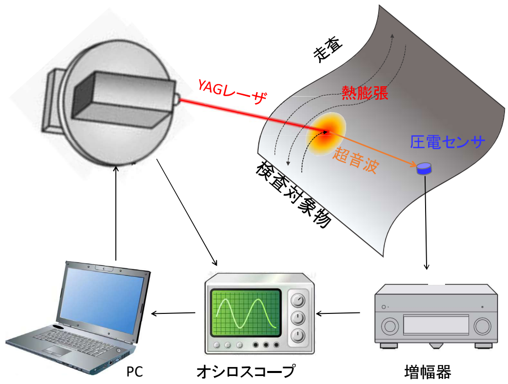
レーザ超音波可視化技術の複合材への適用

レーザ超音波

レーザ照射による超音波の励起
- アブレーション・モード（蒸発反力）
- サーマル・モード（熱膨張） ← 非破壊検査に利用可

レーザ超音波による非破壊検査

検査対象物にレーザ照射
⇩
熱膨張により超音波発生
⇩
検査対象物内を超音波が伝播
⇩
圧電センサで受信

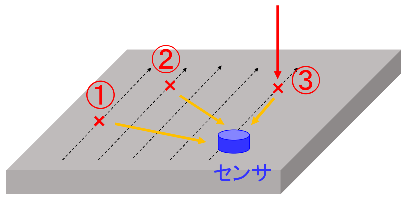


レーザを走査しながら、データを蓄積

欠陥があれば超音波の挙動が変化する

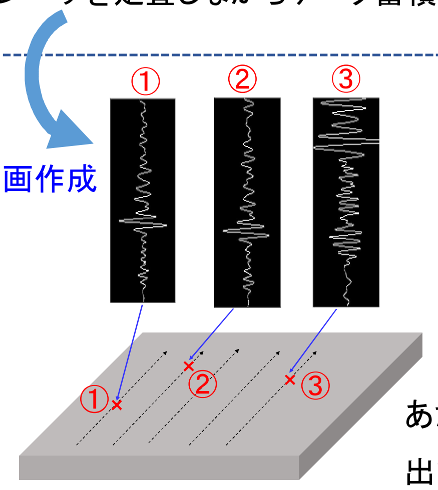
特徴
- 装置が小型
  ⇒狭隘部に持ち込み可
- 曲面に対応可
  ⇒複雑形状の検査可
- 低コスト

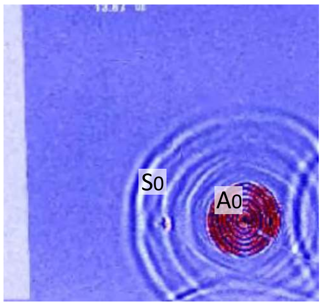
超音波可視化の方法



レーザを走査しながらデータ蓄積

動画作成





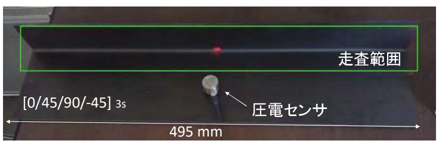
あたかもセンサーから波が出ているように見える

LUVI

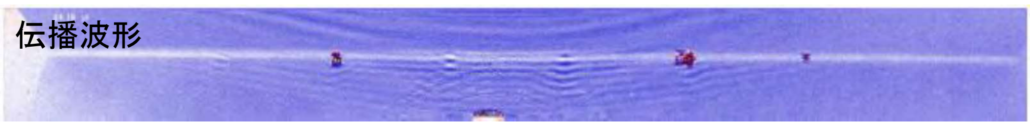
LUVI-CP1 （つくばテクノロジー社製）

最大出力パワー	0.65 μJ
レーザ波長	1064 nm
パルス幅	2 nsec
ビーム径	~0.5 mm
走査速さの最大値	5000 Hz
検査体までの距離	0.1～4m

可視化による欠陥検出



R部に人工欠陥として
テフロンシートを埋設



超音波の挙動変化により欠陥の検出が可能

実機適用までの課題

- レーザ波長の最適化
- 欠陥検出可能性の確認
- 欠陥検出の定量化

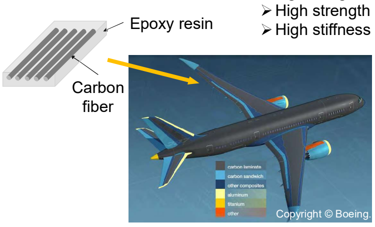
An Analysis on Laser Ultrasonics for Non-destructive Inspection of CFRP

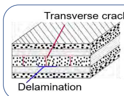
Introduction

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



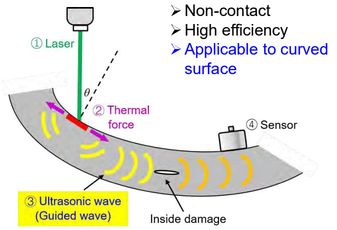


Complex inside damage

Strength reduction

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 :

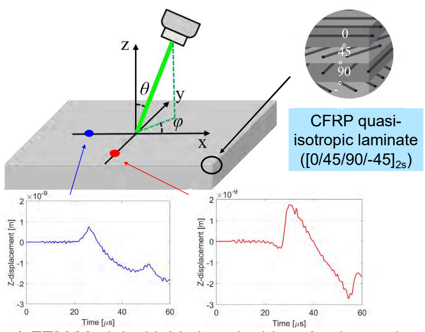
$$\rho \frac{\partial^2 u_i}{\partial t^2} = C_{ijkl}\frac{\partial}{\partial x_j}\frac{\partial}{\partial x_k}u_l - C_{ijkl}\alpha_{kl}\frac{\partial T}{\partial x_j}$$

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

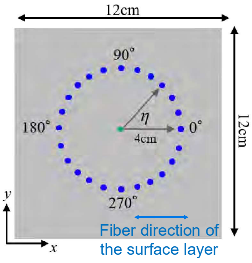
Density (ρ)	1530 [Kg/m^3]
C_{11}	133.1 [GPa]
C_{12} C_{13}	4.98 [GPa]
C_{23}	5.34 [GPa]
C_{22} C_{33}	10.7 [GPa]
C_{44}	2.7 [GPa]
C_{55} C_{66}	4.8 [GPa]

CFRP Thermal Parameters

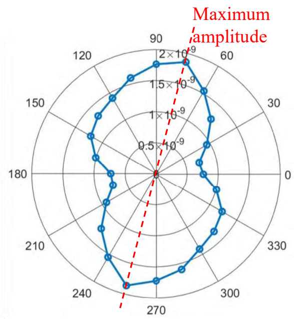
Specific heat (C)	923 [J/Kg/K]
Thermal conductivity (K_1)	60 [W/m/K]
Thermal conductivity (K_2, K_3)	0.591 [W/m/K]
Expansion ratio (α_1)	0.48e-6 [1/K]
Expansion ratio (α_2, α_3)	40.4e-6 [1/K]

Simulation Results

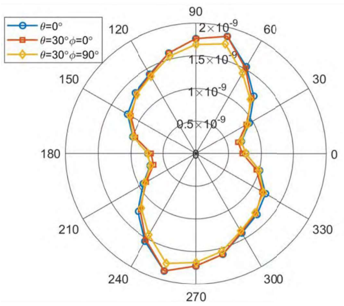
Directive Pattern
(Analysis of out-of-plane displacement)



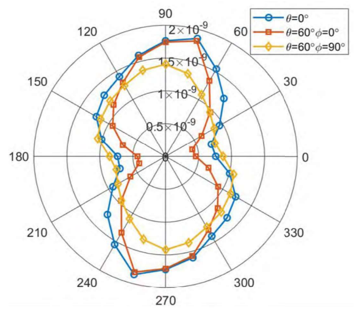
Vertical Incidence : θ = 0°



Oblique Incidence: θ = 30°



Oblique Incidence: θ = 60°

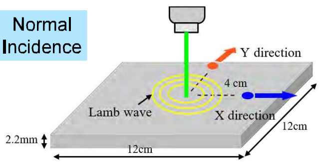


The maximum amplitudes at observation points around the laser injection point are shown in a polar diagram.

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

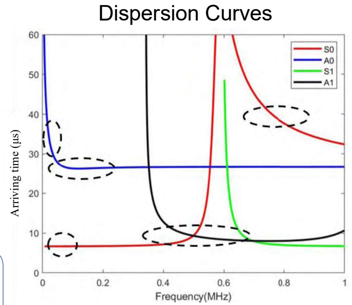
- Multiple modes

  There are symmetric modes (S_0, S_1…) and antisymmetric modes (A_0, A_1…).

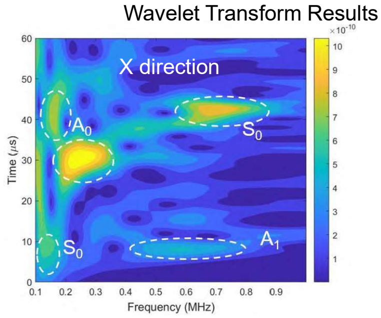
- Velocity dispersion

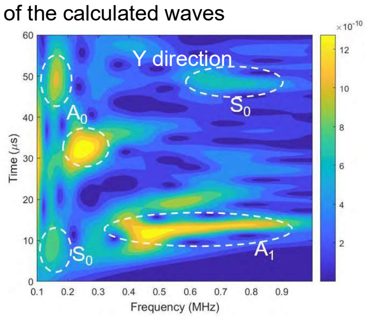
  The velocity of the wave depends on the frequency.

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.