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Fundamental Study on 2D Array Transducer for High-Sensitivity 3D Imaging of Creep Damage

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1. Introduction

In the thermal power plants that are expected as dispatchable generators, the creep damage generated in the fine-grained heat-affected zone (HAZ) of 9Cr-1Mo steel pipe welds has become a severe problem. The creep damage is initiated by the precipitation of μm-sized voids, followed by an increase in the number and the coalescences of voids, leading to creep rupture. To ensure the safe and efficient management of the plants, the early detection of creep damage is required. As nondestructive testing (NDT) method, a local water immersion ultrasonic method using ultra-precise mechanical scanning of an aspherical large-aperture transducer has been proposed for very early-stage creep damage. However, the inspection volume of the current method is limited to a small volume (e.g., 1 mm^3). The application of ultrasonic phased array (PA) using a 1D array transducer has been reported to inspect the whole volume of HAZ.[1)] On the other hand, to improve the sensitivity to the creep voids that can be locally generated at grain boundaries, a 3D ultrasonic imaging system utilizing point focusing would be promising.

In this study, we propose a 3D PA imaging system using a multi-element 2D matrix array transducer to achieve the earlier detection of creep damage. To clarify the optimal design of the measurement system, we utilize numerical simulations before going to costly experimental studies. Note that this requires a 3D numerical simulation, which can encounter a prohibitive computation cost. This study aims to propose a 3D PA imaging system for this application, and then, to obtain a guideline for building appropriate simulation software through the 3D finite element method (FEM) simulation of examining the sound field of 2D matrix array transducers.

2. 3D PA Imaging System with 2D Matrix Array for Earlier Detection of Creep Damage

Figure 1 schematically illustrates a 3D PA imaging system using a 2D matrix array transducer. To avoid the ultrasonic propagation in the weld metal with strong anisotropy, the oblique incidence of shear waves is effective. To this end, a 2D matrix array transducer is placed on a wedge. With respect to a frequency, we selected 10 MHz in consideration of the balance between sensitivity and attenuation. The number of elements can determine the sensitivity, spatial resolution, and equipment cost. We decided to start with 256, which is the maximum number of elements used for NDT applications. Note that we plan to increase the number to 1024 elements, which has been used in state-of-the-art medical research. One of the critical remaining parameters is an element pitch. This can strongly affect sensitivity and spatial resolution. For its design and the analysis of ultrasonic scattering at voids, the systematic analyses based on 3D numerical simulation are promising. Hence, in the following sections, we describe a simple 3D FEM simulation to obtain a guideline for building such simulation software.

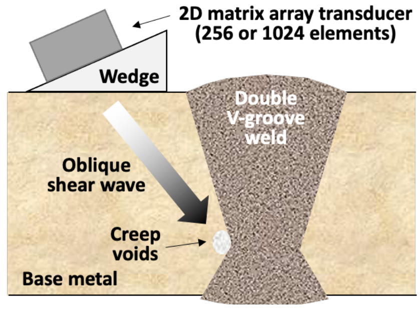

Fig. 1 Concept of a 3D PA imaging method using a 2D matrix array transducer for the detection of creep voids.

3. FEM model for 3D simulation

As a first step to obtain a guideline for builiding a simulation software suitable for the concept illutrated in Fig. 1, we performed a simple 3D simulation that calculates the sound field of a 2D matrix array transducer using FEM software, ComWAVE. **Figure 2** shows the simulation models. We varied the inter-element pitch (0.7, 1.0, and 1.5 mm) for the 2D matrix array trasndcuer with 256 elements (e.g., 16 × 16) , which was in contact with a sample. The longitudinal- and shear-wave speeds were set to 5900 and 3200 m/s, respectively. The voxel size was 0.032 mm. The total number of voxels was 0.3 billion. The Courant number was 0.8. The incident wave was Gaussian-windowed three-cycle burst waves with a center frequency of 10 MHz, which were transmitted from each element following a delay law calculated for a focal point (0, 0, 20).

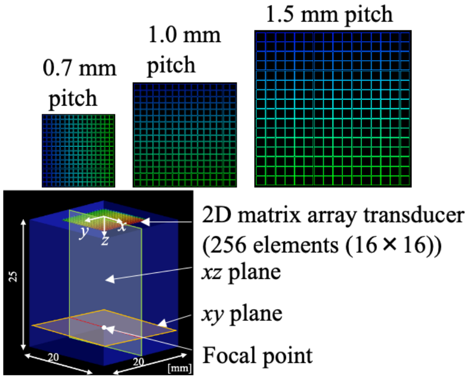

Fig. 2 3D FEM model with 2D matrix array transducers with various inter-element pitch.

4. Simulation Results and Discussion

Figure 3 shows the calculated sound fields depending on the inter-element pitch. The axial (z-direction) resolution for the 1.0 mm pitch [Figs. 3(c)] was higher than the 0.7 and 1.5 mm pitches [Figs. 3(a) and 3(e)]. The same tendency was observed for the in-plane (xy-plane) resolution. On the other hand, no grating lobes were observed for the 0.7 mm pitch [Figs. 3(a) and 3(b)], whereas they appeared for the 1.0 and 1.5 mm pitches [Figs. 3(c)-3(f)]. Note that the grating lobes for the 1.0 mm pitch may be negligible because of their smallness. This can be confirmed in the 1D profile [**Fig. 4**] of the sound field at the focal depth in the x-direction. Furthermore, the peak displacement and full-width at half maximum for the 1.0 mm pitch were superior to the others. This shows that the 1.0 mm pitch will be an appropriate design for the condition [Fig. 2].

Finally, we discuss how to build a 3D simulation software for the concept shown in Fig. 1. In this study, we utilized parallel computation using a GPU (NVIDIA Quadro RTX 6000), which has memory (24 GB) enough to deal with 0.3 billion voxels for the direct contact of the 256-element matrix array transducers (Fig. 2). However, the model for a 1024-element 2D matrix array transducer and the use of wedge for oblique shear-wave incidence would significantly increase the number of voxels. Furthermore, the 3D FEM calculation with a model including µm-sized voids would be impossible for FEM. This implies that we have to work on building a hybrid method combining theoretical solutions and FEM to reduce the computation cost, which will be our future work.

5. Conclusions

We proposed a 3D PA imaging method to achieve the earlier detection of creep damage. To obtain a guideline for building a 3D simulation software, we carried out the 3D FEM simulation on the sound field emitted from the 256-element 2D matrix array transducer. The results suggest the necessity of introducing a hybrid model. In addition, we will experimentally analyze the scattering field[2] from defects.

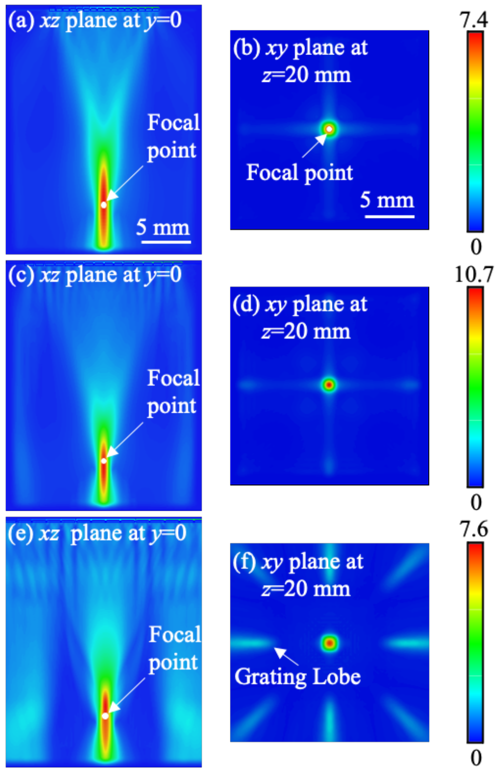

Fig. 3 Inter-element pitch dependence of sound fields calculated by 3D FEM: (a) xz-plane and (b) xy-plane for 0.7mm pitch, (c) xz-plane and (d) xy-plane for 1.0mm pitch, and (e) xz-plane and (f) xy-plane for 1.5mm pitch.

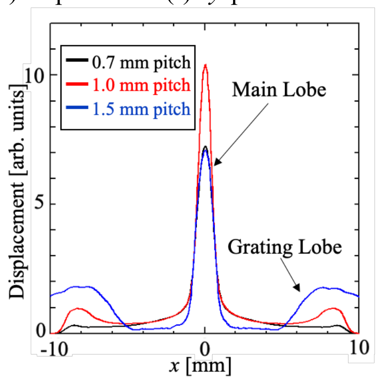

Fig. 4 1D profiles of the displacement at focal depth.

Acknowledgment

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References

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