1P2-10

Development of a defect imaging method using ultrasonic time reversal analysis for heterogeneous anisotropic materials

超音波逆伝搬解析による非均質異方性材料中の欠陥可視化技術の開発

Hirohisa Mizota[1, 2†], Yoshiaki Nagashima[1], Kazuyuki Nakahata[2] ([1]Hitachi, Ltd.; [2]Ehime Univ.)
溝田 裕久 [1, 2†]，永島 良昭 [1]，中畑 和之 [2]（[1] 日立製作所，[2] 愛媛大学）

1. Introduction

In order to evaluate the soundness of structural components, nondestructive inspection methods using ultrasonic phased array (PA) probe and synthetic aperture method [1] have been developed for imaging the inside of the components. These methods require the estimation of flight times from each element of the ultrasonic array probe to specific positions in view of the wave diffraction at interfaces in the inspection area. Therefore, the estimation for heterogeneous and anisotropic material whose velocity distribution is not constant, such as welding and unidirectional solidified metal might become difficult.

To treat with the difficulty, the time reversal approach wave was proposed [2]. In the time reversal method, signals from a defect are recorded at all the array elements, then the signal are reversed by time reversal mirrors (TRMs) device and re-transmitted into the medium. Since the signal is generated from the defect, the time reversal waves return to the positions of the defects according to the reversibility of the elastic wave.

As a time reversal method without the TRMs device, a simulation-based time reversal analysis method has been proposed *by* Nakahata *et al* [3]. They successfully reconstructed an image of an electric discharge machined (EDM) slit in aluminum through a polystyrene wedge. In this report, the simulation-based approach is applied to an anisotropic metallic material. Here the imaging of an EDM slit in the specimen of unidirectional solidified SUS316L stainless steel is demonstrated.

2. Outline of ultrasonic time reversal analysis

The ultrasonic time reversal analysis method is shown in **Fig. 1**. First, the ultrasonic array probe is used to transmit the incident wave to the defect. Then the scattered waves from the defect are measured at each element. All the measured waves are time-reversed and re-transmitted in a simulation model. By performing the transient finite element analysis, the back-propagating wave to the defect is visualized in the numerical model.

In this ultrasonic time reversal analysis, an elastic wave in anisotropic and heterogeneous media is calculated using the two dimensional finite element method with an explicit time-updating scheme. We discretize the spatial domain by using the four node quadrilateral elements because the digital image can be used directly as the simulation data set. The central difference scheme is implemented in the time domain. Therefore, the displacement fields $\boldsymbol{d}$ can be solved as shown in equation (1). The displacement of the step $k+1$ can be obtained directly by using the known solutions at steps k and $k-1$ as

$$\begin{aligned}\boldsymbol{d}^{h+1} &= (2\mathbf{E} - \Delta t^2 \bar{\mathbf{M}}^{-1}\mathbf{K})\boldsymbol{d}^{h} \\ &\quad + \Delta t^2 \bar{\mathbf{M}}^{-1}\boldsymbol{f}^{h} - \boldsymbol{d}^{h-1}\end{aligned} \tag{1}$$

where, $\boldsymbol{f}$ is the nodal force, $\bar{\mathbf{M}}$ is the lumped mass matrix [4], $\mathbf{K}$ is the stiffness matrix, $\mathbf{E}$ is the unit matrix, and Δt is the time step interval. In the simulation, we had to tie up the element stiffness matrix $\mathbf{K}$ to the elastic constants and crystalline orientation of a grain.

3. Defect imaging in heterogeneous anisotropic materials using ultrasonic time reversal analysis

We demonstrate the imaging of the EDM slit with an ultrasonic array probe on a wedge. A schematic image of the experimental setup is shown in **Fig. 2**. The test piece of unidirectional solidified SUS316L stainless steel has a rectangular EDM slit (10 mm in height). A 64-channels linear array probe with 2.0 MHz center frequency is located on a polystyrene wedge. The electronic ultrasonic scanning system (Model ES3300W, Hitachi Engineering & Services Co., Ltd.) was used for the control of transmission and reception of ultrasonic wave. The experimental conditions are shown in **Table I**. All elements were excited simultaneously at the first transmission, and the scattered waves were received individually at each element.

A numerical model for the time reversal analysis is shown in **Fig. 3.** The element size is 0.05 x 0.05 mm and total element number is about 5 million. The elastic constants and density in the polystyrene and metal crystal of the SUS316 are shown in **Table II**. Although the grain of the SUS316L stainless steel has a cubic metal structure, we assume it as a homogeneous transverse isotropic material. Because the SUS316L stainless steel shows a columnar grain structure, and the grains are randomly distributed along the *Z* direction. In the simulation, the time interval Δt is 6 ns, and time incremental number is 20,000.

Fig. 4 shows the normalized von Mises stress obtained in the time reversal analysis using the numerical model (Fig.3). The focal point of the waves shows both the tip and corner of the slit. We could detect a corner echo with SN ratio of 15.6 and a tip echo with SN ratio of 3.7.

4. Conclusion

We applied the simulation-based time reversal analysis method to defect imaging in heterogeneous and anisotropic materials. Unlike conventional PA method, it is not necessary to obtain the delay pattern for the element excitation in advance. The effectiveness of this method was demonstrated with the unidirectional solidified SUS316L stainless steel. The focal point of the ultrasonic waves showed both the tip and corner of the slit.

References

1. J.T. Ylitalo ***et al.***: IEEE Trans. Ultrason. Ferroelectr. Freq. Control., **41**, (1994) 333.
2. M. Fink: IEEE Trans. Ultrason. Ferroelectr. Freq. Control., **39**(5), (1992) 555.
3. K. Nakahata ***et al.***: Journal of Solid Mechanics and Materials Engineering, **6**(6), (2012) 771.
4. K. Nakahata ***et al.***: Ultrasonics, **67**, (2016) 18.

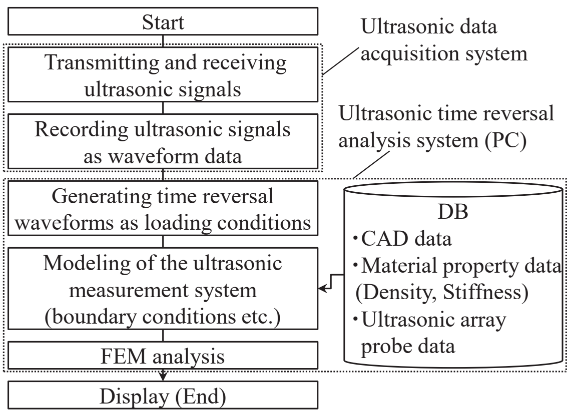

Fig. 1 Flowchart of time reversal analysis method

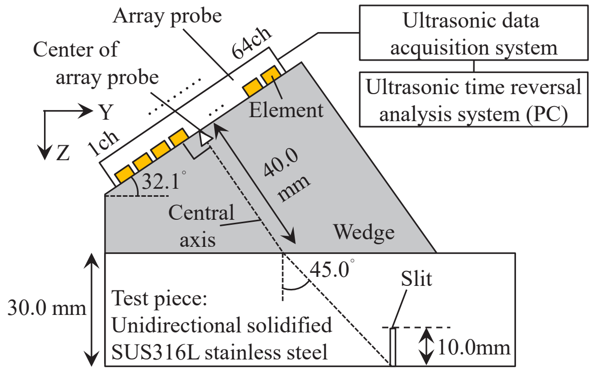

Fig. 2 Schematic image of experimental setup

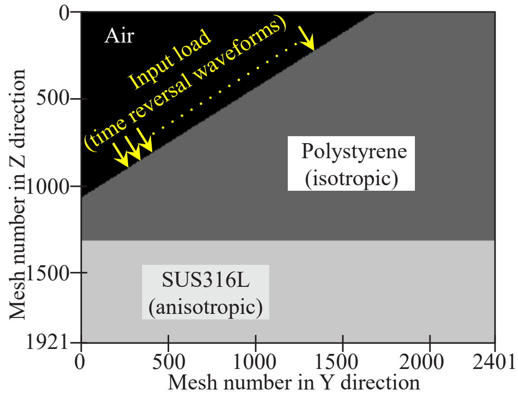

Fig. 3 Numerical model in time reversal analysis

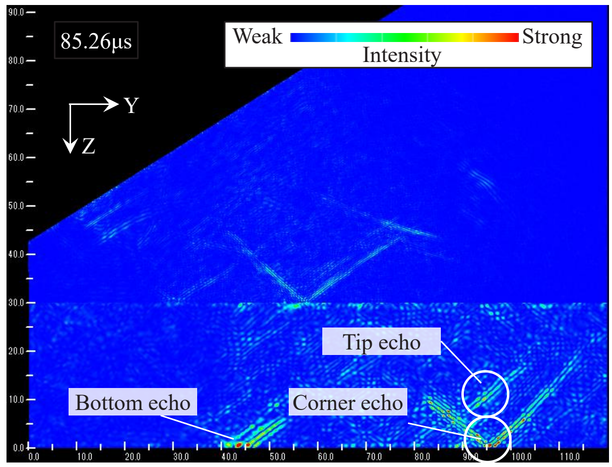

Fig. 4 Defect imaging results

Table I. Experimental conditions

Transmitter	Mode	Simultaneous transmission
	Voltage	160 V
	Pulse width	250 ns
Receiver	Mode	Each element reception
	Sampling frequency	50 MHz

Table II. Material properties for FEM analysis

Material Parameter		Polystyrene	SUS316L
Density	ρ [10^3kg/m^3]	1.03	7.88
Elastic constants	C_{11} [GPa]	5.59	276.5
	C_{12} [GPa]	2.87	113.5
	C_{13} [GPa]	2.87	133.2
	C_{33} [GPa]	5.59	212.0
	C_{44} [GPa]	1.36	119.6
	C_{66} [GPa]	1.36	81.5