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Frequency dependence of images in scanning laser source technique for a plate

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ABSTRACT

Defect imaging using scanning laser source technique has been investigated for a plate with rounded defects and notch-type defects in our previous studies. This paper examines frequency dependence of the defect images with both calculations and experiments in order to acquire clearer images. Both calculation and experimental results for a straight notch revealed that clearer images of notch-type defects can be obtained in the range of low frequency-thickness product below about 200 kHz mm. Moreover, images of the defects of various shapes were obtained by synthesizing images from eight receiving transducers, and similarly to the case of the straight notches, they became more clearly in the low frequency range.

1. Introduction

Laser ultrasonic technique [1] is highly attracted as a non-contact inspection technique, in which ultrasonic is emitted by thermoelastic stress or ablation effect induced by laser pulse emission onto the surface of a material and ultrasonic is received by interferometry between a reference beam and a reflected or scattered beam from the surface.

Thus considering inspection of the existing structures and products in manufacturing lines, the reflected or scattered laser beam cannot be stably received due to surface conditions such as roughness, reflection angle and vibration, even if ultrasonic emission is feasible. As a solution of such a problem in on-line inspections, we took note of scanning laser source (SLS) technique in which ultrasonic emission is done by a pulse laser and ultrasonic is received with ultrasonic transducers fixed on a surface of the material.

The SLS technique provides a wide variety of information on materials from many waveforms acquired when laser beam is scanned over the material with mirrors. Kromine et al. [2], Fomitchov et al. [3] and Shon and Krishnaswamy [4] developed the SLS for surface breaking cracks using amplitude and frequency changes of waveforms. Takatsubo et al. [5] proposed defect detection technique where the animation of wave propagation is created from the waveforms acquired by the SLS and defect were detected from distortions of the wave propagation. Authors [6,7] reported that amplitude distributions of the A0 mode of Lamb waves in the frequency range below the A1 cut-off frequency roughly correspond to thickness distributions for a plate with a rounded shallow defect. Moreover, images of notch-type defects were also obtained by synthesizing plural images from plural receivers [8].

In this paper, frequency dependences of synthesized images using plural receivers in the SLS are investigated with both calculations and experiments for a plate with notch-type defects. The outline of defect imaging by the SLS with plural receivers for a plate with notch-type defects is described first, and the frequency dependences of the amplitude distributions are analyzed by calculations, and finally the frequency dependences of images are investigated by SLS experiments.

2. Outline of defect imaging with scanning laser source with plural receivers

Characteristics of A0 mode of Lamb waves are utilized in the defect imaging technique with the SLS for a plate. Fig. 1 is a schematic figure of signals received at the fixed transducer when laser beam is emitted onto the surface of a plate with a rounded defect. Large signals are detected when the laser beam is emitted on the thin defected region (Fig. 1b), while detected signals become small when laser beam is on the thick intact regions (Fig. 1a and c). As a result, an amplitude distribution can be obtained by scanning the laser source as shown in Fig. 1d. These phenomena appear when reflection is small at a defect, and our previous paper [6] demonstrated that thickness distribution images can be obtained when A0 mode of Lamb waves from the SLS is detected in the low frequency region below the A1 cut-off frequency for a shallow rounded defect.

However, for defects that generate large reflected waves such as notches and deep defects, the amplitude distributions do not correspond to the thickness distributions even using the A0 mode in

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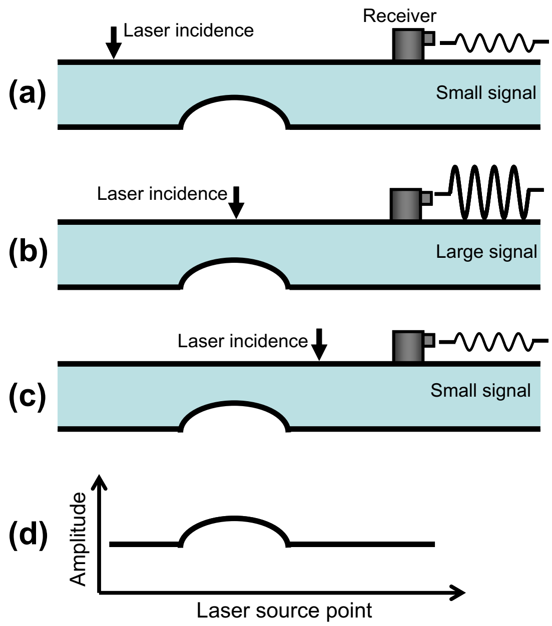

Fig. 1. Schematic figures representing the relationship between location of laser incidence and amplitude of receiving signals.

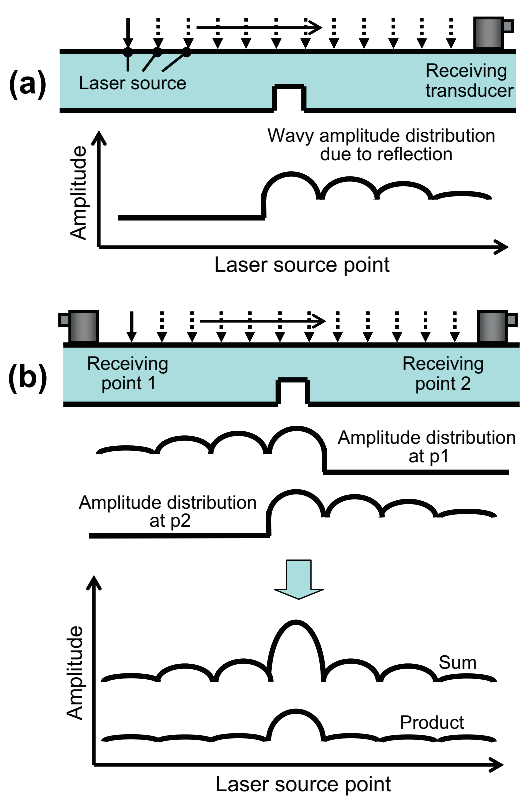

Fig. 2. Schematic figures of amplitude distributions affected by large reflections and synthesized distributions using two receiving transducers.

the low frequency range. Fig. 2a shows a schematic figure of an amplitude distribution around a notch-type defect. Wavy amplitude distribution at the transducer side is caused by interferences of direct and reflected waves, and it results in the spurious images in two dimensional amplitude distributions (defect images). Thus, our previous work [8] introduced imaging technique using plural receivers where defect images are enhanced by taking summation or product of plural images. Fig. 2b is a schematic figure of the synthesizing process of two amplitude distributions. The two upper distributions show amplitude distributions measured at receiving points 1 and 2. These two amplitude distributions commonly have large values at the defect area, while have different distributions at the intact regions. Taking summation or product of these two amplitude distributions gives enhanced amplitude distributions where the defect area has large value and the other intact areas become small.

Although the amplitude distribution measured by the SLS corresponds to thickness distribution in a case of small reflection [6], the amplitude distribution affected by large reflection as shown in Fig. 2a has no physical meaning. Therefore, the synthesizing process using summation or product of plural images is just an enhancement process of defect images, and one can choose an effective means in each measurement. In this study, we use the synthesizing technique by summation.

3. Theoretical investigation on frequency dependence of amplitude distributions

In the previous work [6], amplitude distributions were calculated for rounded defects of various shapes by the combined model of a semi-analytical finite element (SAFE) method and a finite element (FE) method [9,10]. In this section, using the same calculation model, amplitude distributions are calculated for a plate with a notch-type defect.

Now, we consider an aluminum plate (longitudinal wave velocity $c_L = 6260$ m/s, transverse wave velocity $c_T = 3080$ m/s) of thickness d having a rectangular defect of width w and depth h as shown in Fig. 3. The SAFE regions on the both side of the plate model are divided into 16 layers, and the FE region with the length of $20d$ between the SAFE regions is divided into a 16×160 rectangular mesh. A harmonic vibration of frequency f in the thickness direction is applied at FE nodes on the upper surface from $x = -9.875d$ to $x = +9.875d$, and then normal displacements of A0 mode on the upper surface of the right SAFE region are calculated. Since attenuation of ultrasonic is not considered in the calculation, the amplitude of the normal displacement of a single A0 mode is constant at any places in the right SAFE region.

In the calculation described above, the loading points of harmonic vibration x and the receiving point of the normal displacement of A0 mode correspond to laser source points and a location of a receiving transducer in the SLS, respectively. Amplitude distributions are calculated from receiving signals at a single receiver or dual receivers for various loading points. Note that this calculation does not strictly express ultrasonic generation by laser in the experiments discussed below. In the experiments, ultrasonic is generated in the thermoelastic regime where in-plane stresses are mainly generated. However, since many parameters have to be considered for the precise model of laser generation such as laser spot size, surface condition of a material, and pulse energy of the laser [1,4], this paper uses normal loading condition for qualitative analyses of A0 mode with out-of-plane displacement.

In theoretical studies and calculations of Lamb waves, a frequency and thickness product fd is used instead of frequency f for generalization, and all lengths are often represented by the ratio to thickness d. This paper also uses the notation, fd, w/d, h/d, x/d, and temporally calls them frequency, width, depth and location, respectively.

3.1. Amplitude distributions around a notch with a single receiver

Fig. 4 shows the amplitude distributions (loading point x/d versus normalized amplitude) around the notch of width $w/d = 0.5$