ABSTRACT

This paper proposes a method to reduce noise and extract crack indications from detection signals of a 48-channel ECT system based on its signal phase characteristics. Because this 48-channel ECT system performs two kinds of scanning patterns: U-scan and T-scan, and obtains two sets of signal distributions for one scanning area simultaneously, the proposed method uses a two-stage process that includes so-called main filter and sub filter. Using these two filters imposes more strict conditions on extracting crack indications so as to reduce more noise. The experimental results show that the proposed filtering method is effective to extract only crack indications from detection signals including complicated noises.

INTRODUCTION

We have so far dealt with numerical simulations for eddy current testing (ECT)\textsuperscript{1} and designed some multi-coil ECT probes with the aid of numerical simulation for improving the detectability of the probes\textsuperscript{2}. However, in practical application, detection signals obtained with ECT sometimes include significant noises caused by the unsteady lift-off distance of a probe or local variation of conductivity or permeability of the material of a test object. These noises make it difficult to distinguish crack indications in detection signals. This paper shows phase characteristics of crack indications obtained with the multi-coil ECT system described below, and proposes a method to reduce noise and extract crack indications from detection signals of this multi-coil ECT system based on these phase characteristics.

48 CHANNEL ECT SYSTEM

System configuration

The multi-coil ECT system used for this study consists of a 48-channel ECT instrument, a multi-coil ECT probe, and a laptop PC (Fig. 1). The multi-coil ECT probe has two rows of coils that consist of 17 coils and 18 coils respectively. The probe is a transmit-receive type and uses 48 combinations of an excitation coil and a pick-up coil selected from 35 coils of the probe by the multiplexer built in this ECT instrument. Each pair of excitation and pick-up coils makes one channel. In Fig. 2, each arrow represents a pair of excitation and pick-up coils (headed from the excitation coil to the pick-up coil), and these pairs realize two kinds of scanning patterns: T-scan and U-scan. Because a strong indication appears when a pair of coils is aligned along a crack, U-scan excels in detecting a crack perpendicular to the rows of coils, and T-scan excels in detecting a crack parallel to the rows of coils. U-scan comprises channel 1 through 32, and T-scan comprises channel 33 through 48. The correspondence between the channels and the channel numbers is shown in Fig. 2 by attaching the first and last channel numbers of U-scan and T-scan to the corresponding pick-up coils.

The 48-channel ECT instrument outputs the $V_x$ and $V_y$ voltage components of ECT signals for each of U-scan and T-scan. These data are stored in the laptop PC connected to this ECT instrument. The amplitude and phase of signal voltages can be calculated from these data.
Characteristics of crack indications

Fig. 3 shows two-dimensional distributions of the \( V_x \) and \( V_y \) components of the detection voltages due to a crack of 10 mm length, 0.3 mm width and 2 mm depth in a 10 mm-thick 316 stainless steel plate obtained from numerical simulation, and also shows the Lissajous curve on the center line \( X=0 \) of these distributions. Each coil of the probe is 2.5 mm in outer diameter, 1.0 mm in inner diameter, 2.5 mm in height and 520 turns. The interval of coils in the same row is 2.6 mm, and the interval of two rows of coils is 4.6 mm. The excitation frequency is 100 kHz.

To compensate manufacturing tolerances and variations between the coils and make a reference example of the detection signals, the detection signals due to a 0.5 mm-wide and 2 mm-deep EDM slot across the full width of a 316 stainless steel reference block are used as the reference signals. The components of the detection voltages are, after inspection, multiplied by the prepared calibration coefficients which make the detection voltages due to the EDM slot of the reference block become \( (V_x, V_y) = (0, 2.0) \) for each channel. To make the sensitive directions the reference directions, the signals of U-scan are adjusted by using the detection signals when the EDM slot is perpendicular to the row of coils as the reference, and the signals of T-scan are adjusted by using the detection signals when the EDM slot is parallel to the rows of coils as the reference. In other words, a crack perpendicular to the rows of coils is in the reference direction for U-scan and in the non-reference direction for T-scan whereas a crack parallel to the rows of coils is in the reference direction for T-scan and in the non-reference direction for U-scan.

Fig. 4 shows the relations between crack depth and amplitude of crack indication and between crack depth and phase of crack indication for the 48-channel ECT system obtained from numerical simulation. The detection signals due to a 0.3 mm-wide rectangular crack across the full width of a 10 mm-thick 316 stainless steel plate were calculated while the depth of the rectangular crack was changed from 1 mm to 5 mm. The excitation frequency is 100 kHz. For the relations between crack depth and phase of crack indication, the detection
signals due to a crack not only in the reference directions but also in the non-reference direction were used for each of U-scan and T-scan.

These graphs show that the amplitude of a crack indication is saturated at the crack depth of about 3 mm, and that the phase of a crack indication does not change significantly with respect to the crack depth. The phase of a crack indication in the reference direction for each of U-scan and T-scan always has a value around 90 degrees, and the phase of a crack indication in the non-reference direction for each of U-scan and T-scan always has a value around 200 degrees. Also, almost the same results were obtained in actual experiments.

**EXTRACTION OF CRACK INDICATIONS BASED ON SIGNAL PHASE CHARACTERISTICS**

In this section, we propose a two-stage filtering method based on signal phase characteristics to reduce noise and extract crack indications in ECT signals obtained with the 48-channel ECT system described in section 2.

Because, as shown in Fig. 4 (b), the phase of a detection signal induced by a crack is always in a certain small range, a crack indication is identified by focusing on its phase. Noises, indications caused by the other factors, are filtered out by cutting off the signals whose phase is out of a range given for identifying a crack. Because the phase of a crack indication in the reference direction always has a value around 90 degrees, the phase range for filtering may be set to be 60 to 120 degrees, which has 30-degree margins for 90 degrees. Note that this process results in extracting crack indications...
only in the reference direction for each of U-scan and T-scan. Just to apply this process reduces most of simple noises in ECT signals. However, noises caused by a composite factor sometimes have a phase value within a phase range specified for indentifying crack indications. This may result in remaining noise over a wide area of a filtered signal distribution. To solve this problem, we extended the above-explained filtering method.

Because the phase of a crack indication in the non-reference direction always has a value around 200 degrees, we also use this property to add one more condition for identifying a crack indication. The reference direction for one of the two scanning patterns is, at the same time, the non-reference direction for the other scanning pattern. The 48-channel ECT probe performs two kinds of scanning patterns and obtains two sets of signal distributions for one scanning area simultaneously, which makes it possible to use a two-stage filtering method that includes so-called main filter and sub filter. While the main filter uses the phase information of the same scanning pattern by which the target signals are obtained, the sub filter uses the phase information of the other scanning pattern for the target signals. Using these two filters imposes more strict conditions on extracting crack indications so as to reduce more noise. The phase range of the main filter is set to be 60 to 120 degrees as mentioned above. The phase range of the sub filter is set to be 180 to 240 degrees, which is determined from Fig. 4 (b).

Because U-scan and T-scan have the different channel configurations, the channel correspondence between U-scan and T-scan must be considered to use the phase information of the other scanning pattern for the sub filter.

RESULTS

This section shows two examples of application of the filtering method explained in the previous section.

A stainless steel plate with cracks in a weld line

Fig. 5 shows a 304 stainless steel plate that has two EDM cracks in a weld line. One crack extends along the weld line, and the other crack extends across the weld line. The probe was moved across the weld line when the surface of this stainless steel plate was inspected with the 48-channel ECT system. Then, a signal distribution of T-scan was used for a crack along the weld line, and a signal distribution of U-scan was used for a crack across the weld line. The excitation frequency is 100 kHz. Fig. 6 shows the original amplitude and phase distributions and the amplitude distribution after only the main filter was applied. The horizontal axis represents the travel distance of the probe, and the vertical axis represents the channel numbers of the probe. Indications of the weld line can be observed as well as crack indications in both original amplitude distributions.
Also, the obvious difference in phase between crack part and weld part can be confirmed. The phase tends to vary intricately where the amplitude is almost zero because the phase is easily changed by even a small noise in such a region. After the main filter was applied, indications of the weld line disappeared.

**PINC round robin specimens**

We applied the proposed filtering method to a round robin test (RRT) of the Program for the Inspection of Nickel-alloy Components (PINC), which is an international cooperative project established by the U.S. Nuclear Regulatory Commission (NRC) to assess NDE techniques for primary water stress corrosion cracking (PWSCC) in components made of Alloy 600 and related materials in nuclear power plants\(^3\).

In the PINC RRT on dissimilar metal weld, the target area to be inspected of the specimens is a weld line made of alloy 600 that connects a stainless steel safe end and a low alloy steel nozzle as shown Fig. 7 (c). Cracks that simulate PWSCC exist on the inner surface of a weld line of the specimens. As examples, we here use the results obtained from the inspection of the specimens PINC2.9 and PINC2.10 shown in Fig. 7 (a) and (b) with the 48-channel ECT system. The inner diameter of both specimens is about 300 mm.

The probe was moved along the inner surface of the weld line during the inspection of PINC2.9 and PINC2.10 with the 48-channel ECT system. The excitation frequency is 100 kHz. Fig. 8 shows two examples of amplitude distributions of the detection signals obtained from the inspection of PINC2.10. These amplitude distributions represent, starting from the left, the original amplitude distributions, those after only the main filter was applied and those after both the main and sub filters were applied. These RRT specimens gave rise to complicated noises on the detection signals obtained with the 48-channel ECT system. Applying only the main filter could not remove the noises enough, but applying both the main and sub filters successfully removed the noises.
These noises are supposed to come from the unsteady lift-off distance of the probe or local variation of conductivity or permeability of the material.

As shown in subsection 4.1, a simple noise can be eliminated by only the main filter. However, in real applications, detection signals sometimes include noises whose phase is similar to that of a crack indication, or the phase of a crack indication itself may be a little changed by noises. In such cases, using both main and sub filters is effective to extract crack indications.

We found 19 cracks out of the 21 cracks that exist in PINC2.9 and PINC2.10, but we got false calls as a crack indication in about four places for each specimen. Although the proposed filtering method requires somewhat improvement, this method can find cracks even from detection signals include complicated noises like those shown in Fig. 8.
CONCLUSION

This paper showed signal characteristics of the 48-channel ECT system introduced in section 2, and proposed a two-stage filtering method to reduce noise and extract crack indications from ECT signals based on the signal phase characteristics. The results showed that this method is effective to extract crack indications from detection signals include complicated noises.

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REFERENCES