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# Time-reversal Analysis of Ultrasonic Waves for Defect Imaging in Anisotropic Materials

超音波時間反転解析による異方性材内部の欠陥イメージング

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## 1. Introduction

Ultrasonic imaging methods have been developed and utilized to certify product quality or structural health in industrial fields. Although these methods enable rapid inspection using an array probe, reconstruction of a clear image requires an accurate phase matching process based on ray-tracing theory. In the case of inspection for anisotropic materials such as unidirectional solidification materials of austenic steels or nickel-based alloys, it is till difficult to reconstruct an accurate inspection image because acoustic anisotropy and heterogeneity complicate the derivation of phase matching conditions.

We focused on the time-reversal method using a phase conjugate device originally proposed by Fink in the 1990s[1]. The time-reversed received waves re-emit into a structure by using an array probe and they re-focus on a position of a reflection source without calculating phase matching conditions, in other words, without making a delay time pattern. On the other hand, in order to reconstruct a defect image, a phase matching process is required as in the case of the phased array and the aperture synthesis methods. A challenge in image reconstruction was remained. This challenge can be adressed by a technique called “Reverse Time Migration (RTM)” developed in the field of seismic imaging[2]. In this technique, a cross-correlation image is obtained between the wave field generated at the epicenter and the wave field of time-reversed wave propagating from receiving points. As an application to non-destructive inspection, defect imaging is possible in principle by replacing both the epicenter and the receiving position with the position of ultrasonic probe elements.

In our previous report, we proposed a simulation-aided defect reconstruction method using an ultrasonic time-reversal approach that uses elastic constants determined by a laser scanning ultrasonic visualization method[3],[4]. In this report, an imaging result of anisotropic metallic materials by applying the time reversal and RTM methods is shown. Here, the imaging of an EDM slit in the test piece of unidirectional solidified SUS316L stainless steel with acoustic anisotropy is demonstrated.

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## 2. Outline of ultrasonic time reversal analysis and reverse time migration

The flowchart of ultrasonic time reversal analysis and RTM method is shown in **Fig. 1**. The first step is to generate the Ricker waves at a point source on the numerical model and analyze the wave propagation. In the next step, the scattered waves recorded by the array probe are time-reversed and analyze on the same numerical model. Finally, we reconstructed a defect image by correlating the images with respect to the time-ordered propagation analysis results and the time-reversed propagation analysis results. The conceptual diagram of the spatial cross-correlation for image reconstruction is shown in **Fig. 2**. A high correlation is obtained between the time-reversed received wave and the incident wave at the position of the reflection source. Here, the spatial cross spectrum of the re-emitted waves and the incident waves is considered as an index of defect imaging, and this value is numerically calculated.

## 3. Experimental conditions and imaging result

The experimental conditions are the same in previous our report [3]. 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. 3**. 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. A numerical model for the time reversal analysis is shown in **Fig. 4**. The element size is 0.05 x 0.05 mm and total element number is about 5 million. The elastic constants and density given to the numerical model are shown in **Table I**. The elastic constants of SUS316 were derived from the laser Doppler measurement.

The correlation results are shown in **Fig. 5**. A 10mm height slit shape could be reconstructed clearly.

## 4. Conclusion

The output processing method was improved by introducing RTM method so that a single inspection image was uniquely determined without observing the individual imaging results of the time-reversal analysis. Using a 2MHz 64 element array sensor mounted on a polystyrene wedge, we measured a 10mm height slit in unidirectional solidified stainless steel SUS 316L and verified our proposed method. The defect image was reconstructed as a slit image with a side surface unlike the conventional image showing a corner echo and a tip echo. This provided a proof of principle that the method was effective for nondestructive imaging of complex structures.

## References

1. M. Fink: IEEE Trans. Ultrason. Ferroelectr. Freq. Control **39** (1992) 555.
2. J. Yan and P. Sava: Geophysics **73** (2008) 229.
3. H. Mizota, Y. Nagashima, and K. Nakahata: Symposium on USE2017 1P2-10.
4. H. Mizota, Y. Nagashima, Y. Amano, and K. Nakahata: Insight **61** (2019) 669.

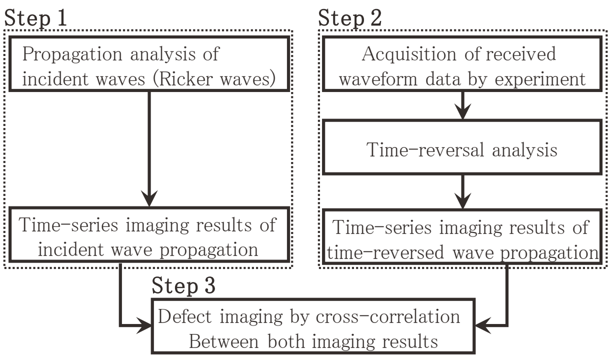


Fig. 1 Flowchart of time reversal analysis and RTM method.

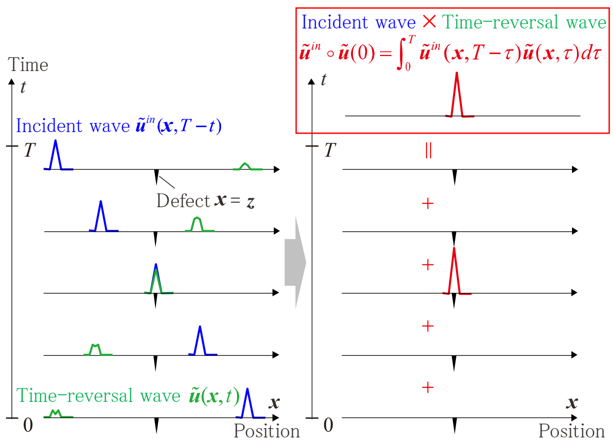


Fig. 2 Conceptual diagram of the spatial cross-correlation for image reconstruction

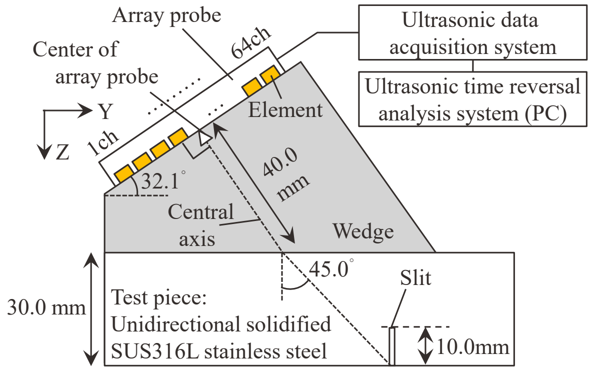


Fig. 3 Schematic image of experimental setup[3]

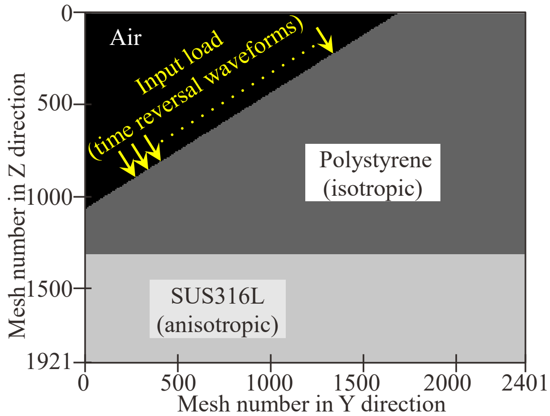


Fig. 4 Numerical model in time reversal analysis[3]

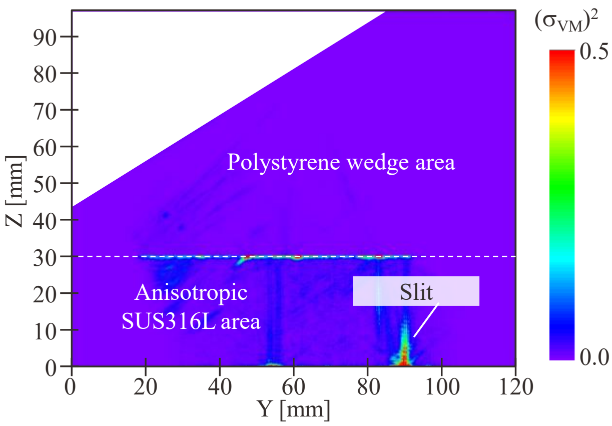


Fig. 5 Defect imaging results

Table I. Material properties for FEM analysis[4]

| Material Parameter | | Polystyrene | SUS316L |
|---|---|---|---|
| Density | ρ [$10^3$kg/m$^3$] | 1.03 | 7.88 |
| Elastic constants | $C_{11}$[GPa] | 5.59 | 247.3 |
| | $C_{12}$[GPa] | 2.87 | 131.6 |
| | $C_{13}$[GPa] | (=$C_{12}$) | 150.8 |
| | $C_{33}$[GPa] | (=$C_{11}$) | 213.2 |
| | $C_{44}$[GPa] | 1.36 | 62.8 |
| | $C_{66}$[GPa] | (=$C_{44}$) | 57.9 |