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Defect imaging of a thin plate using evanescent modes of guided waves

ガイド波エバネッセントモードを利用した薄板の損傷画像化

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1. Introduction

Instantaneous local heat expansion on a plate by pulsed laser irradiation generates flexural vibrations. Our previous study described that the flexural vibration is generated larger as the plate is thinner[1]. Using the characteristic of the flexural vibration, we can measure an amplitude distribution (or energy distribution), showing the presence of a wall-thinning in a plate[2].

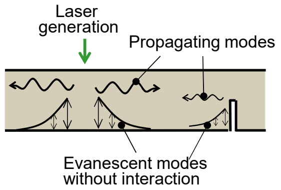
The scanning laser source (SLS) technique can be used in the measurement of the amplitude distributions. In the SLS technique, elastic wave source by laser irradiation is rastered and the flexural vibration is detected at a fixed position. As the receiver position does not change in the SLS, stable measurements are feasible even with laser Doppler vibrometer (LDV) and advanced wave analyses can be applied using multiple waveforms for multiple source positions. The SLS has been used mainly for high sensitive detection of surface cracks with the broadband pulse wave in the frequency range of MHz[4-6]. On the other hand, authors have been developing defect detection in a thin plate using the low frequency range of kHz[1-3].

In this study, the principle of energy enhancement at a notch type defect in the SLS measurements are described, and then the characteristics of this imaging technique are discussed from experimental results.

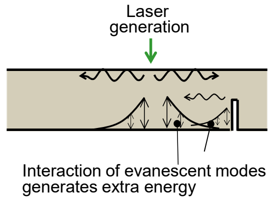
2. Energy enhancement by coupling of evanescent modes

Pulse laser irradiation onto solid media generates elastic waves by thermo-elastic effect or ablation. Because the ablation damages the surface of solid media, elastic waves by the thermo-elastic effect are often used for nondestructive inspection. When laser beam is incident on a thin plate, in-plane normal stresses are generated at the surface of the laser spot in thermo-elastic regime. The in-plane stresses at the plate surface, being dipole loading on the plate cross-section, generate bending moment in the plate. Authors proved with two dimensional analyses based on the plane strain condition that energy of flexural vibration by the dipole loading is proportional to $h^{-3/2}$, where h is the plate thickness[1]. The flexural vibration is nothing but an A0 mode of Lamb wave. When laser beam is irradiated onto the plate surface, the propagating A0 mode and non-propagating modes such as A1 and S1 modes are generated simultaneously. It should be noted that we now consider a frequency range much lower than the cut-off frequency of the A1 mode, where the wavenumber of A1 mode is pure imaginary. The non-propagating evanescent modes, having the displacement distributions exponentially decreasing with the distance, do not transmit the energy, as shown in **Fig. 1**. On the other hand, when the propagating incident wave arrives at the reflective object, it generates reflected waves consisting of propagating modes of A0 and S0 together with non-propagating evanescent modes such as A1, S1 and other higher order modes.

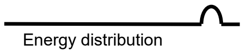
As for the propagating modes, incident waves and reflected waves independently travel with no coupling due to their orthogonality. However, some of the evanescent modes generated at the laser and the reflective object do not hold orthogonality and interact with each other. Because the incident flexural wave energy increases by their interaction, the coupling of the evanescent modes behaves as the source of the energy enhancement[3].



(a) Laser source far from a notch



(b) Laser source in the vicinity of a notch



(c) Distribution of flexural vibration energy

Fig. 1 Principle of energy enhancement in the vicinity of a defect

Because the evanescent modes exponentially decay from the laser source and the reflective object, respectively, the evanescent modes do not couple when these are far from each other (Fig. 1 (a)). On the other hand, if the laser source locates in the vicinity of the reflective object, these evanescent modes couples strongly, leading to the energy enhancement (Fig. 1 (b)). It can be estimated that the range of energy enhancement depends on the dominant distance of the evanescent modes.

In order to discuss the dominant distance, **Fig. 2** shows the imaginary parts of wavenumber s of A1, S1, A2 modes in gray solid lines, together with the wavenumber of an A0 mode in a black solid line. The dispersion curves are calculated for a 3 mm thick aluminum plate which is used in the experiments shown later. Defining the dominant distance $x_{1/2}$ is the distance at which the evanescent mode becomes half in amplitude, the A1 mode with the smallest imaginary part of wavenumber has the longest dominant distance. From the following equation,

$$e^{-\mathrm{Im}(k_{A1})x_{1/2A1}} = 1/2 \tag{1}$$

the dominant distance of the A1 mode is obtained as,

$$x_{1/2A1} = \ln 2 / \mathrm{Im}(k_{A1})\,. \tag{2}$$

Now we consider that the imaginary part of the wavenumber of A1 mode $\mathrm{Im}(k_{A1})$ can be approximated to the wavenumber of A0 mode k_{A0} in a low frequency range as,

$$k_{A0} \approx \mathrm{Im}(k_{A1})\,, \tag{3}$$

which is shown in Fig. 2, eq. (2) can be rewritten as,

$$x_{1/2A1} = \ln 2 / k_{A0} = (\ln 2 / 2\pi)\lambda_{A0} \approx 0.11\lambda_{A0}\,, \tag{4}$$

where λ_{A0} is the wavelength of A0 mode. This equation indicates that the dominant distance of A1 mode is much smaller that the wavelength of A0 mode, and therefore it can be predicted that the energy enhancement by the evanescent modes occurs in small region compared with the wavelength of the flexural propagating wave.

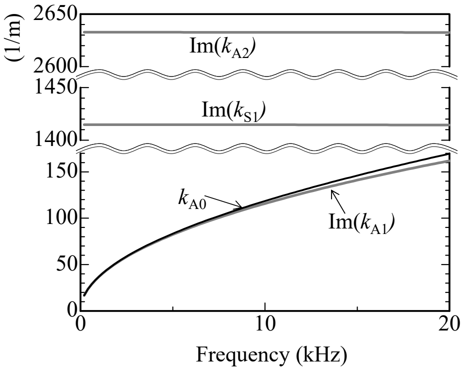


Fig. 2 Imaginary part of wavenumbers of A1, S1, A2 modes and a wavenumber of an A0 mode in a 3.0 mm thick aluminum plate.

3. Experimental results

A defect image was obtained for a 3.0 mm thick aluminum plate with 1.5 mm deep straight notches on the back surface as show in **Fig. 3** to investigate the resolution of the defect imaging. Two notches were located with the spacing of 20 mm, 10 mm, 5 mm, 2 mm, respectively, and the bottom one was one straight notch. The image on the right of Fig. 3 shows that two notches were seen separately up to 5 mm spacing, while two notches were seen in one line in the 2 mm spacing. Considering that the wavelength of A0 mode at the frequency used in the experiment (8 kHz) was about 59 mm, the resolution was much smaller than the wavelength and the prediction shown above agree well with the experimental result.

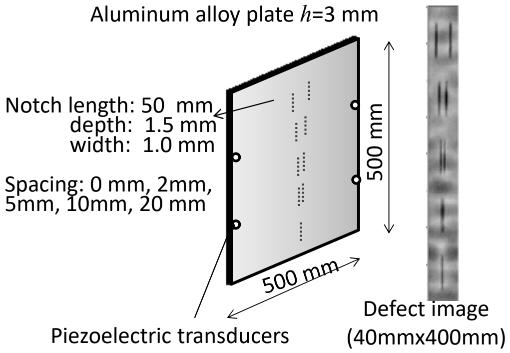


Fig. 3 Specimen used and a defect image.

4. Conclusions

The role of evanescent modes was discussed in imaging for a plate with a notch type defect on the back surface. Theoretical prediction and an experimental result show that the defect imaging technique realizes much higher resolution than wavelength of the A0 mode and the dominant distances of evanescent modes affect the resolution.

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