Accelerating Laser-Induced Phased Array Ultrasonic Inspection via Multimode TFM and Sparse Transmit-Receive Aperture

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1. Introduction

Laser-Induced Phased Array ultrasonic inspection (LIPA) enables non-contact ultrasound and is thus applicable to high-temperature objects such as in-process weldments[1], but Full Matrix Capture (FMC) imaging can make data acquisition time-consuming [2]. In this study, FMC data were acquired by LIPA on specimens with near-surface side-drilled holes (SDHs) under various transmit/receive element counts and pitches, and defect detectability was evaluated while reducing the transmit and receive elements to identify the sparsest element combination—and hence the shortest inspection time—that preserves detection. Inspection images were reconstructed by multimode TFM using longitudinal/shear combinations with phase coherence imaging (PCI); since the wave mode effective for detection varies with defect depth, a multimode combination rather than a single mode was employed. Detection was judged by the appearance of a defect pixel at the expected location, comparing defect and defect-free measurements, aiming to determine the fastest LIPA inspection that does not compromise detectability.

2. Signal measurement by LIPA

The measurement principle of LIPA is illustrated in Fig. 1. On the specimen surface, m ultrasonic transmit and receive points are arranged at a uniform pitch (p). A laser pulse is irradiated at one point to generate ultrasound, and the wave reflected within the specimen and arriving at the same or a different point is received by a laser Doppler vibrometer (LDV) to acquire a single signal. With the generation point fixed, signals are measured at the various receive points; the generation point is then moved and the process is repeated, completing signal acquisition over all m points to form the full matrix. Figure 2 shows the LIPA apparatus used to implement this. The generation point is moved by a linear stage and the reception point by a galvanometer, and this mechanical scanning is what makes full-matrix acquisition time-consuming.

Figure 3 shows the specimen. In a SUS304 block measuring 20 × 22 × 70 mm (height × depth × length), side-drilled holes of 1.1 mm diameter were machined along the length direction at depths of 1, 2, and 3 mm from the surface to simulate internal defects. For each defect, the measurement elements were arranged on the top surface, centered on the defect location, to acquire the signals. Three element counts (m = 9, 13, and 15) were used, each with two element pitches (p) of 0.2 mm and 0.4 mm.

For each transmit–receive combination, 1500 signal samples were acquired at a sampling frequency of 50 MHz, and the measured signals were band-pass filtered with a center frequency of 5 MHz and a bandwidth of 4 MHz. Because the mode of the reflected wave varies with the defect location (depth), in this study defect images were reconstructed on a multimode basis combining longitudinal and shear waves. The vector coherence factor (VCF) was computed within the same delay-and-sum process as the TFM focusing and used to weight the focused amplitude. Figure 4 shows the images computed with the multimode combinations from the full-matrix data measured at the defect-free and defect regions for m = 15 and p = 0.2 mm. In the defect cases, the defect signal clearly appears at the expected depth.

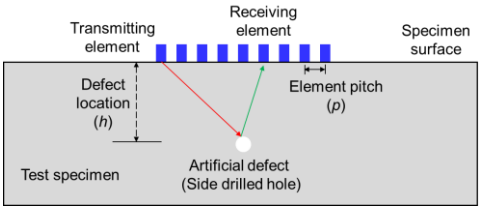


Fig. 1. Measurement principle of LIPA

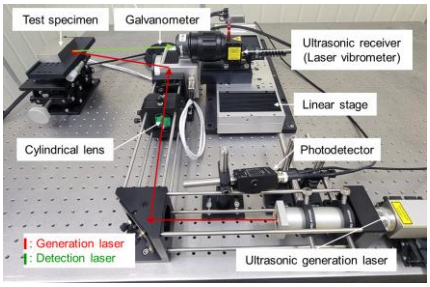


Fig. 2. Configuration of the LIPA hardware

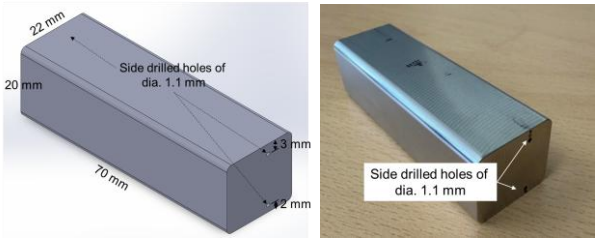


Fig. 3. Test specimen

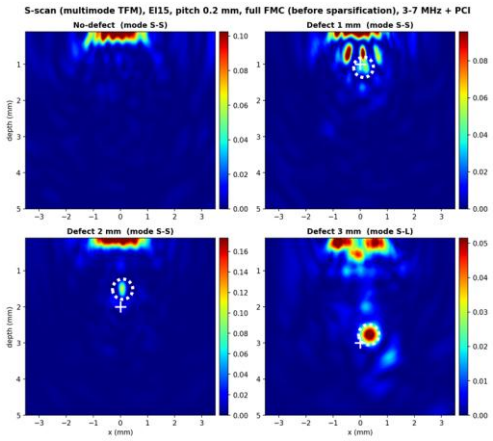


Fig. 4. S-scan images based on full-matrix data for m = 15, p = 0.2 mm

3. Transmit–receive element sparsification

The feasibility of element sparsification arises because the effective aperture of TFM is determined by the combination of transmit and receive element positions rather than by either set alone. As long as one side—transmit or receive—remains densely sampled, the other can be substantially reduced without loss of detectability, whereas reducing both simultaneously causes the focusing quality to collapse and detection to fail. In practice, since the transmit point in LIPA is translated by a slow linear stage while the receive point is steered by a fast galvanometer, reducing the transmit elements while keeping the receive aperture dense yields a greater reduction in acquisition time without compromising detectability. Figure 5 shows the sparsification result for the data in Fig. 4, demonstrating that defects at each depth are still detected using only about one-third of the full FMC data by reducing the number of transmit elements.

Across all element counts and pitches, detection was preserved (green) as long as either the transmit or receive count remained high, and failed (red) only when both were reduced together; Figure 6 shows two representative heatmaps of this behavior. The

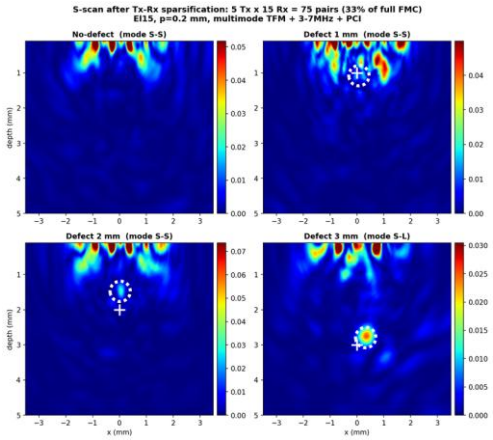
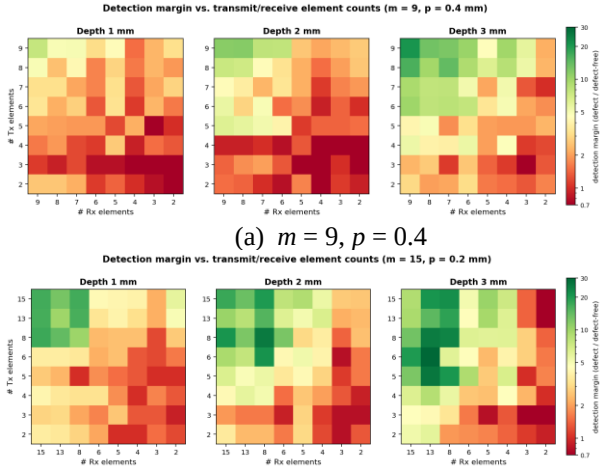


Fig. 5. S-scan images after transmit–receive sparsification (33% of full FMC) for m = 15, p = 0.2 mm



(a) m = 9, p = 0.4

(b) m = 15, p = 0.2

Fig. 6 Example heatmats of the sparsification results

sparsification margin was widest for the finer pitch (p = 0.2 mm), whereas the coarser pitch (p = 0.4 mm) allowed little symmetric reduction: grating-lobe aliasing, which is suppressed while one aperture remains dense, re-emerges once both apertures are sparsified, particularly for shallow defects.

4. Conclusion

This study applied multimode TFM with PCI to LIPA-acquired FMC data to assess defect detectability and the feasible range of transmit–receive element sparsification. The effective wave mode varied with depth, and since the effective aperture is set by the transmit–receive combination, detection was preserved when one aperture stayed dense while the other was greatly reduced. Accordingly, at m = 15 and p = 0.2 mm, defects at all three depths were detected using only about one-third of the full FMC while keeping the receive aperture full. As the transmit point is moved by a slow linear stage, reducing the transmit elements offers a practical route to shorter inspection; future work includes quantifying the false-alarm rate and validating on realistic defects.

ACKNOWLEDGEMENT

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