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Ultrasonic imaging using signal post-processing for a flexible array transducer

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ABSTRACT

In this study, we used a flexible array transducer to obtain images of flaws in materials with irregular surfaces. The transducer was manufactured from a 1–3 composite made of piezoelectric zirconate titanate and epoxy resin, and covered with neoprene rubber layers. An approach that involved combining a flexible array transducer and full matrix capture (FMC) is effective, because the surface geometry and flaw signal data can be separately measured and merged during post-processing. The disadvantage of the flexible array transducer is its narrow frequency band due to the thin damping material. To enhance the spatial resolution, we used the scattering amplitude extracted from raw signal data. We also introduced a numerical apodization technique to suppress the influence of side lobe. We validated the performance of the proposed method by measuring the signals from artificial flaws in aluminum specimens, performing high-speed FMC imaging using graphic processing unit computation.

1. Introduction

The use of ultrasonic arrays for conducting non-destructive evaluation has been drastically increased in recent years [1]. Conventional ultrasonic-array imaging systems set a number of time delays to stagger the firing of elements in an array during the emission process. A high-pressure wave generated from the transducer propagates in a specific direction. The signal received at each element is properly delayed and summed, and an image line is obtained. Then, to obtain a new image line, new emission and reception delays are set to orient the beam in a different direction. These operations can be rapidly performed using an electronic scanning device. Thus, a wide range of imaging is possible with existing ultrasonic beam-steering and -focusing techniques. These advantages have led to the successful growth of array inspection usage in the engineering industry.

In recent years, a post-processing beam-forming technique has been proposed that utilizes a complete set of signals of all combinations of transmission and reception elements. This approach is referred to as either full matrix capture (FMC) [2] or sampling phased array [3]. In FMC, each array element is sequentially used as an emitter and all other array elements with number N are used as receivers. By changing the emitting element, we obtain a set of $N \times N$ signals that is used to form the beam. The combination of all signals enables the generation of focal beams at any point in the region of interest. The delay-and-sum approach based on post-processing imaging technique is referred to as the total focusing method (TFM) [2]. In terms of summing up of all signals while accounting for the beam path, TFM is similar to synthetic aperture focusing technique (SAFT) [4]. Although the complexity of the acquisition process and the computational requirements for beam-forming had initially made this method impractical [1], the number of non-graphical applications being ported to graphics processing units (GPUs) has recently been rapidly increased. Implementation on massively parallel hardware with GPUs for accelerating the TFM processes has been reported [5]. The increased rate of GPU computation is because of a programming paradigm with the Compute Unified Device Architecture (CUDA) by NVIDIA Corp. Moreover, the application of a field-programmable gate array has been reported for speeding up TFM [6]. Thus, industrial fields today have a fairly wide knowledge of FMC and TFM.

FMC is beneficial for the inspection of a material with irregular surfaces because it can be used to separately measure the surface geometry data and the signal data from flaws. The surface geometry and signal data from flaws can be merged during post-processing. In previous studies, the usages of flat and rigid array transducers with a soft rubber wedge, a rubber-based gel, and other approaches [7–9] were proposed to cope with such irregular surface. One approach is to use an array transducer that can conform to the curvature of the target surface [10–12]. While this array transducer has a number of independent spring-loaded positioning sensors and allows direct contact inspection, the contact

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surface of this transducer is a staircase pattern; therefore, the array transducer could not be perfectly adjusted to a target position, especially one with a small radius of curvature.

In this study, we propose the usage of an array transducer manufactured from a 1–3 composite made of piezoelectric zirconate titanate (PZT) and epoxy resin, and covered with neoprene rubber layers. Here, two types of inspection strategies using the flexible array transducer are proposed. The one is for an on-site inspection when the surface geometry is simple, the other is for an off-site inspection when the geometry is complicated. For the on-site inspection, we can introduce GPU computation to accelerate the post-processing of beam-forming in TFM. Here, imaging of artificial flaws is demonstrated using aluminum specimens with flat and circular surface. The image quality in the case that the surface geometry is misestimated is also discussed. For the off-site inspection, all signal data and the surface profile are separately measured. It does not matter which procedure is prior in practice. In this study, prior to inspection, the surface geometry data is measured and stored in a memory table. Then, we can combine the surface geometry data with flaw signal data within the FMC framework.

The disadvantage of the flexible array transducer is its narrow frequency band due to the thin damping material. Moreover, the ultrasonic side lobe increases when the flexible transducer is placed on a concave surface. Although Lane [13] has already proposed an array inspection method using this type of transducer, the solutions for the disadvantages have not been considered. In this paper, we use the scattering amplitude extracted from raw signal data [14,15] to enhance the spatial resolution. We also introduce an apodization technique [16] to suppress the influence of the side lobe. We accelerate the calculation of the scattering amplitude using fast Fourier transform from the CUDA library (cuFFT). Also a mathematical weighting processing is introduced to the apodization, which can be accelerated with GPU calculation.

2. Flaw imaging technique

2.1. Flexible array transducer

The array transducer was manufactured from a 1–3 composite made of PZT and epoxy resin, and these were bonded onto a flexible polyimide film containing electrical connectors. The array elements were covered with layers of neoprene rubber. Fig. 1 shows a picture of the flexible array transducer. The one has 64 elements with a 1.0 mm element pitch and a total thickness of 2 mm. The bendable area is approximately 110 mm in length.

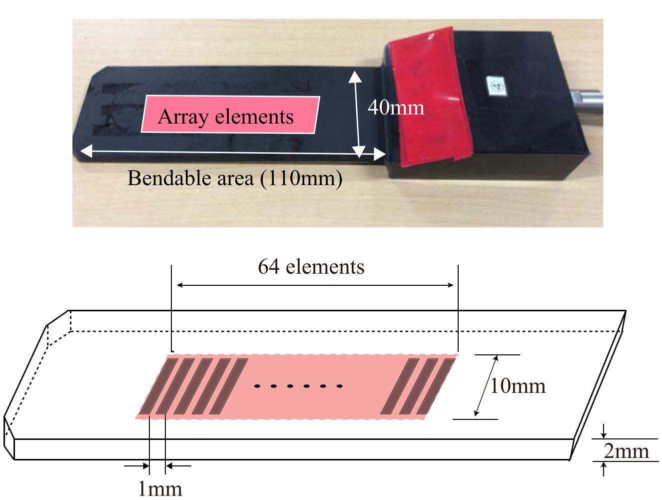

Fig. 1. Images of the flexible ultrasonic array transducer with 64 elements.

Fig. 2 shows the back wall signal measured at an element when an ultrasonic wave is emitted from the same element with a square-pulse excitation. The peck frequency is approximately 5.5 MHz, and the transducer exhibits a narrow band property due to a long wave tail. This is because the thin damping material in the array transducer, which results in a low spatial resolution in flaw imaging. In Section 2.3, we introduce a signal processing technique to enhance the spatial resolution.

2.2. FMC and TFM

Consider an ultrasonic array transducer, in which N elements are arranged on the target surface (Fig. 3(a)). The TFM [2] is a delay-and-sum beam-forming algorithm. The beam can be focused on any pixel in the imaging region (x_1–x_3 plane). Each element is successively used as the transmitter, while all other elements are used as receivers. The transmitting wave is emitted by the i-th element, and the scattered waves are received at all elements individually. The received signal at the j-th element is stored in a signal matrix M_{ij}. The number of signal samples in each transmission and reception combination is N_t, and the signal samples are recorded in a signal matrix that contains all the acquired $N \times N$ combinations (Fig. 3(b)). This TFM is a post-processing technique that utilizes the dataset to generate a focal beam at an arbitrary point. The position $\boldsymbol{x}[k, l]$ represents the target pixel where the focal beam is being generated. The flight time $T_{kl}{}^{o}$ of the ultrasonic wave between the target pixel $\boldsymbol{x}$ and the center of the array $\boldsymbol{x}^o$ is described as follows:

$$T_{kl}^{o} = \frac{2|\boldsymbol{x} - \boldsymbol{x}^o|}{c} \tag{1}$$

where c is the wave velocity of the material. The flight time from the i-th to j-th element via $\boldsymbol{x}$ can be expressed as $T_{kl}^{o} - \Delta t_{kl}^{ij}$. To obtain the focal beam, we stack the signal data by considering the delay Δt_{kl}^{ij} as follows:

$$F(\boldsymbol{x}[k, l], t) = \sum_{i=1}^{N}\sum_{j=1}^{N} M_{ij}(t - \Delta t_{kl}^{ij}), \quad k = 1, \ldots, K, \quad l = 1, \ldots, L \tag{2}$$

In Eq. (2), K and L are the pixel numbers in the x_1 and x_3 directions, respectively. After the beam forming, we determine the amplitude I at the flight time $T_{kl}{}^{o}$ as follows:

$$I(\boldsymbol{x}) = F(\boldsymbol{x}[k, l], T_{kl}^{o}) \tag{3}$$

Using Eqs. (2) and (3), the flaw imaging procedure allows a complete scan with a fine pitch in a target area. If there is a flaw at $\boldsymbol{x}$, the amplitude I will be high. A color map of I is output on the PC monitor.

2.3. Scattering amplitude

As shown in Fig. 2, the flexible array transducer has a narrow frequency band and the use of signals without any processing yields images with low spatial resolution. In this study, we used the scattering amplitude [14,15] to achieve high-resolution imaging. Based on a linear time-invariant system model for elastodynamic scattering problems, the scattering amplitude, which depends directly on the flaw properties, can be obtained by the following deconvolution calculation. The received signal M_{ij} in the experimental system can be expressed [14] in the angular frequency domain ω as follows:

$$M_{ij}(\omega) = \beta(\omega)T_i(\omega)P_i(\omega)C_i(\omega)A_{ij}(\omega)C_j(\omega)P_j(\omega)T_j(\omega) \tag{4}$$

where $\beta(\omega)$ is the system efficiency factor, $P_i(\omega)$ is the path from the i-th element to the flaw, the $T_i(\omega)$ values are the energy