ADVANCED ULTRASONIC FLAW SIZING OF STRESS CORROSION CRACKING IN THICK STAINLESS STEEL

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Abstract: The TOFD (Time-of-Flight Diffraction) method is the one of the most accurate flaw sizing methods. This study aimed to increase the sophistication of the TOFD system by utilizing time-frequency analysis (wavelet transform) for flaw sizing on thick stainless steel welds. A wavelet algorithm was implemented into our TOFD system, and a preliminary test was conducted for a 46.2 mm-thick stainless steel specimen with an artificial penetration slit (0.8 mm width, 8.4-9.9 mm height). As a result, we found that the frequency component of the three main echoes observed used for sizing (lateral wave, diffraction echo and back surface echo) were different. This feature can be effectively used for signal type classification during flaw size testing. The crack depth was measured by using the extracted specific frequency component of TOFD signals by wavelet transform. We confirmed that the sizing accuracy of the proposed method is similar to the traditional method using raw data. Finally, a weld joint austenitic stainless steel specimen with stress corrosion cracking was prepared for a feasibility study. Crack tip diffraction echoes can be separated from other waves by the proposed method, and the S/N ratio of the detected signal was enhanced by our method. Overall, the method proposed in this study makes relevant contributions to the flaw sizing of thick stainless steel (especially at welds).

1. INTRODUCTION
Accurate ultrasonic flaw sizing is an important issue for predicting the remaining life of industrial plants such as atomic power plants [1]. The TOFD (Time-of-Flight Diffraction) method is said to be one of the most accurate flaw sizing methods [2]. The TOFD method is not based on the amplitudes of echoes, but uses the travel time of a diffracted wave at the crack tip to determine crack depth. However, the method is not applicable to thick steels due to the amplitude of the crack tip diffraction echo being weak, and that this weak echo is attenuated in thick materials. Moreover, when the TOFD method is utilized for austenitic stainless steel welds, the ultrasonic beam is subjected to many perturbations: deviation, partition, distortions and sometimes ghost echoes due to the anisotropic and heterogeneous metallurgical structures of welds [3]. When ultrasonic flaw sizing is carried out, it needs to distinguish the main echoes (crack tip diffraction echo, surface back echo and lateral wave) from other many perturbations. Following this, signal type classification of the three types of main echoes is also required. A high level of skill and knowledge is required for this discrimination [4]. Hatanaka et. al., [5] used discrete wavelet transform as post-processing for TOFD signals detected on 9% of nickel steel weld joints. They reported that flaw indications in D-scan images were remarkably clear using their approach. E. P. Moura et. al., [6] used continuous wavelet transform for preprocessing of TOFD signals for pattern recognition of weld defects. In this study, in order to enhance the S/N ratio of TOFD signals and to provide additional significant information for discrimination of the main echoes, the usefulness of continuous wavelet transform is examined.

2. SPECIMEN AND PRINCIPLE OF TOFD TECHNIQUE
Figure 1 schematically shows the principle of the TOFD technique (upper) and an A-scan image of a TOFD signal (bottom). The technique utilizes two transducers, one as a transmitter and the other as a receiver. The first echo to reach the receiving transducer corresponds to the lateral wave (indicated by “L” in the figure). If there is a crack in the specimen, a weak amplitude of the crack tip diffraction echo (indicated by “D”) will be observed in front of a large amplitude of the back wall echo (indicated by “B” in the figure). The crack height can be estimated by using the arrival time differences between these echoes. Figure 2 shows a picture of
transducers mounted on a specimen (45.3mm×200mm×46.2mm) made of austenitic stainless steel (SUS304) with a penetration slit (0.8 mm width, 8.4-9.9mm height). A pair of commercial longitudinal ultrasonic transducers for the TOFD method (5MHz in the center frequency and 60 degrees of incident angle, Japan probe: B5K5 X 5LA60) was used for these measurements. The distance between the two transducers was set at 96 mm. Detected signals were digitized by an A/D converter (sampling frequency: 100 MHz) and fed to a computer to be analyzed by software especially developed for this study.

Fig. 1 Principle of the TOFD technique (upper) and typical A-scan image (bottom).

Fig. 2 Specimen with a penetration slit and the experimental setup.

**3. ADVANCEMENT OF TOFD TECHNIQUE USING WAVELET TRANSFORM**

Figure 3 shows TOFD signals observed on the specimen where the distance of crack tip from surface is 37.5mm. The symbol “L” indicates a lateral wave, “D” a diffraction echo and “B” the back wall echo. In spite of the small amplitude of noise signals observed between “L” and “D” signals, sharp peaks of “L” and “D” signals were observed. Crack depth (distance between the crack tip and the front surface) was estimated using arrival time differences between the “L” and “D” signals. When the first peaks (L1 and D1 in Fig. 3) were used for the estimation, the crack depth was estimated as 37.6 mm. On the other hand, when the second peaks (L2 and D2) were used, a crack depth of 37.3 mm was estimated.

Continuous wavelet transform [7] of 1 MHz to 7MHz was conducted and the wavelet contour map is shown in Fig. 4. The main echoes of “L”, “D” and “B” clearly appear in the contour map, and the frequency components of “L”, “D” and “B” are clearly different. The wave “L” contains a low frequency component; hence the “D” contains a high frequency component. The wave “B” contains a wide band frequency. This feature can be effectively used for signal type classification during flaw sizing tests. Next, we attempted to estimate crack depth by using the wavelet coefficient of the TOFD signal. Since “L” and “B” waves have a 3MHz component in common, we extracted the 3MHz wavelet component by wavelet transform as shown in Fig. 5. Unlike raw signals (Fig. 3), “L” and “D” waves have a single peak. This suggests that flaw sizing independent of inspector skill and experience can be conducted using this treatment. Furthermore, there is a possibility to automate flaw sizing utilizing a computer, since it is easy to find peak arrival time for a single peak with a computer. Crack depth was estimated using arrival time differences between “L” and “D” coefficients. Crack depth estimated by these two peaks was 37.7 mm.

**Fig. 3 Observed TOFD signal for the specimen shown in Fig. 2.**

**Fig. 4 Wavelet contour map of a TOFD signal (shown in Fig. 3).**

**Fig. 5 Wavelet coefficient of a TOFD signal (shown in Fig. 3) at 3 MHz.**
Figure 6 shows a D-scan image, which is constituted by stacking multiple raw signals that are acquired scanning the transducer-receiver pair in the Y direction (see Fig. 2) on the specimen surface. The D-scan image represents a cross-sectional view of the specimen and shows the presence of defects (see “D” of Fig. 6). When the time scale of the waveform is converted to a depth scale through the thickness of the specimen, flaws can readily be sized directly from the D-scan. In Fig. 6, the arrival time of D comes early as Y (sensors position) becomes large. This represents that the crack depth becomes shallow at the point where Y is large, and this agrees with the distribution of the actual crack depth. Although it was a small amplitude, a noise signal is observed between L and D. Moreover, several peaks were observed in each echo, which may cause trouble for accurate flaw sizing. In order to overcome these two points, wavelet transform is used for constructing a D-scan image. Figure 7 shows a D-scan image constituted by stacking multiple 3MHz wavelet coefficients of TOFD signals. Although the peak of each echo became single and the S/N ratio was improved, the image became indistinct compared to the original image. This is due to the peak of the wavelet coefficient at this frequency range becoming broad. Since each echo has a single peak, a threshold value is set and peaks are emphasized. The result is shown in Fig. 8. The image is reasonably improved compared to the original one (Fig. 6).

4. FEASIBILITY STUDY USING A WELD JOINT SPECIMEN WITH STRESS CORROSION CRACKING

To investigate the feasibility of our developed system, ultrasonic testing was conducted for a weld joint austenitic stainless steel specimen with SCC (Fig. 9). An enlarged side view of the welded part is shown at upper left. The crack is traced and emphasized by a thick line. The distance of the pair of transducers is set to 34 mm and ultrasonic testing is conducted from the upper surface. Since the crack height in the specimen is unknown, the neighbourhood area on the side (5mm away from the side) was inspected and the estimation result is compared to the crack height observed from the side (21.9 mm). The actual crack height at the inspected area was estimated to be around 22 mm from this visual observation.

Figure 10 shows the TOFD signals detected at 5 mm away from the side. Several peaks are observed and it is difficult to distinguish each echo. Arrival times for the lateral wave (L) and the diffraction echo (D) estimated from the assumed crack height (around 22 mm) and the sensor distance are surrounded by the dotted line. Figure 11 shows a wavelet contour map of the TOFD signal (shown in Fig. 10). This result shows that the observed signal consists of two frequency bands. If the result of the fundamental study (Chap. 3, Fig. 4) is taken into consideration, it can be estimated that the wave packet that arrives 4.5~7.0 µsec with a low frequency is a lateral wave, while the packet that arrives 6.0~7.5 µsec with a high frequency is a diffraction echo. Figure 12 shows the extracted wavelet coefficient at 3 MHz. Two distinct peaks are
observed and the crack height estimated from these two peaks was 23.4 mm. Although the true crack height is unknown, the measured crack height (23.4mm) is similar to the crack height (21.9mm) visually observed from the side. Further examination will be needed for applying the developed system to a real crack at an actual work site.

Fig. 10 Observed TOFD signal for the specimen shown in Fig. 9.

Fig. 11 Wavelet contour map of the TOFD signal (shown in Fig. 10)

Fig. 12 Wavelet coefficient of the TOFD signal (shown in Fig. 10) at 3 MHz.

5. CONCLUSION
In this study, an advanced TOFD technique implementing a wavelet algorithm was proposed for thick austenitic stainless steel crack sizing. The results in summary are;
1) A wavelet transform algorithm was implemented for the TOFD system and a preliminary test was conducted on a thick stainless steel specimen with an artificial penetration slit.
2) It was found that the frequency components of the main echoes used for sizing were different. This feature can be effectively used for signal type classification.
3) The crack depth can be measured using extracted specific wavelet coefficients of TOFD signals. Single peaks for each echo are observed and show the possibility of automating flaw sizing utilizing a computer.
4) The D-scan image constituted by stacking wavelet coefficients with emphasis treatment is improved compared to the original D-scan image.
5) The sizing of stress corrosion cracking in a weld joint austenitic stainless steel specimen was conducted. The crack tip diffraction echo can be separated from other echoes with the proposed method. The estimated crack height was similar to the crack height visually observed from the side of the specimen.

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7. REFERENCES