yu, L. ; Jenkins, C.; Kendall, J. (2007) “In situ imaging of crack growth with piezoelectric wafer active sensors”, *AIAA Journal*, Vol. 45, No. 11, pp. 2758-2769, Nov. 2007)

Sparse Array Hole Detection



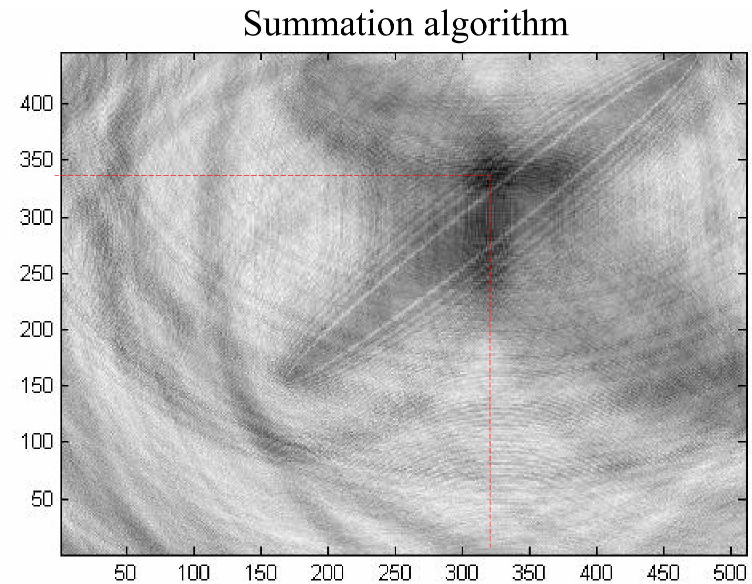
Hole (328, 326)
P#1(190,430)
P#2(170,155)
P#3(510,125)
P#4(475,445)
All units in mm.

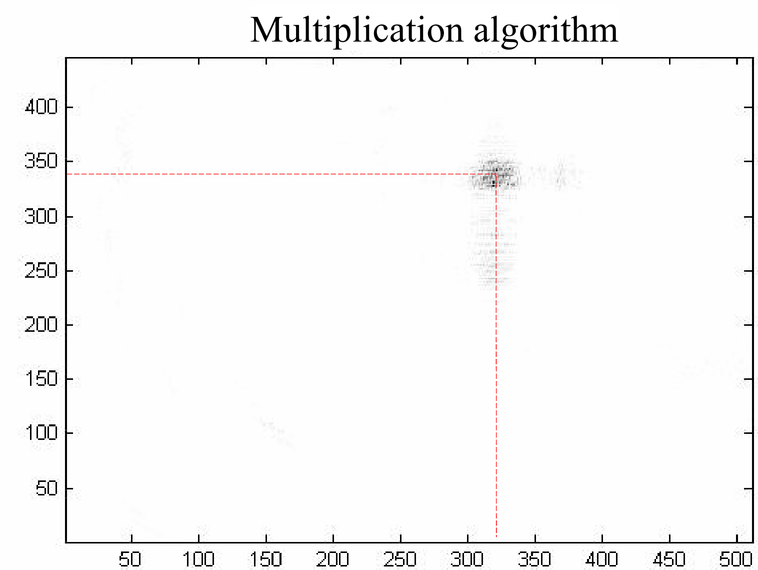
S0 mode @310 kHz
Vg=5.503 mm/µs



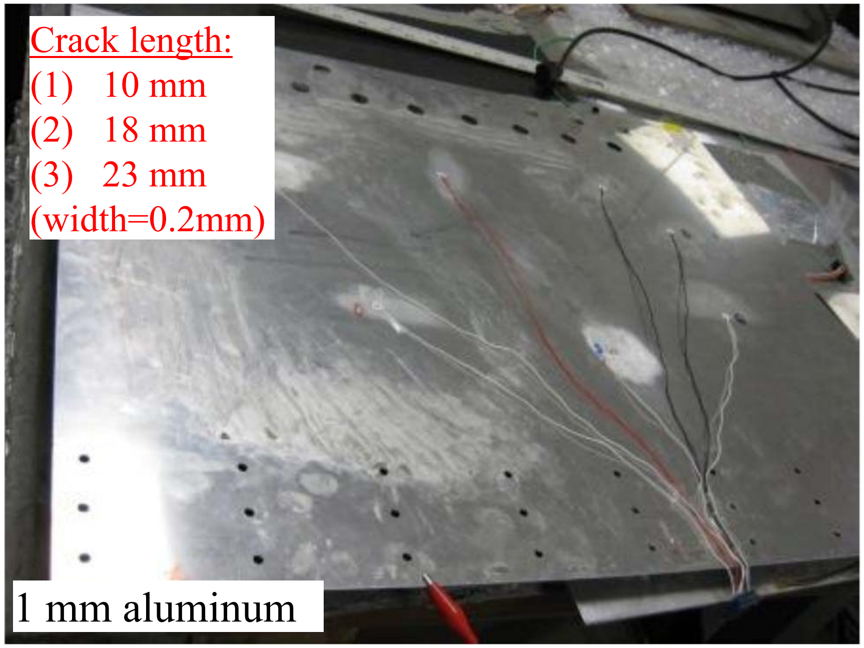
2-mm hole

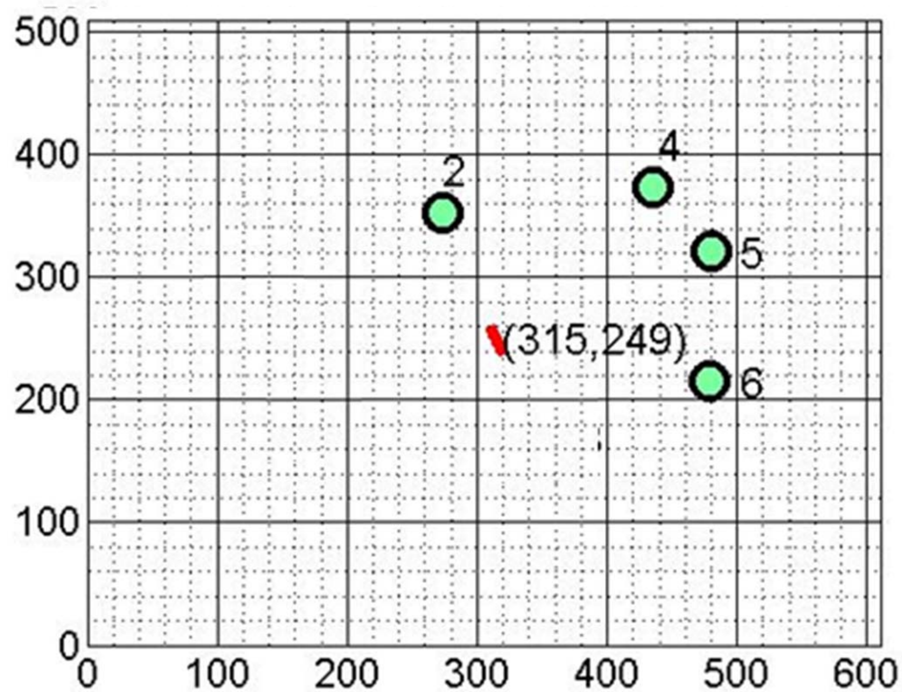
6-mm hole





Sparse Array Crack Detection





- S0 Lamb wave mode (310 kHz)
  - In-network crack detection: network 0/2/3/6
  - Out-network crack detection: network 2/4/5/6

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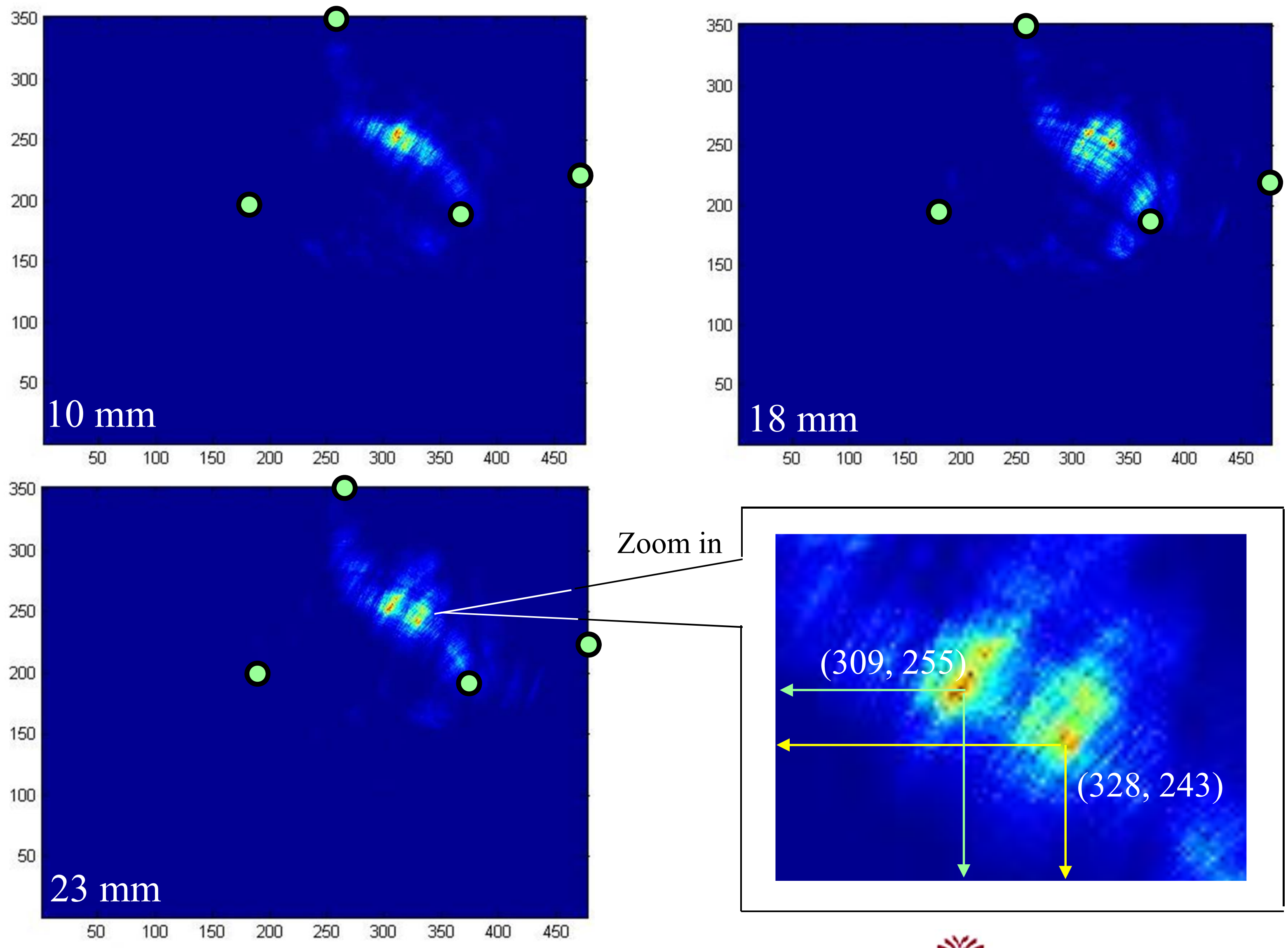
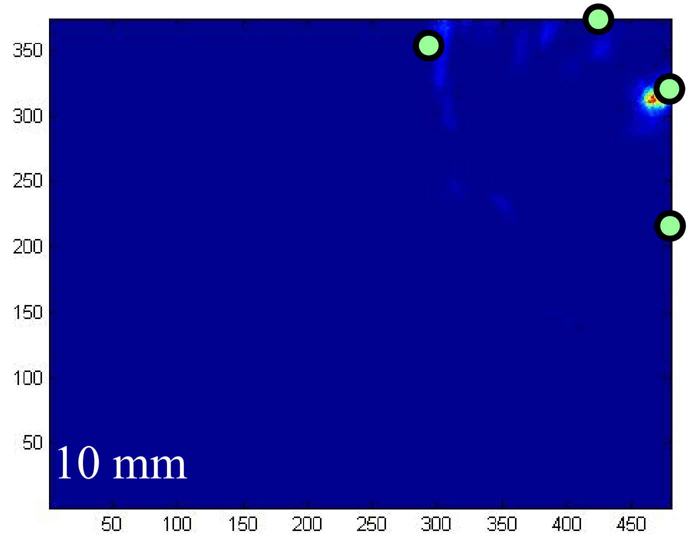
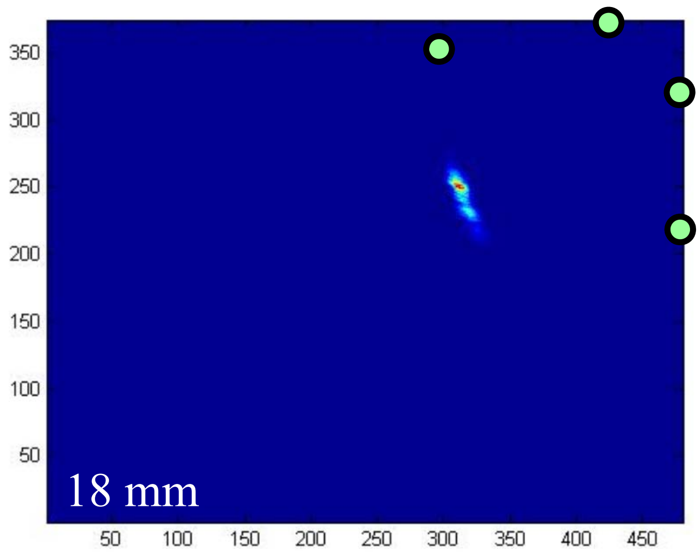
In-Network Crack Detection

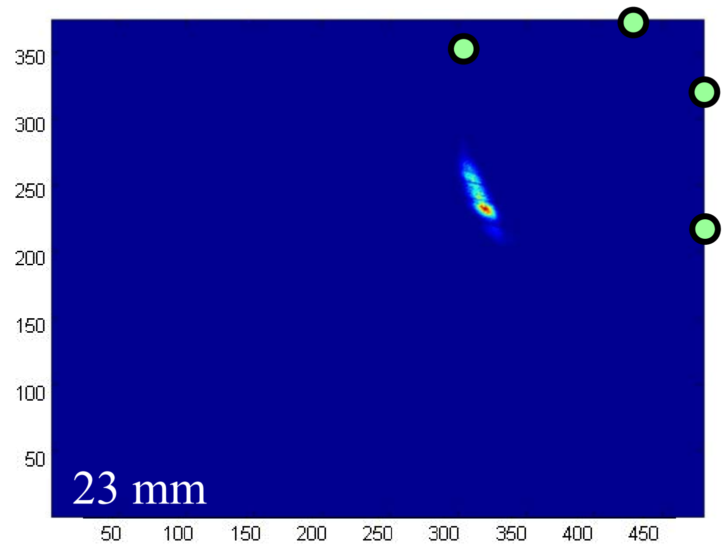


Crack=22.47 mm (ε =2.3%)

Out-Network Crack Detection







Summary and Conclusions

- PWAS transducers can detect damage: (a) pitch-catch, (b) pulse-echo, (c) thickness wave, (d) phased-arrays, and (e) E/M impedance modal sensing
- Theoretical developments:
  - Shear lag transfer at high f-d values and N guide modes
  - Power and energy transduction
- Experimental/data processing developments:
  - Thickness mode PWAS
  - Acoustic emission PWAS
  - Damage imaging with phased arrays and sparse arrays
- Sustained theoretical and experimental work is needed