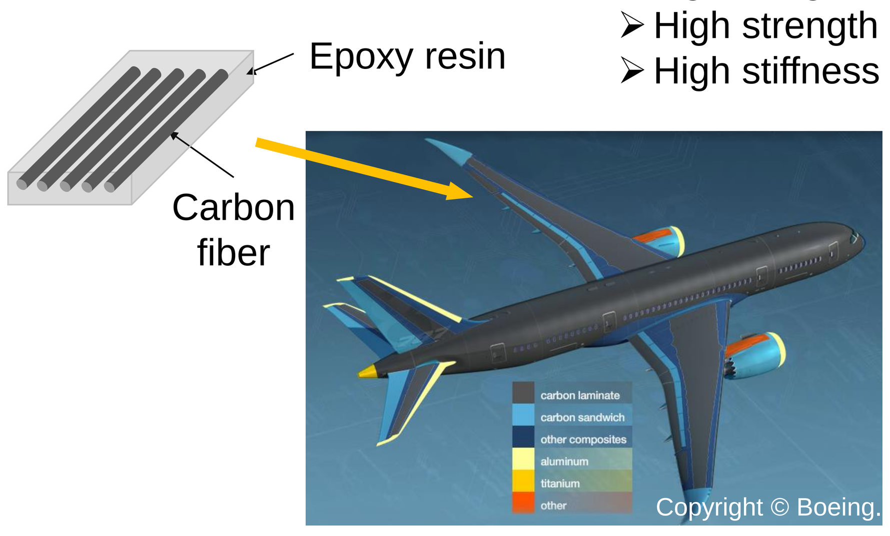
An Analysis on Laser Ultrasonics for Non-destructive Inspection of CFRP

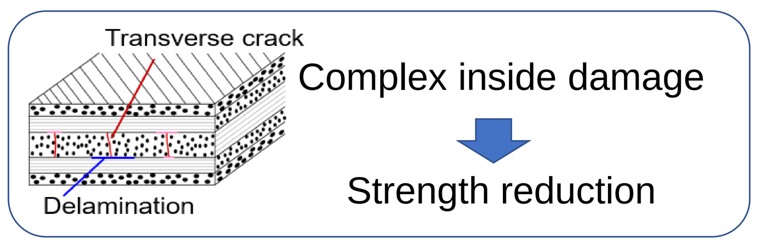
Introduction

Carbon fiber reinforced plastic (CFRP) composites have been used in airplanes to reduce the weight. Since the inside damage caused by impact loads may reduce the strength, non-destructive inspection must be conducted. The laser ultrasonics is an effective inspection method, because it can be applied to curved surfaces. To improve the accuracy of the inspection, we analyze the generation mechanism and propagation behavior of the laser ultrasonic waves.

CFRP

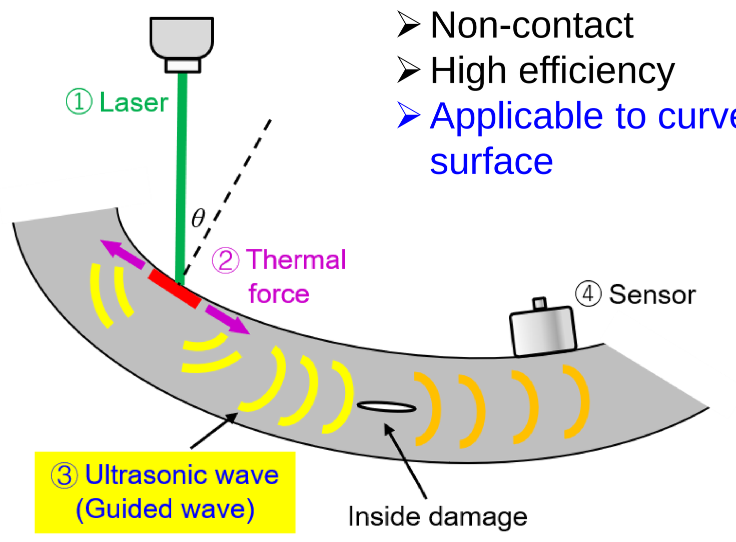
- Light weight
- High strength
- High stiffness





Laser Ultrasonics

- Non-contact
- High efficiency
- Applicable to curved surface



Laser injection → Ultrasonic wave generation

Inside damage → Change in the ultrasonic wave propagation

Calculation Method

Generation mechanism

Laser Absorption
↓
Temperature Rising
↓
Thermal Expansion
↓
Generation of Ultrasonic Waves

Governing Equations

Heat conduction equation :

$$\rho C \frac{\partial T}{\partial t} = k_{ij}\partial_i \partial_j T + q$$

Absorbed Energy (q)

→ Calculation of temperature

Wave equation :

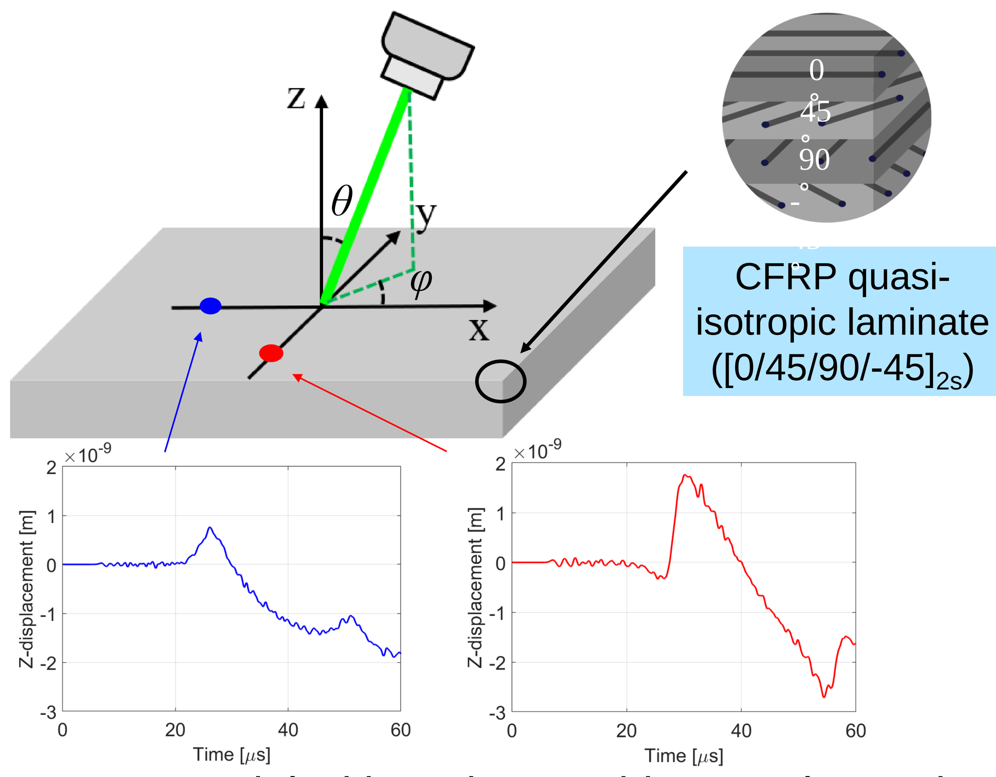
$$\rho \frac{\partial^2 u_i}{\partial t^2} = C_{ijkl} \frac{\partial}{\partial x_j}\frac{\partial}{\partial x_k} u_l - C_{ijkl}\alpha_{kl}\frac{\partial T}{\partial x_j}$$

Thermal Force

→ Generation and propagation of ultrasonic waves

FEM analysis

ComWAVE (ITOCHU Techno-Solutions Corp.)



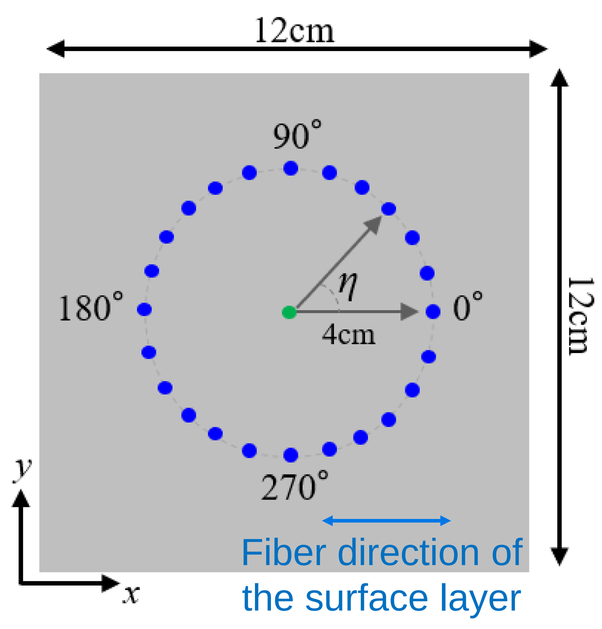
A FEM Model with Various Incident Angles and Directions of Laser Beam for a CFRP Plate

Parameters

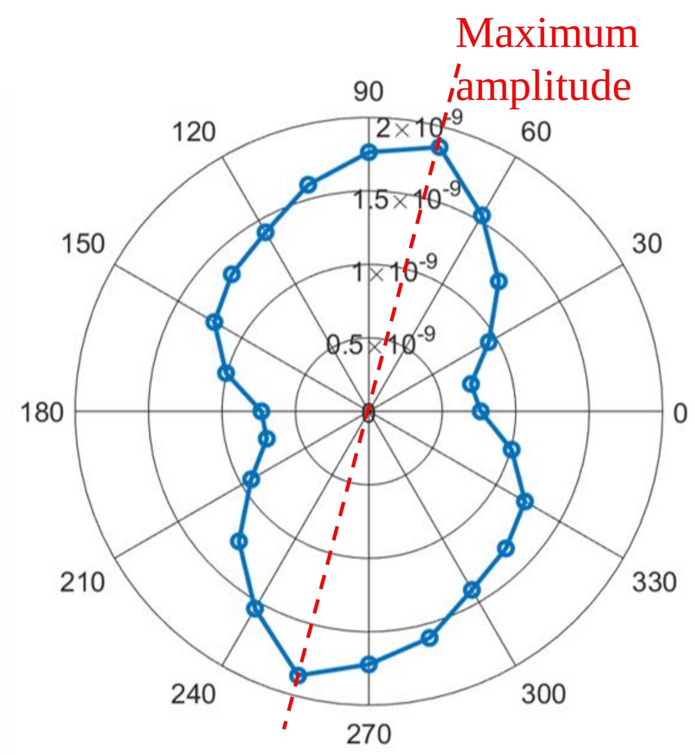
Laser Parameters	
Radius of laser beam	2.0 [mm]
Time duration	8.5 [ns]
Absorbed laser energy	6.0 [mJ]
CFRP Elastic Parameters	
Density (ρ)	1530 [Kg/m^3]
C_{11}	133.1 [GPa]
C_{12} C_{13}	4.98 [GPa]
C_{23}	5.34 [GPa]
C_{22} C_{33}	10.7 [GPa]
C_{44}	2.7 [GPa]
C_{55} C_{66}	4.8 [GPa]
CFRP Thermal Parameters	
Specific heat (C)	923 [J/Kg/K]
Thermal conductivity (K_1)	60 [W/m/K]
Thermal conductivity (K_2, K_3)	0.591 [W/m/K]
Expansion ratio (α_1)	0.48e-6 [1/K]
Expansion ratio (α_2, α_3)	40.4e-6 [1/K]

Simulation Results

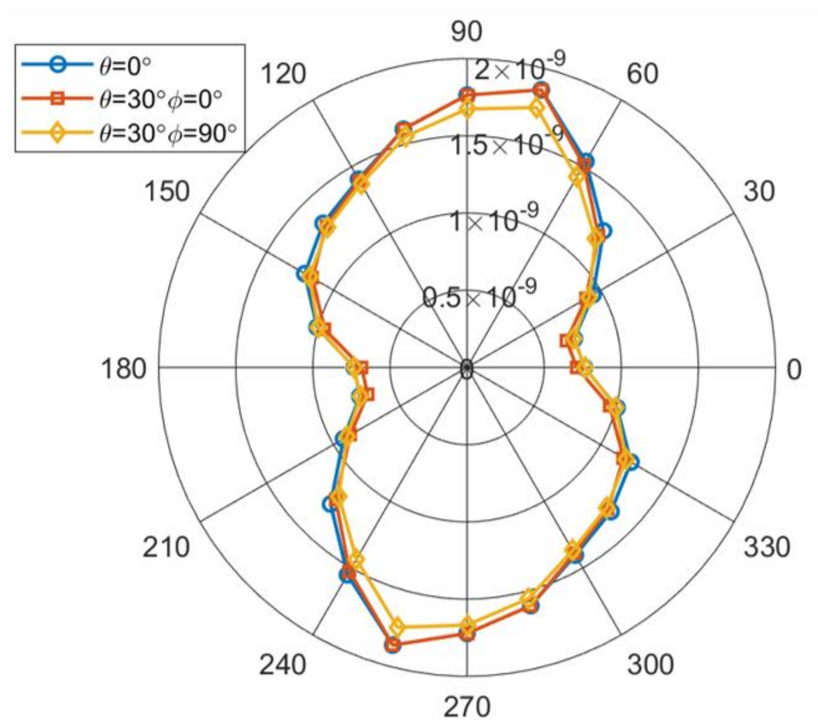
Directive Pattern
(Analysis of out-of-plane displacement)



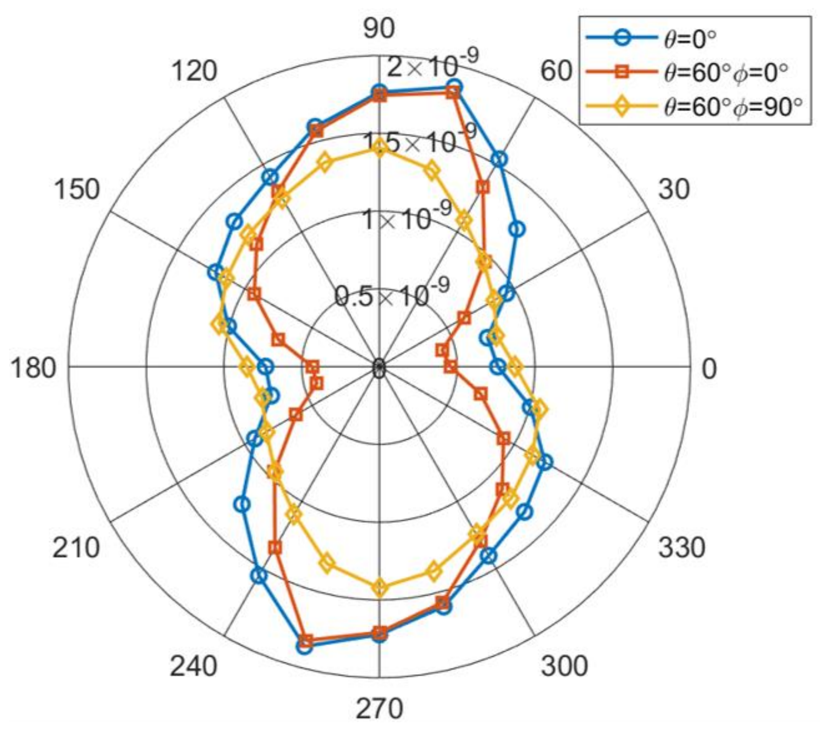
Vertical Incidence : $\theta = 0^\circ$



Oblique Incidence: $\theta = 30^\circ$



Oblique Incidence: $\theta = 60^\circ$

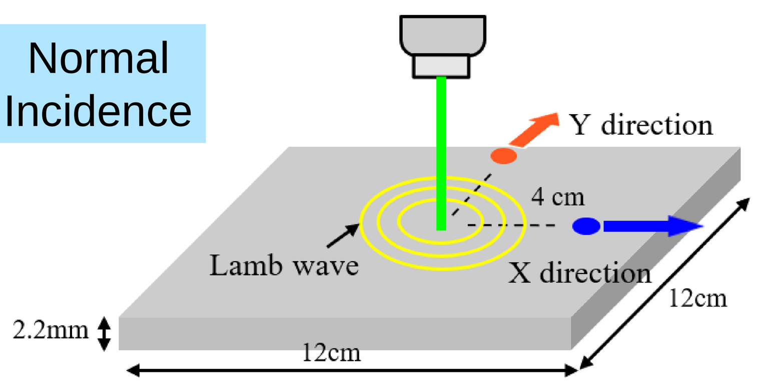


The maximum amplitudes at observation points around the laser injection point are shown in a polar diagram.

The directivity of amplitude is obvious in CFRP due to the anisotropic properties. A slight inclination (θ = 30°) of the laser beam does not influence the directivity, but in the case of the large incident angle (θ = 60°) the directivity pattern depends on the incident directions (φ).

Generated Lamb Wave Modes
(Analysis of in-plane displacement)

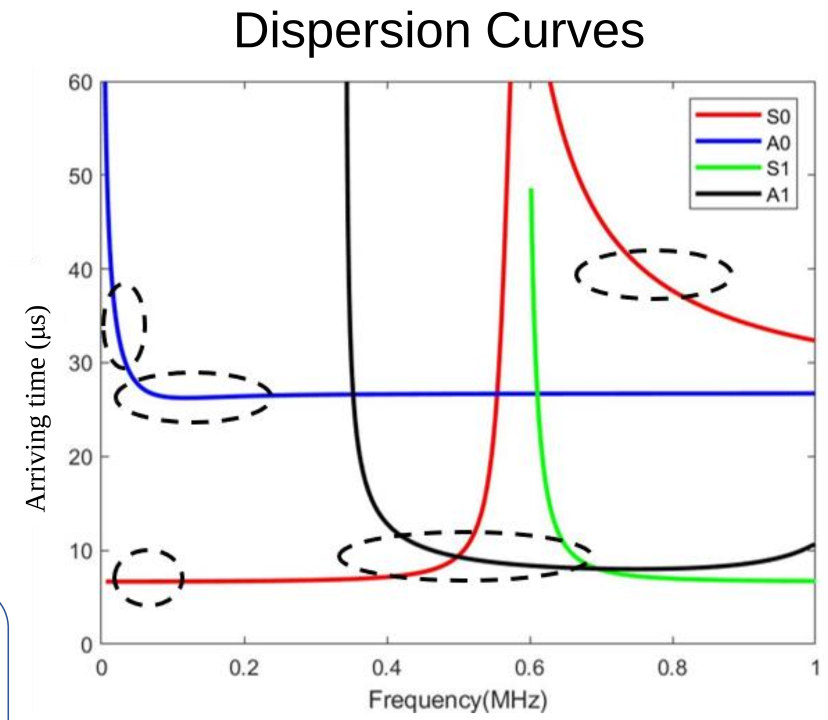
Normal Incidence



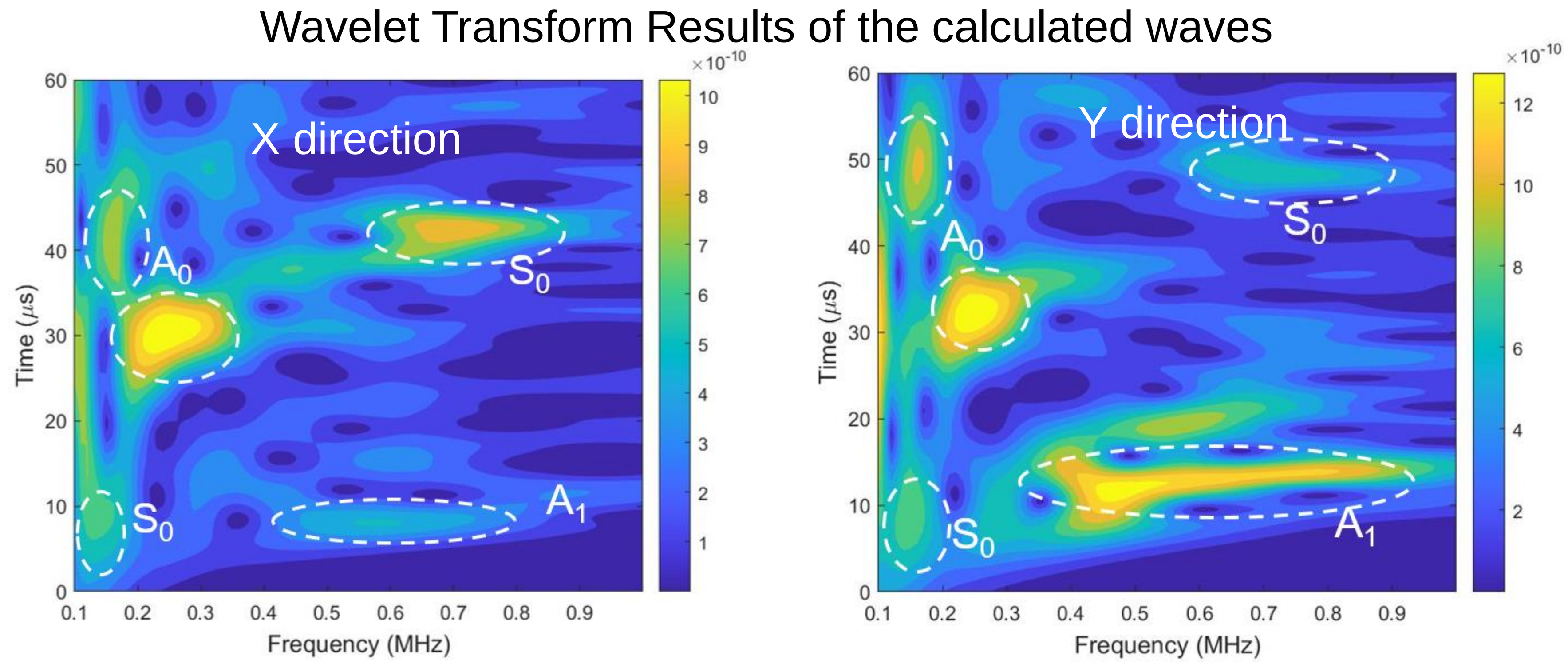
Lamb wave

- Multiple modes
  There are symmetric modes (S_0, S_1…) and antisymmetric modes (A_0, A_1…).
- Velocity dispersion
  The velocity of the wave depends on the frequency.

Dispersion Curves



Wavelet Transform Results of the calculated waves



By comparing between dispersion curves and wavelet transform results, we found that the modes S_0, A_1 and A_0 arrive in sequence with different amplitudes. Waves along x axis have strong S_0 mode and weak A_1 mode while waves along y axis have strong A_1 mode and weak S_0 mode.

Summary

In this research, we have analyzed ultrasonic waves generated in an anisotropic CFRP by laser incidence with various angles and directions. We found that the excited waves have obvious directivity in displacement and the generated modes of Lamb waves are different depending on the propagation direction.

If we would like to receive strong signals, it is preferable that the propagation path is selected to be perpendicular to the carbon fiber direction of the surface layer in CFRP laminates. If we would like to use specific modes during a laser ultrasonic inspection, it is worth noting that the amplitude balance of generated modes in CFRP changes depending on the propagation direction.