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Ultrasonic Inspection of Cracks in Stud Bolts of Reactor Vessels in Nuclear Power Plants by Signal Processing of Differential Operation

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Abstract The stud bolt is one of crucial parts for safe operation of reactor vessels in nuclear power plants. Crack initiation and propagation were reported in stud bolts that are used for closure of reactor vessel and head. Stud bolts are inspected by ultrasonic technique during overhaul periodically for the prevention of stud bolt failure which could induce radioactive leakage from nuclear reactor. In conventional ultrasonic testing for inspection of stud bolts, cracks are detected by using shadow effect. It takes too much time to inspect stud bolts by using conventional ultrasonic technique. In addition, there were numerous spurious signals reflected from every oblique surfaces of thread. In this study, the signal processing technique for enhancing conventional ultrasonic technique was introduced for inspecting stud bolts. The signal processing technique provides removing spurious signal reflected from every oblique surfaces of thread and enhances detectability of defects. Detectability for small crack was enhanced by using this signal processing in ultrasonic inspection of stud bolts in Nuclear Power Plants.

Keywords: ultrasonic testing, nuclear power plant, stud bolt, signal processing, crack, shadow effect

1. Introduction

The reactor vessel is one of crucial components of nuclear power plants. The reactor vessel body and closure head are fastened with stud bolt as shown in Fig. 1 (a). In maintenance of nuclear power plants, the inspection of the reactor vessel and its components is limited to be carried out only in overhaul. Typical defect of stud bolts is fatigue crack initiated from the root of thread. In conventional ultrasonic testing of stud bolt, special ultrasonic transducers which have cylindrical shape are inserted in bore hole of stud bolt to inspect stud bolt as shown in Fig. 1 (b). The special ultrasonic transducer is single element transducer and has fixed refraction angle (60°). The crack is too small to detect it in its early stages. It could grow during the long overhaul interval and cause a failure of stud bolt.(Suh et al., 1999) However, detection of this type of small cracks is very difficult due to iterative signals reflected from the bunch of inclined surfaces of the thread. Recently, it was required to increase efficiency of nuclear power plant for the decrease of time spent for inspection for safety and evaluating residual life of component in overhaul of the nuclear power plant.(Choi et al. 2004) Therefore, inspecting stud bolt should be conducted with high speed and accuracy.

Ultrasonic testing is one of the widely used techniques because it is sensitive to most flaws,

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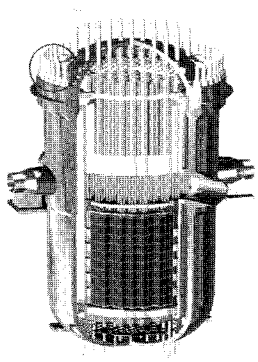
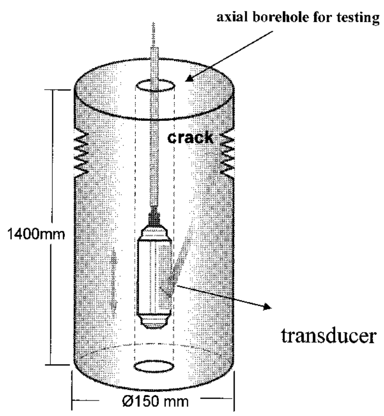
with no radiation hazardous and gives many features for flaw characterization. It is also expected to detect small cracks in the thread region without remove of studs and bolts using ultrasonic test. For these reasons the stud bolts in reactor vessels are inspected periodically by ultrasonic technique at many sites of nuclear power plants.



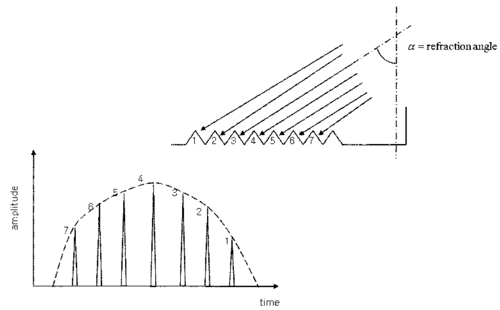
(a) Reactor vessel



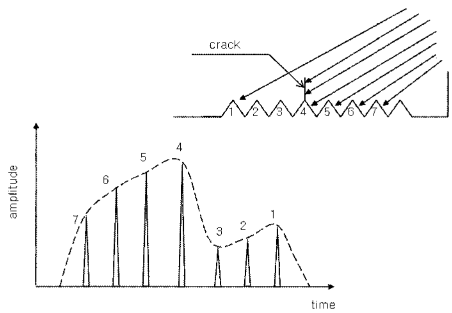
(b) Inspection of stud bolt

Fig. 1 Reactor vessel and stud bolt

In general, the shadow effect technique has been used for inspecting flaws in stud bolts according to ASME Pressure Vessel and Boiler Code Section XI (1989). The shadow effect technique is that the ultrasonic signals reflected from threads in front of the crack are clearly indicated whereas the ones immediately behind the crack are hidden in its shadow, as shown in Fig. 2. The ultrasonic beams generated from transducer are reflected at the inclined surfaces of threads, and return to the transducer from thread 7 to thread 1 in distance order, as shown in Fig. 2 (a). However, the crack interrupts the path of ultrasonic wave and the amplitudes of thread 2 and 3 decreases suddenly as shown in Fig. 2 (b). From this abnormal decreasing of amplitude, the flaw signals can be distinguished from normal waveforms of threads. The main objective of this study is to establish new methodology based on shadow effect technique combined with new signal processing technique for evaluating small crack in stud bolts by extracting pure distortion of signals due to crack.



(a) Signals from defect free threads



(b) Shadow effect due to a crack

Fig. 2 Shadow technique to detect crack in stud bolts

2. Experimental Methodology

2.1 A new approach for signal processing

The waveforms from thread roots include the sound thread signals and crack signals with some measurement noise. Suh et al. (1999) used deconvolution signal processing method that removes repetitive spurious thread signals with constant period to extract flaw signal from complicate signals. However, this method is not efficient for inspection of stud bolts since the time interval from each oblique surface of thread is not same and some errors can be occurred. Oh et al. (2004) proposed that whole signal waveforms received from threads are used to remove spurious signal and to extract only distortion components due to existing crack. The key idea of this novel method is based on the fact that the shape of whole waveforms from threads is uniform since the intervals of the threads in a bolt are same, even interval between each signal reflected from each oblique surface is not same in time domain signal. The novel signal processing technique uses the invariable waveforms as reference signal. If some cracks exist in the thread, the waveforms from the flaws are distorted because of the shadow effect. By the signal processing, these distorted flaw signals are separated purely through subtraction of the reference waveforms. The basic concept for signal processing is represented in Fig. 3.

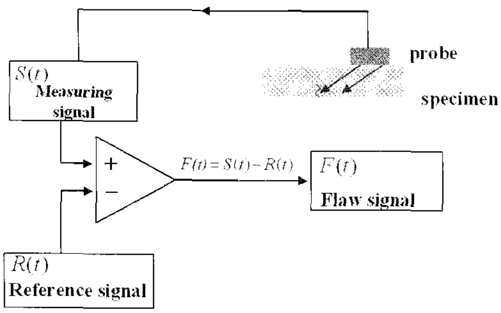


Fig. 3 Schematic diagram of signal processing

When $S(t)$ is ultrasonic signal in time domain which may contain distortion due to residence of the crack and $R(t)$ is the reference waveform reflected from normal threads, the flaw signals, $F(t)$ are extracted by differential operation processing of subtracting $R(t)$ from $S(t)$ as shown in Eq. (1).

$$F(t) = S(t) - R(t) \tag{1}$$

2.2 Experimental procedure

The real stud bolts used in the reactor vessels have an axial borehole as shown in Fig. 1(b). There are special probes of which shape is cylindrical inserted inside of the bore hole to inspect the stud bolt as shown in Fig. 4.

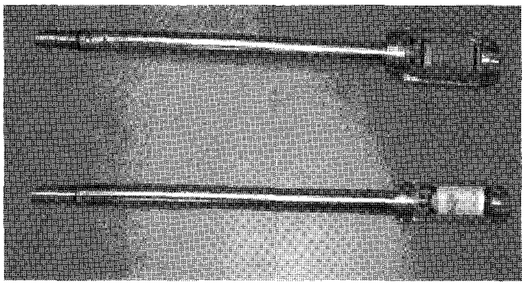
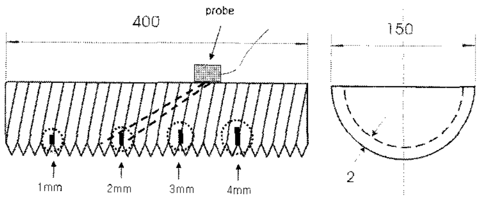
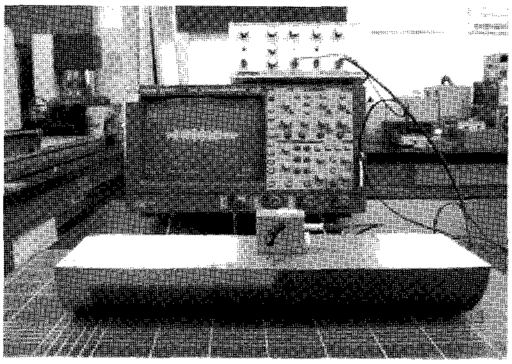


Fig. 4 Special probe for inspection of the stud bolt

Since these special ultrasonic transducers are single element transducers and have fixed refraction angle (60°), various inspection condition of the ultrasonic transducer could not be applied. To develop the signal processing technique, stud bolt specimens were simplified for using conventional universal angle ultrasonic transducer as shown in Fig. 5. These specimens have half circle cross-section and flat surface parallel to axis. Diameter of these specimens is 150 mm and length is 400 mm as shown in Fig. 5 (a). Artificial defects with the sizes from 1 mm to 5 mm with 1 mm step in depth and supplementary 0.5 mm was fabricated with EDM method. The specimen was made of carbon steel that is same material used for the stud bolt in reactor vessel of nuclear power plant. A commercial 4 MHz transducer which has the variable incident angle was used to generate ultrasonic wave in the test specimen instead of the special probe as shown in Fig. 5 (b). The experimental system comprised a digital oscilloscope (LeCroy9310A), pulse/receiver (JSR-PR35), universal angle beam transducer (KrautKramer) and specimen. Measurements were taken by moving the transducer on the top surface of the specimen.



(a) Simplified stud bolt specimen with artificial defects



(b) Experimental set-up

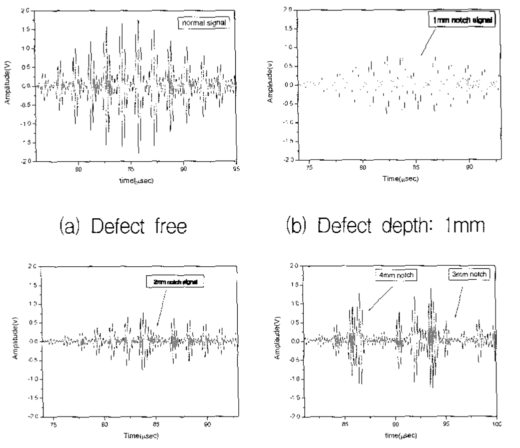
Fig. 5 Dimension of specimen and experimental set-up

The velocities of the longitudinal and the transverse waves in test specimen were measured, considering the first and second critical angles. Therefore, incident beam angles used in this study were between the two critical angles to generate shear wave without longitudinal wave. The optimum beam angle depends on the shape of the thread. Generally, the refracted beam angle for evaluation of stud bolt is 60° that is perpendicular direction to the inclined plane of thread. The ultrasonic wave was generated at various refraction angles (50°, 60°, 65° and 70°) and the waveforms were compared with each other for verifying the optimal refraction angle. In order to understand the effective use of shadow effect technique for the detection of very small size of crack that is made as notch slot, ultrasonic testing was conducted on the different sizes of defects, and the results were compared. The signal processing technique was carried out for the detection of small flaw by operation in the digital oscilloscope.

3. Experimental Results and Discussion

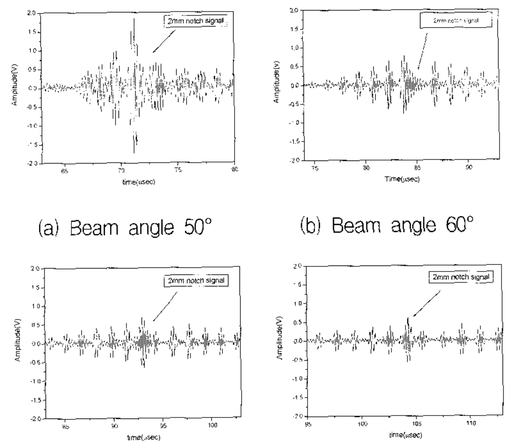
The oblique angle of thread is 30° and the oblique plane of thread is normal to the ultrasonic wave of which refraction angle is 60°. There are multiple echoes reflected from each oblique plane of thread as shown in Fig. 6. When there was a defect in the stud bolt, it was detected by reducing amplitude of ultrasonic wave reflected thread behind of defect due to the shadow effect. However this small defect could not be detected easily and it is impossible to inspect smaller defects because there are numerous echoes reflected from oblique surface of thread and defect signal could not be distinguished from these spurious thread signals.

Generally, refraction angle is 60° for inspection stud bolt and the typical waveforms were compared with variation of defect depths as shown in Fig. 6. If there was no defect, the amplitude distribution of received signals reflected from oblique surfaces of thread has simple, such as Gaussian distribution in time domain. When the ultrasonic beam was directed to defects, some portion of ultrasonic wave was terminated due to defects by shadow effect. Therefore the reflected ultrasonic signal was decreased, as shown in Fig. 6 (c) and (d) which is ultrasonic waveform detect defects of which depths were 3 mm and 4 mm or 2 mm respectively. It can be shown that the decreasing amount of ultrasonic signal is depend on depths of defects. However, the decrease of ultrasonic signal could not be recognized for the smaller defect like 1mm as shown in Fig. 6 (b).



(a) Defect free (b) Defect depth: 1 mm (c) Defect depth: 2 mm (d) Defect depth: 3 mm and 4 mm

Fig. 6 Typical waveforms at refraction angle 60°

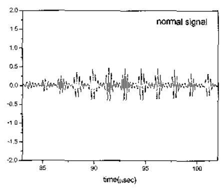


(a) Beam angle 50° (b) Beam angle 60° (c) Beam angle 65° (d) Beam angle 70°

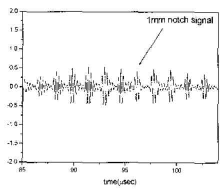
Fig. 7 Ultrasonic waveforms due to variation of refraction angles (defect depth: 2 mm)

The signal characteristics were analyzed due to variation of the ultrasonic beam angle, as shown in Fig. 7. When the refraction angle is 50° as shown in Fig. 7 (a), the amplitudes of the waveforms are highest since the traveling path of ultrasonic beam from the probe to the thread decreases with the refraction angle decreasing and it makes attenuation effect weak. However, when the refraction angle is 50°, it is difficult to distinguish the flaw signal because shadow by small defect is not effective to obscure next thread signal. In the case of the refraction angle 60° as shown in Fig. 7 (b), the shadow effect is better than previous Fig. 7 (a). When the refraction angles are 65° and 70° as shown in Fig. 7 (c) and (d) respectively, the number of thread signals obscured by the crack became larger than the one at refraction angle 60° since the projected shadow area increases with the refraction angle increasing. However, the amplitudes of echo reflected from thread and defect decreased since attenuating became stronger by alignment of ultrasonic beam went out of normal direction to the thread with the traveling path increase. In case of large crack, the flaw signals were well distinguished by shadow effect as the refraction angle increases.

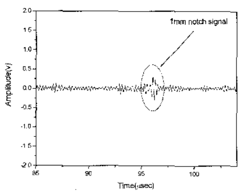
Defect should be detected by shadow effect as shown in previous result waveform. However, a defect of which size is 1.0 mm could not be detected as shown in Fig. 6 (b), since the shadow effect caused by the small defect was weak and signal variation due to the weak shadow effect could not be distinguished from spurious signals reflected from oblique surfaces of thread. In order to distinguish defect signal from regular signal, signal reflected from normal thread should be removed. For enhancement of extracting defect signal, differential operation signal processing was introduced. Firstly, normal signal received for sound region of stud bolt without defect was stored as reference signal as shown in Fig. 8 (a). Then, the measuring signal interfered by defect was received, as shown in Fig. 8 (b). Finally, subtraction between the reference signal and measuring signal was carried out, as described in Eq. (1). The resultant waveform of subtraction is shown in Fig. 8 (c) which shows only defect signal without spurious thread signal. Detectability of small defect was enhanced by differential operation signal processing through subtraction of reference signal. Visibility of defect signals was enhanced by removing signals of spurious ultrasonic waves reflected from sound thread by using differential operation signal processing. In conventional ultrasonic testing using shadow effect technique, inspector should monitor waveform carefully and consumed much time for distinguishing defect signal. However, this differential operation signal processing provide defect signal clearly therefore inspection speed and accuracy were enhanced.



(a) Reference ultrasonic waveform without defect



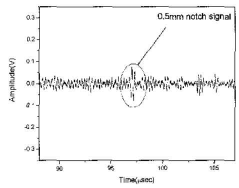
(b) Typical ultrasonic waveform with 1mm defect



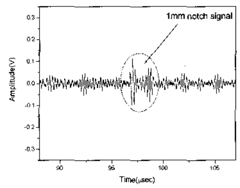
(c) Extracted defect signal through differential operation signal processing technique

Fig. 8 Extraction of defect signal through differential operation signal processing technique

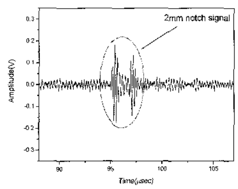
Differential operation of signal processing extract only defect signal by subtraction of reference signal waveform which is reflected ultrasonic wave from sound thread. Therefore, the defect could be inspected more clearly and detectability was increased as shown in Fig. 9. Defect of which size is 1.0 mm is too small to detect in raw ultrasonic waveform by using shadow effect as shown in previous result, Fig. 6. However, differential operation of signal processing makes it detectable and smaller defect like defect of which size is 0.5 mm could be detected as shown in Fig. 9 (a). In addition, differential operation signal processing makes evaluation of defect size easy compared with conventional shadow effect technique. The amplitude and the width of defect signal increased gradually due to increasing size of defect as shown in Fig. 9. There was one echo signal received for 0.5 mm defect. There were two echo signals received for from 1.0 mm to 2.0 mm defects and amplitude of 2.0 mm defect was higher than that of 1.0 mm defect. There were three echo signals received for 3.0 mm defect and the amplitude is highest than those of other size defects.



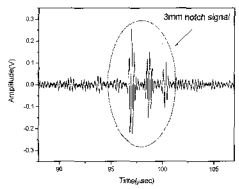
(a) Defect depth : 0.5mm



(b) Defect depth : 1.0mm



(c) Defect depth : 2.0mm



(d) Defect depth : 3.0mm

Fig. 9 Extracted defect signals through differential operation signal processing due to the variation of defect depth

4. Conclusions

The variation of ultrasonic beam angle and the signal processing technique were developed for the enhancement of efficiency of inspection of the stud bolt in the nuclear power plant.

In conventional ultrasonic technique using shadow technique with variation of ultrasonic beam angle, the shadow effect for the detection of the cracks in the thread was stronger but signal amplitude was decreased. Therefore, variation of ultrasonic beam could not be applied for enhancement of detectability for defect in the stud bolt by using shadow technique.

In order to increase detectability of smaller cracks initiated from the root of threads in the stud bolt, the shadow effect technique combined with differential operation signal processing was introduced in this study. The differential operation of signal processing technique based on subtraction of reference waveform received for sound thread from the measured waveform with flaw. It was found that the proposed technique can be an effective tool for the detection of relatively small crack, whereas conventional technique was not detectable.

Acknowledgement

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