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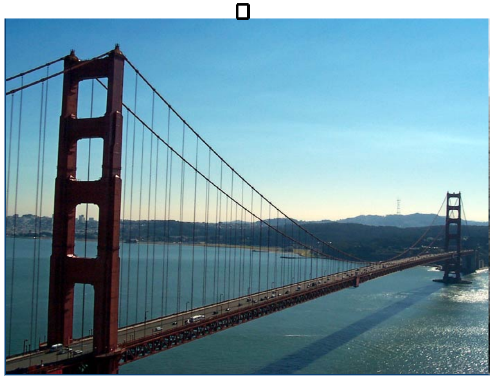
THE UNIVERSITY of ADELAIDE




14th Annual Workshop for Australian Network of Structural Health Monitoring

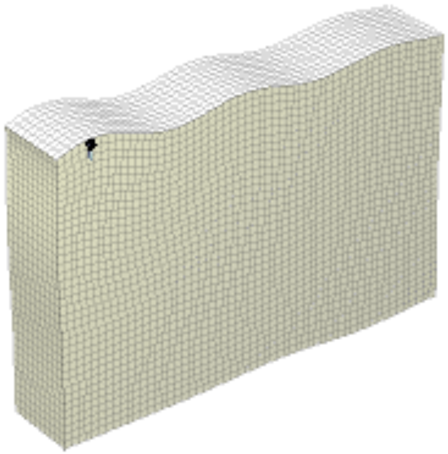
Damage Detection Using Nonlinear Ultrasonic Guided Waves

Prof. (Alex) Ching-Tai Ng

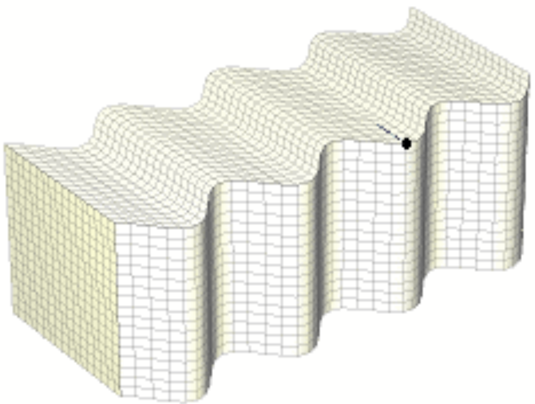
Ultrasonic Guided Waves

Ultrasonic guided waves propagate in solid media, interacting with boundaries in such a way that boundary conditions could be satisfied.

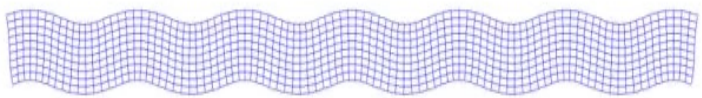
- Sensitive to small and different types of damages
- Relatively long travel distance
- Inaccessible location of structures can be inspected



Rayleigh Wave



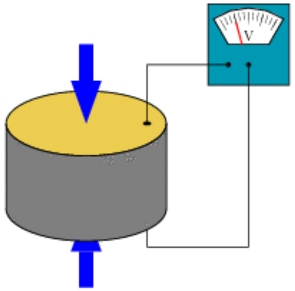
Shear Horizontal Wave



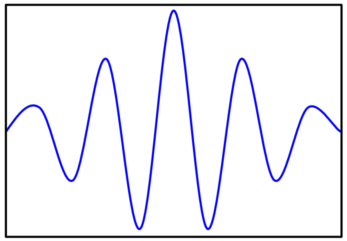
Lamb Wave

Ultrasonic Guided Waves

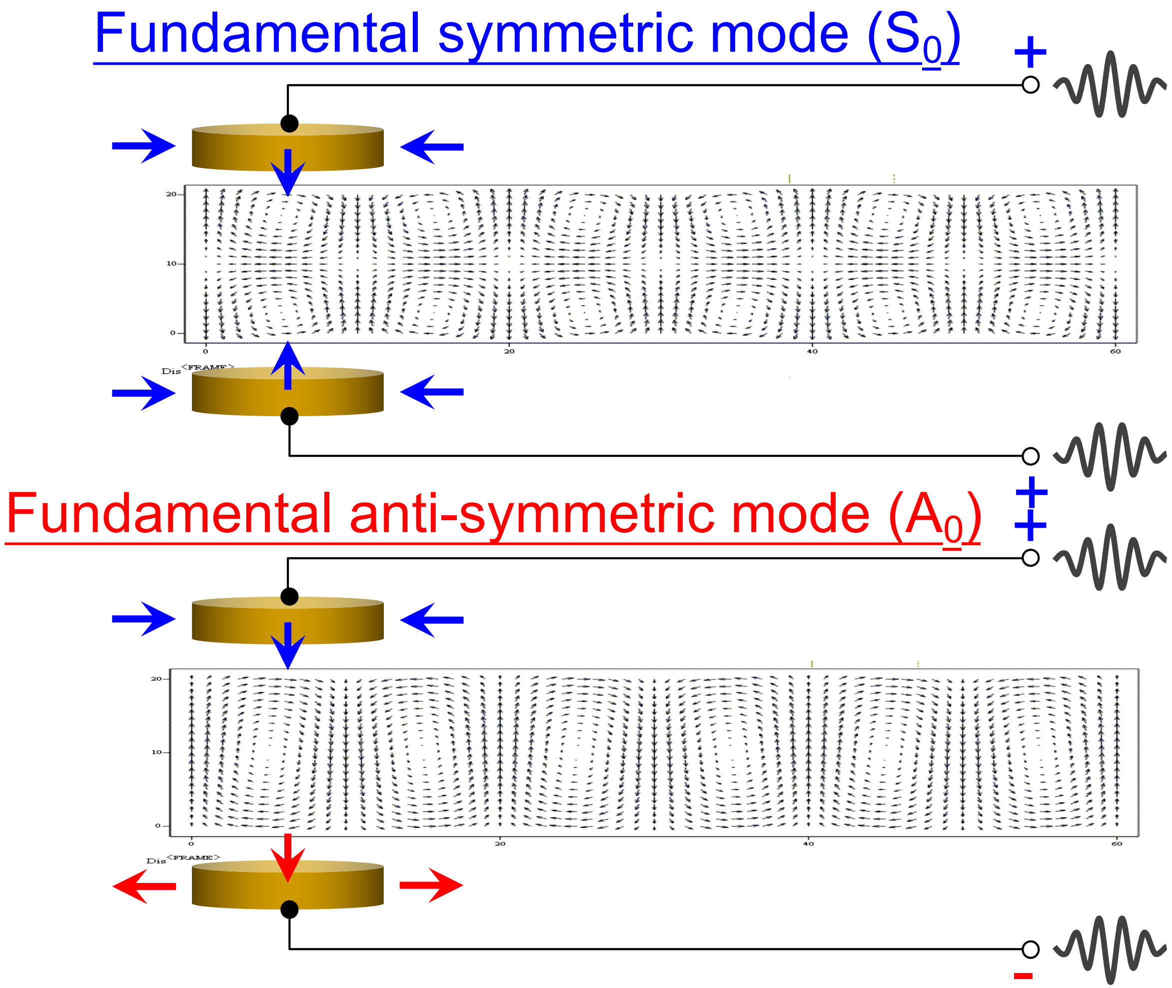
- Guided Wave Modes



Piezoceramic transducer



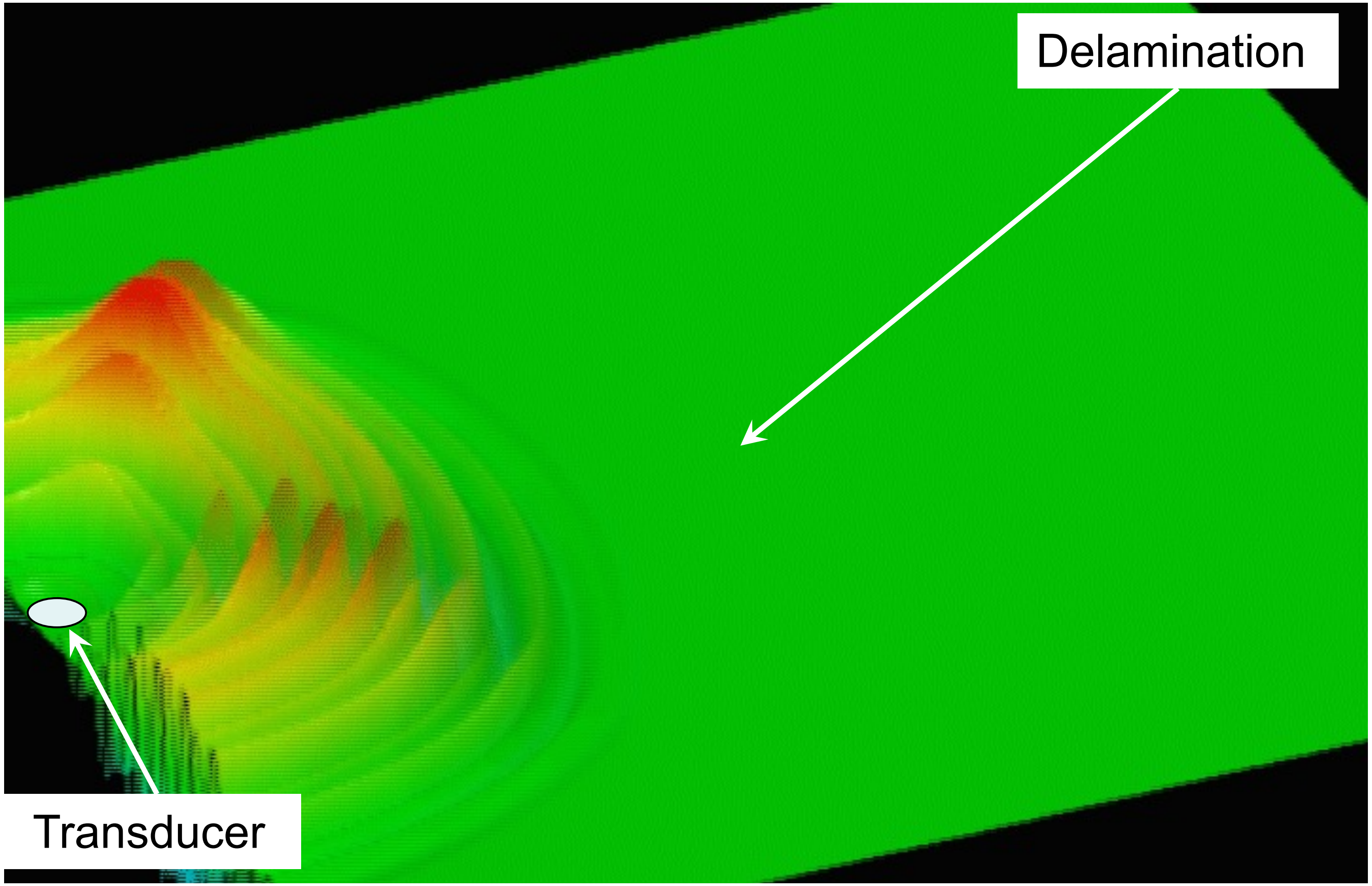
Hanning windowed sinusoidal tone burst pulse



Giurgiutiu & Bao (2004) Struct. Health. Monitor. Animation from [www.me.sc.edu/Research/lamss/]

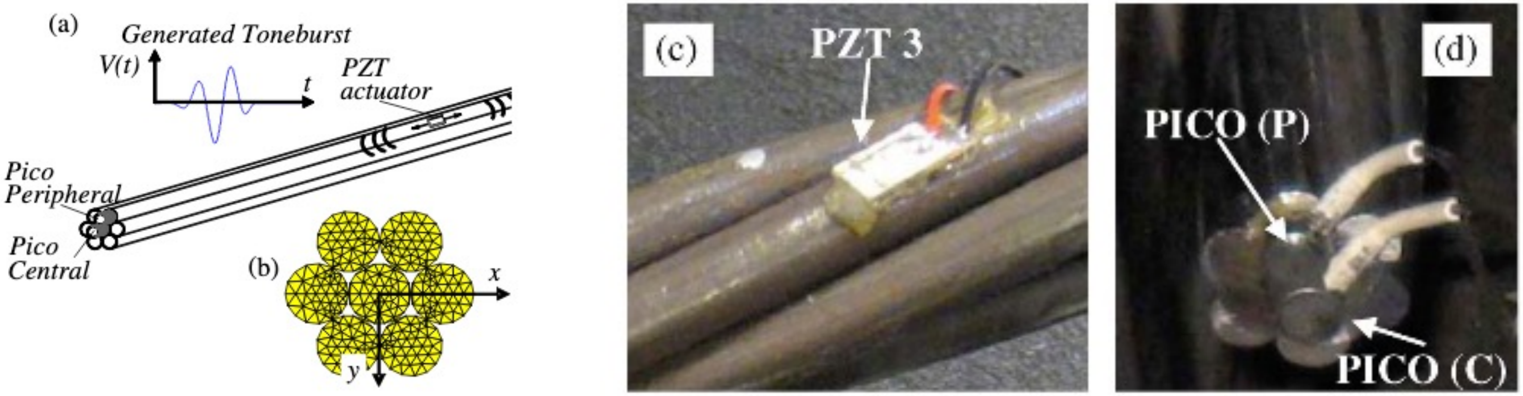
Guided Waves in Plates (Lamb Waves)

- Example of guided wave propagation and interact with damage



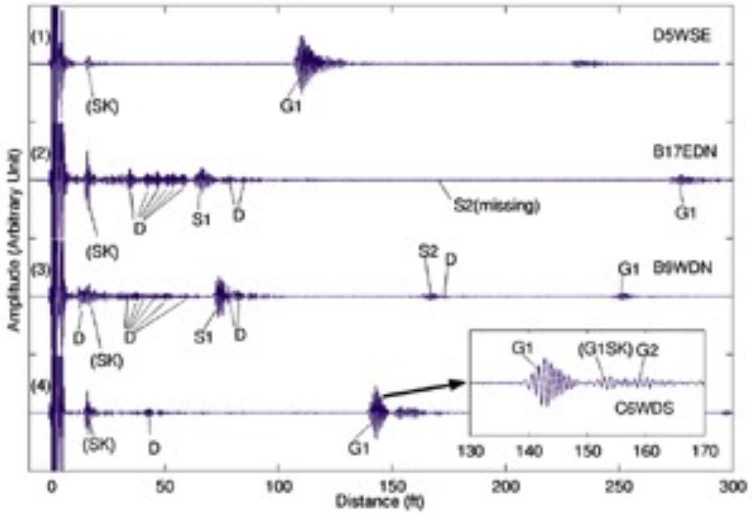
Scaled displacement contour plot

Applications of Ultrasonic Guided Waves



Determination of prestress loss in multiwire tendons

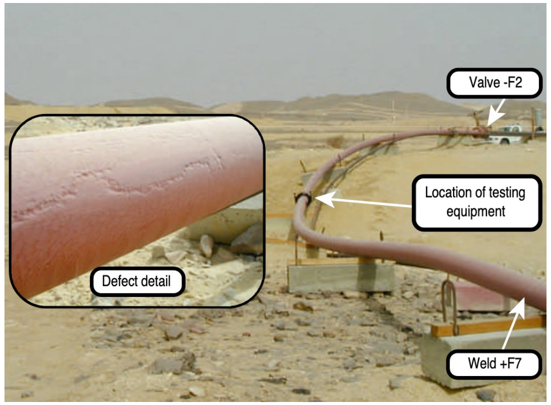
Bartoli I, Salamone S., Phillips R., Lanza di Scalea F., Sikorsky C.S. (2011). Use of interwire ultrasonic leakage to quantify loss of prestress in multiwire tendons. J. Eng. Mech. ASCE, 137(5):324-333.



Inspection of cables in suspension bridge

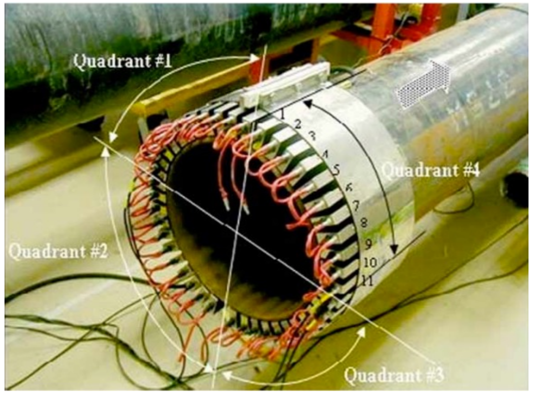
Kwun H. (2003). Waves of the future, Technology Today, Fall: 16-20.

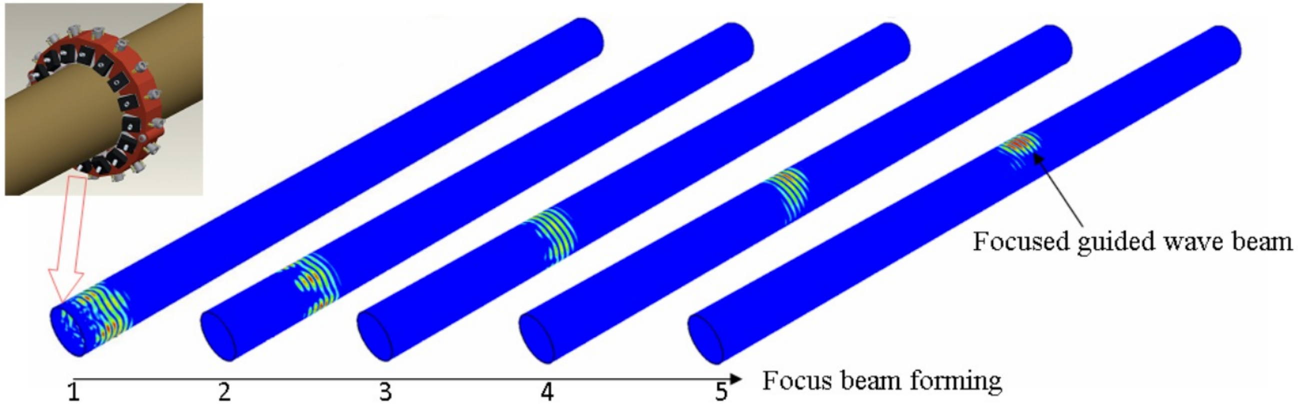
Applications of Ultrasonic Guided Waves



Long range inspection of pipe

Alleyne D.N., Pavlakovic B., Lowe M.J.S., Cawley P. (2001). Rapid, long range inspection of chemical plant pipework using guided waves. AIP Conf. Proc. 557:180-187.





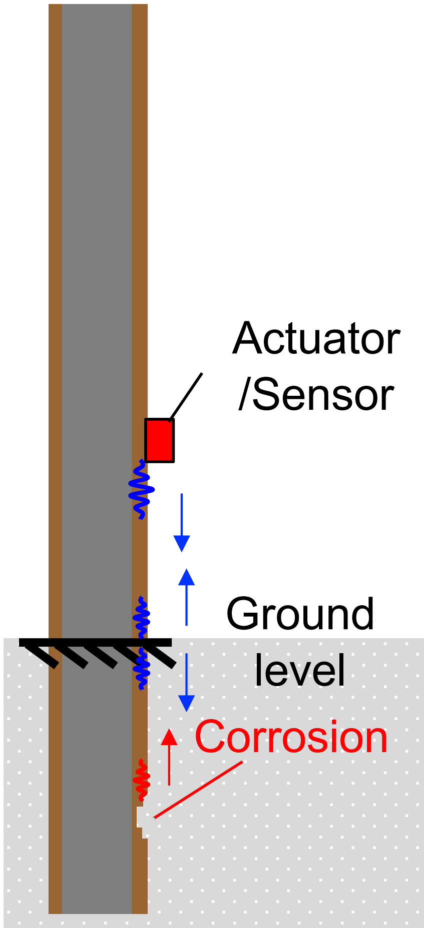
Focused guided wave inspection for pipes

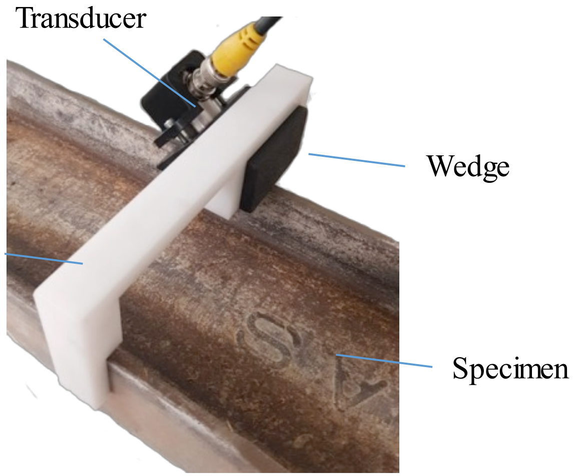
Mu J., Hua J. Rose J.L. (2010). Ultrasonic guided wave focus inspection potential of bare and coated pipes. AIP Conf. Proc. 1211:239-246.

Applications of Ultrasonic Guided Waves

Corrosion detection at inaccessible location (University of Adelaide)

There are 720,000 Stobie poles in South Australia





(SA Asset Management Plan 3.1.05 Poles 2014 to 2025 (2014))

Applications of Ultrasonic Guided Waves

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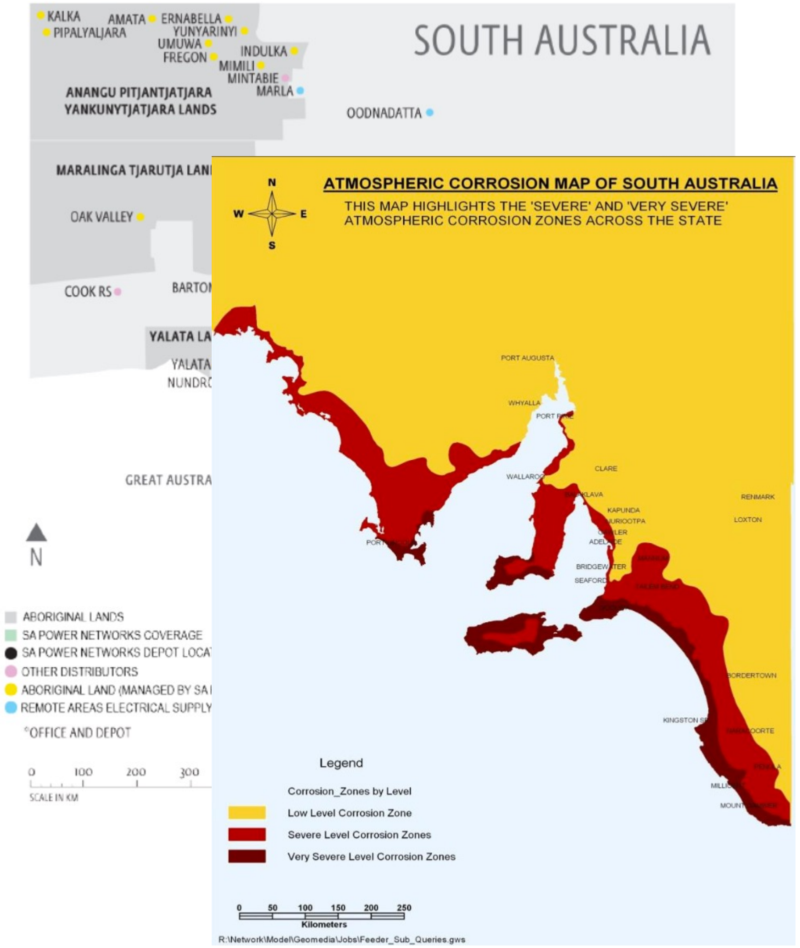
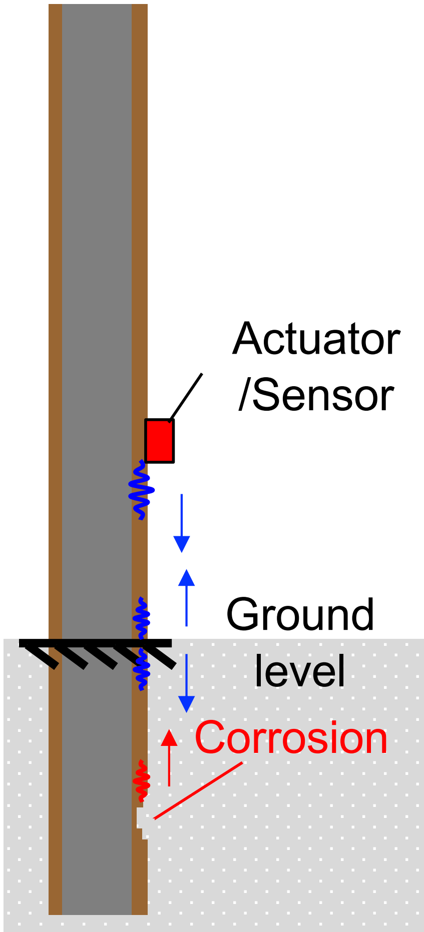
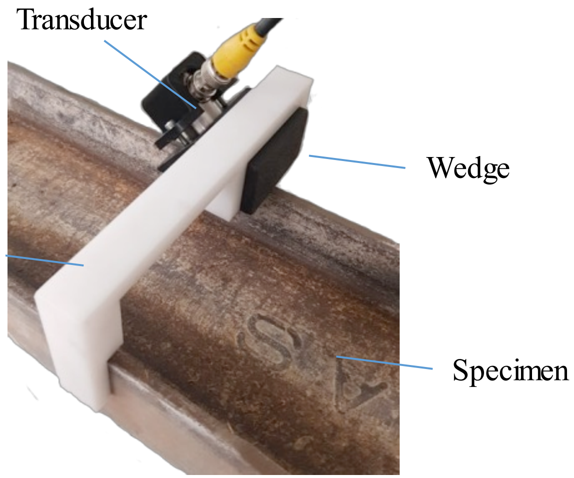
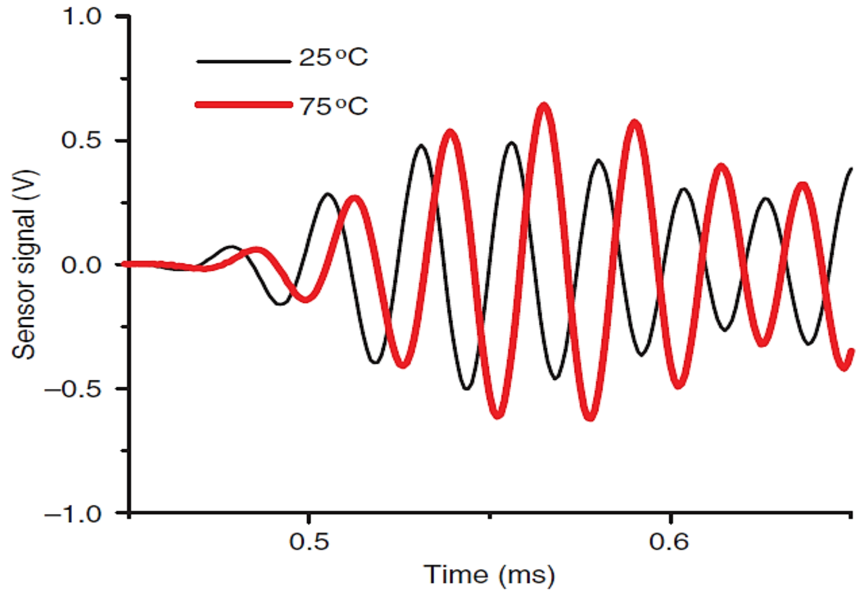






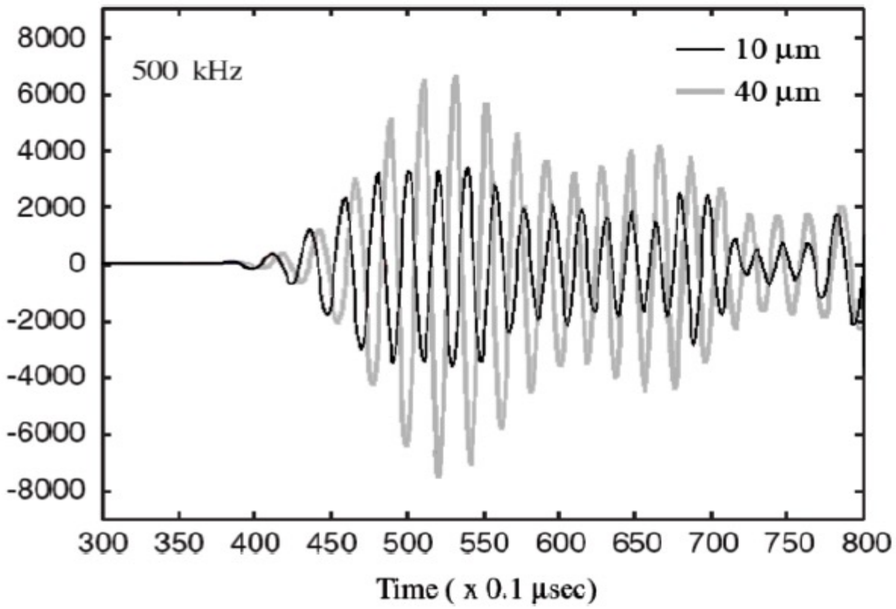
(SA Asset Management Plan 3.1.05 Poles 2014 to 2025 (2014))

Limitations of Linear Guided Wave

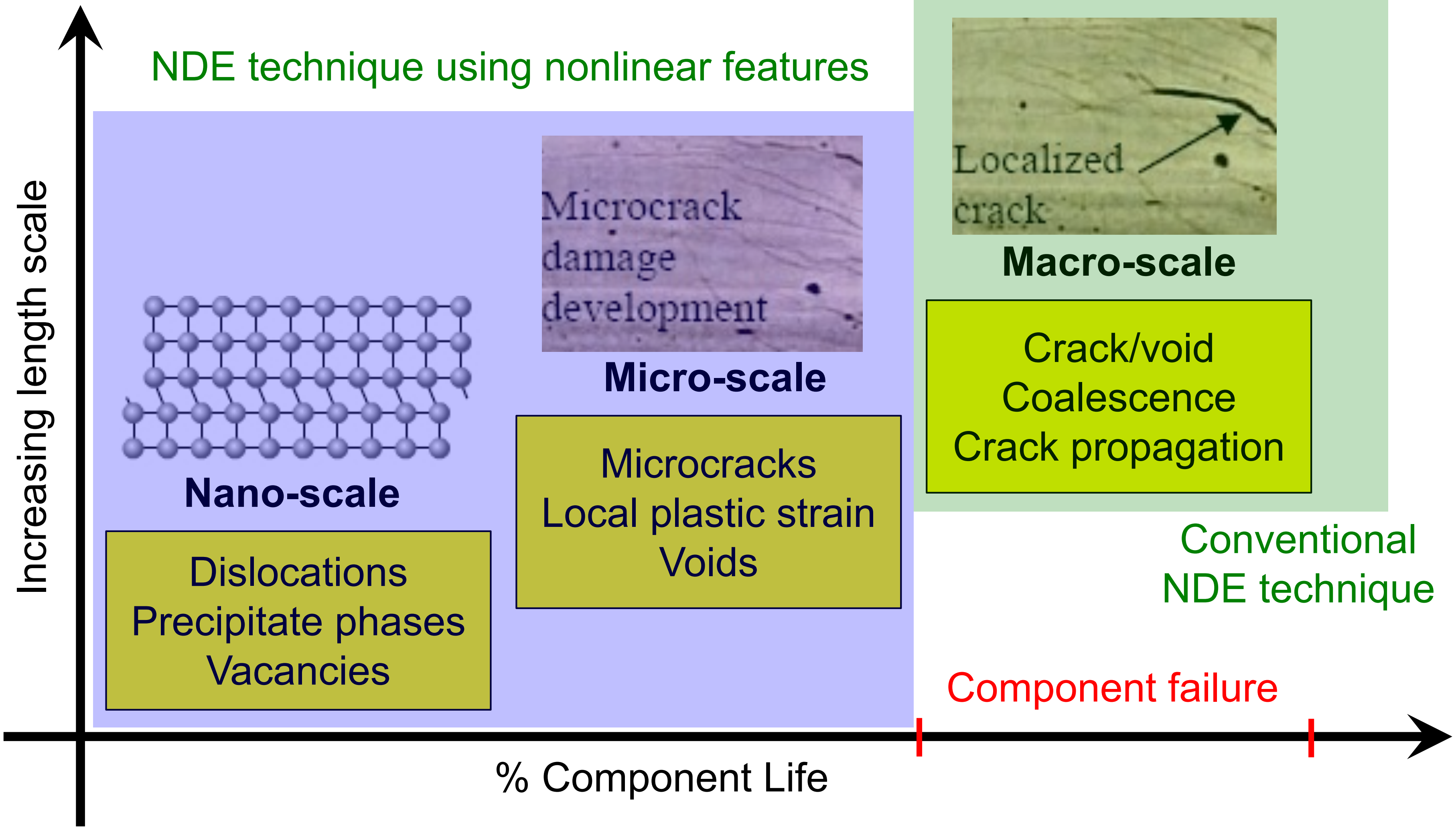


Temperature effect on PZT sensor signals at *f*=300 kHz
(Ha et al. 2010)

The effect of adhesive layer thickness change on sensor signals (for 10 μm to 40 μm)
(Ha and Chang 2010)



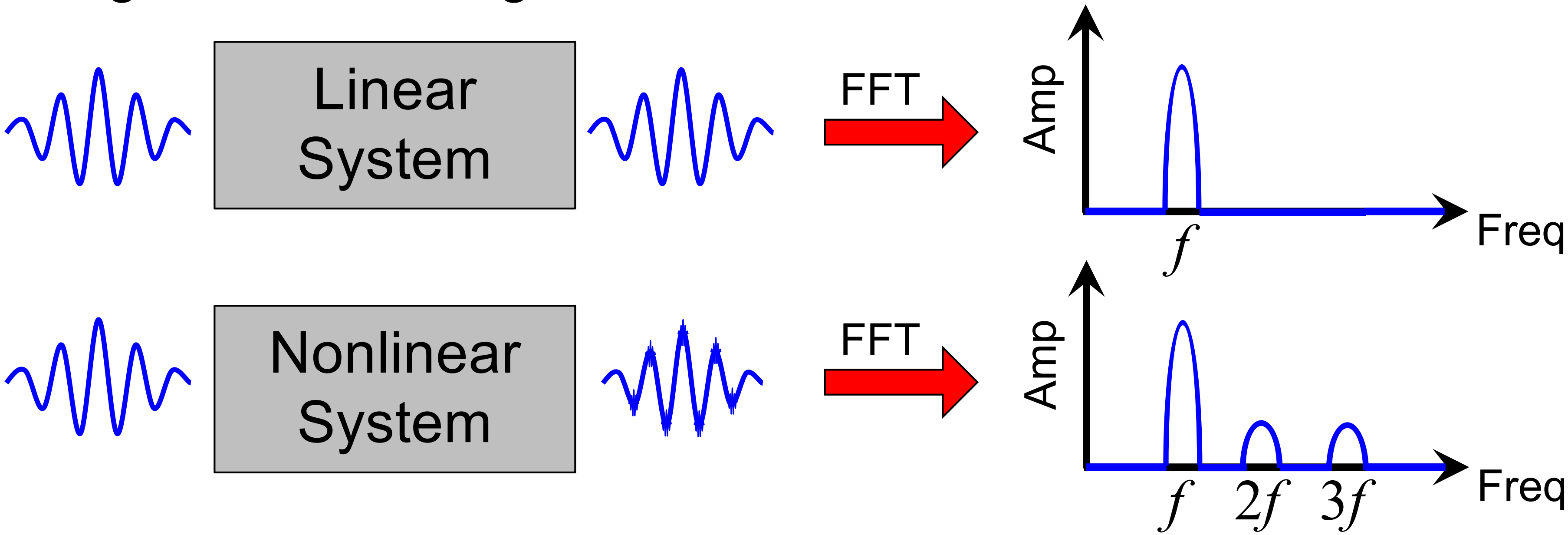
Nonlinear Guided Wave: Life of Structural Components



- **Microstructural evolution drives macroscopic damage**
- **How can we monitor features at lower length scales?**

Nonlinear Guided Wave: Higher Harmonic Generation

❖ Higher harmonic generation due to nonlinearities

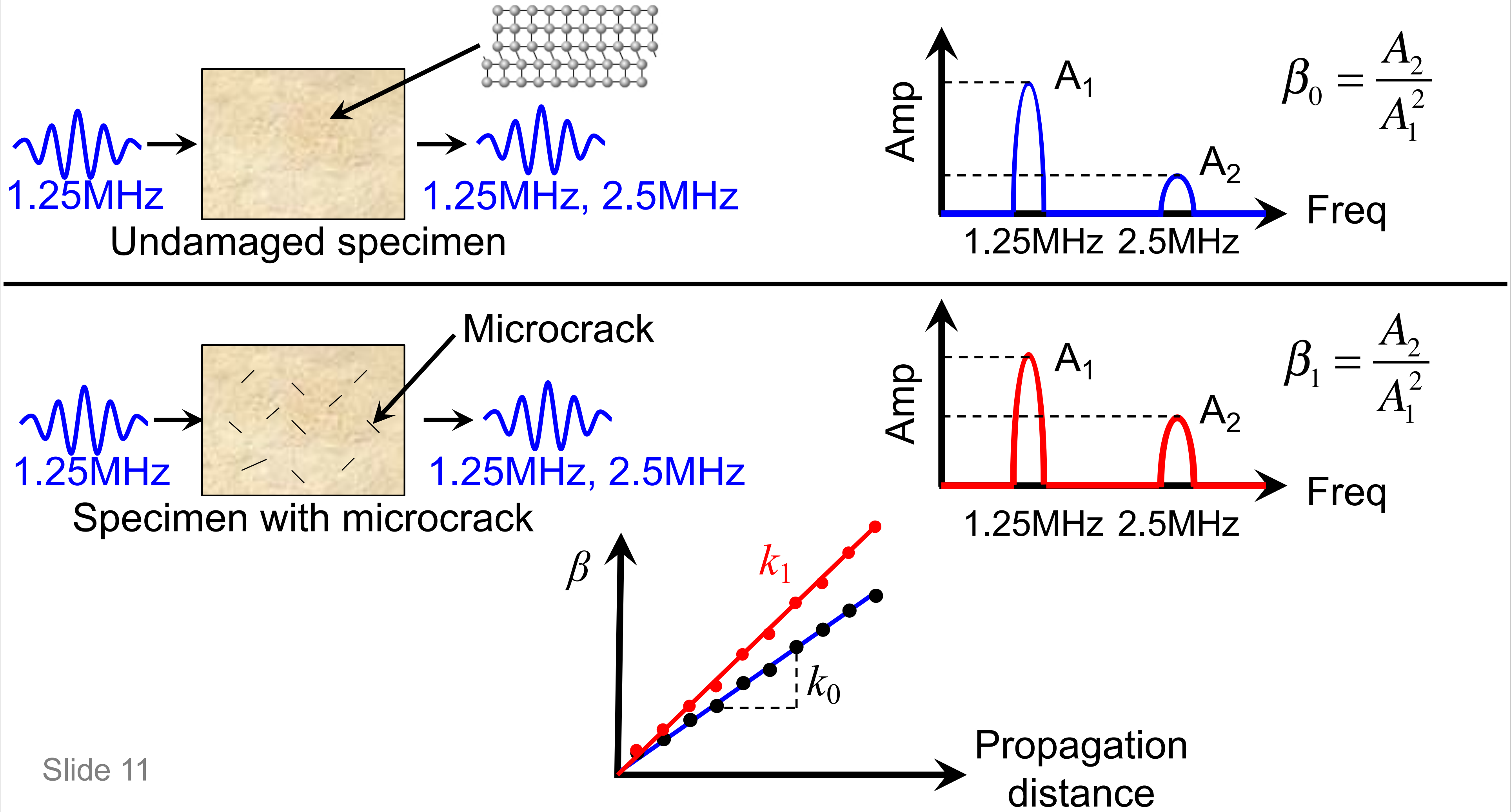


❖ Sources of nonlinearity:

- Material nonlinearity
- Contact nonlinearity
- Equipment, e.g. amplifier
- Transducer
- Structural connections

Nonlinear Guided Wave: Material Nonlinearity

- When fulfilling specific conditions, accumulative second harmonic is linearly increase with the wave propagation distance



Advantages and Challenges of Using Nonlinear Guided Waves

Advantages:

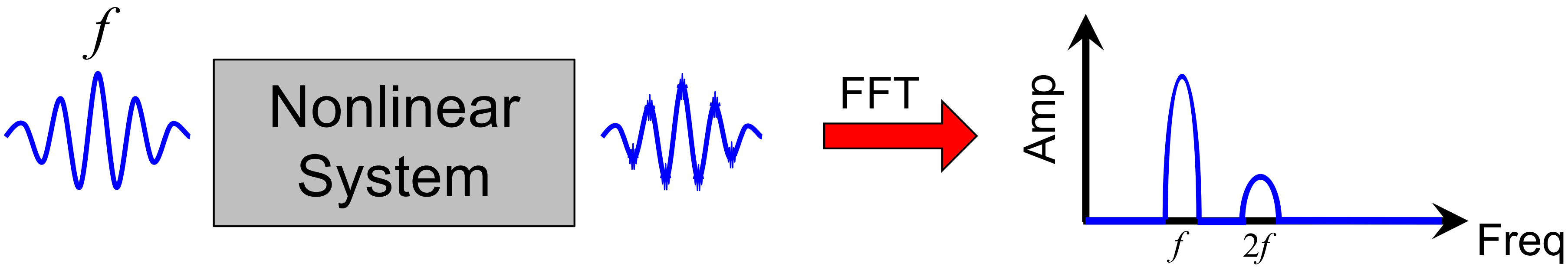
- Higher sensitivity to early-stage damage
- Potential to be a non-baseline damage detection approach

Challenges:

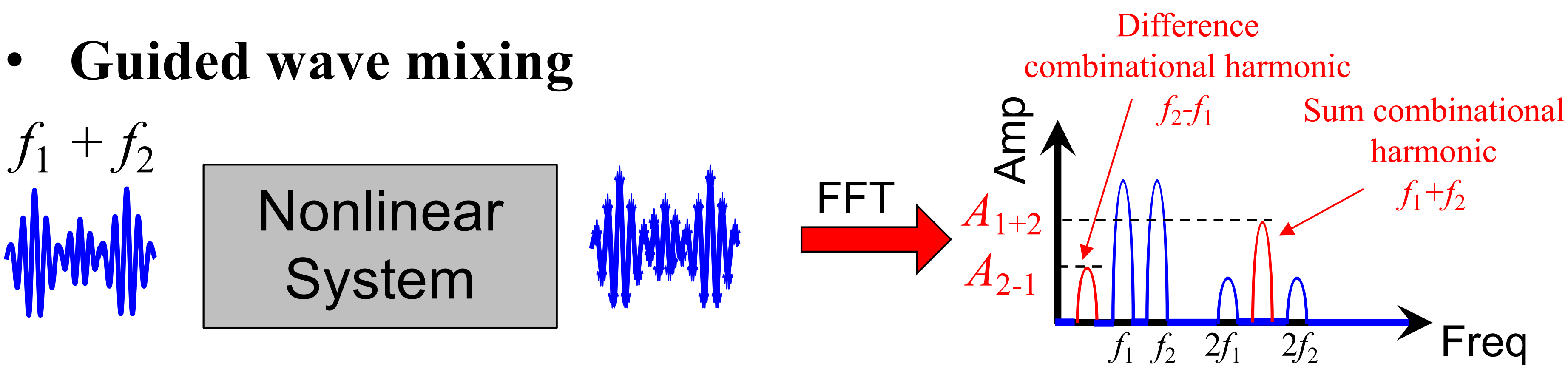
- Extraction of nonlinear features
  (1) Small magnitude of generated higher harmonic,
  (2) Damage induced vs non-damage induced nonlinearities

Ultrasonic Guided Wave Mixing

- **Single frequency nonlinear guided wave**



- **Guided wave mixing**



$$\beta_{Sum} = \frac{A_{1+2}}{A_1 A_2} \qquad \beta_{diff} = \frac{A_{2-1}}{A_1 A_2}$$

Phase Reversal Approach

Nonlinear wave equation:

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} + c^2 \beta \frac{\partial u}{\partial x} \frac{\partial^2 u}{\partial x^2}$$

Solution of the nonlinear wave equation:

$$u\,(x,t) = u_a{}^{(1)} + u_a{}^{(2)} + u_b{}^{(1)} + u_b{}^{(2)}$$

Final solution of displacement field:

Linear wave components

Nonlinear wave components

$$u\,(\tau)^{(0°)} = A_a \, sin(\omega_a \tau) + A_b \, sin(\omega_b \tau) - \frac{\beta x}{8c^2} \{A_a{}^2 \omega_a{}^2 \, cos2(\omega_a \tau) + A_b{}^2 \omega_b{}^2 \, cos2(\omega_b \tau) + 4A_a A_b \omega_a \omega_b [cos(\omega_a \tau) \, cos(\omega_b \tau)]\}$$

Phase reversed displacement field:

$$u\,(\tau)^{(180°)} = A_a \, sin(\omega_a \tau + \pi) + A_b \, sin(\omega_b \tau + \pi) - \frac{\beta x}{8c^2} \{A_a{}^2 \omega_a{}^2 \, cos2(\omega_a \tau + \pi) + A_b{}^2 \omega_b{}^2 \, cos2(\omega_b \tau + \pi) + 4A_a A_b \omega_a \omega_b [cos(\omega_a \tau + \pi) \, cos(\omega_b \tau + \pi)]\}$$

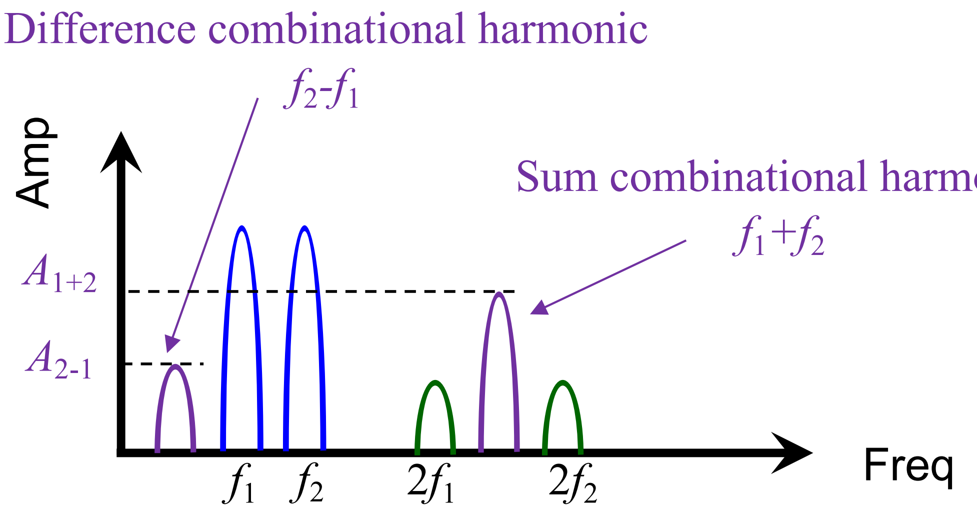
Phase Reversal Approach for Extracting Higher Harmonic

Superposition of original and phase reversed displacement field:

$$u\,(x,t)^{(0°+180°)} = -\frac{\beta x}{8c^2}\{2A_a{}^2\omega_a{}^2\cos 2(k_a x - \omega_a t) + 2A_b{}^2\omega_b{}^2\cos 2(k_b x - \omega_b t)$$
$$+4A_a A_b \omega_a \omega_b \cos[(k_a + k_b)x - (\omega_a + \omega_b)t]$$
$$+4A_a A_b \omega_a \omega_b \cos\,[(k_b - k_a)x - (\omega_b - \omega_a)t]\}$$

Second harmonics

Sum and difference combination harmonics



$$\beta_{Sum} = \frac{A_{1+2}}{A_1 A_2}$$

$$\beta_{diff} = \frac{A_{2-1}}{A_1 A_2}$$

Experimental Studies

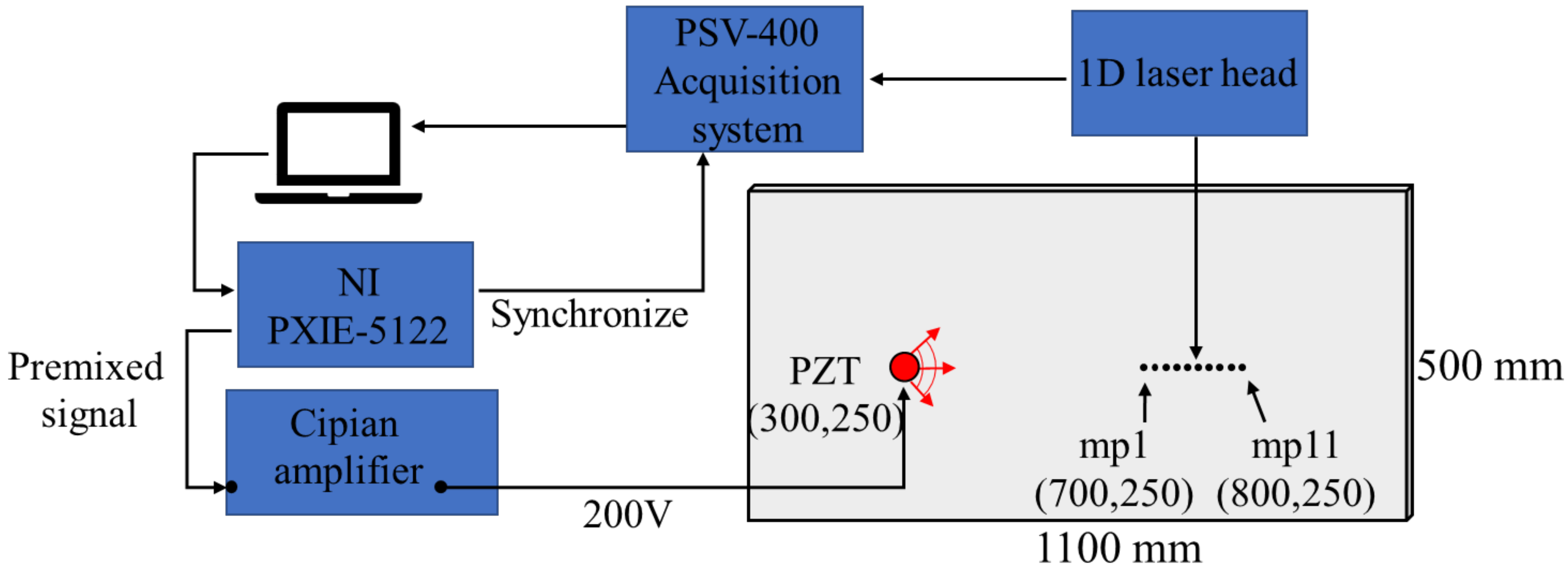
Specimen: 6061-T651 aluminium plate (1100mm x 500mm x 1.6mm)

Guided wave mode: Fundamental symmetric mode (S_0)

Actuator: Piezoelectric transducer, 10mm diameter, 0.5mm thick

Excitation signal: pre-mixing tone-burst pulse, the signal is amplified to 160V (peak-to-peak voltage)

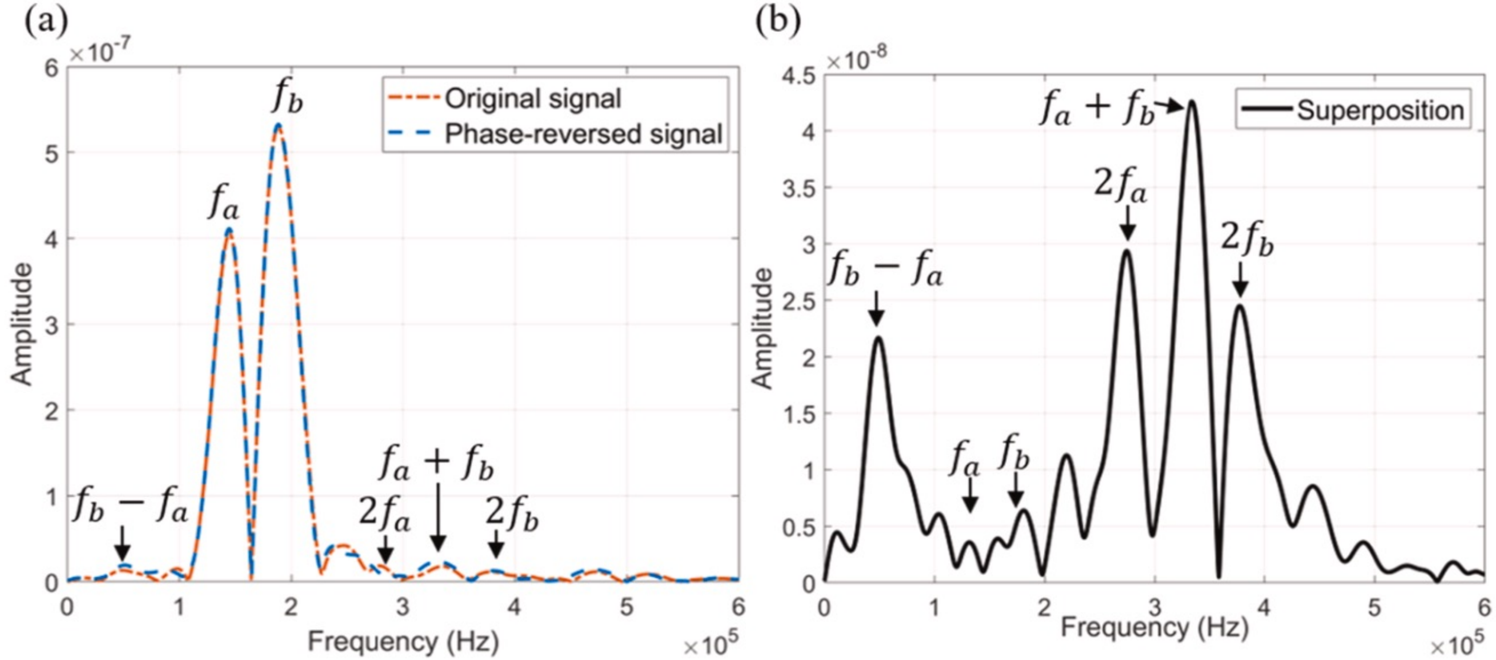
Sensing: 1D scanning laser vibrometer, 400mm from excitation, 10 measurement points with interval 10mm



Experimental Studies

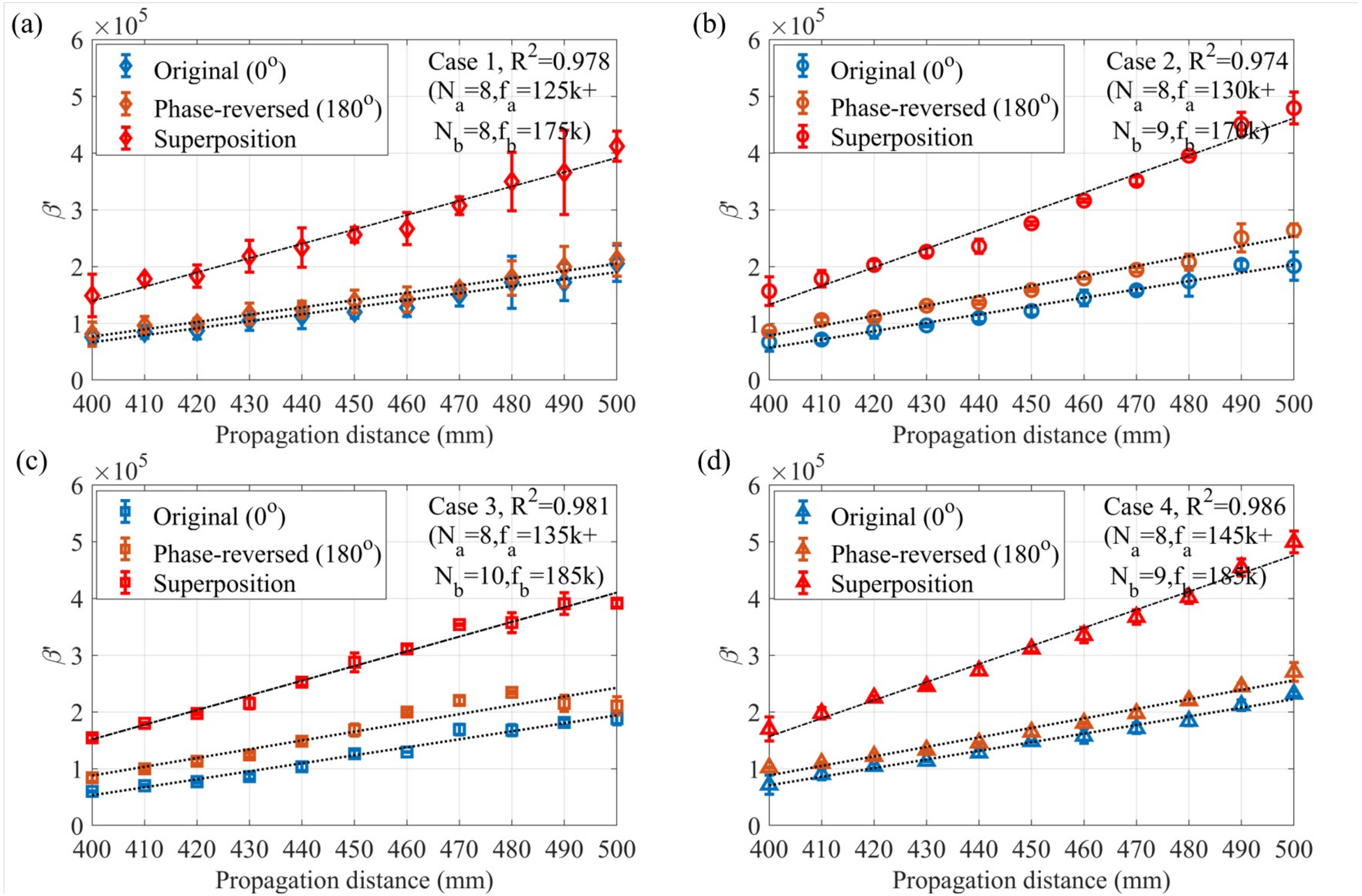
Different cases of wave mixing frequency pairs with varying excitation frequencies.

Case	Fundamental frequency (f_a)	Number of cycles (N_a)	Fundamental frequency (f_b)	Number of cycles (N_b)
1	125 kHz	8 cycles	175 kHz	8 cycles
2	130 kHz	8 cycles	170 kHz	9 cycles
3	135 kHz	8 cycles	185 kHz	10 cycles
4	145 kHz	8 cycles	185 kHz	9 cycles



Measured signal in the frequency domain of Case 4: a) original and phase reversed signal, and b) signal obtained after phase reversal

Experimental Studies



Relative nonlinear parameters of sum combinational harmonic due to weak material nonlinearity, a) Case 1, b) Case 2, c) Case 3, and d) Case 4

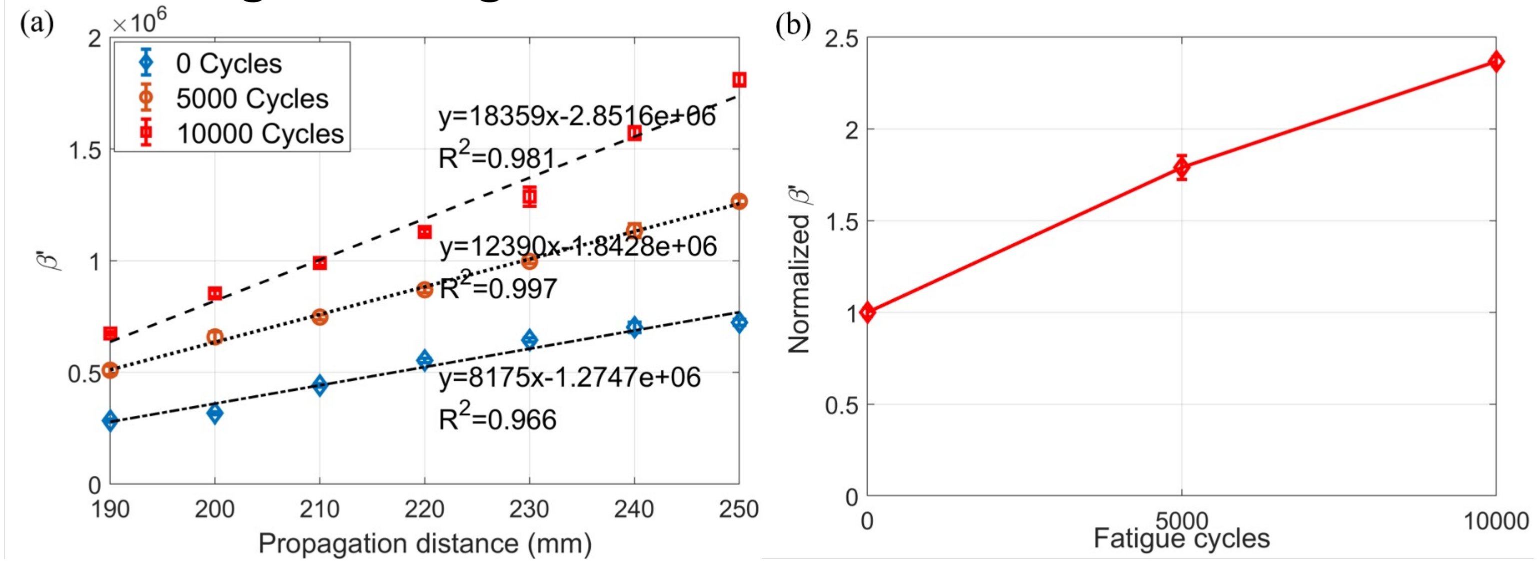
Experimental Studies

Progressive fatigue damage

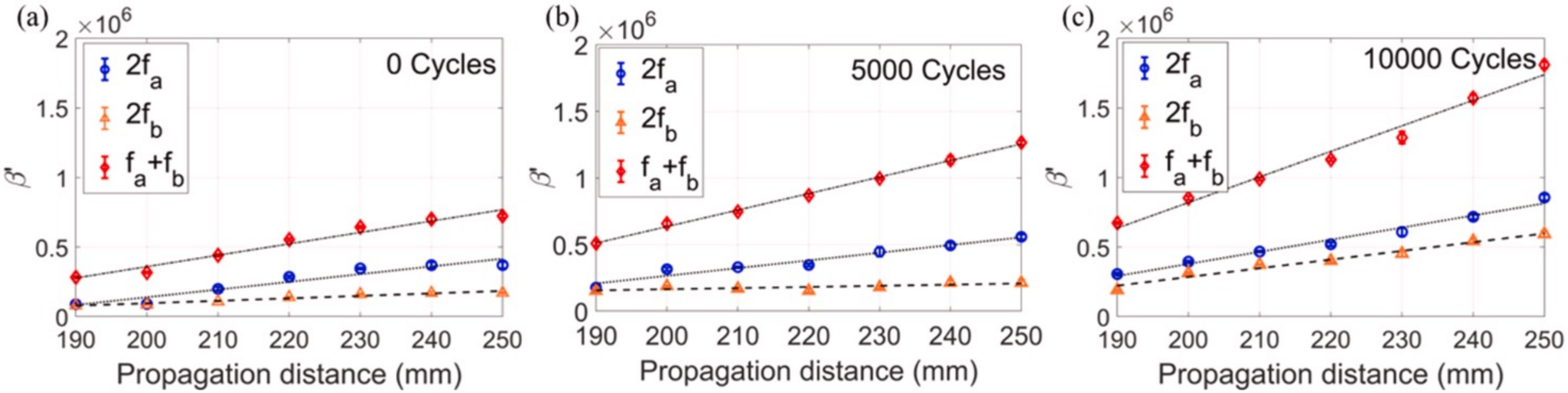
- Cyclic tensile loading
  - INSTRON 1242
  - Low cycle fatigue
  - Max. tensile loading = 90 kN (1.5Hz)
- Guided wave testing at:
  - 0 cycles
  - 5000 cycles
  - 10000 cycles
- Specimen fails at 12,417 cycles
  - Failure occurs in the bolting region (stress concentration)

Experimental Studies

Progressive fatigue damage



Relative nonlinear parameters of sum combinational harmonic at different fatigue cycles



Combination harmonic vs second harmonic at different fatigue cycles

Conclusions

- A guided wave mixing approach is demonstrated to provide early detection of fatigue damage
- The phase reversal approach is used to enhance the extraction of the nonlinear guided wave information
- Experimental results show that the combinational harmonics:
  - can be extracted robustly,
  - is sensitive to the early stage of fatigue damage,
  - can be used to monitor the fatigue damage, and
  - is more sensitive than second harmonic.

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Thank You

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