ABSTRACT
An eddy current testing (ECT) system has been developed for inspecting nickel-based alloy weld surfaces of components in the reactor pressure vessel of nuclear power plants. The system can be applied to curved surfaces, it can discriminate flaws from other signal factors by using a combination of arrayed coils signals and it can estimate flaw length accurately by a decibel drop method. The system is applied to a mockup of core internal components and its validity is confirmed.

INTRODUCTION
Importance has come to be placed on understanding the aging of nuclear power plants, so non-destructive testing (NDT) methods has been developed for their core internal components. Of concern is stress corrosion cracking (SCC) of nickel-based alloy welds on the bottom head of a reactor pressure vessel (RPV) as illustrated in fig. 1. It is difficult to inspect the weld surface due to its curved and complex form. Therefore, the development of a more flexible inspection system was begun. In the NDT, ultrasonic testing (UT) and eddy current testing (ECT) are applied to the flaw sizing evaluation\(^1\).

ECT has been widely used for metal materials. The advantages of high detectability and high-speed response to surface-breaking flaws have been applied to practical inspections of the steam generator tubes of nuclear power plants\(^2\). However, extra development is necessary before it can be applied to weld surfaces on the bottom head of the RPV. The ECT system developed in the present work enables us to attach an ECT probe to a complex form, derive flaws and estimate their lengths. The probe consists of sensor coils regularly arranged on a flexible substrate which allows attachment to curved areas such as found for weld surfaces and vessel penetrations\(^3\). Signals are obtained as an image with sufficiently high resolution. The two detection modes of the probe allow extraction of flaw information from noise\(^4\). The system estimates flaws length and position to specify the area for flaw repair. In this paper we report on the ECT system and present verification test results.
EDDY CURRENT TESTING PROBE

To inspect components in the RPV, e.g. the CRD stub tube, a probe must be in contact with the curved surface so it needs flexibility. Therefore, we have developed a probe that can be flexibly bent. Figure 2 shows a photograph of our flexible multi-coil probe used to inspect components in the RPV. We use a flexible printed base plate, on which each coil is set and then covered with a flexible resin for shielding. The probe scans in the direction of the large arrow along the surface of the components. Two scanning modes (H-mode and V-mode) enable sensitive detection of flaws which is direction-independent. Using the probe, we are able to inspect the curved surface in the RPV.

Figure 2 - Flexible multi-coil eddy current testing probe
ECT SIGNAL ESTIMATION

Signal Discrimination
Weld surfaces of component in the RPV have changing curvature and locally uneven surfaces due to grinding. In their inspection, the probe should be scanned while it remains in contact with the weld surface. Therefore, there are some factors affecting the ECT signals as shown in fig. 3. The factors in the probe response during a lap scan are classified into the following four measurement situations:

1. Flaw disturbs eddy current conduction due to air gap of the metal.
2. Lift-off affects sensor coupling because of the distance between the coil(s) and the metal surface.
3. Uneven surface affects sensor coupling because of the change in the relative position of coils.
4. Probe bending affects sensor coupling because of the change in the relative position of coils.

Figure 4 summarizes the signal patterns obtained in these measurement situations. Based on Lissajous patterns, we found that H- and V- modes give distinctive responses depending on the situations of the probe. First, the flaw signal shows that one of the detection modes gives a high-intensity Vy signal component according to the standard crack signal, whereas the other mode displays large differences in signal amplitude and phase. Second, the lift-off of the probe gives the same signal pattern for both detection modes. Third, the uneven surface gives a small signal variation for both detection modes, and they display almost the same signal patterns. Finally, bending of the probe during the lap scan only affects the V-mode signal. Thus, our probe obtains a variety of information which is useful to classify the cause of the signals. The signal discrimination map representing signal-phase combinations of H- and V- modes at the same location shows the regions to classify the signals. The idea of signal-phase combination clearly classifies the signals into measurement situations that accompany the curved surface inspection.

Figure 3 - Signal patterns of the ECT probe
Method for Estimation of Flaw Length

It is desirable that ECT specify the area in need of flaw repair. Therefore, it is important to establish methods for evaluating the flaw length. In this work, we used the 12dB down method which is a simplified method. Figure 5 shows typical ECT waveforms measured with the probe. A feature of the decibel down method is to set an appropriate threshold level which is focused on the peak points near both edges of the signal. For the example of fig. 5, we found that the estimated length of the -12 dB threshold level agrees with the actual length.
VERIFICATION TEST OF SIGNAL DISCRIMINATION

We performed a verification test on a mockup using the ECT system. Figure 6 shows the experimental setup. The mockup used for this verification simulates the H9 and CRD stub tube welded joint explained in fig. 1. SCC flaws were fabricated on the curved surface of a nickel-based alloy weld. The flexible probe is attached to one end of the manipulator and it is simply pushed against the specimen. Then, the manipulator shifts to slide the probe. A personal computer (PC) controls the ECT main unit and evaluates the measured data by means of the signal discrimination map.

Figure 7 shows results of the flaw signal identification in the mockup. In fig. 7(a), high intensity areas were found around the SCC flaws. They also contained noise signal components, i.e., lift-off and uneven surface, etc. Our ECT system extracted the positions of the flaw signals. Figure 7(b) expresses the flaw signal positions derived from the method of the signal discrimination map in fig. 7(c). The data points in fig. 7(c) indicate the evaluated results obtained when the measured signal in fig. 7(a) was applied. We found that our signal discrimination map identified the flaw and noise signals regardless of the signal amplitude.

Figure 8 shows the results of an estimation of flaw lengths using the 12dB down method. We verified several kinds of flaws such as SCC, solidification flaws and electrical discharge machining (EDM) slits. The accuracy of the estimations was within ±3 mm. The method was able to maintain the same accuracy, irrespective of the object shape, using the flexible multi-coil ECT probe. We confirmed that ECT was suitable for length sizing by the 12dB down method.

![Experimental setup for verification](image-url)
Figure 7 - Results of flaw signal identification (Frequency: 100 kHz)

Figure 8 - Results of flaw length estimation (Frequency: 100 kHz)

CONCLUSIONS

We have developed an ECT system to inspect weld surfaces of components in the reactor pressure vessel. The ECT system can be applied to curved surfaces, it can discriminate flaws from other factors causing signals by using a combination of arrayed coil signals and it can estimate flaw length accurately by the 12dB down method. Investigation on the signals obtained by the probe flexibility and curved surface measurements led to a method of signal discrimination. The signal discrimination map representing the signal-phase combinations of H- and V- modes of the probe clearly separated flaw and noise signals independently of signal amplitude. The accuracy of the length sizing by the 12dB down method was within ±3 mm.
REFERENCES


