Reference-free Structural Health Monitoring for Detecting Delamination in Composite Plates

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Outline

1 Introduction

2 Reference-free Delamination Detection Technique

3 Numerical Simulation

4 Experimental Setup and Test Results

5 Summary and Conclusion

What Makes the Detection of Delamination Challenging ?

Technology

Lamb wave, embedded PZT transducer, pitch-catch sensing

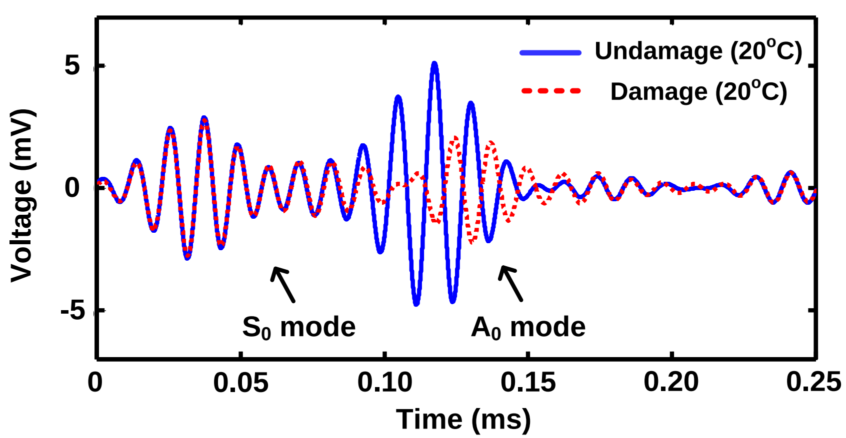
Challenges

- Lamb wave mode complexity
- Similarity of delamination and temperature effects on Lamb wave modes
- Autonomous decision making

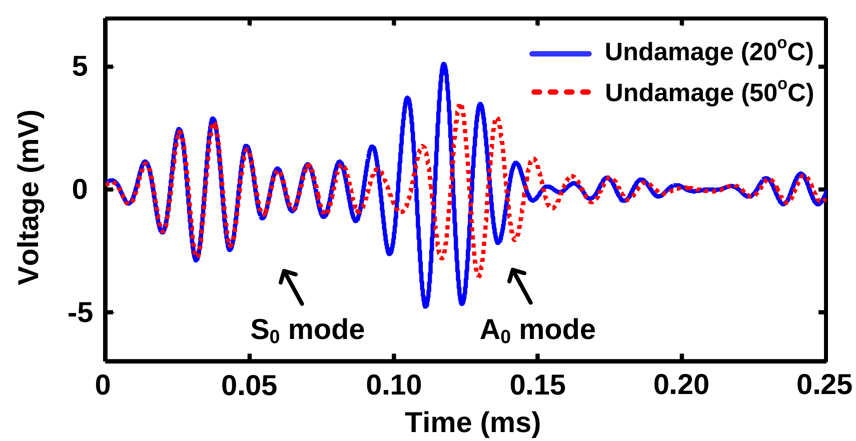
Final target

Real-time autonomous delamination detection

Delamination effect



Temperature effect



Research Objective and Uniqueness

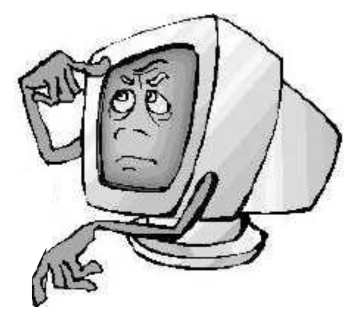
Objective

Development of a delamination detection technique in a single wave propagation path without using prior baseline data or a predetermined decision boundary even under changing operational and environmental conditions of a structure

Uniqueness

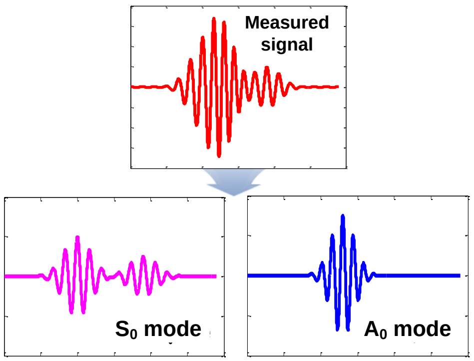
Invariant of environmental variation (real-time monitoring)

Autonomous delamination detection



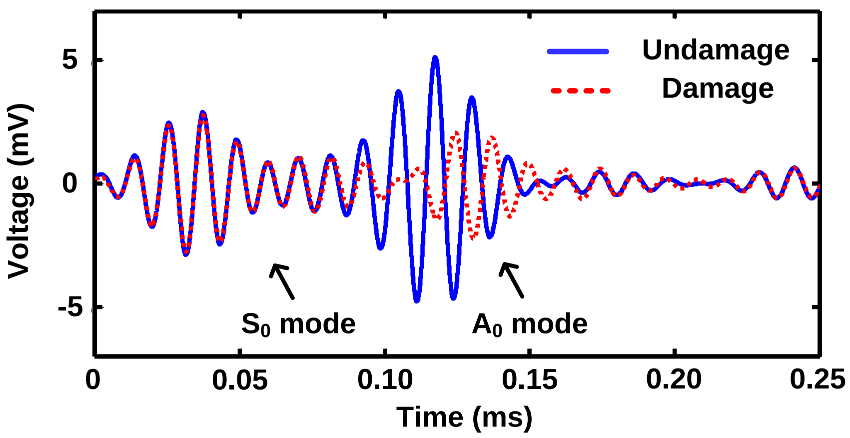
Health? **Damage?**

Mode extration using a dual PZT

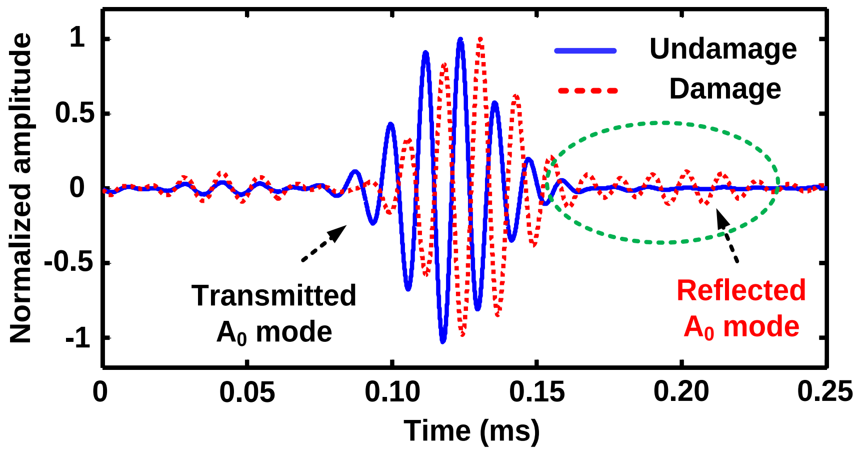


Interaction of Lamb Waves with Delamination

Reference-free delamination detection technique



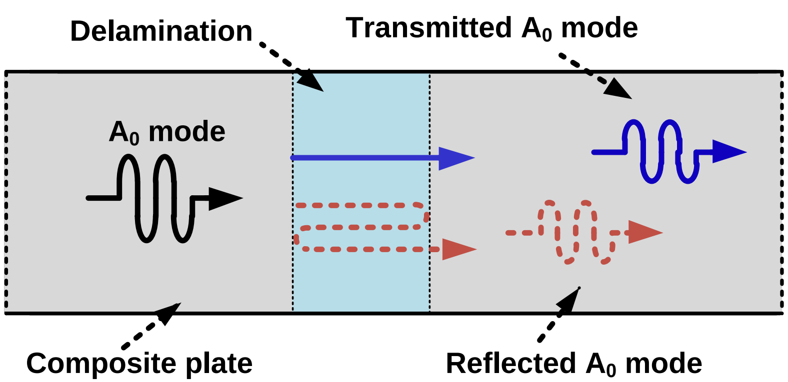
Pitch-catch Lamb waves obtained from undamaged and damaged conditions



Extracted A_0 mode obtained from undamaged and damaged conditions

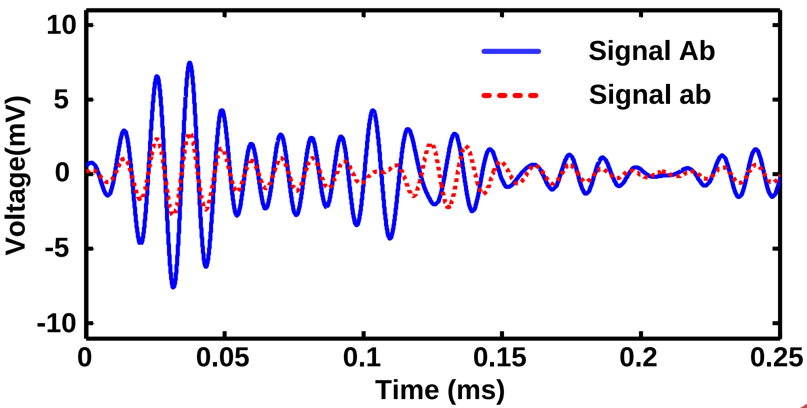
Effects of delamination on Lamb waves

1. Attenuation and delay of the A_0 mode rather than the S_0 mode
2. Hardly distorted waveforms of the A_0 and S_0 modes by delamination
3. Little mode conversion
4. **Creation of the reflected A_0 mode**

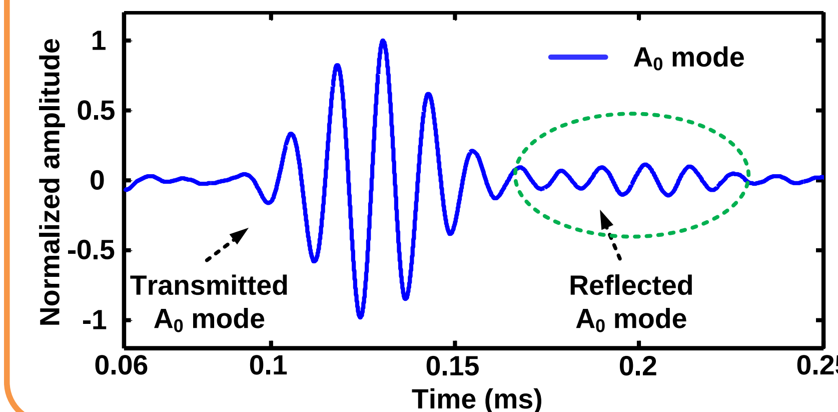


Procedure of the Proposed Reference-free Delamination Detection Technique

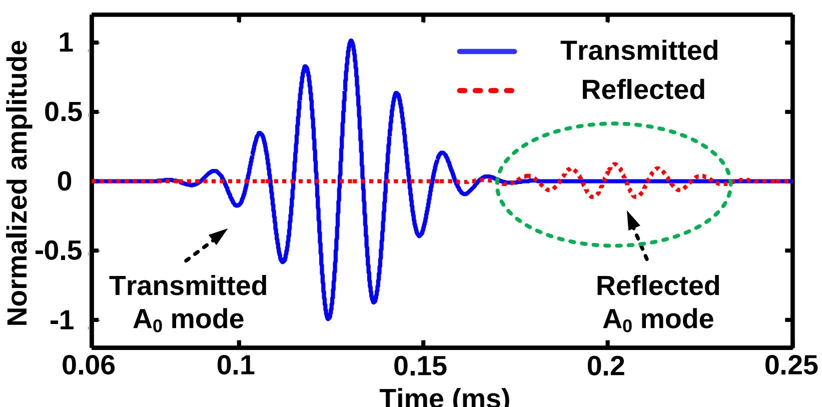
(1) Measurement of pitch-catch Lamb wave signals using dual PZT



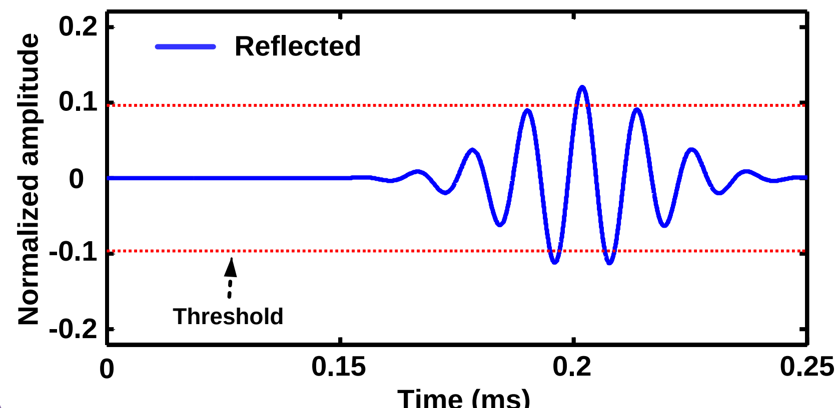
(2) Extraction of the A_0 mode using the mode extraction technique (*)



(3) Decomposition of the A_0 mode reflected off from delamination using a matching pursuit algorithm

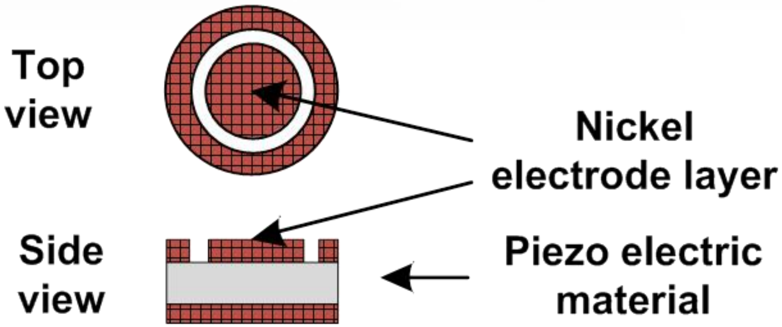


(4) Damage diagnosis using instantly estimated threshold

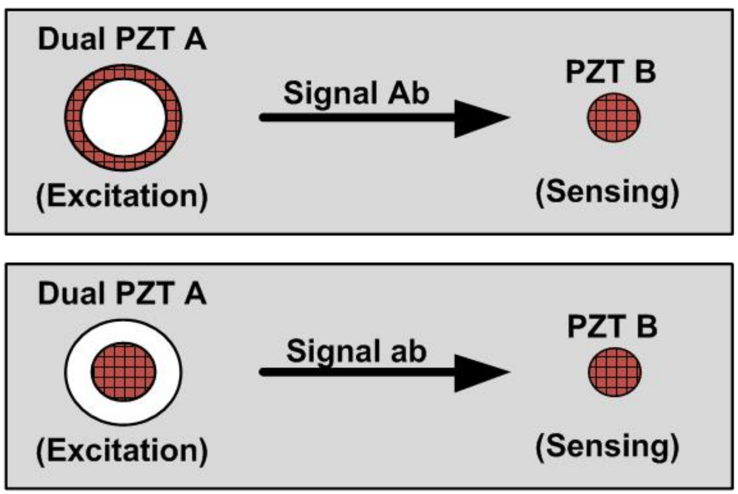


(*): Chul Min Yeum et al "Lamb wave mode decomposition using concentric ring and circular PZT Transducers," Wave Motions, Vol. 48, pp. 358-370, 2011.

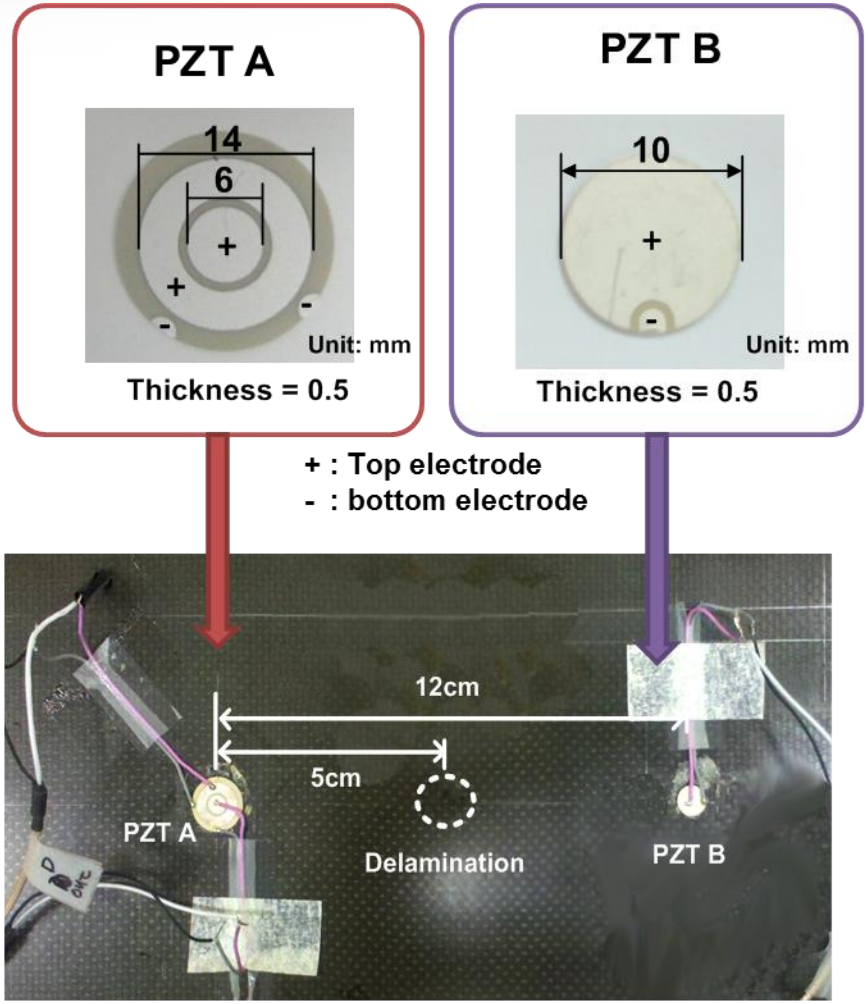
Introduction of a Dual PZT and Signal Notations



Schematic drawing of a dual PZT



Notations of signals



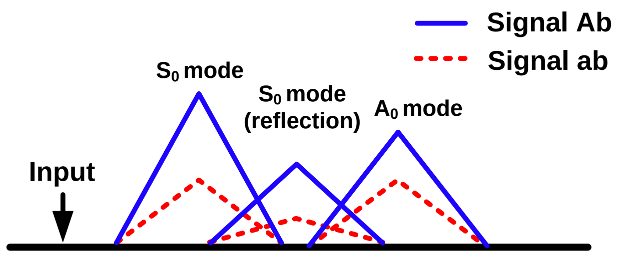
A composite specimen with PZTs and a delamination location

Extraction of the A_0 mode from Measured Signals

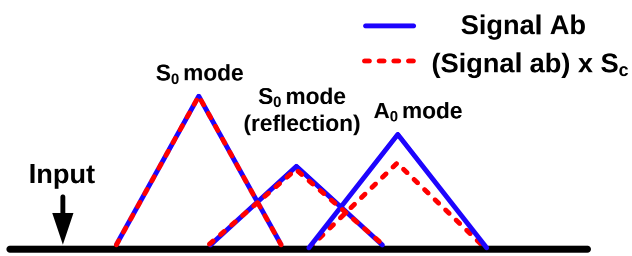
Reference-free delamination detection technique

Schematic drawings of the A_0 mode extraction technique

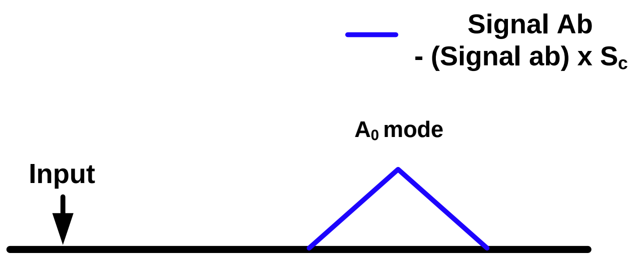
1) Signals excited the at ring and disk PZTs



2) Matching of the amplitude of the S_0 mode

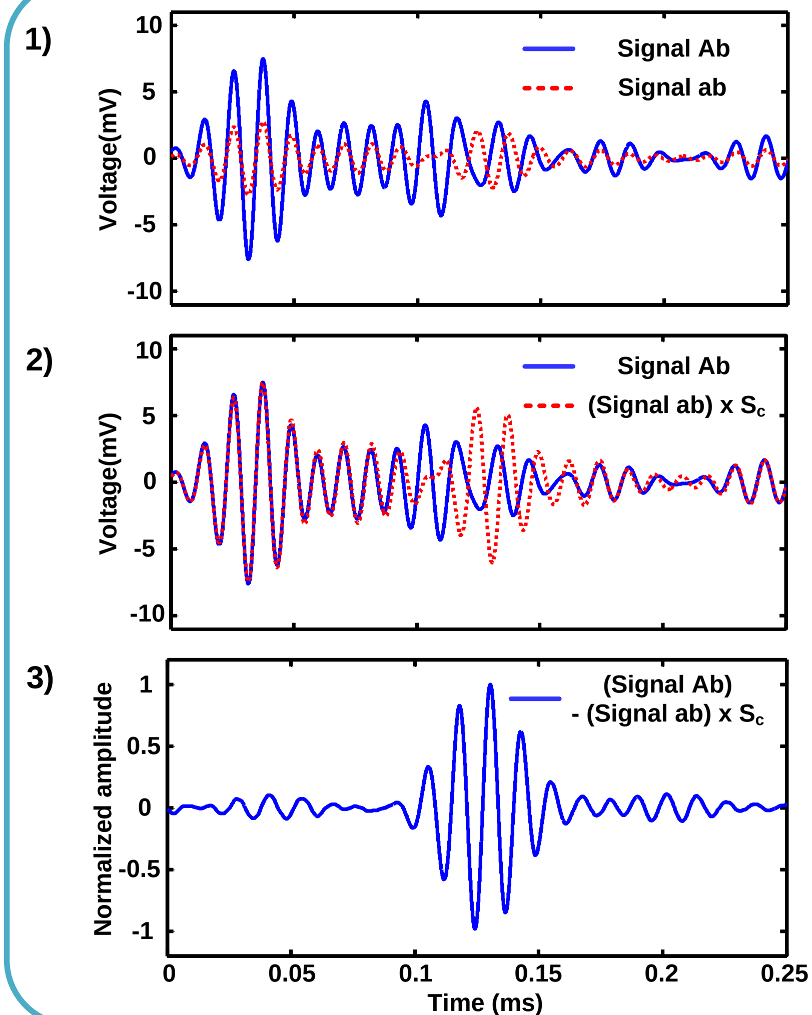


3) Extraction of the A_0 mode



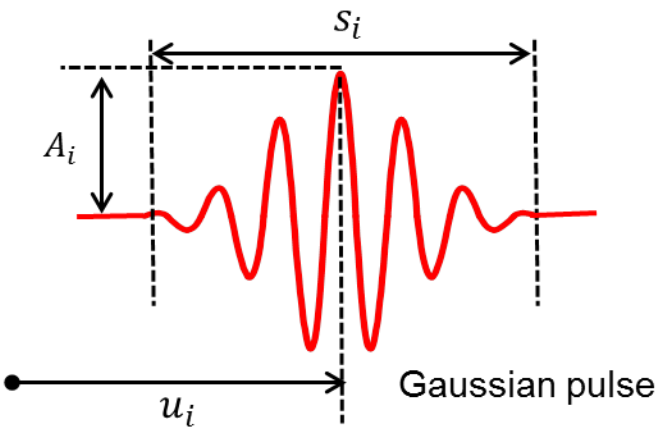
S_c is the amplitude ratio of the S_0 mode in signal Ab to that in signal ab.

The proposed technique using signals Ab and ab obtained from the test specimen



Mode Decomposition Using the Matching Pursuit Algorithm

Basis Function $g_i = (u_i, s_i, \xi_i, \phi_i)$



Let $f(t)$ is the measured signal to be analyzed

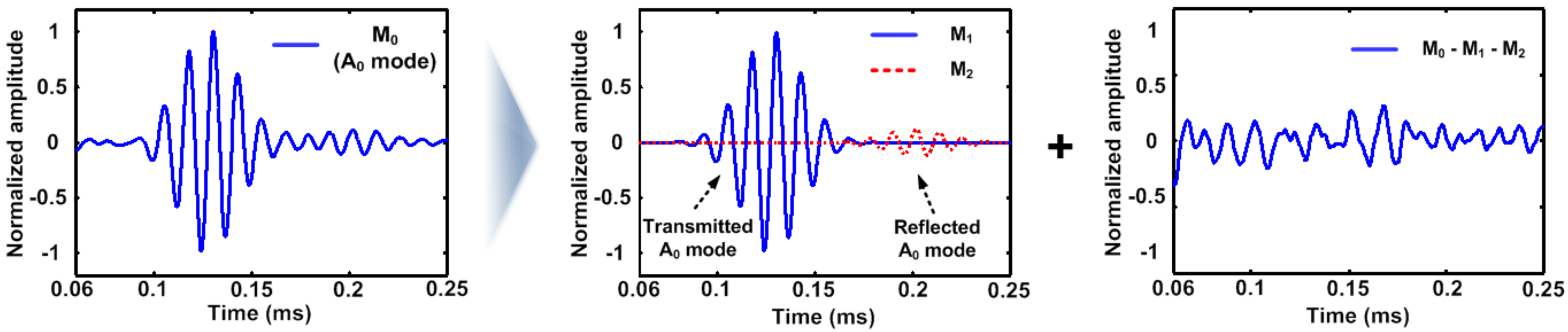
$$f(t) = \sum_{i=0}^{m-1} A_i g_i(t) + R_m f(t)$$

$R^{i+1} f$: the residual after i iterations

g_i : the basis Gaussian function

A_i : the amplitude ; u_i : the arrival time; ; ϕ_i : the phase

s_i : the pulse duration; ξ_i : the central frequency

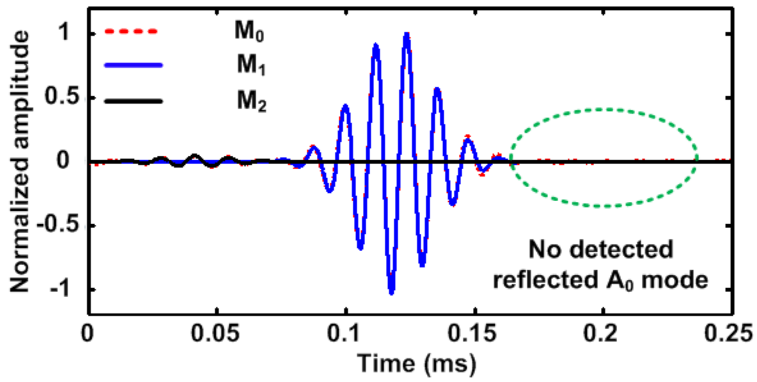


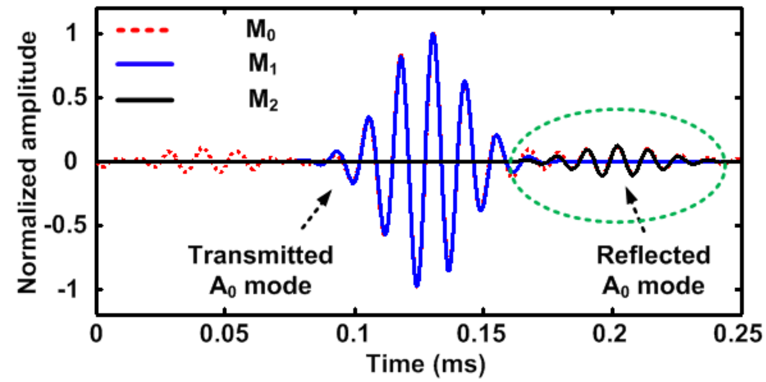
M_0: Extracted A_0 mode; M_1: 1st decomposed A_0 mode (transmitted A_0 mode);
M_2: 2nd decomposed A_0 mode (reflected A_0 mode)

Reference: Hong JC et al, 2005

Reference-free Damage Classification

Step 1. Check whether the appearance of M_2 is observed after the transmitted A_0 mode, M_1, is arrived

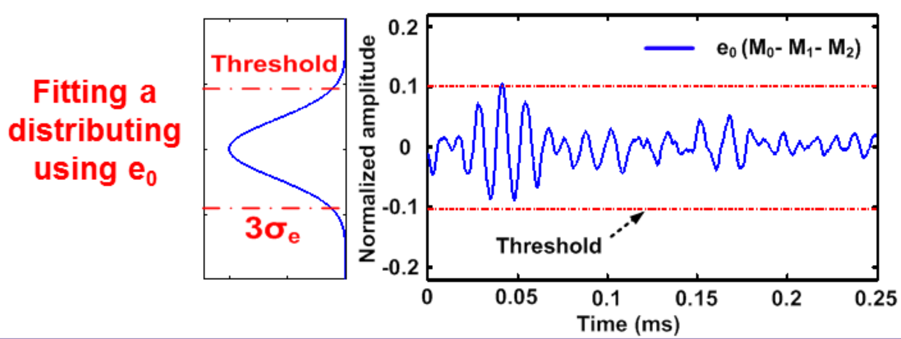


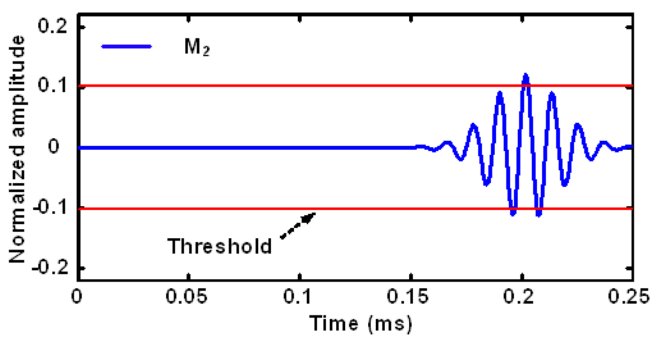


Step 2. Check if M_2 is the reflected A_0 mode using a threshold value instantaneously obtained from an error signal

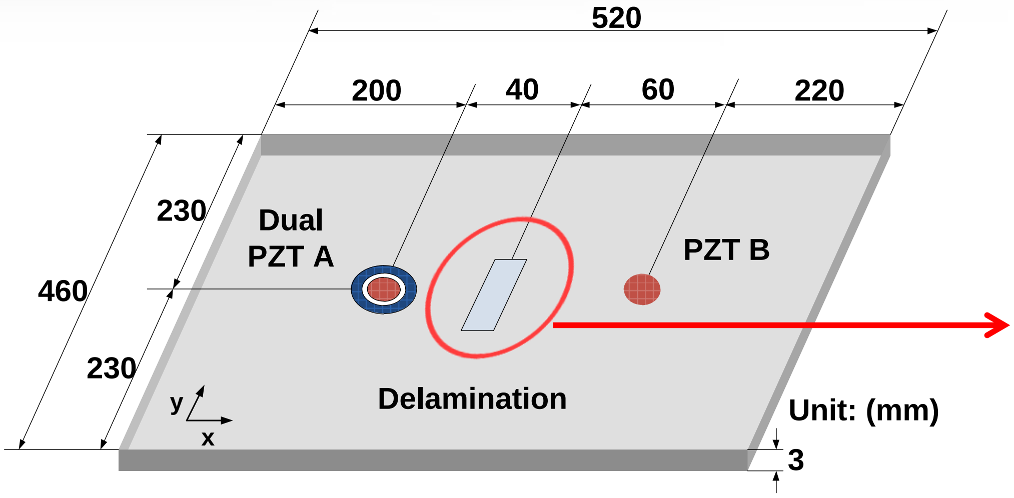
Fit a parametric distribution to the e_0 and compute a threshold value ($e_0 = M_0 - M_1 - M_2$, σ_e is the standard deviation of $M_0 - M_1 - M_2$)

If maximum amplitude of $M_2 > 3\sigma_e$, a delamination exists.

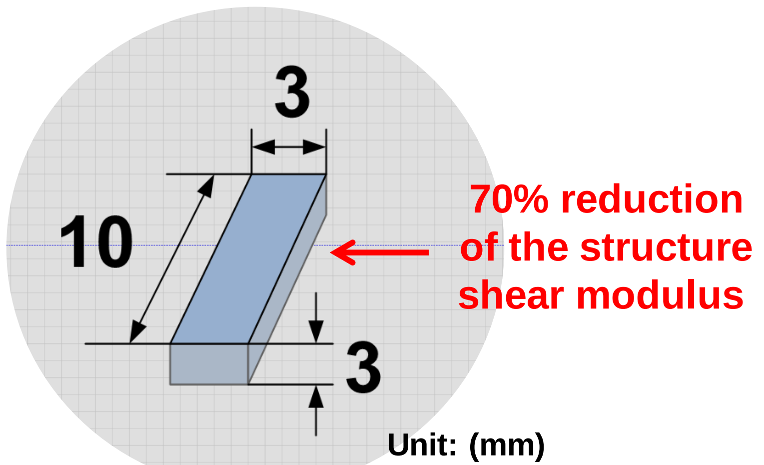




Numerical Simulation Setup

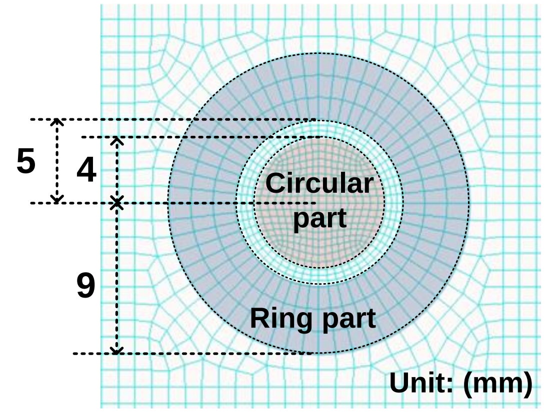


Configuration of the simulated plate



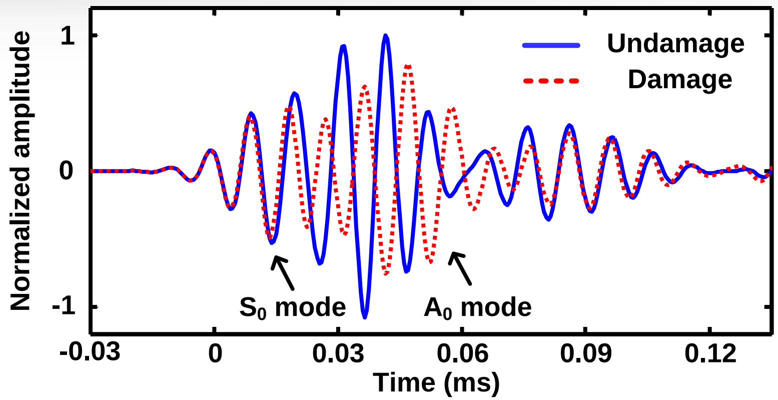
Delamination

Input	Pin-force, 100 kHz, 7 cycle toneburst
Material (structure)	E = 50G pa, G = 18.7Gpa
Material (delamination)	E = 50G pa, G = 5.61Gpa (↓ 70%)
Sampling rate	2 MHz
Mesh size	1 mm x 1mm x 1mm
Software	MSC/NASTRAN

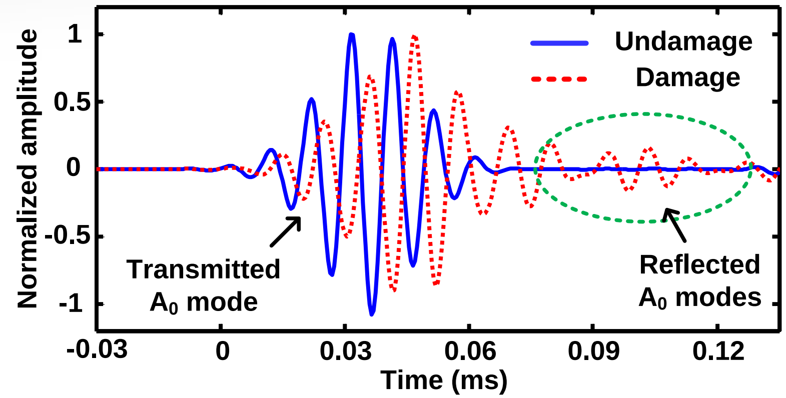


Dimension of the dual PZT

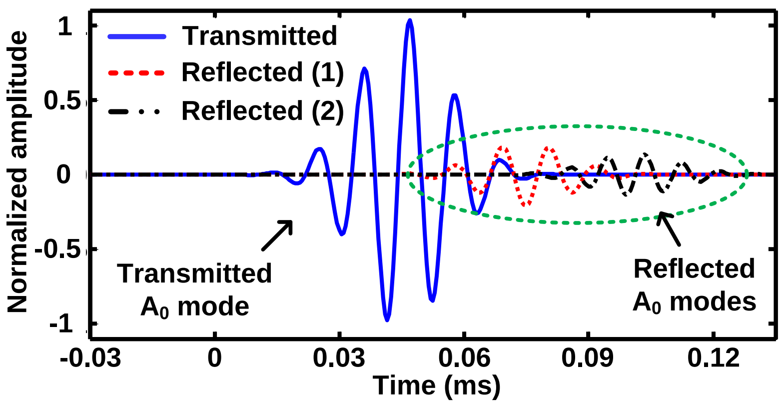
Numerical Simulation Results



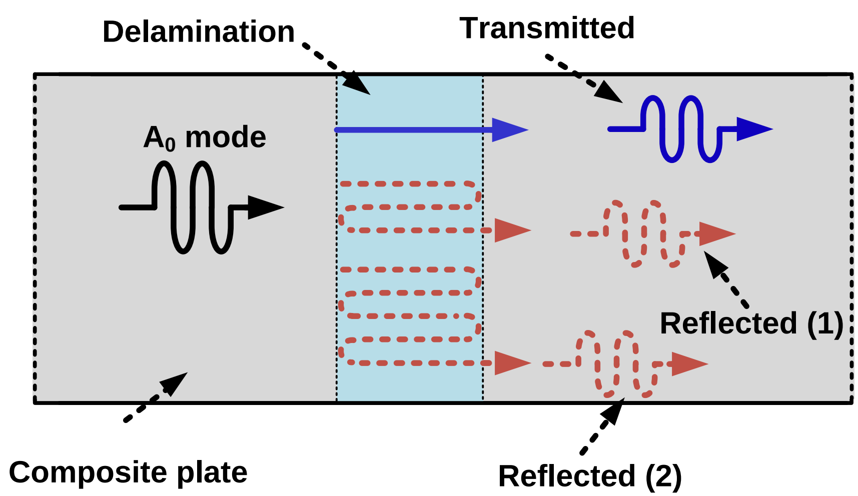
Raw signals obtained from undamaged and damaged conditions



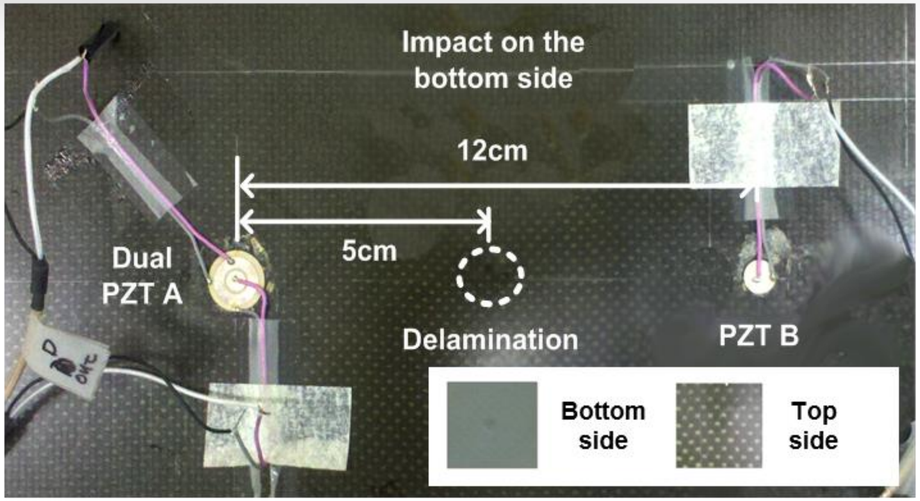
Extracted A_0 modes obtained from undamaged and damaged raw signals



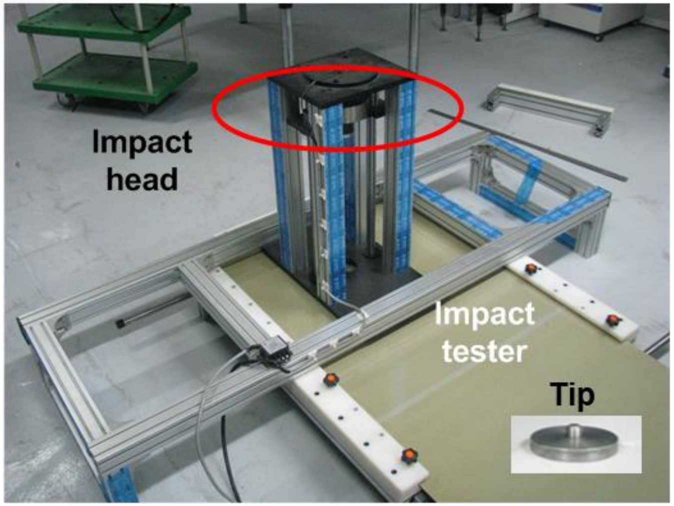
Decomposed A_0 modes using the matching pursuit algorithm



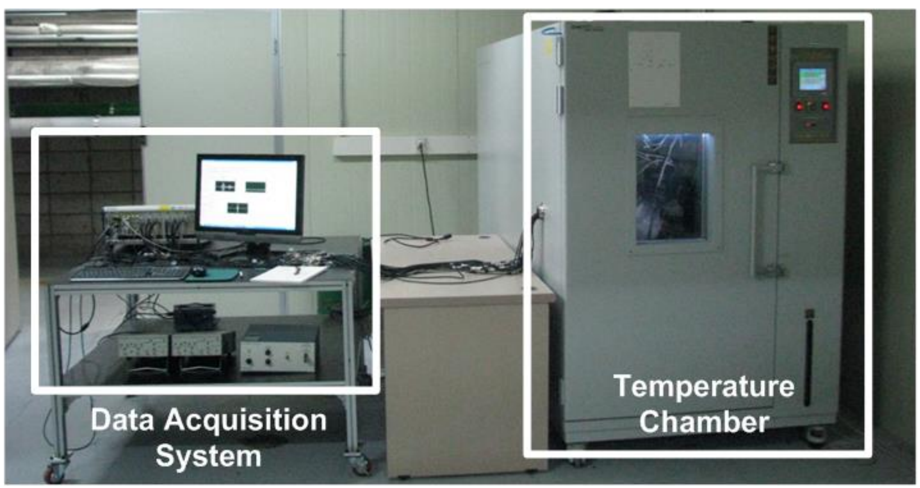
Experimental Setup



Test specimen



Impact tester

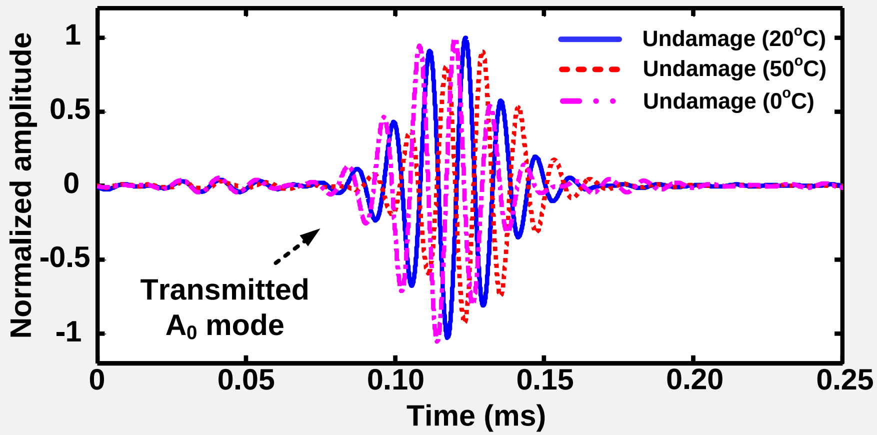


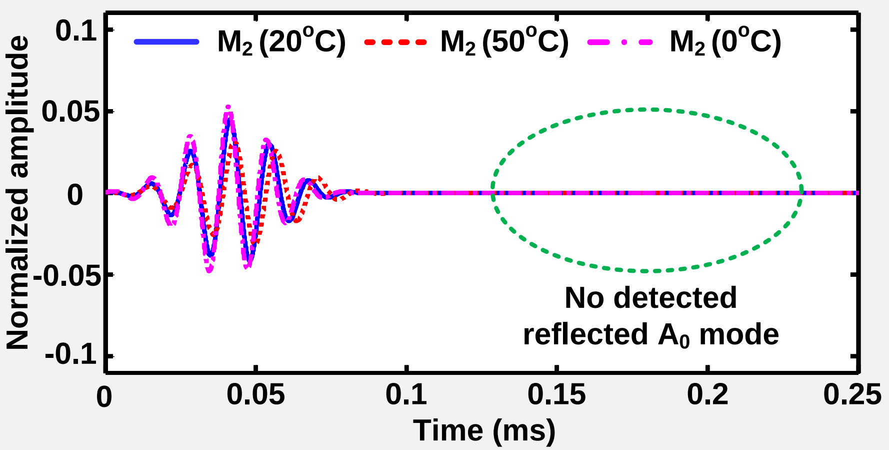
DAQ system & Temperature chamber

- PSI-5A4E PZT
- Input signal: A 80kHz tone-burst signal with $\pm$ 10 peak-to-peak voltage
- Sampling rate: 20MS/s
- Data averaging: 30 times
- Testing temperature: -10, 20, 50 °C

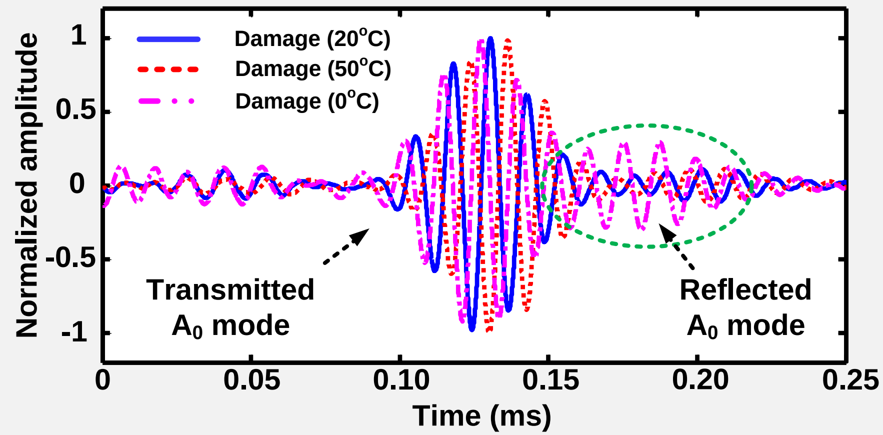
Reference-free Damage Classification

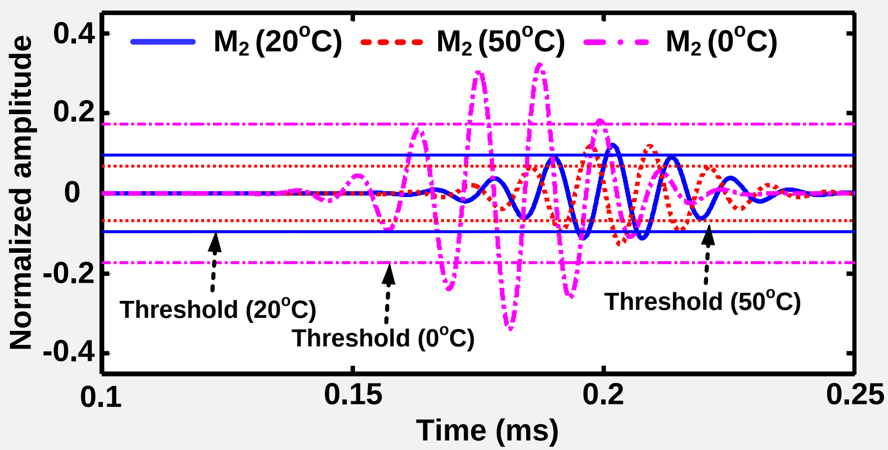
Undamage





Damage





For undamaged and damaged conditions, temperature chamber experiments are conducted at ‘20°C’, ‘50°C’ and ‘0°C’.

Summary and Conclusion

- An reference-free delamination detection technique is developed and validated using data obtained from damage states of a composite plate.
- The effectiveness of the proposed technique is demonstrated explicitly under varying temperatures.
- A fundamental Lamb wave mode (A_0 mode) was successfully extracted by the proposed mode extraction technique using a dual PZT at any desired frequency without any other special tuning.
- Further investigation will be underway to extend the proposed concept to more complex structures and other types of damage.

THANK YOU!

Do You Have Any Questions?

Back up slides

Why Do You Use the Mode Extraction Technique?

Double sided PZT installation?

- **The PZT cannot be installed on the both side of the aircraft structure.**

Frequency tuning?

- **A tuning curve is the function of the material properties of the structure so it is varied depending on the temperature of the structure.**

  Ex) At normal temperature, a specific mode is dominant but, at a different temperature, this tuned mode may not be dominant.

Question and Answer

Q1: What kinds of composite material are you use for your experiment?

A1: The material properties and prepreg lay-up information of the specimen are unknown to us. The Boeing company didn’t let us know these information.

Q2: Is your technique able to apply complex structures?

A2: Not yet. A critical problem is that complex geometries produce reflected and converted modes, making extraction of delamination reflected A0 mode challenging.

Q3: is the damage delamination or surface breaking? How did you know about that?

A3: We have scanned delamination area in our previous works so we know the proper impact energy to produce impact damage.

Q4: Is it correct the assumption of shear modulus reduction as a delamination model?

A4: In reality, when the composite plate get impact damage, the fibers are broke down and dent is made on the surface. However, we deal with the delamination as a global aspect. The testing frequency of 80khz that doesn’t have wave length enough sensitive to detect such small specific damage phenomenon.

Question and Answer

Q5: Is the S0 mode able to be fully cancelled?

A5: Depending on the experimental setup. About the mode decomposition errors, I dealt with one chapter in my paper. Briefly saying that, the size difference of dual PZT make spreading errors because outer ring and disk parts of the dual PZT are differently installed spatially extended on at the structure. However, my conclusion is this error is too small to be consideredt.

Q6: How do you decompose the A0 mode when the first arrival and boundary reflected A0 mode are overlapped?

A6: This is the constraint of the proposed technique. The A0 mode reflected from structural boundary should not be overlapped with the first arrival A0 mode and the A0 mode reflected off from delamination. However this constraint is not a big issue on the composite material because the velocity of the A0 mode in composite material is approximately half of that in metallic material. It is more flexible to install sensors.