

# INFLUENCE OF SIGNAL-TO-NOISE RATIO ON EDDY CURRENT SIGNALS OF CRACKS IN STEAM GENERATOR TUBES

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This work presents the influence of noise originating from the tube itself on the detectability and sizing accuracy for laboratory-induced outer diameter axial cracks in nuclear steam generator tubes. The variations of signal amplitude and phase angle of the same cracks were analyzed when increasing the signal-to-noise ratio of the tube itself from 9 to 18. It was experimentally verified that the detectability for small cracks was enhanced by increasing the signal-to-noise ratio. The phase angle also rotated to a value representing the actual position and depth of a crack when increasing the signal-to-noise ratio.

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KEYWORDS : Signal-to-Noise Ratio, Detectability, Sizing Accuracy, Eddy Current Test, Stress Corrosion Crack

## 1. INTRODUCTION

Steam generator tubing is a pressure boundary between a primary coolant system and a secondary coolant system in a pressurized water reactor (PWR). These tubes have been affected by corrosion degradation such as stress corrosion cracking, intergranular attack, and pitting, and by mechanical damage such as wear and fatigue. Therefore, the detection and characterization of these defects is very important for the safety and integrity of steam generators. The eddy current test (ECT) method is widely used to detect new defects occurring in steam generator tubes and to monitor the growth of the pre-existing flaws during an in-service inspection.

The detection capability and sizing accuracy of a flaw depends on the quality of the eddy current (EC) signals. The EC signals generated from the tubes contain an undesirable signal, i.e., noise. Common noise sources are tube support structures, corrosion products, changes in tube dimensions and geometry, and probe wobble and lift-off [1-3]. The probe response associated with the material property variations, non-uniform surface conditions, and electronic noise from the test equipment can also be categorized as a noise source [1,4]. These noise signals complicate the detection and interpretation of flaw signals. In detail, the noise signal distorts the phase angle and the amplitude of the defect signal. Several approaches have

been implemented to reduce the noise and hence enhance the signal quality, including signal processing techniques [5,6], probe design modification [7], and the tube fabrication process [8].

This paper examines the influence of the noise originating from the tube itself on the detectability and sizing accuracy for outer diameter (OD) axial cracks in steam generator tubes. The influence of the signal-to-noise (S/N) ratio is discussed from the viewpoint of the phase angle and amplitude of the crack signals.

## 2. EXPERIMENTAL METHODS

Alloy 600 steam generator tubes with an outer diameter of 19.04 mm and a wall thickness of 1.06 mm were used to induce outer diameter axial cracks in a laboratory. The tubes were manufactured using a pilgering process, and finally mill-annealed at 1070°C. Each tube specimen was 20 cm long. To make a single axial crack, the OD surface of the tube was masked except an area for crack initiation. The tubes were internally pressurized at a pressure of about 200 bar, and then exposed to an oxidizing solution of 0.1M sodium tetrathionate at room temperature. The crack was made on the OD free span of a clean and straight tube. Thus, there was no interference from either tube geometry changes or sludge.

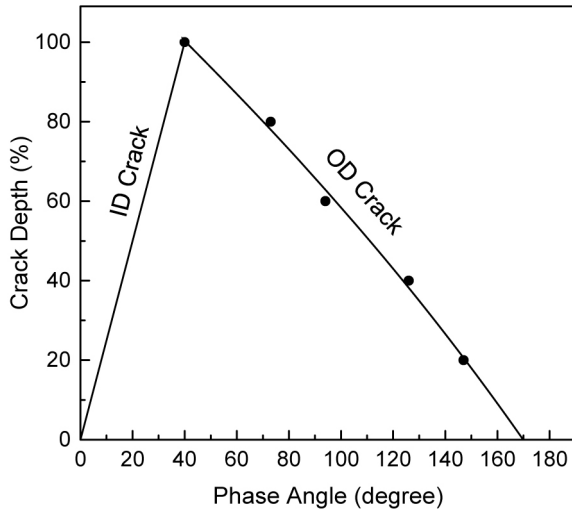


Fig. 1. Relationship Curve of Signal Phase Angle Versus Crack Depth.

The ECT signals were acquired using the Zetec MIZ-70 digital data acquisition system with a conventional bobbin coil probe, which is used for in-service inspection in PWRs. The probe is inserted into the inside of the tube and is moved along the length of the tube at a pulling speed without rotation. In this work, the tube specimens were inspected at a pulling speed of 30.5 cm/sec. The signal amplitude was calibrated to produce a peak-to-peak value of 4 V at 550 kHz in differential mode from the four 20% flat-bottom OD holes in the ASME standard. The phase angle was adjusted to 40 degrees from the 100% hole of the ASME standard. A relationship curve of the signal phase angle versus crack depth was developed using the ASME standard with 20, 40, 60, 80, and 100% OD holes. This method is standardized by ASME Code Section V, Article 8, Appendix I. The depth and position of cracks were evaluated using this curve, as shown in Fig 1. According to this curve, the phase angle of a through-wall defect is 40 degrees. The reference signal amplitude used to calculate the S/N ratio was 3.73 V, which was established according to the guidelines specified in reference 9.

To precisely evaluate the effect of the S/N ratio on the detection and characterization of a defect, only the level of noise should be changed, while the length and depth of the defect are fixed in a tube. To achieve this condition, the inner surface of the original tube with an OD crack was polished using silicon carbide paper with #400 grit. The EC signals were acquired again. The S/N ratio of the original tube was about 9, but the S/N ratio of the polished tube was enhanced to about 18 through this process.

Finally, the cracks were destructively examined to measure their actual length and depth using scanning electron microscopy (SEM). The overall experimental procedures are summarized in Fig. 2.

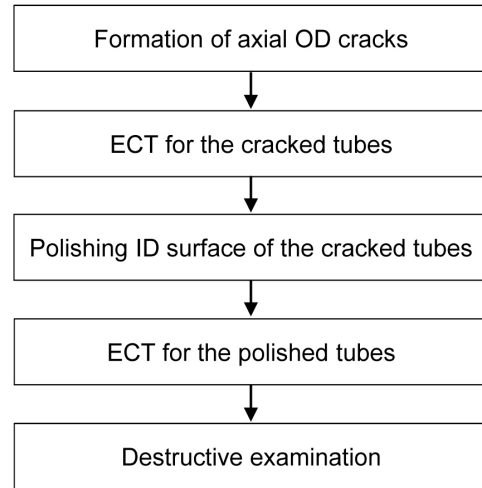


Fig. 2. Overall Experimental Procedures.

### 3. RESULTS AND DISCUSSION

Fig. 3 shows the fracture surface of OD axial cracks observed using SEM. The laboratory-induced cracks initiated and propagated along the grain boundaries, showing nearly the same nature of stress corrosion cracks occurring in operating steam generator tubes. Therefore, it was verified that these cracks are adequate for an evaluation of the detectability and sizing accuracy. The measured length and depth of each crack are summarized in Table 1.

Fig. 4 shows the EC signals of the original tubes with cracks A, B, and C at a test frequency of 550 kHz. The magnitudes of the crack signals were very small and thus these specimens were adequate to evaluate the detection and characterization capability of cracks at an early stage. The noise level of each tube was measured to be in the range of 0.42~0.44 V. Thus, the S/N ratio was calculated to be about 9 on all three tubes. Fig. 4(a) shows the EC signal of crack A with a length of 2.25 mm and a depth of 62.2%.  $V_{max}$  and  $V_{pp}$  of the crack signal were measured to be 0.06 V and 0.28 V, respectively. Here,  $V_{max}$  and  $V_{pp}$  indicate the vertical component and peak-to-peak amplitude of a crack signal, respectively.  $V_{pp}$  incorporates the noise signal, and this crack is also located on the trace toward the negative direction of the large noise signal. Therefore,  $V_{pp}$  was measured to be large, although  $V_{max}$  was very small. Fig. 4(b) shows the EC signal of crack B with a length of 1.64 mm and a depth of 68.9%. Although a  $V_{max}$  score of 0.09 V was very small,  $V_{pp}$  was measured to have a large value of 0.21 V. This is because the crack was generated on the trace toward the positive direction of the large noise signal. Fig. 4(c) shows the EC signal of crack C with a length of 2.88 mm and a depth of 88.7%.  $V_{max}$  and  $V_{pp}$  of this crack signal were measured to have similar values of 0.12 V and 0.13 V, respectively. That is, the signal amplitude  $V_{pp}$  was not affected by the noise.

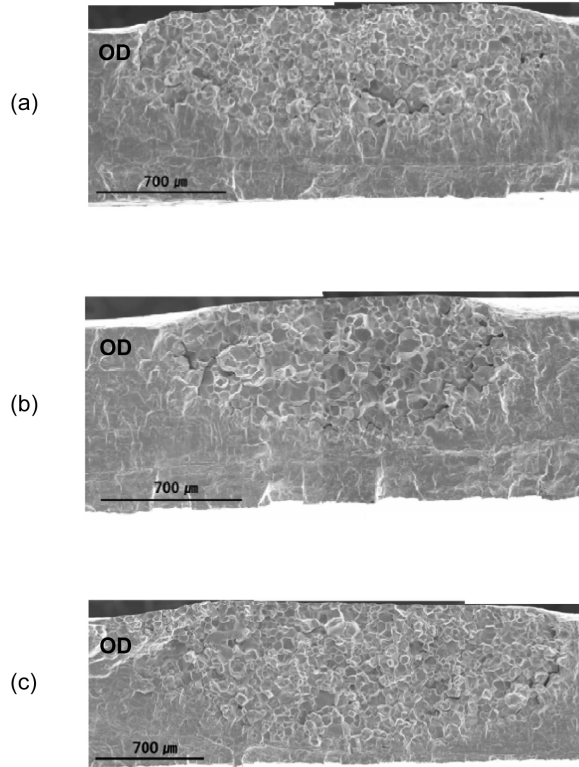


Fig. 3. Fracture Surface of (a) Crack A, (b) Crack B, and (c) Crack C.

Table 1. Actual Length and Depth of the Cracks

	Tube A	Tube B	Tube C
Crack length (mm)	2.25	1.64	2.88
Crack depth (%)	62.2	68.9	88.7

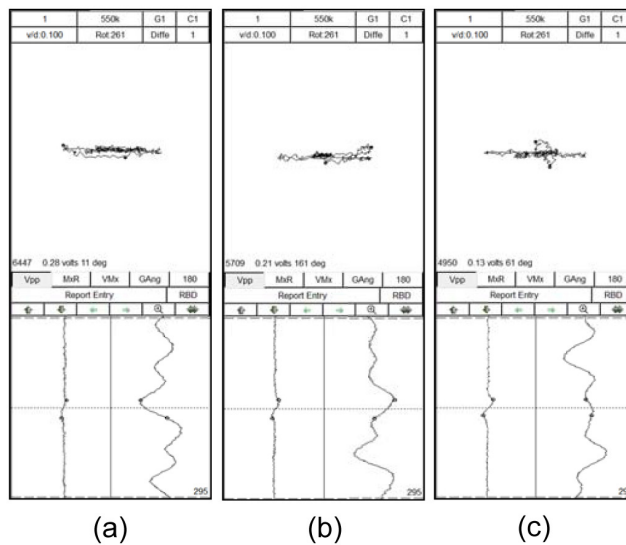


Fig. 4. Bobbin Signals of (a) Crack A, (b) Crack B, and (c) Crack C at an S/N Ratio of 9.

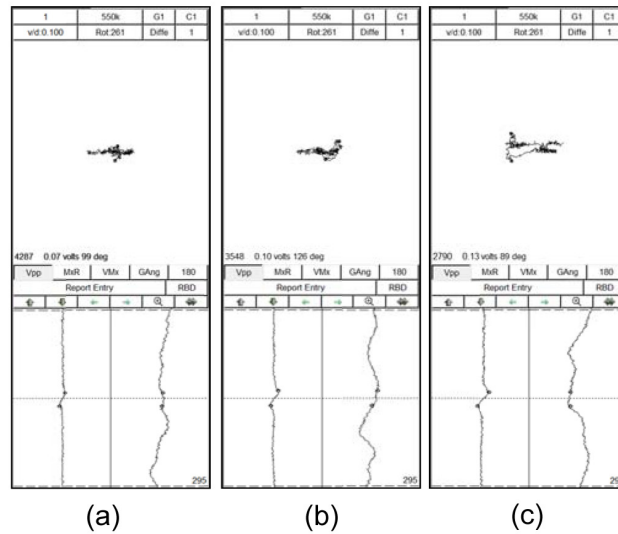


Fig. 5. Bobbin Signals of (a) Crack A, (b) Crack B, and (c) Crack C at an S/N Ratio of 18.

Table 2. Variation of Amplitude of Crack Signal with Tube S/N Ratio

Tube	S/N = 9		S/N = 18	
	$V_{max}/V_{noise}$	$V_{pp}/V_{noise}$	$V_{max}/V_{noise}$	$V_{pp}/V_{noise}$
Crack A	0.14	0.65	0.33	0.35
Crack B	0.21	0.50	0.48	0.48
Crack C	0.27	0.30	0.57	0.57

This is because the crack occurred at the position with a very weak noise signal.

Fig. 5 shows the EC signals of the polished tubes with cracks A, B, and C at a test frequency of 550 kHz. In comparison with the original signals in Fig. 4, it was noted that the level of noise decreased by about a factor of 2. The noise level of each tube was measured to be in the range of 0.20~0.23 V. Thus, the S/N ratio was calculated to be about 18 on all three polished tubes. The increase in the S/N ratio can be attributed to a partial removal of the pilgering noise.

The  $V_{max}$  to  $V_{noise}$  ratio and  $V_{pp}$  to  $V_{noise}$  ratio are summarized in Table 2. The value of  $V_{max}/V_{noise}$  more than doubled when increasing the S/N ratio from 9 to 18. This increase is entirely due to a decrease in the noise level, since the values of  $V_{max}$  were not affected by the polishing process. Because the detection capability is basically related to  $V_{max}$ , it was experimentally verified that detectability for small cracks is enhanced by increasing the S/N ratio of the tube itself. It should be noted that the value of  $V_{max}/V_{noise}$  is nearly the same as that of  $V_{pp}/V_{noise}$  at an S/N ratio of 18, although they have no correlation at an S/N ratio of 9. This means that the effect of noise on  $V_{pp}$

is negligible at a higher S/N ratio. Consequently, it was verified that sizing accuracy is also improved by increasing the S/N ratio of the tube itself because the sizing of a defect is based on the phase angle measurement of  $V_{pp}$ .

Table 3 shows the variation of the phase angle of each crack with the tube S/N ratios. The depth and position of each crack was estimated using the relationship curve of phase angle versus crack depth, shown in Fig. 1. According to this figure, OD cracks are determined by a phase angle in the range of 40-169 degrees, while inner diameter (ID) cracks are determined by a phase angle in the range of 0-40 degrees. The phase angle of crack A at an S/N ratio of 9 was 11 degrees, corresponding to an ID defect with a depth of 28%. This indicates that the noise led to a false estimation of the crack position from the OD side to the ID side, although the actual depth of the crack was 62.2%. However, it showed a phase angle of 99 degrees at an S/N ratio of 18, indicating an OD defect with a depth of 59%. In the case of crack B at an S/N ratio of 9, the phase angle of 161 degrees was too large to be evaluated as an OD defect. However, its phase angle at an S/N ratio of 18 moved to 126 degrees, indicating an OD defect with a depth of 38%.

**Table 3.** Variation of Phase Angle of Crack Signal with Tube S/N Ratio

Tube	Actual crack depth (%)	S/N = 9		S/N = 18	
		Phase angle (deg)	Depth from phase angle (%)	Phase angle (deg)	Depth from phase angle (%)
Crack A	62.2	11	ID 28	99	OD 59
Crack B	68.9	161	OD 8	126	OD 38
Crack C	88.7	61	OD 86	89	OD 67

In in-service inspection, the detection of flaws primarily depends on a bobbin probe, whereas defect sizing is performed using a three-coil rotating probe. Therefore, it may be said that the defect depth evaluation by the phase angle of a bobbin probe is not important. However, the phase angle is an essential parameter to estimate the defect depth and determine the position of a defect at either the internal wall or the external wall [10]. Consequently, the result shown in Table 3 indicates that the phase angle rotated to a value representing an actual position and depth of a crack when increasing the S/N ratio of the tube itself.

Bakhtiari et al. reported that the simulated composite noise would result in a significant degradation of the detection and sizing capability, by using various algorithms for the simulation, superposition, and measurement of noise that were developed at Argon National Laboratory [1]. To the best of the author's knowledge, however, this paper is the first experimental work using real stress corrosion cracks to verify the effect of the S/N ratio on the capabilities of detection and characterization. In addition, early detection and accurate characterization for a shallow defect are crucial to assure the tube integrity. In this regard, the crack size and corresponding EC signals used in this work were small enough to evaluate the cracks at the early stage.

Although tubes with similar material properties were equipped in a steam generator, the level of noise varied, depending on their locations [11]. This is because the extent of noise distribution is affected by the tube support structures and sludge deposited on the tubes. These noises reduce the probability of detection [1,11,12]. It has also been proposed that the in-service inspection frequency be extended depending on the tubing material [13]. Therefore, the intrinsic noise level of the manufactured tube itself should be minimized, although the noise added in a steam generator during operation can be unavoidable. Recently, steam generator tube manufacturing specifications including the S/N ratio have been strengthening [14]. The results of this paper provide experiment-based data to verify the validity for the requirement strengthening trend.

#### 4. CONCLUSIONS

The effect of S/N ratio on the eddy current response of a bobbin coil probe was investigated using axial stress corrosion cracks on the OD side of steam generator tubes. The value of  $V_{\max}/V_{\text{noise}}$  more than doubled and the value of  $V_{\max}/V_{\text{noise}}$  became nearly the same as that of  $V_{\text{pp}}/V_{\text{noise}}$  when increasing the S/N ratio of the tube itself from 9 to 18. In addition, the phase angle rotated to a value representing the actual position and depth of a crack with an increased S/N ratio. Therefore, it is expected that the capabilities of detection and characterization, including sizing and positioning accuracy for cracks, will be enhanced by strengthening the design requirement for the S/N ratio of steam generator tubes.

#### ACKNOWLEDGEMENTS

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