Journal of the Korean Society for Nondestructive Testing
Vol. 26, No. 6 (2006. 12)

Ultrasonic Phased Array Techniques for Detection of Flaws of Stud Bolts in Nuclear Power Plants

Joon-Hyun Lee*,† and Sang-Woo Choi**

Abstract The reactor vessel body and closure head are fastened with the stud bolt that is one of crucial parts for safety of the reactor vessels in nuclear power plants. It is reported that the stud bolt is often experienced by fatigue cracks initiated at threads. Stud bolts are inspected by the ultrasonic technique during the overhaul periodically for the prevention of failure which leads to radioactive leakage from the nuclear reactor. The conventional ultrasonic inspection for stud bolts was mainly conducted by reflected echo method based on shadow effect. However, in this technique, there were numerous spurious signals reflected from every oblique surfaces of the thread. In this study, ultrasonic phased array technique was applied to investigate detectability of flaws in stud bolts and characteristics of ultrasonic images corresponding to different scanning methods, that is, sector and linear scan. For this purpose, simplified stud bolt specimens with artificial defects of various depths were prepared.

Keywords: Ultrasonic Phased Array Technique, Nuclear Power Plants, Reactor Vessel, Stud Bolt, Crack

1. Introduction

The reactor pressure vessel is one of crucial components of nuclear power plants. The reactor vessel body and the closure head are fastened with stud bolts as shown in Fig. 1 (a). Typical defect of stud bolts is fatigue cracks initiated from the root of thread. The crack of stud bolts was inspected by an inserted specialized ultrasonic transducer as shown in Fig. 1 (b). This crack is so small in its early stages but grows during the long overhaul interval and would cause a failure of the stud bolt. However, detecting this type of small cracks is very difficult due to complicate signals reflected from the threads. Recently, it was required for the increase of efficiency of nuclear power plants to decrease time used for evaluation of safety and residual life of component in overhaul of the nuclear power plant. Therefore, inspection of stud bolt should be conducted with high speed and accuracy.

Ultrasonic testing is one of the widely used techniques because ultrasonic waves are sensitive to most flaws, are not cause radiation hazardous, and provide many features for flaw characterization. It is also expected to detect small cracks in the thread region without remove of studs and bolts using the ultrasonic testing. For these reasons the stud bolts in reactors are inspected periodically by the ultrasonic technique at many sites of nuclear power plants. In general, a shadow effect technique has been used for the inspection of flaws in stud bolts according to ASME Boiler and Pressure Vessel Code Section XI (1989). The shadow effect technique is that the threads in front of the crack are clearly indicated whereas the ones immediately behind it

Received: November 15, 2006, Accepted: December 18, 2006. * School of Mechanical Engineering, Pusan National University, San 30, Jangjeon-dong Kumjeong-gu, Busan 609-735, Korea, ** Technical Research Laboratories, Instrumentation Research Group, POSCO, 1, Goedong-dong, Namgu, Pohang, Gyeongbuk 790-785, Korea † Corresponding author: johlee@pusan.ac.kr

are hidden in its shadow, as shown in Fig. 2. The ultrasonic beam generated from the transducer is reflected at the root of threads, and return to the probe from thread 7 to thread 1 in distance order. However, the crack interrupts the path of ultrasonic wave and the amplitudes of thread 2 and 3 decreases suddenly as shown in Fig. 2. From this abnormal decreasing of the amplitude, the flaw signals can be distinguished from normal waveforms of sound threads. While, in this technique, there were numerous spurious signals reflected from every oblique surface of thread. In order for reducing these spurious signals, numerical operation was applied as mentioned by Oh *et al.* and *Choi et al.*

Recently, there is novel technique required to enhancing operating efficiency by saving inspection time in the overhaul. The ultrasonic phased array technique was introduced for a novel ultrasonic technique for fast and precise inspection. In this study, the ultrasonic phased array technique was applied to investigate the detectability of flaws in stud bolts and the characteristics of ultrasonic images corresponding to different scanning methods, that is, sector and linear scan.

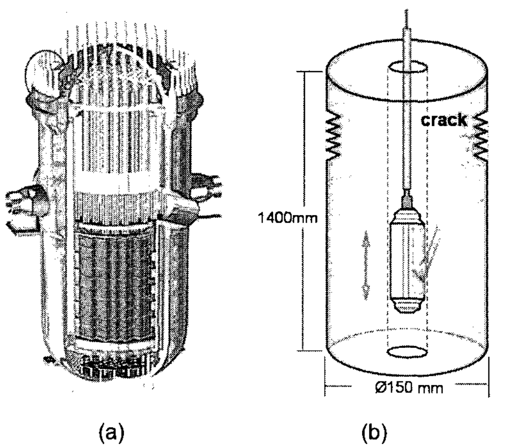


Fig. 1 Reactor vessel and stud bolt (a) reactor vessel; (b) inspection of stud bolt

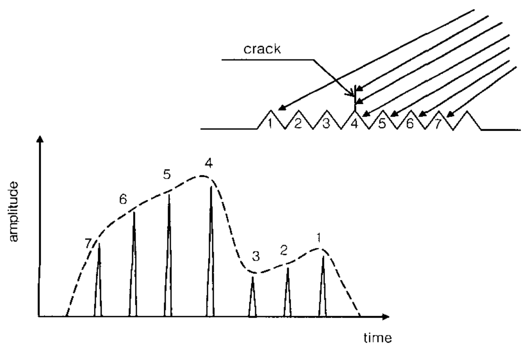


Fig. 2 Crack detection by using shadow technique

2. Stud Bolt Specimen and Phased Array Technique

2.1 Simplified Stud Bolt Specimen

In the conventional ultrasonic testing of stud bolts, special ultrasonic transducers which have cylindrical shape are inserted in bore holes of stud bolts to inspect stud bolts as shown in Fig. 1 (b). Since these conventional special ultrasonic transducers have single element and have fixed refraction angle (60°), various inspection condition of the ultrasonic transducers and the phased array technique could not be applied. In this study, to apply the conventional phased array technique in the state of fundamental research, stud bolt specimens were simplified for using conventional phased array transducer, as shown in Fig. 3. These specimens have half circle cross-section and flat surface parallel to axis. Diameter of these specimens is 150mm and length is 400mm. Sizes of artificial defects made by EDM are from 1mm to 5mm with 1mm step in depth. The material of specimen is carbon steel used for stud bolts in reactor vessel of nuclear power plants.

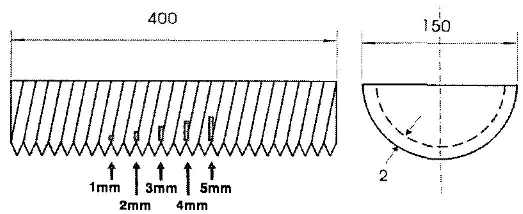


Fig. 3 Shapes and dimensions of stud bolt model specimen

2.2 Ultrasonic Phased Array Technique

Recently, it is required that less consumption of inspection time in overhaul in order to increase efficiency of nuclear power plants. Since the conventional ultrasonic transducer is used to inspect narrow region as shown in Fig. 4 (a), it takes too much time to inspect the long stud bolt. However, the phased array transducer configured with multiple elements produces dynamic ultrasonic beam steering and fast inspection as mentioned by Lee *et al.* (2000). Therefore the phased array technique provides cross section images through the ultrasonic scanning, broad region of inspection as shown in Fig. 4 (b) and real time scanning. Fast inspection of stud bolts can be enabled by using this ultrasonic phased array technique.

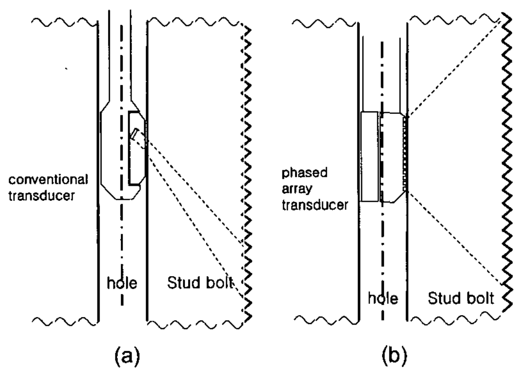


Fig. 4 Beam coverage of stud bolt through conventional UT and phased array technique (a) conventional UT; (b) phased array technique

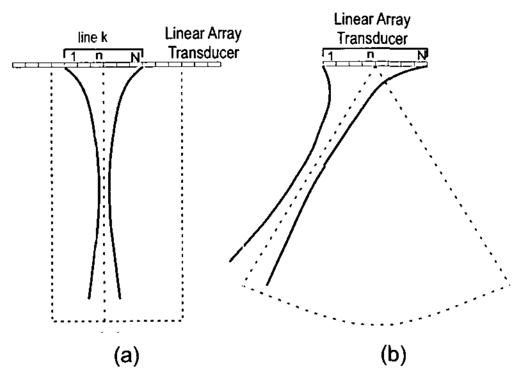


Fig. 5 Scanning using array transducer (a) linear scanning; (b) sector scanning

The ultrasonic array transducer provides two types of scanning method as shown in Fig. 5. One is linear scanning as shown in Fig. 5 (a) and the other is sector scanning as shown in Fig. 5 (b). In the linear scanning, a small portion of element group was excited at once and this partial element group would be shifted for scanning. The linear scanning provides rectangular scanning area and width is limited up to aperture size of the transducer. In the sector scanning, all of elements were excited with a sequence of excitations. The ultrasonic beam can be steered to and focused at any arbitrary point in sectorial area beyond the transducer according to calculated delay time of pulse excitation of elements. The sector scanning provides scanning region of larger area than the linear scanning compared to aperture of the transducer due to the dynamic beam steering. In this study, the numbers of elements in the array transducer was 64 and 16 elements of them were activated for the sector scanning and one group in the linear scanning.

3. Experimental Results and Discussion

3.1 Characteristics of Scanning Image

Ultrasonic phased array system (R/D Tech : Omni scan MX) shown in Fig. 6 drives 16 channels of transducer with multiple elements. The phased array transducer has 64 elements but just 16 elements were activated in the sector scanning. In the linear scanning, all of elements were used in whole scanning sequence to obtain cross section image but just 16 elements excited at once with offsetting group of elements shifting step by step. In the sector scanning, each element was excited after delay time calculated for each element. The ultrasonic beam was steered to arbitrary azimuth angle for dynamic beam steering. In the linear scanning, the beam angle was fixed because the delay times were constant. Therefore, the linear scanning provides rectangular images. In addition, angle beam scanning is available in the linear scanning with

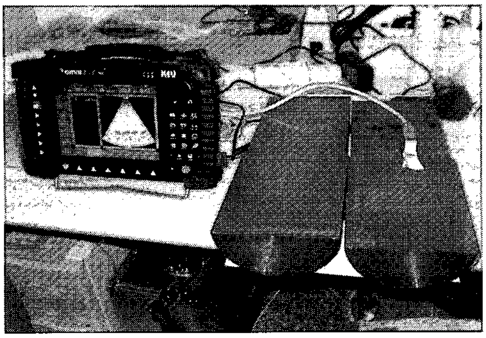
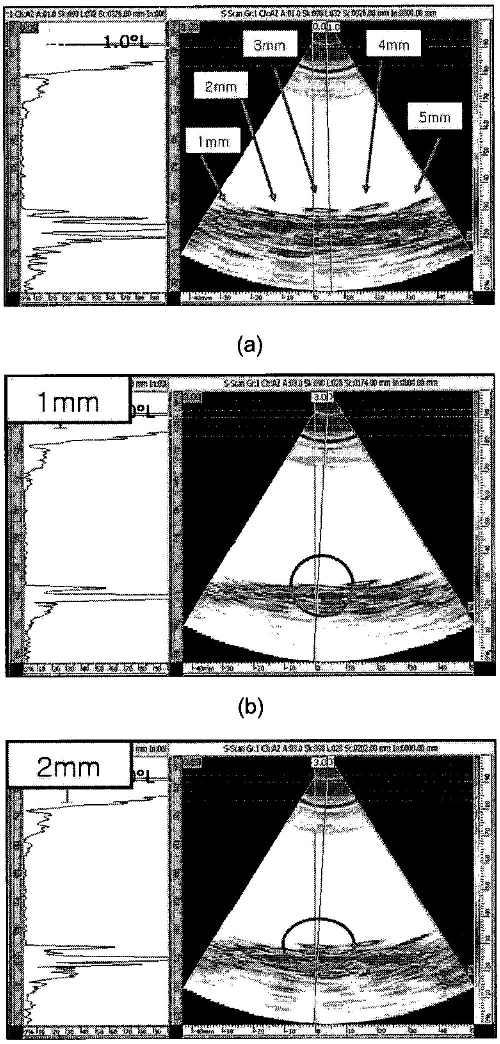


Fig. 6 Phased array system for inspection of stud bolt model



(a) (b) (c)

Fig. 7 Inspecting images of stud bolt by sector scanning (a) defect depth: 1, 2, 3, 4, 5 mm; (b) defect depth: 1 mm; (c) defect depth : 2 mm

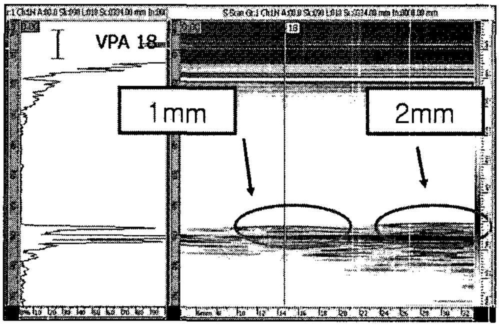
constant beam angle by combination of beam steering from the sector scanning and offsetting from the linear scanning and provides parallelogram scanning image. The frequency of the phased array transducer is 5 MHz, inter-element spacing is 0.6 mm and the width of element is 0.52 mm.

3.2 Sector Scanning

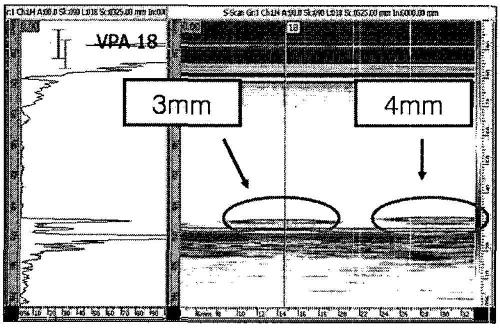
Cross section scanning images of stud bolts were shown in Fig. 7 obtained from the sector scanning. Since the ultrasonic beam was steered wide region by the phased array method, the phased array system inspects large area at once. In these results, ultrasonic beam scanned over 80 mm in axial direction of stud bolts. The outer surface was represented with higher amplitude in result scanning images. There were five sizes of defects from 1 mm to 5 mm in one scanning image as shown in Fig. 7 (a). However, axial resolution became worse by increasing the beam steering angle. Some defects of which depths are not less than 3 mm could be detected reasonably but the other defects of which sizes are 1 mm and 2 mm could not detected because of bad resolution in axial direction. Since signal reflected from small defect was overlapped with signal reflected from outer surface of stud bolts. The axial resolution should be enhanced to distinguish signal reflected from small defect from signal reflected from outer surface. The phased array transducer was moved to locate smaller defect on center region of scanning area to increase detectability of small defects for 1 mm and 2 mm defects as shown in Fig. 7 (b) and (c). Since the resolution of ultrasonic beam is better at center than left and right side in scanning field. Small defects of which size are 1mm and 2 mm could be distinguished from outer surface of stud bolt in Fig. 7 (b) and (c). However resolution for larger defect such as 3mm defect in Fig. 7 (b) and 4mm defect in Fig. 7 (c) became wore due to wore directivity of the ultrasonic beam by the increasing steering angle. The width of defect in scanning image was about 10 mm, however the artificial defect is very thin less than 0.3 mm. This estimating error in sizing width was caused from weak focus effect at defect area. Since focal length was too long, aperture size of the transducer should become large by increasing the number of elements and the inter-element spacing as studied by Lee *et al.* (2000). However, the number of channel was limited by 16 and the inter-element spacing was limited lower than half wavelength, in this study.

3.3 Linear Scanning (Straight Beam)

In the sector scanning, signal resolution in axial direction was varied due to the steering angle of the ultrasonic beam, but the linear scanning provides invariable resolution during scanning in whole region. In order to inspect stud bolts with homogeneous resolution, the linear scanning was applied in this study. There were five defects inspected on one scanning image in the sector scanning. However, there were just two defects inspected on one scanning image in the linear scanning method as shown in Fig. 8. The range of scanning image was no more than 30 mm in lateral direction. Since the dynamic beam steering was not used in the linear scanning, scanning range could not be so wide as scanning range in the sector scanning. Benefit of the linear scanning is invariant resolution in scanning. Defects of which depth were 1 mm and 2 mm were distinguished well from outer surface of the stud bolt as shown in Fig. 8 (a). Size of defect that was depth of defect was evaluated from distance from outer surface of the stud bolt to the defect tip. The distance was increased as the increase of the defect size such as 3 mm and 4 mm as shown in Fig. 8 (b). The width of defect was oversized because of low focusing effect due to small aperture of the transducer. It is same situation of sector scanning because the number of active element was 16. The number of elements or the inter-element spacing should be increased to enhance resolution in scanning direction.



(a)



(b)

Fig. 8 Inspecting images of stud bolt by linear scanning (a) defect depth: 1 mm & 2 mm; (b) defect depth: 3 mm & 4 mm

3.4 Linear Scanning (Angle Beam)

The angle beam could be available in the linear scanning by importing beam steering of the sector scanning technique. The ultrasonic beam was steered and fixed at 30° by controlling delay time of each element excitation. Therefore, shape of scanning image is a parallelogram as shown in Fig. 9. There were numerous oblique line patterns which were caused from reflection of ultrasonic waves from each oblique surface of the thread. If there was defect at the thread, defect signal was found at upper region of these oblique line patterns, marked with circle in Fig.

9. When the size of defect was more than 3 mm, shadow effect could be expected, as shown in Fig. 9 (c) and (d). Each oblique line represents the oblique surface of the thread. One of oblique lines was omitted by shadow of defect when the size of defect was 3 mm and 4 mm. In addition, length of these oblique lines under the defect was shortened also. There was low amplitude region under oblique line pattern by shadow effect as similar to A-scan signals acquired from conventional UT using the shadow effect technique as recommended in ASME Boiler and Pressure Vessel Code Section XI. Therefore, the defect was inspected by the signal upper region of the oblique line pattern and low amplitude region by shadow effect. Benefit of this linear scanning with angle beam is application of shadow effect on real time scanning image using the array transducer.

Since the number of element was limited to 16, focusing effect was weak and resolution was not enough to evaluate width of defects. The number of elements and inter-element spacing of the linear array transducer should be increased to improve focusing ability of the ultrasonic beam and to enhance resolution of scanning images.

4. Conclusions

For the purpose of reducing time consuming at inspecting the stud bolt during the overhaul of the nuclear power plant, the phased array technique was applied in evaluation of the stud bolts used for fastening the reactor vessel and head. The sector scanning covered largest region at one scanning. However, the axial resolution was varied due to the variation of azimuth angle in beam steering. Best resolution was provided at center of scanning region and resolution became worse as the increase of steering angle to left and right side.

In the linear scanning with straight normal

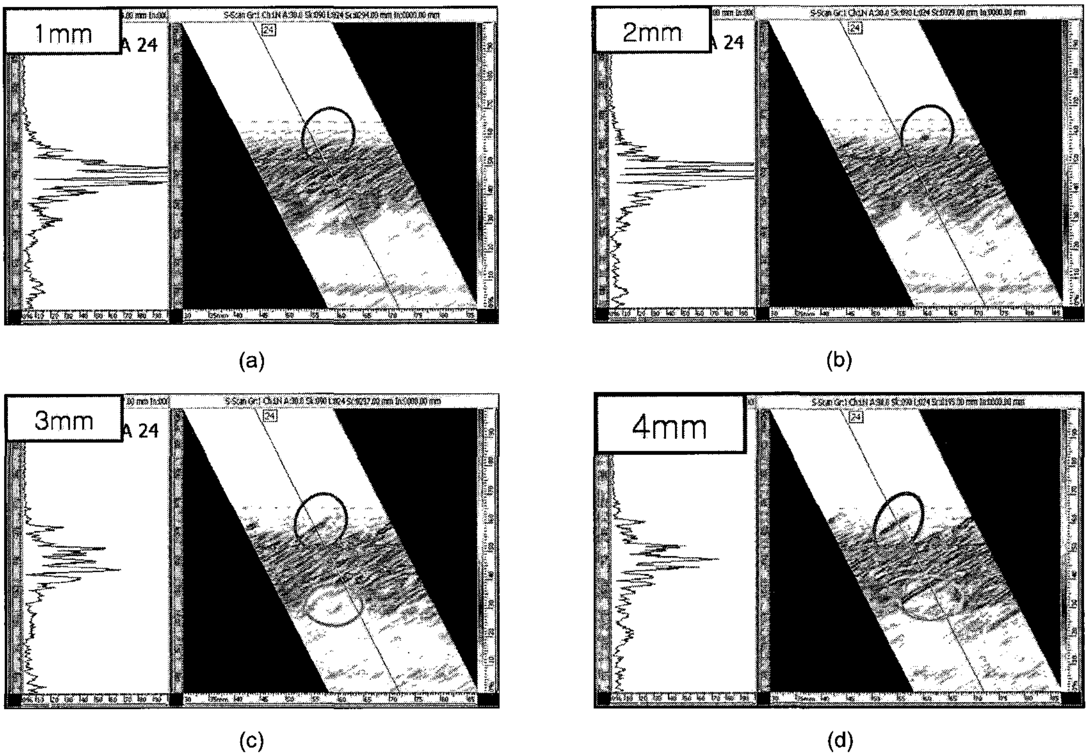


Fig. 9 Inspecting images of stud bolt by linear scanning using angle beam (a) defect depth : 1mm; (b) defect depth: 2 mm; (c) Defect depth: 3 mm; (d) defect depth: 4 mm

beam, ultrasonic images were constructed with invariant lateral resolution in ultrasonic scanning and it provided better detectability of smaller defect. However, scanning region through the linear scanning was limited by the total number of elements in the linear array transducer.

In the linear scanning with angle beam, benefits of the conventional shadow effect technique and the linear array scanning were available simultaneously in inspecting cracks in the stud bolts. The crack was detected from two features in images such as reflecting signal on upper region of the oblique line pattern and low amplitude region of the line pattern caused by shadow effect.

The width of defect was overestimated because of weak focusing effect due to the long focal length in all of sector scanning and linear scanning. Therefore, the focusing of ultrasonic beam should be improved by the increase of the number of element and inter-element spacing within optimal design condition for the enhancement of resolution.

Acknowledgements

This study was supported by research grant from Pusan National University.

References

ASME (1989) ASME Boiler and Pressure Vessel Code Section XI Rules for Inservice Inspection of Nuclear Power Plant Components, The American Society of Mechanical Engineers, New York, New York.

Suh, D. M., Kim, W. W. and Chung, J. G.(1999), Ultrasonic Inspection of Studs (bolts) Using Dynamic Predictive Deconvolution and Wave Shaping, IEEE Transaction on Ultrasonics, Ferroelectrics and Frequency Control, Vol. 45, No.2, pp. 457-463.

Lee, J. H. and Choi, S. W.(2000), A Parametric Study of Ultrasonic Beam Profiles for a Linear Array Transducer, IEEE Transaction on Ultrasonics, Ferroelectrics and Frequency Control, Vol. 47, No. 3, pp. 644-650.

Lee, J. H. and Choi, S. W.(2000), Optimum Design of Linear Array Transducer for NDE, Key Engineering Materials, Vol. 183-187, pp. 619-624.

Oh, W. D., Lee, J. H., Choi, S. W. and Park, M. H.(2004), Detection of Cracks in Stud Bolts of Nuclear Reactor by Novel Ultrasonic Technique, Key Engineering Materials, Vol. 270-273, pp. 2284-2289.

Choi, S. W., Lee, J. H. and Oh, W. D.(2005), Ultrasonic Inspection of Cracks in Stud Bolts of Reactor Vessels in Nuclear Power Plants by Signal Processing of Differential Operation, Journal of KSNT, Vol. 25, No. 6, pp.439-445.