Instantaneous Delamination Detection in a Composite Plate using a Dual Piezoelectric Transducer Network

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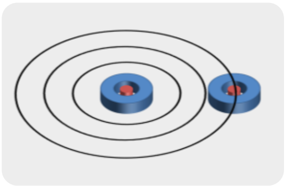
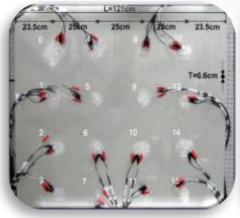
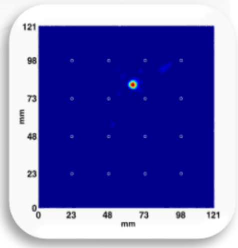
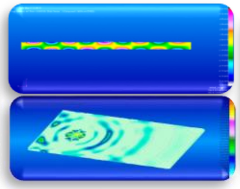








June 4th, 2010

Outline

Motivation


Chicago Tribune
SUNDAY
SEPTEMBER 2, 2007

U.S. Mint file photo

Boeing coining plan for composite parts

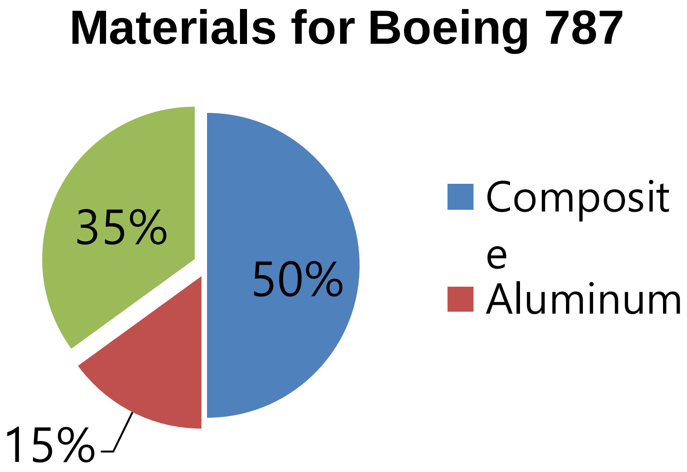
Greater use of superstrengthened plastics in the 787 raises concerns about detecting damage–now done using a quarter–but company says visual inspections will be enough

Greater use of super strengthened plastics in the 787 raises concerns about detecting damage- now done using a quarter- but company says visual inspection will be enough

….. Like Boeing, Airbus says it also has designed the A380 so that invisible damage cannot produce a significant subsurface flaw, and **that ultrasounds and other imaging methods are needed only if there's visible damage**……

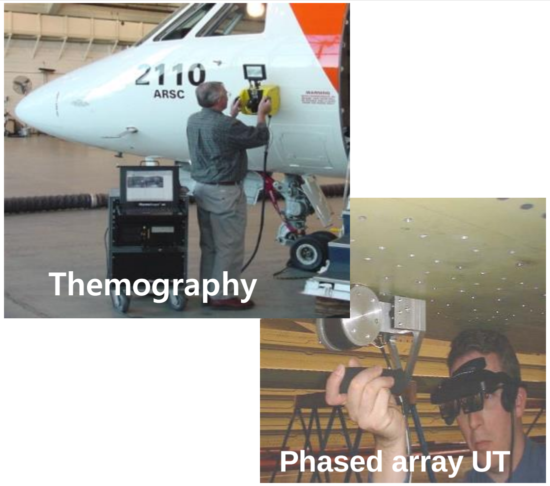
Chicago Tribune September 02, 2007

Non-destructive Inspection

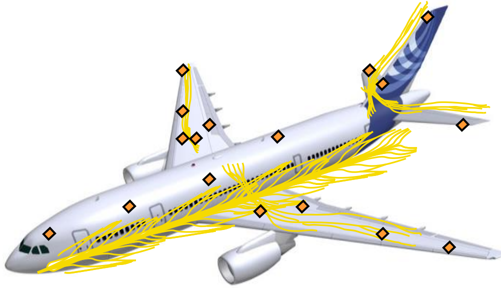


Visual Inspection

Non-destruction Testing



Structural Health Monitoring



The Objective of This Study

- Development of a delamination detection technique on a composite plate
- Robustness of the proposed technique against environmental effects such as temperature variation
- Application of the Lamb wave mode decomposition technique using concentric ring and circular PZTs

- Identification of delamination without using prior measured baseline data
- Propose the instantaneous delamination detection algorithm using the time delay of the A_0 Lamb wave mode
- Extraction of the A_0 Lamb wave mode without changing the PZT size and/or spacing configuration

Journal and Patent Publication

Chul Min Yeum, Hoon Sohn and Jeong Beom Ihn, “Lamb wave mode decomposition using concentric ring and circular PZT Transducers,” *Submitted to Journal of Acoustical Society of America*, 2010. (Impact factor: 2.018)

Hoon Sohn, Chul Min Yeum and Jeong Beom Ihn, “A lamb wave mode decomposition technique using amplitude matching,” *Submitted to the Us patent office*, Docket No. 09-0869.

Chul Min Yeum, Hoon Sohn and Jeong Beom Ihn, “Reference-free delamination detection and localization in a composite plate using a dual piezoelectric transducer network,” *In preparation for Composites Structures*, 2010. (Impact factor: 2.53)

Characteristics of Laminate Composites

Laminate composites

- Laminate composites involve two or more layers of the same or different materials.
- The layers can be arranged in different directions to give strength.
- Advantage : Lightweight, superior specific strength
- Disadvantage : Invisible impact damage, expensive

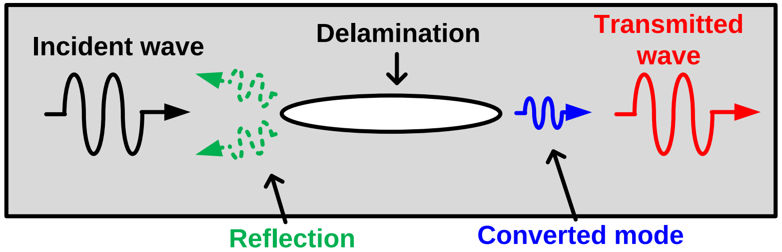
Advantages of Lamb wave based damage detection technique

- Inspection of large areas with little attenuation
- Excellent sensitivity to multiple defects
- Te lack of need for complicated and expersive insertion/radiation devices

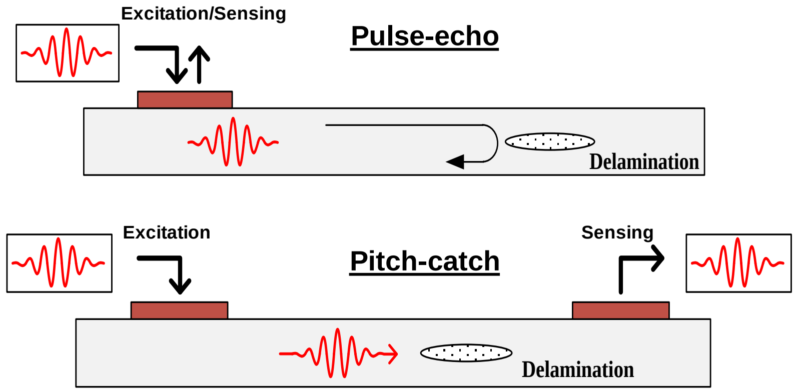
Difficulties of Lamb wave based damage detection technique on the laminate composite

- Anisotropic nature of a laminate composite
- A very fast wave velocity (The S_0 mode is four or five times faster than the A_0 mode)
- Highly damping coefficients

Literature Reviews



The effect of dealmination on Lamb wave propagation

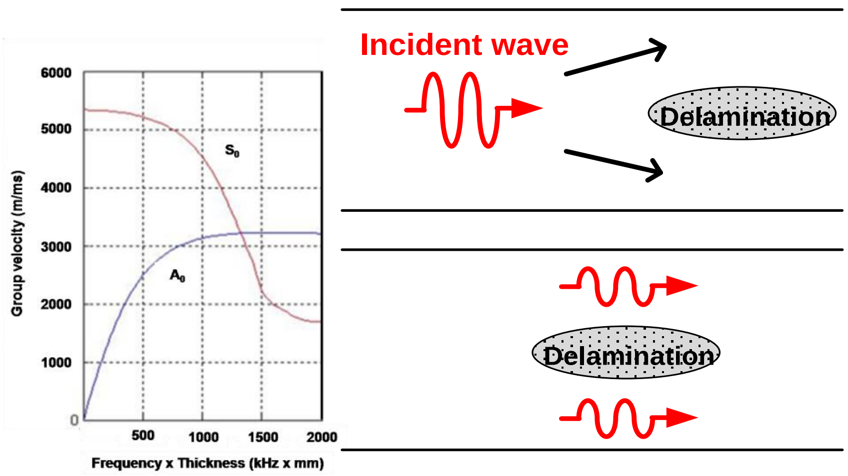


1. Measuring the group velocity and/or energy of the reflected modes [Valdes(2002);Ip(2004)]
2. Image construction using the cross-correlation of the scatter signal envelop [Ng (2009)]
3. Damage quantification based on the changes in energy contents of scatter waves [Ihn(2008)]
4. Compute the probability of damage using correlation coefficients of measured signals [Wang(2008)]
5. Group delay measurements using modally selective Lamb wave [Petculescu(2008)]
6. Delamination size detection using time of flight of the converted A_0 mode [Ramadas(2010)]

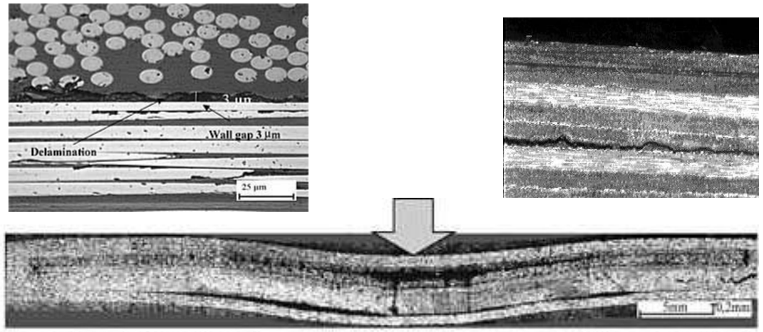
Outline

The Effect of Delamination on the A_0 Mode

A_0 mode delay

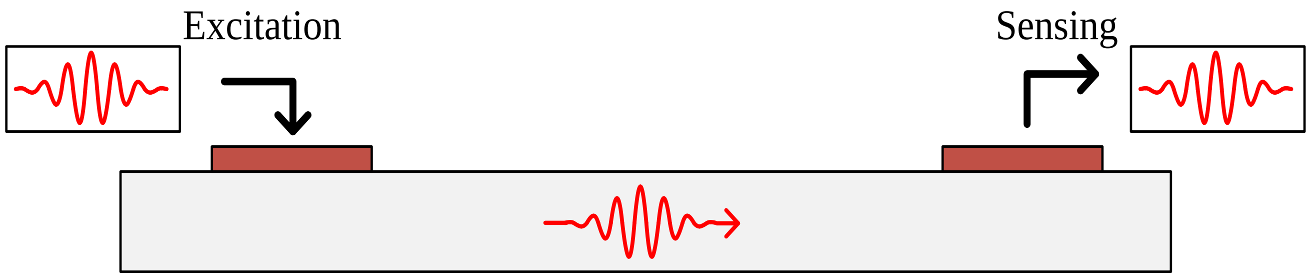


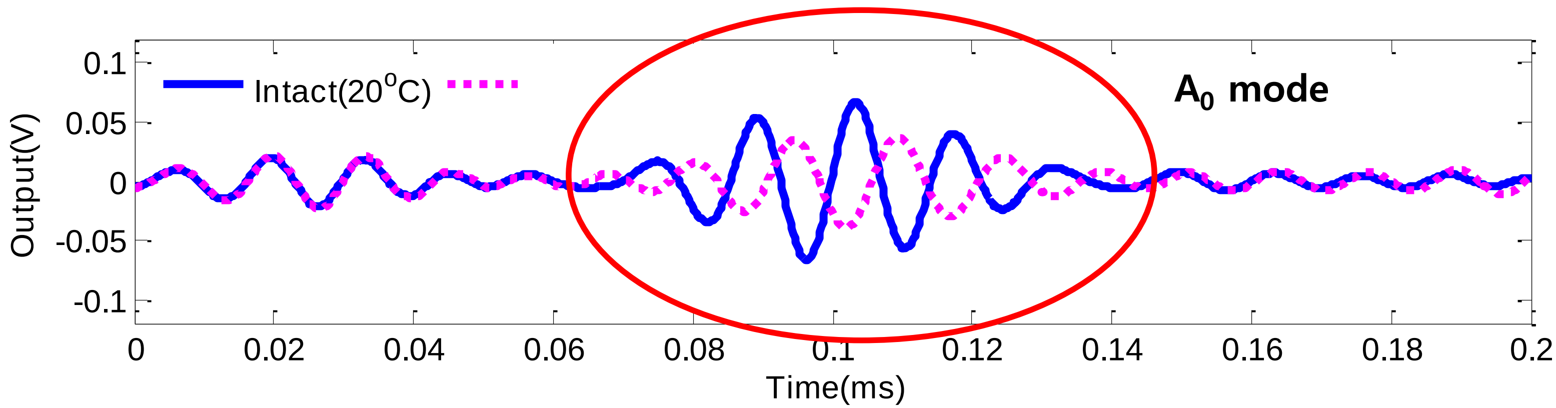
A_0 mode attenuation

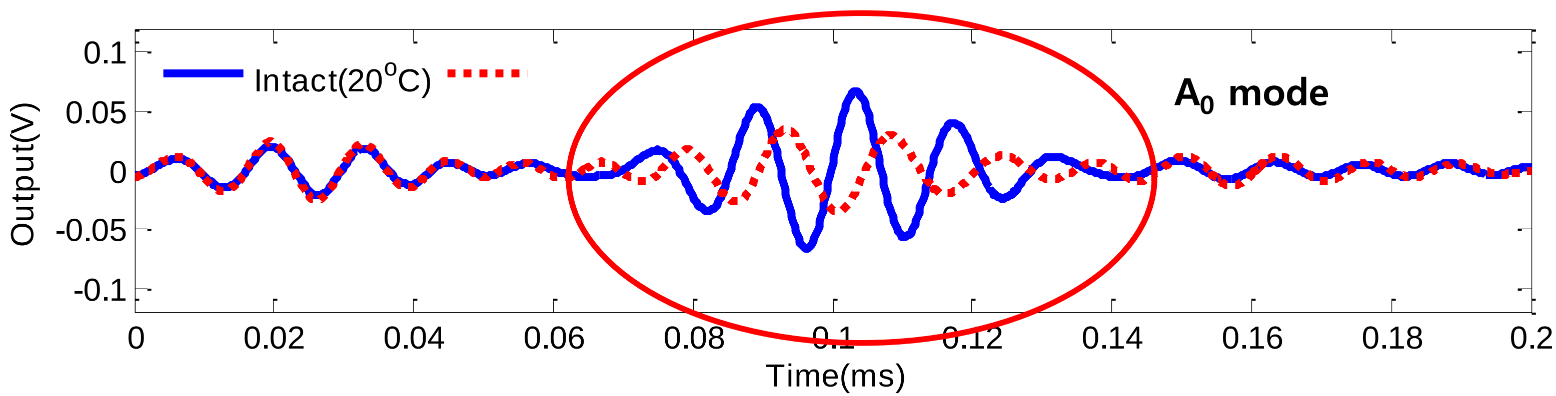


If Lamb waves propagating along a thin plate encounter delamination, some portion of waves are scattered or reflected at the boundary and others are transmitted through it. Especially, the transmitted A_0 mode is more delayed and attenuated than the transmitted S_0 mode. [Petculescu at all (2008)]

Why Should We Apply the Reference-free Damage Detection Technique?

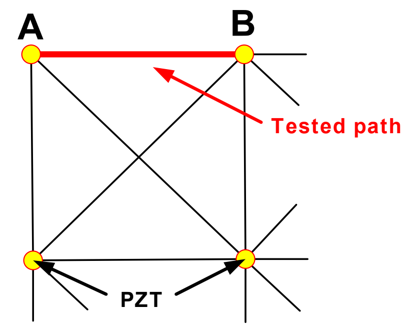




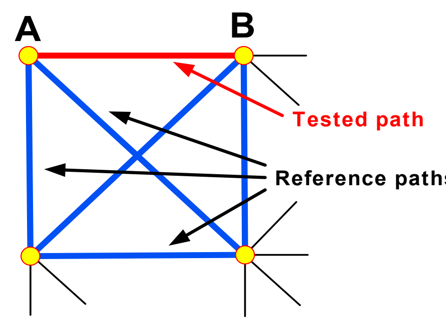


Reference-free Damage Detection Techniques

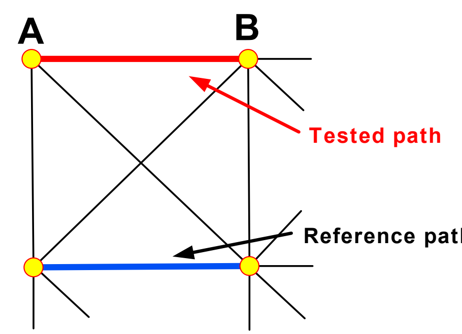
1. Damage identification using instantaneously measured Lamb wave signals obtained from <u>only one pair of PZTs</u>



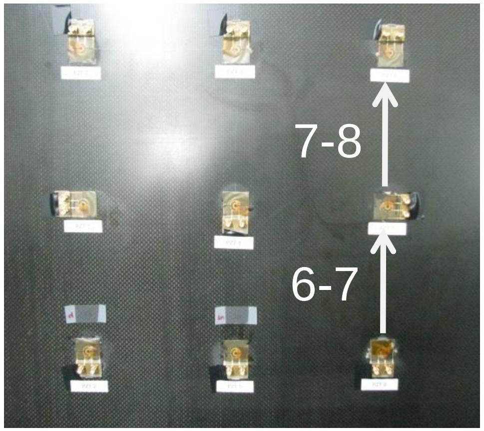
2. Damage identification using instantaneously measured Lamb wave signals obtained from <u>other undamaged paths (Independent of path lengths and directions)</u>



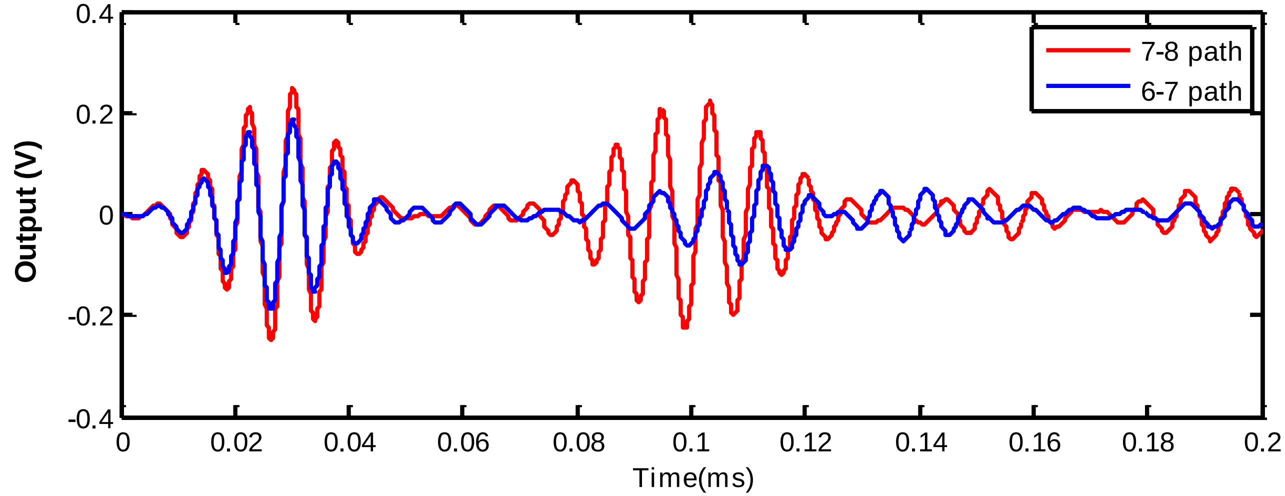
3. Damage identification using instantaneously measured Lamb wave signals obtained from <u>other undamaged paths having same directions and lengths</u>



Experimental configuration



Undamaged condition



- Multimodal characteristic
- Complex boundary conditions
- Very fast S_0 mode velocity
- Sensitive to the bonding condition

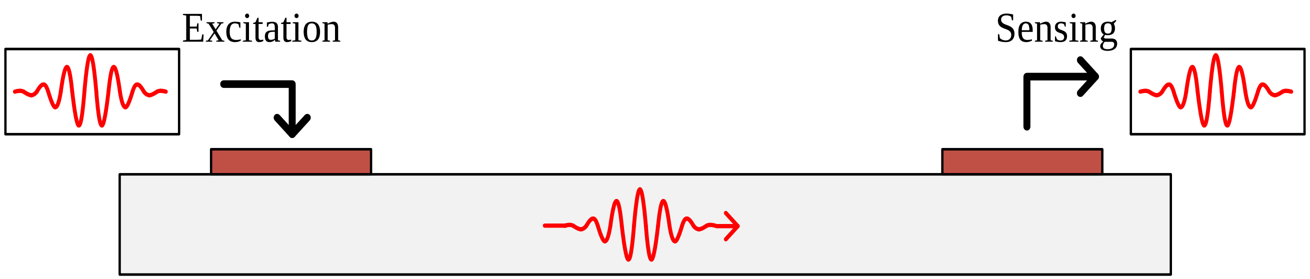
A0 mode

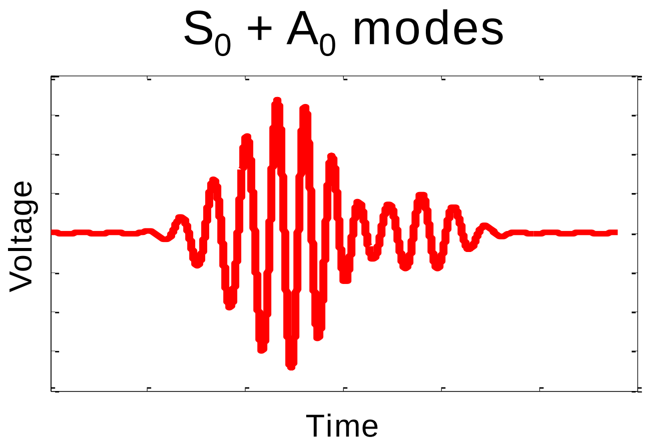
Time delay

Outline

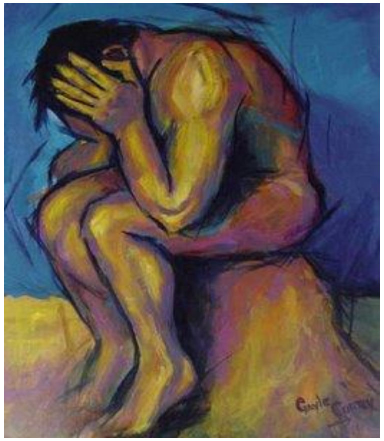
1. **Introduction**
2. **Instantaneous Damage Detection Algorithm**
3. **Extraction of the A_0 Lamb Wave Mode**
4. **Damage Classification**
5. **Experimental Results**
5. **Conclusion**

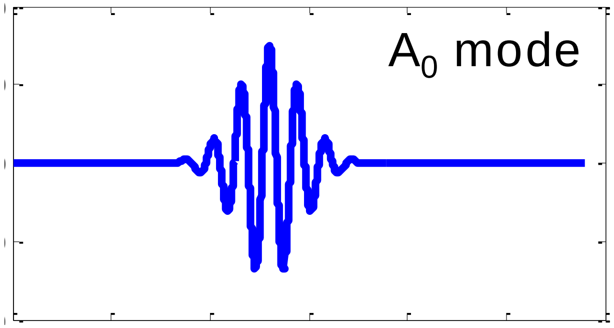
What is the Lamb Wave Decomposition ?

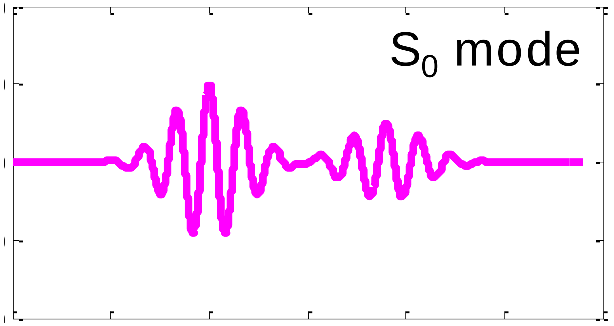




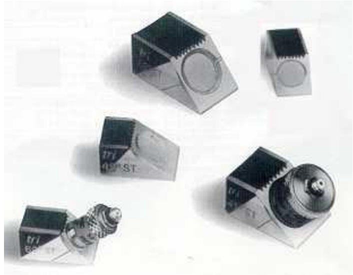
How (?)



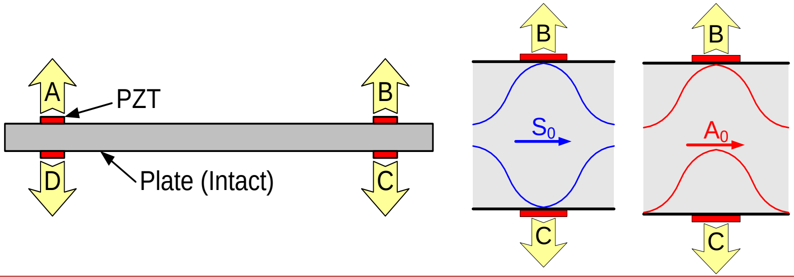




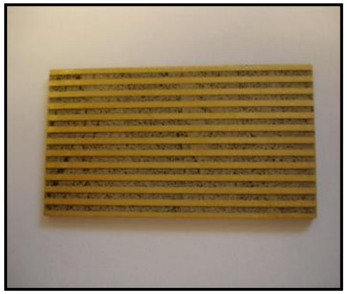
Wedge transducer [Wilcox (2002)]

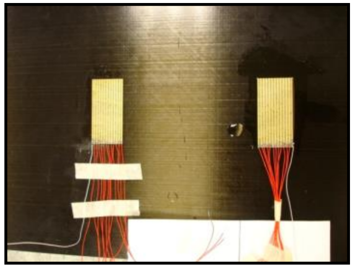


Collocated PZTs on both surfaces [Kim (2007)]

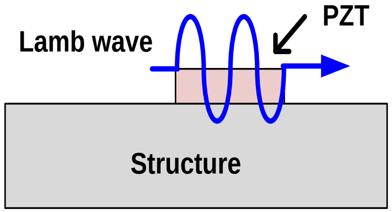


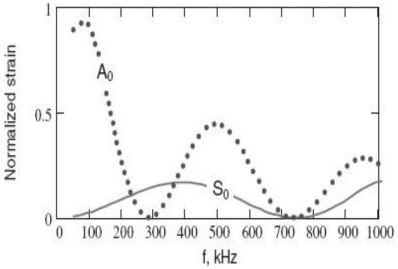
Comb transducer [Rose (1998)]
An array of PZTs with time delays [Gao (2007)]





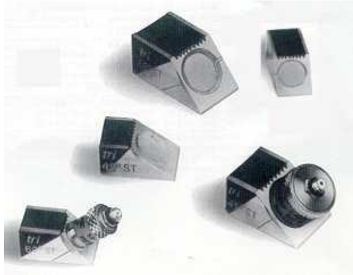
Tuning of the driving frequency [Giurgitiu (2003)]

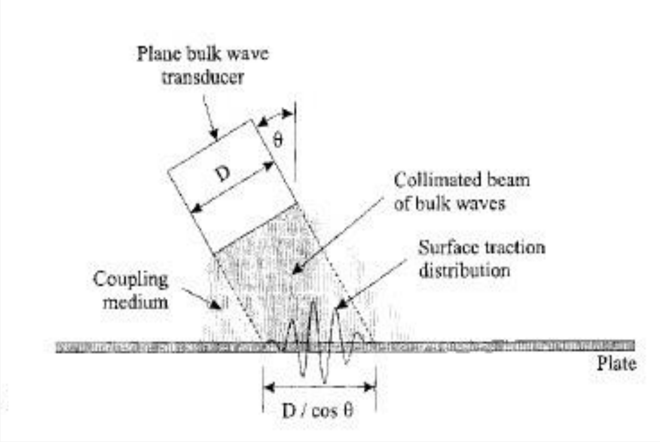




Conventional Techniques for the Lamb Wave Decomposition
- Wedge transducer -

Wedge transducer [Wilcox (2002)]

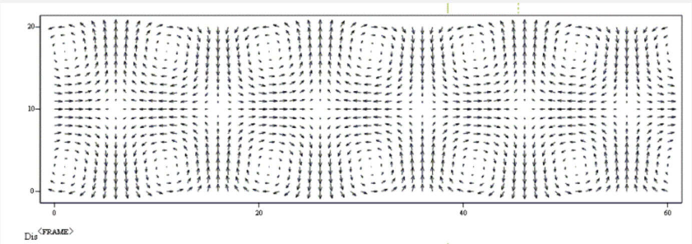




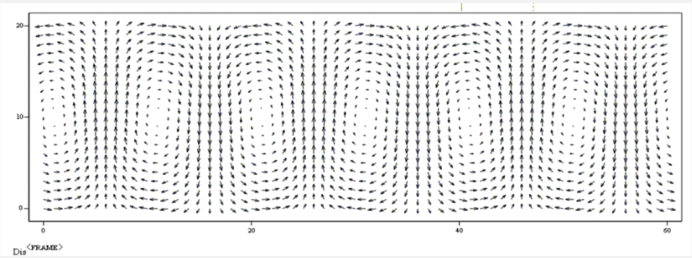
Problems

- Difficulty of setting the angle of incidence with appreciable accuracy
- Consideration of time delay due to block.
- Significant signal attenuation before impinging the inspection material
- Generation of additional reflected waves from interfaces

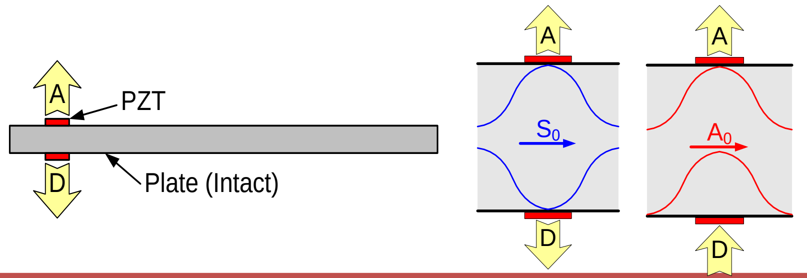
S_0 mode



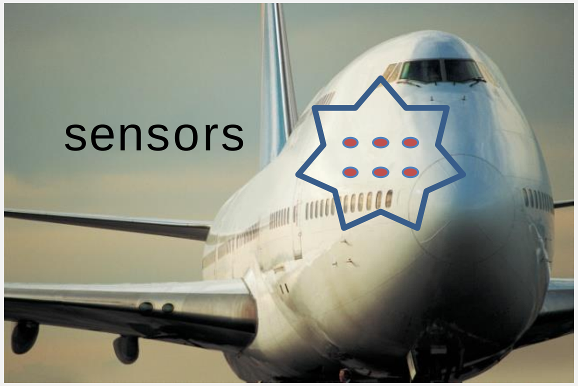
A_0 mode



Collocated PZTs [Kim and Sohn (2007)]



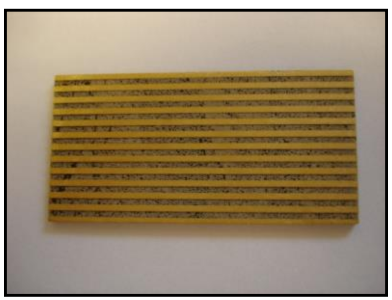
Problems

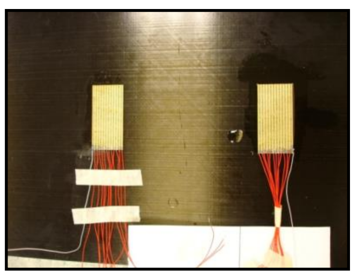


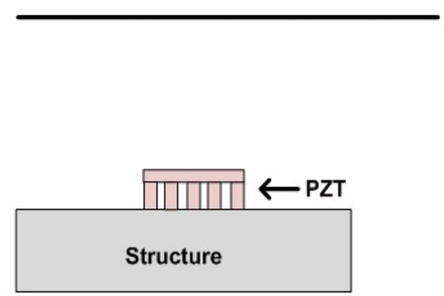
Problems

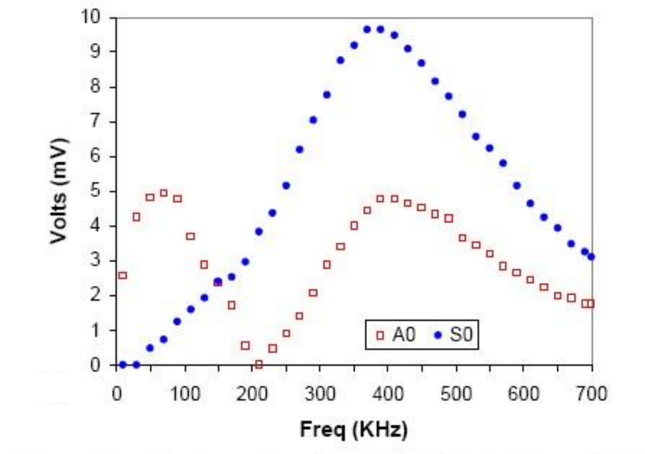
- Decomposition of Lamb waves at a specific frequency
- Needs for a multi channel data acquisition system
- Sensitive to prescribed time delay profiles or wavelength

Comb transducer [Rose (1998)]
An array of PZTs with time delays [Gao (2007)]

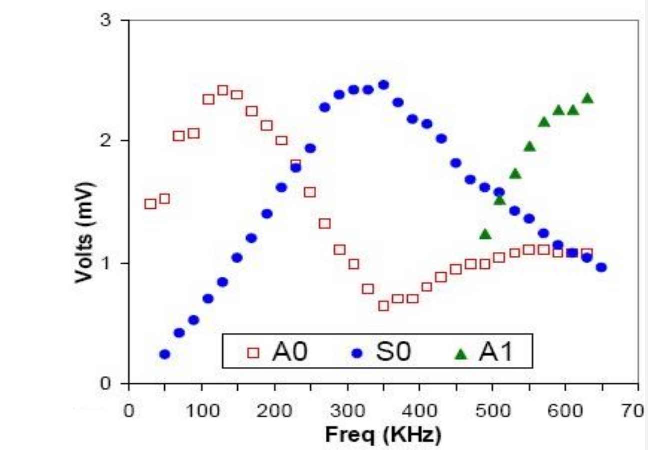








Aluminum 2024-T3 1.07 mm

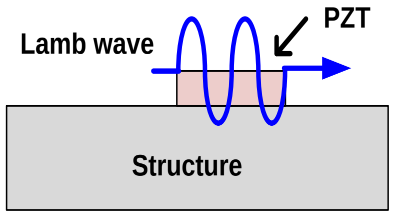


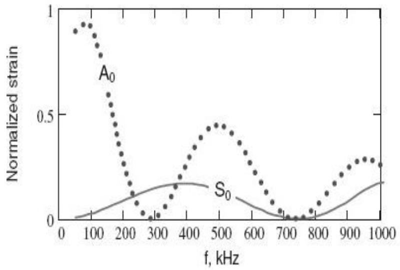
Aluminum 2024-T3 7 mm

Problems

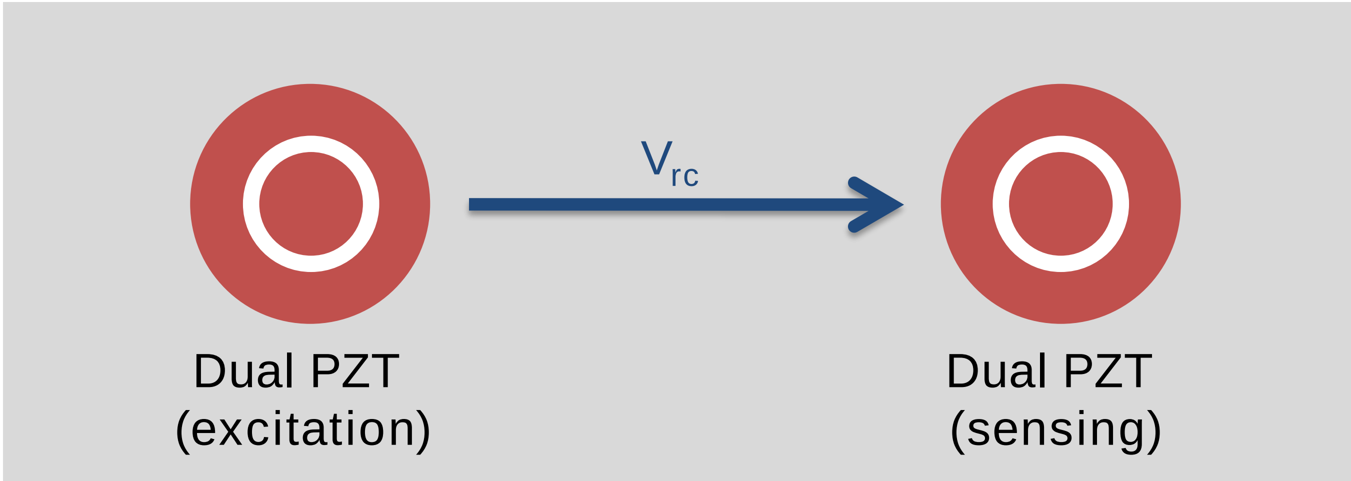
- Decomposition of Lamb waves at a specific frequency
- Needs for a baseline tuning curve

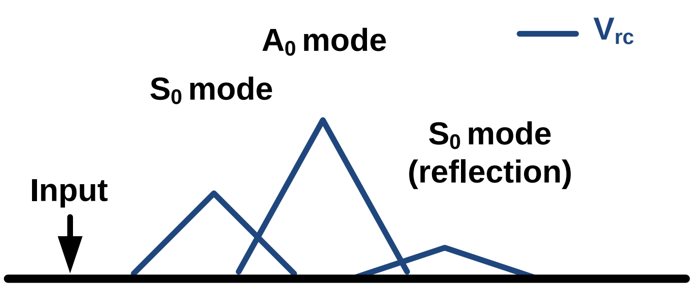
Tuning of the driving frequency [Giurgitiu (2005)]



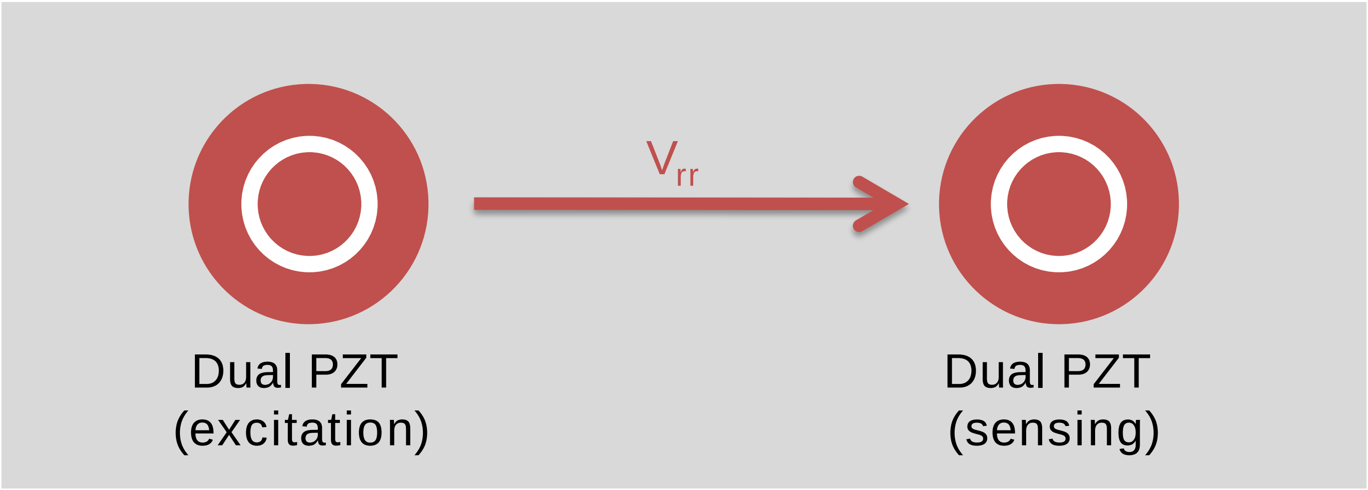


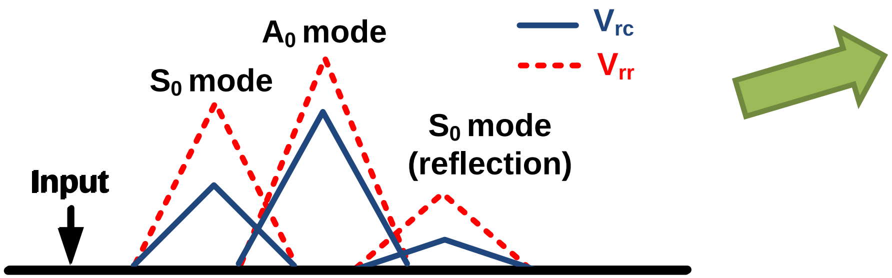
Overview of the Proposed Technique

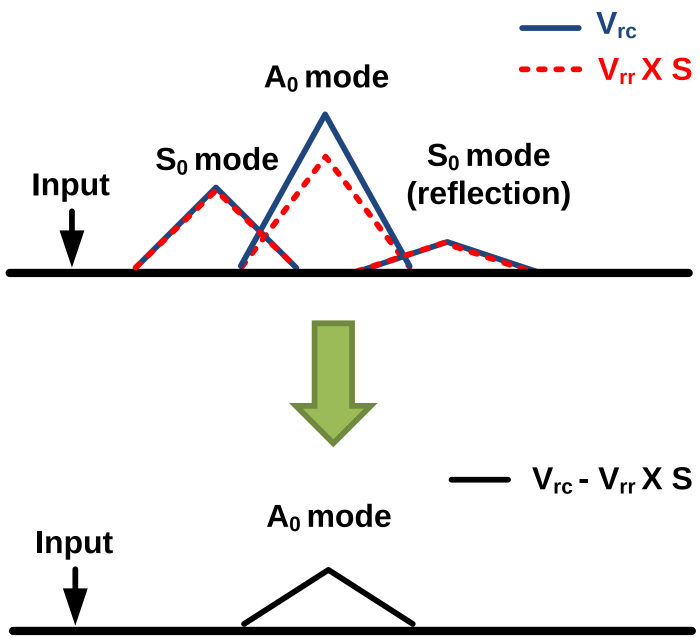




* **Subscript s '*r*' and '*c*'** : ring and circular PZTs
* **'S' is an ratio of S_0** mode scaling at a specific frequency

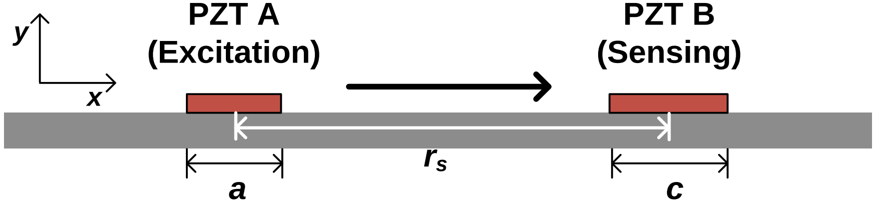






* **Subscript s *'r'* and *'c'*** : ring and circular PZTs
* **'S' is an arbitrary scaling at a specific frequency**

Theoretical Response Model for 2D PZTs



$$u_x \propto \sin(\xi a)$$

$$V(t) \propto \frac{\sin(\xi a)\sin(\xi c)}{c}$$

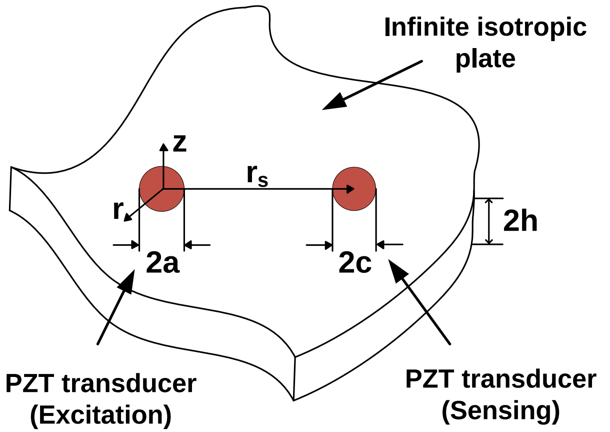
Displacement at *x* from the PZT A [Giurgiutiu (2003)]

$$u_x(t) = -i\frac{\tau_0}{\mu}\cdot\left[\frac{\sin\xi^{S_0}a}{\xi^{S_0}}\frac{N_S\left(\xi^{S_0}\right)}{D_S'\left(\xi^{S_0}\right)}e^{i(\xi^{S_0}x-\omega t)} + \frac{\sin\xi^{A_0}a}{\xi^{A_0}}\frac{N_A\left(\xi^{A_0}\right)}{D_A'\left(\xi^{A_0}\right)}e^{i(\xi^{A_0}x-\omega t)}\right]$$

Voltage Response at PZT B [Giurgiutiu (2003)]

$$V(t) = \frac{\tau_0 E_s h_s g_{31}}{\mu}\left[\frac{\sin\xi^{S_0}a}{\xi^{S_0}}\frac{\sin\xi^{S_0}c}{2c}\frac{N_S\left(\xi^{S_0}\right)}{D_S'\left(\xi^{S_0}\right)}e^{i(\xi^{S_0}r_s-\omega t)} + \frac{\sin\xi^{A_0}a}{\xi^{A_0}}\frac{\sin\xi^{A_0}c}{2c}\frac{N_S\left(\xi^{A_0}\right)}{D_S'\left(\xi^{A_0}\right)}e^{i(\xi^{A_0}r_s-\omega t)}\right]$$

Theoretical Response Model for 3D Circular PZTs



$$u_r(t) \propto aJ_1(\xi a)$$

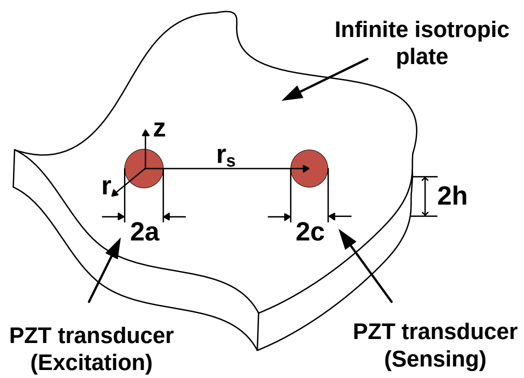
$$\boxed{V(t) \propto aJ_1(\xi a) \times ?}$$

Displacement at *x* from the PZT A [Ajay(2004)]

$$u_r(r, z=b) = -\pi i \frac{\tau_0 a}{\mu} e^{i\omega t} \cdot \left[J_1\left(\xi^{S_0} a\right) \frac{N_S\left(\xi^{S_0}\right)}{D_S'\left(\xi^{S_0}\right)} H_1^{(2)}\left(\xi^{S_0} r\right) + J_1\left(\xi^{A_0} a\right) \frac{N_A\left(\xi^{A_0}\right)}{D_A'\left(\xi^{A_0}\right)} H_1^{(2)}\left(\xi^{A_0} r\right) \right]$$

Voltage Response at PZT B [Lee and Sohn (2010)]

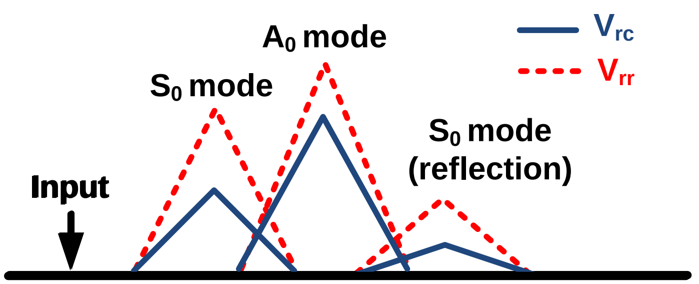
$$V(t) = -i \frac{\tau_0 E_s h_s g_{31} a}{\mu c^2} e^{i\omega t} \cdot J_1\left(\xi^{S_0} a\right) \frac{N_S\left(\xi^{S_0}\right)}{D_S'\left(\xi^{S_0}\right)} \int_{r_s - c}^{r_s + c} \left\{ \xi^{S_0} r H_0^{(2)}\left(\xi^{S_0} r\right) \cdot 2 \tan^{-1}\left(\sqrt{\frac{4r^2 r_s^2}{\left(r^2 + r_s^2 - c^2\right)^2} - 1} \right) \right\} dr$$



$$V(t) = -i\frac{2\tau_0 E_s h_s g_{31} a}{\mu c}\sqrt{\frac{2\pi}{r_s}}\left[\frac{1}{\sqrt{\xi^{S_0}}} J_1\left(\xi^{S_0} a\right) J_1\left(\xi^{S_0} c\right)\frac{N_s\left(\xi^{S_0}\right)}{D_s^{'}\left(\xi^{S_0}\right)} e^{i\left(\omega t - \frac{\pi}{4} + \xi^{S_0} r_s\right)} + \frac{1}{\sqrt{\xi^{A_0}}} J_1\left(\xi^{A_0} a\right) J_1\left(\xi^{A_0} c\right)\frac{N_s\left(\xi^{A_0}\right)}{D_s^{'}\left(\xi^{A_0}\right)} e^{i\left(\omega t - \frac{\pi}{4} + \xi^{A_0} r_s\right)}\right]$$

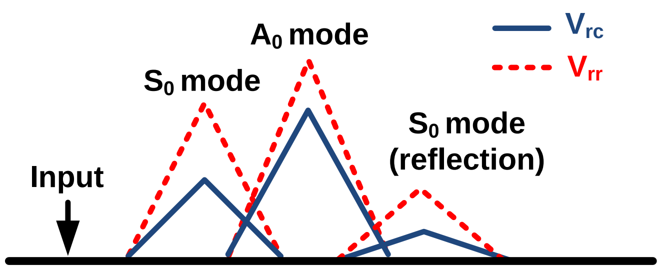
$$V(t) \propto a J_1(\xi a) \times \boxed{\frac{J_1(\xi c)}{c}}$$

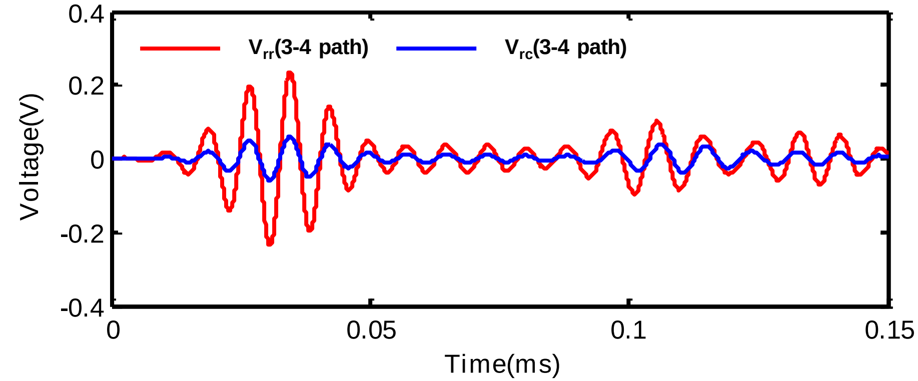
- The amplitudes of the S0 and A0 modes are fucntions of the excitation and sensing PZT sizes (**a** and **c**)
- In the fixed distance between the sensing and excitation PZTs, signal phases does not change with respect to the variations of the PZT size



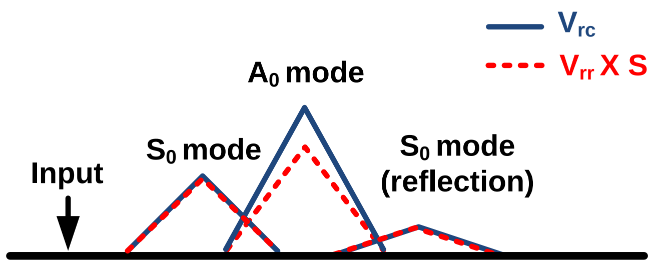
Example of the A_0 Mode Extraction from Raw Signals

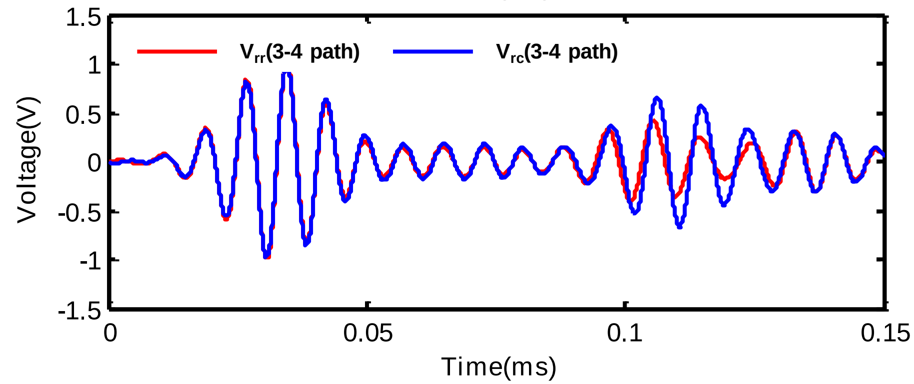
1) Signals measured different sensing size



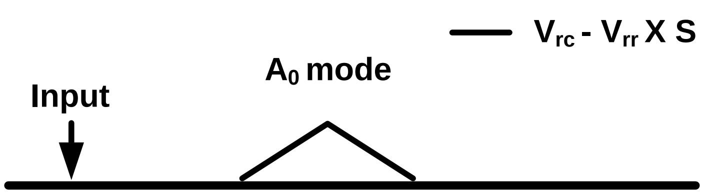


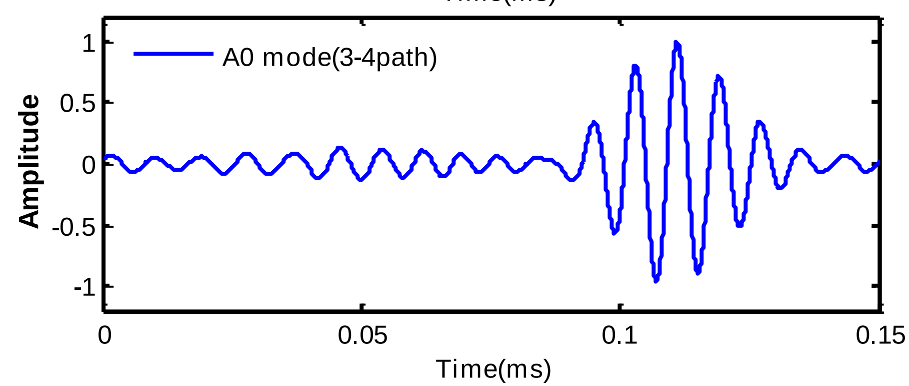
2) Matching of the amplitude of the S_0 mode





3) Extraction of the A_0 mode





Outline

Summary of the Proposed Delamination Classification

Delamination classification procedure

1) Attach dual PZTs to the host composite plate

2) Decide an input frequency range using experimental tuning curves

3) Measure responses from all actuator and sensor pairs

4) Extract the A_0 Lamb wave mode

5) Establish the damage classification

Technical details

1. Determination of the time range of the A_0 mode using experimental group velocity
2. Calculation of correlation coefficients using instantaneous measured signals having same directions and lengths
3. Computation of the damage index from all paths
4. Setting up the threshold values based on
   1) Generalized extreme value distribution
   2) K-mean clustering
   3) Outlier analysis
   4) **Beta distribution**
5. Decision making

Cross Correlation based a Damage Detection Technique

Cross correlation

Cross-correlation analysis is used to determine the degree to which two signals are linearly related. This algorithm is sensitive to signal shape changes, but insensitive to amplitude changes.

Damage index (**DI**)

$$DI(i) = \frac{1}{2}\left(1 - \frac{1}{n_d}\sum_{j}^{n_d - 1} corr(a_i, a_j)\right)$$

$$d = 0^\circ, 45^\circ, 90^\circ, 135^\circ$$

$$1 \le i \le 20$$

$$0 \le DI \le 1$$

where **corr** is the cross correlation

a_i is the A_0 mode obtained from the path **i**.

d is the direction of the path **i**.

n_d is the number of paths of the **d** direction

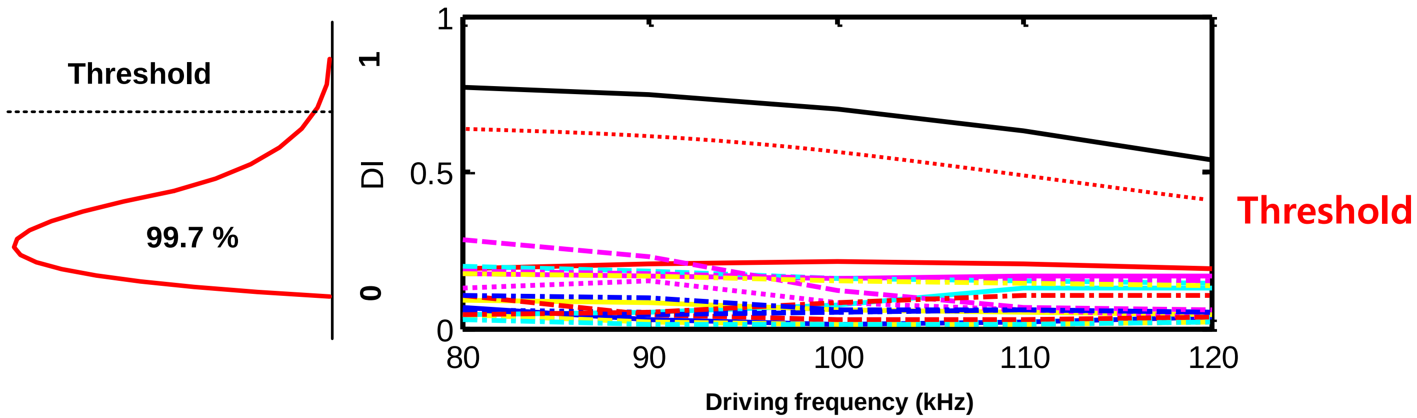
a_j is the A_0 mode obtained from the same direction of path **i**.

Beta distribution

The beta distribution is a family of continuous probability distributions defined on the interval (0, 1) parameterized by two positive shape parameters, typically denoted by α and β.

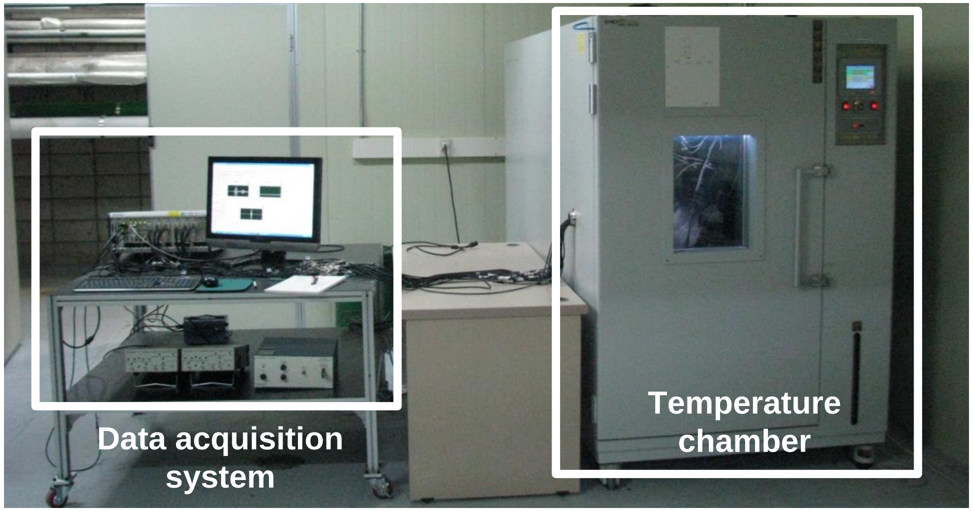
The damage index is bounded on (0, 1)

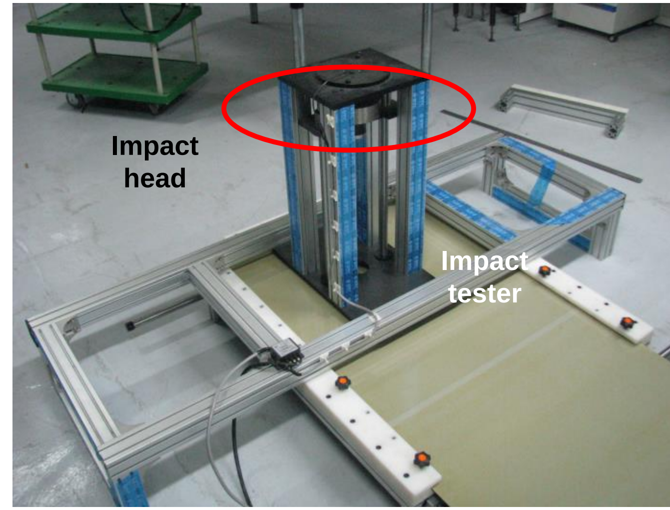
The double bounded distribution should be used

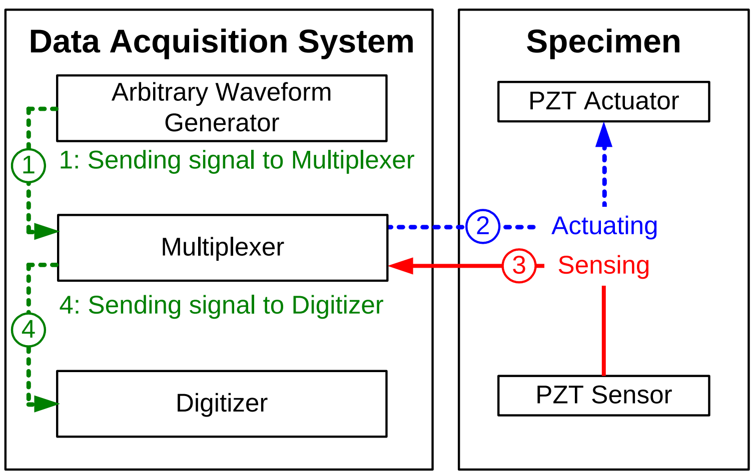


Outline

Experimental Setup

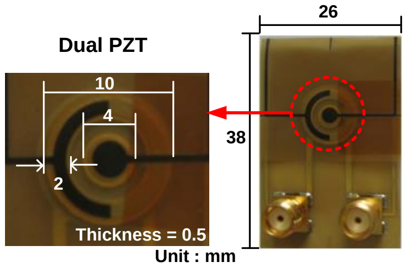




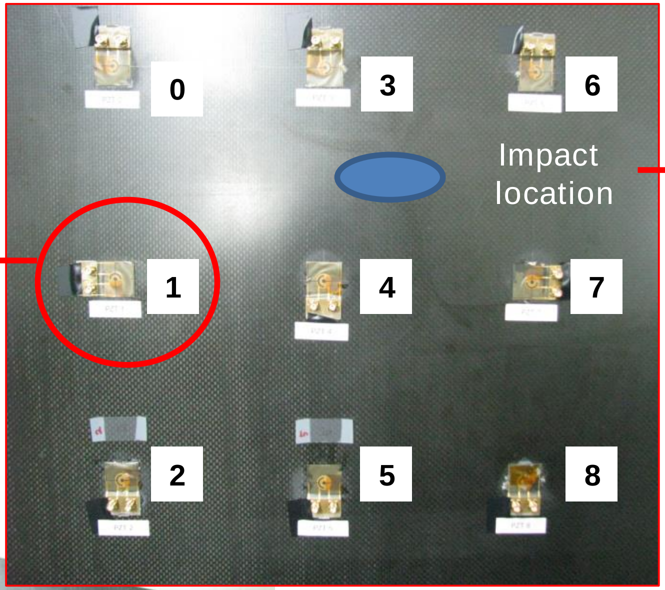


- The dimension of each PZT :
  * 9 packaged dual PZTs
  * PSI-5A4E type
- Input signal :
  A tone-burst signal with ± 10 peak-to-peak voltage
  A frequency range 80 kHz to 120 kHz with an increment of 10 kHz
- Sampling rate : 20MS/s
- Power amplifier gain : 5
- Data averaging : 120 times
- Temperature : -10, 20, 50 ^{o}C

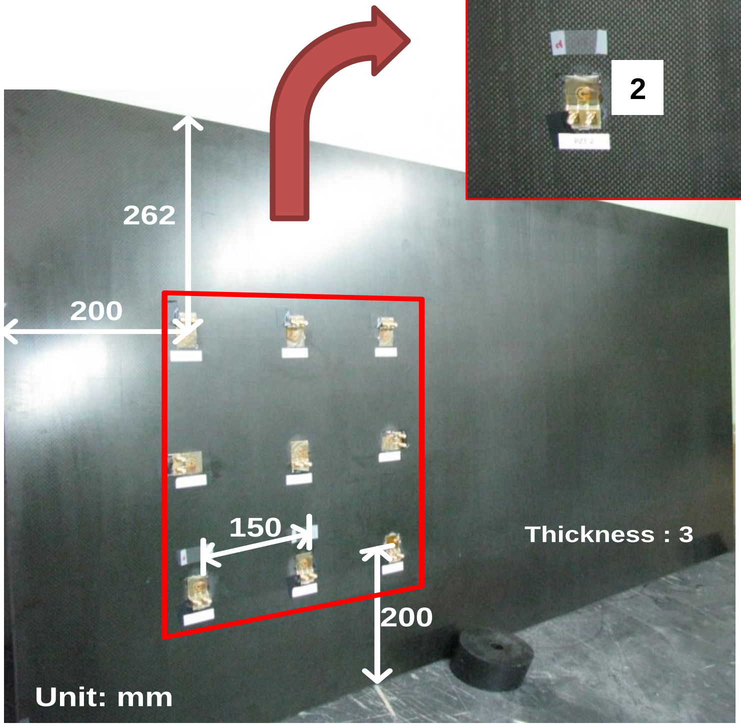
Sensor Configuration

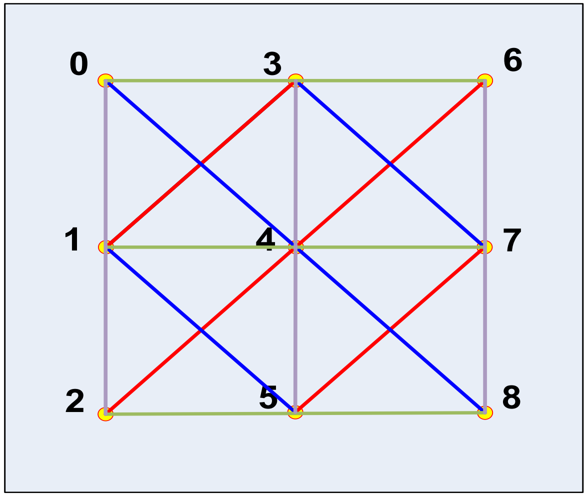


Dual PZT



Impact on the back side

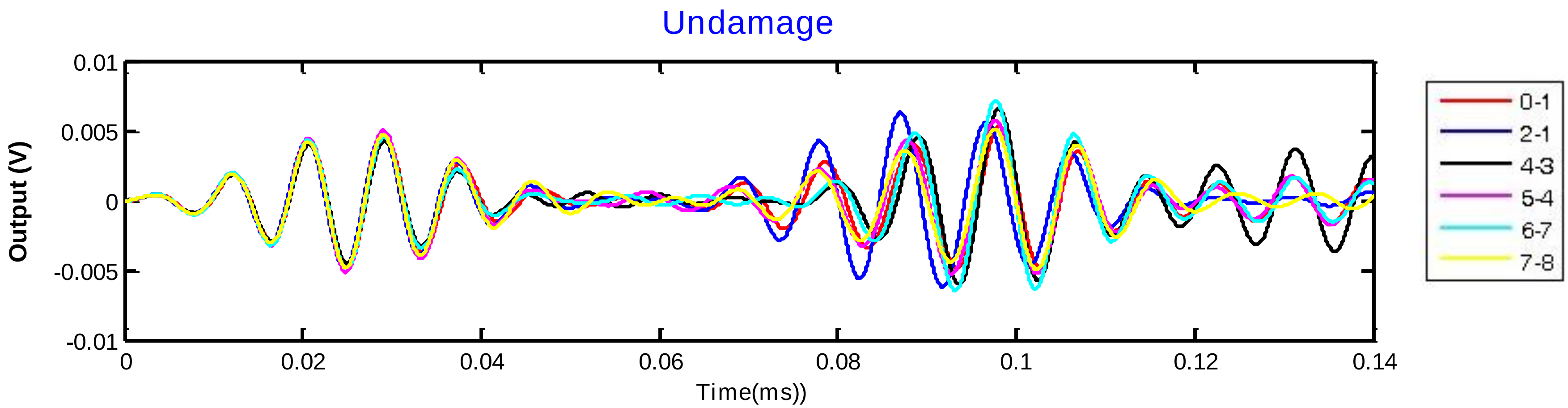


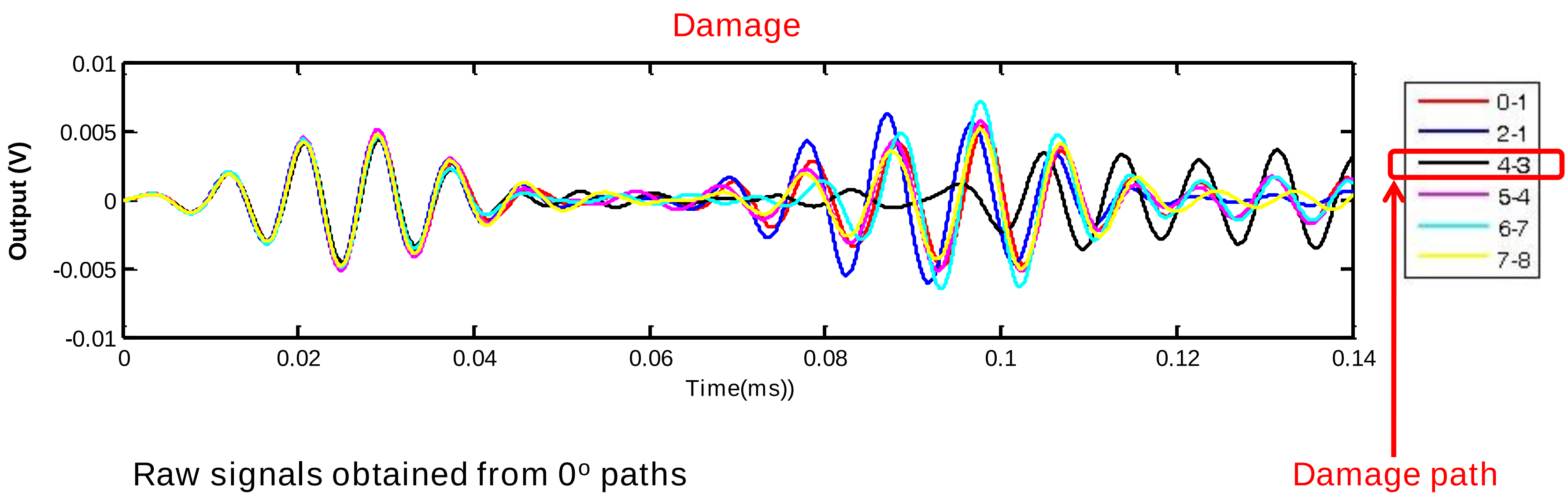


Path directions

- 0^{o} : 6
- 45^{o} : 4
- 90^{o} : 6
- 135^{o} : 4

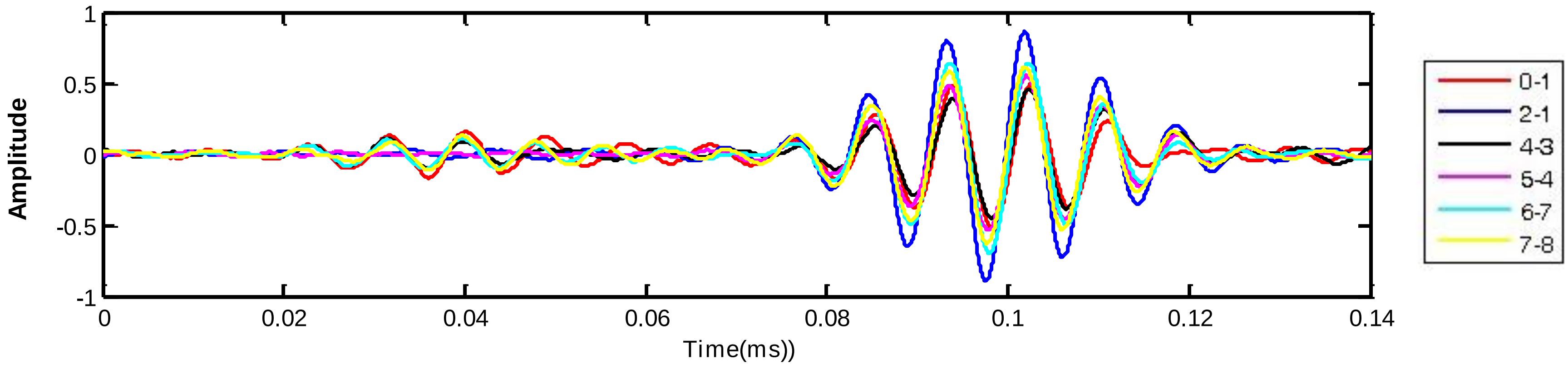
Comparison of the Raw Signals



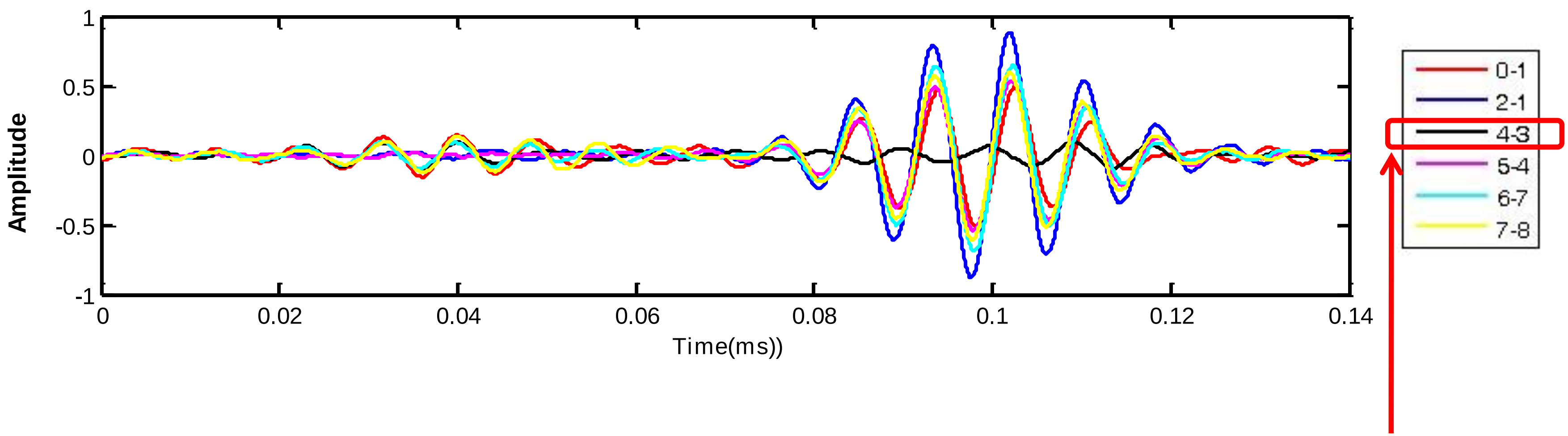


Raw signals obtained from 0° paths

Undamage



Damage

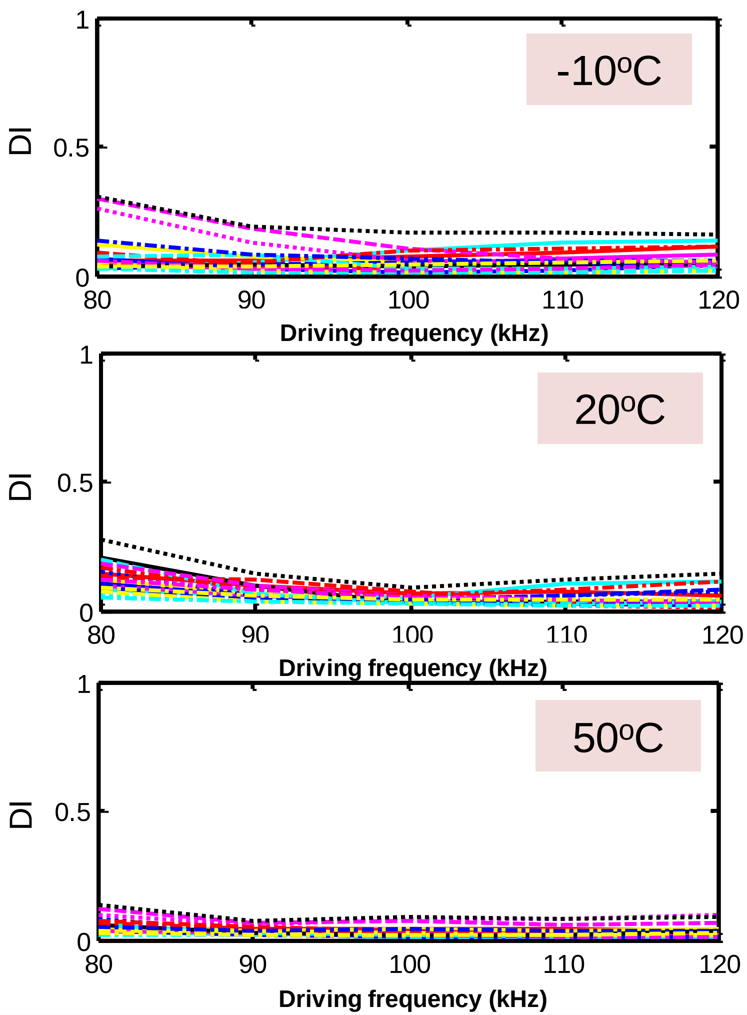


Extracted A_0 mode from 0^o paths

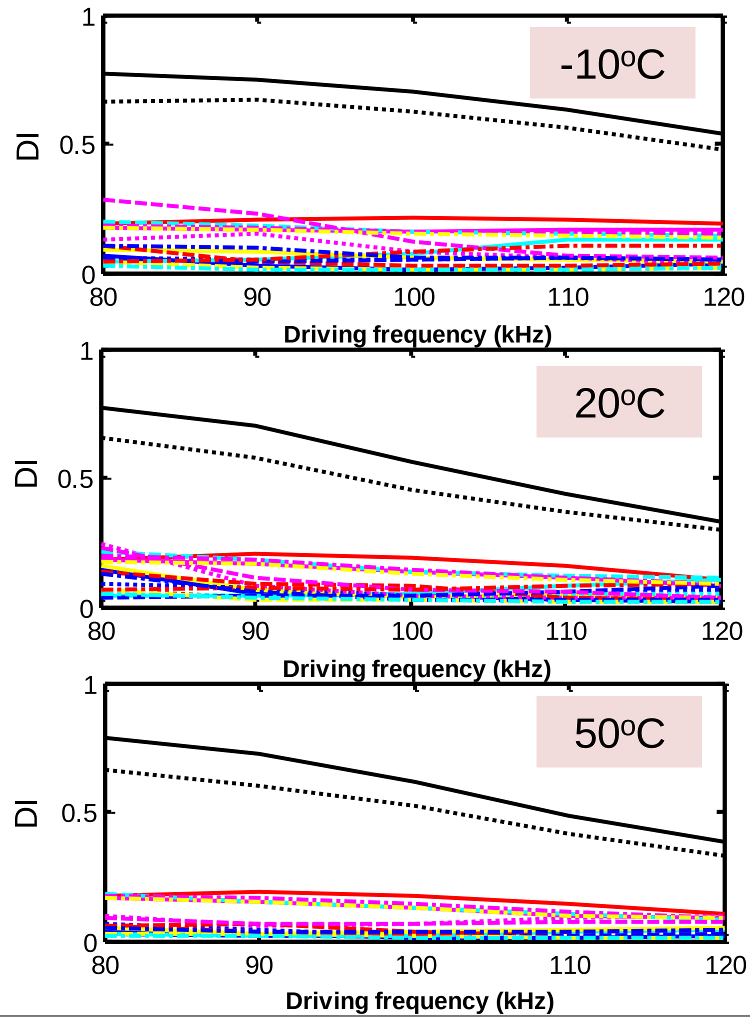
Damage path

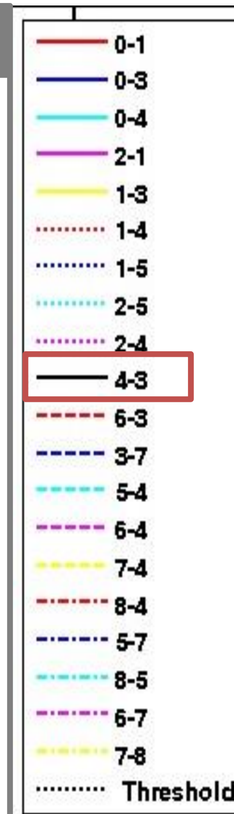
Comparison of Correlation Coefficients

Undamage



Damage





Outline

Limitations of the Proposed Technique

1. Enough paths with <u>same direction and length</u> are needed

2. Majority of the collected data will be recorded over <u>undamaged sections</u>

3. The group velocities do not change with respect to the input energy or propagation distance

4. Contributions of <u>converted modes or scatter waves</u> to measured signals are relatively small rather than those of the first arrival of the A_0 mode

5. The first arrival A_0 mode should not be overlapped with its reflection wave from structural boundaries

Concluding Remarks

Summary

1. Development of the reference-free damage detection technique
2. Propose the A_0 mode extraction technique
3. Investigation of environmental effects on the proposed technique

Future study

1. Development of a reference-free damage detection technique without using other reference paths
2. Investigation of sensor installation techniques to improve bonding condition between sensors and a structure
3. Works on the more reliable damage classifier

Reference

S. H. Diaz Valdes and C. Soutis, "Real-time non-destructive evaluation of fibre composite laminates using low-frequency Lamb waves," J. Acoust. Soc. Am. 111, 2026–2033 (2002). [ISI]

K. H. Ip and Y. W. Mai, ”Delamination detection in smart composite beams using Lamb waves ,” Smart Mater. Struct. 13 544-51 (2004).

C. T. Ng and M. Veidt, “A Lamb-wave-based technique for damage detection in composite laminates,” Smart. Mater. Struct. 18, 074006 (2009).

J. B. Ihn and F. K. Chang, “Pitch-catch active sensing methods in structural health monitoring,” Smart Mater. Struct. 7 5–19 (2008).

D. Wang, L. Ye and Z. Su, ”Probability of the presence of damage estimated from an active sensor network in a composite panel of multiple stiffeners,” Compos. Sci. Technol. 69 2054-63 (2009)

G. Petculescu, S. Krishnaswamy and J. D. Achenbach, ” Group delay measurements using modally selective Lamb wave transducers for detection and sizing of delaminations in composites,” Smart Mater. Struct. 17 015007 (2008).

C. Ramadas, M. J. Padiyar , K. Balasubramanjam, M. Joshi and C. V. Krishnamurthy, “Delamination size detection using time of flight of ani-symmetric(A0) and mode converted A0 mode of guided Lamb waves,” J. Intell. Mater. Syst. Struct. 21, 817–825 (2010).

P. D. Wilcox, M. J. S. Lowe, and P. Cawley, "Mode and transducer selection for long range Lamb wave inspection," J. Intell. Mater. Syst. Struct. 12, 553–565 (2001).

S. B. Kim, and H. Sohn, “Instantaneous reference-free crack detection based on polarization characteristics of piezoelectric materials,” Smart Mater. Struct. 16, 2375-2387 (2007).

J. L. Rose, S. P. Pelts, and M. J. Quarry, "A comb transducer for mode control in guided wave NDE," IEEE Ultras. Symp. Proc. 857–860 (1996).

Reference

H. Gao, J. Rose and C. Lissenden, “Ultrasonic guided wave mode selection and tuning in composites using piezoelectric phased arrays”, International workshop on Structural health monitoring (2007)

V. Giurgiutiu., "Lamb wave generation with piezoelectric wafer active sensors for structural health monitoring," SPIE. 5056, 111-122 (2003)

A. Raghavan and C. E. S. Cesnik, “Modeling of piezoelectric-based Lamb-wave generation and sensing for structural health monitoring,” SPIE. 5391 (2004)

H. Sohn, S. J. Lee, “Lamb wave tuning curve calibration for surface-bonded piezoelectric transducers,” Smart Mater. Struct. 19, 015007 (2010).

S. R. Anton and D. I. Inman DJ, “Reference-free damage detection using instantaneous baseline measurements,” AIAA. **47,** 1952-64 (2009).

S. S. Kessler, S. M. Spearing, and C. Soutis, “Damage detection in composite materials using Lamb wave methods,” Smart Mater. Struct. 11, 269–278 (2002).

I. A. Viktorov, Rayleigh and Lamb Waves (Plenum, New York, 1967).

S. C. Wooh and Y. J. Shi, "Synthetic phase tuning of guided waves," IEEE Trans. Ultrason. Ferroelectr. Freq. Control 48, 209–223 (2001).

Z. Su, L. Ye, and Y. Lu, “Guided Lamb waves for identification of damage in composite structures: A review,” J. Sound Vib. 295, 753–780 (2006).

Do You Have

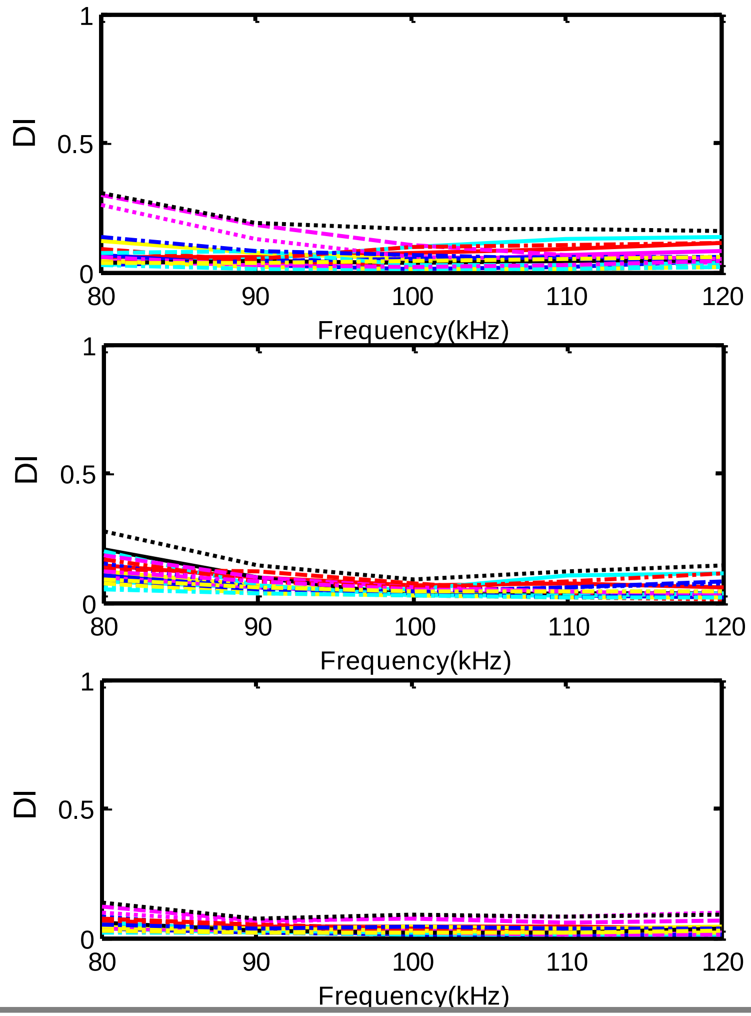
Any Questions ?

I would be happy to help

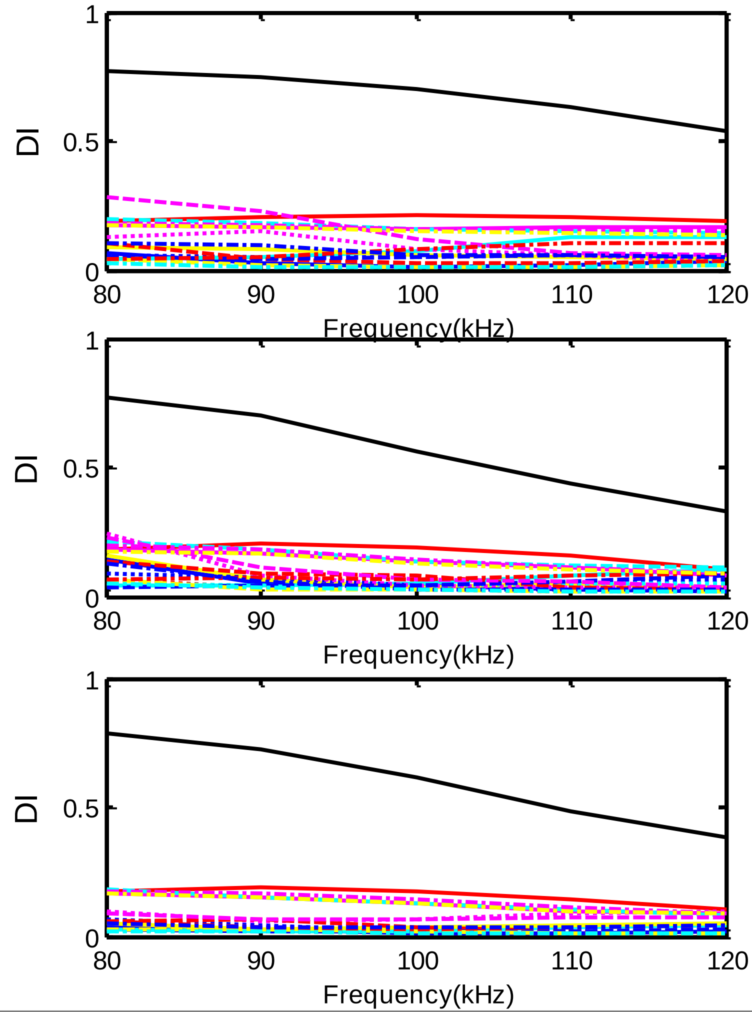
Back up

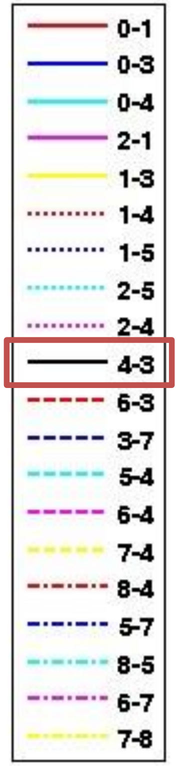
Comparison of Correlation Coefficients Obtained from Undamage and Damage Conditions

Undamage



Damage





Comparison of Correlation Coefficients Obtained from same path direction and lengths

20°C

50°C

-10°C