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《Technical Note》

Detectability and Sizing Ability of Rotating Pancake Coil Technique for Cracks in Steam Generator Tubes

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Abstract

Many nuclear power plants have experienced unscheduled shutdown due to the leakage of steam generator tubes. The leakages are normally due to the crack, possibly stress corrosion cracking (SCC) near the tube expansion at the top of tubesheet or at the tangential point of the row-1 U-bend region. The conventional eddy current technique, which makes use of a differential bobbin coil, has been found to be inadequate for the early detection of SCC. During the in-service inspection, therefore, it is a general practice that the rotating pancake coil (RPC) is used for detecting the cracks. Even in using RPC, however, it is difficult to determine the depth of the cracks quantitatively. This paper attempts to determine the detectability and sizing ability of RPC technique for axial or circumferential cracks at the tube expansion region. The simulated cracks with various dimensions were fabricated by electro-discharge machining (EDM) method. Experimental results are discussed with theoretical calculations.

1. Introduction

One of the causes of unscheduled shutdown in nuclear power plant is leakage of steam generator tubes. Leakage is normally due to the defects in the steam generator tubes, i.e., crack, pitting, denting, fretting wear, etc. Until the middle of 1980's major defects found in the Korea's steam generator tubes were denting in tube support plates, pitting on the outer surface of tubes, and fretting wear at the anti-vibration bar in the U-bend region. These defects could be detected by conventional eddy current technology, usually bobbin coil and 8×1 pancake coil technique. Since the late 1980's, however, the destructive tests for the defective tubes revealed many cracks, possibly stress corrosion crack (SCC) near the tube expansion region. Referring to steam generator operating experiences, SCC would increase as the operating year of the nuclear power plant. The volumetric defects, like pitting or fretting wear, could be detected and characterized with the conventional eddy current technology, but non-volumetric defects, like cracks, could not. At present, the rotating pancake coil (RPC) technique is known as one of the possible method for detecting cracks. However, even if a crack is detected with the RPC technique, it is only possible to determine the orientation and length but difficult to determine the depth of the crack quantitatively.

There is no universal code or regulation for the method of detection and characterization of crack, even guidelines for plugging criteria. Each country or utility has set its own plugging criteria after consideration of operating conditions and history of the steam generator, laboratory test results, and theoretical analysis with the leak-before-break concept. Once a crack is found, the possibility of leakage to the next outage should be reviewed carefully and conservative plugging criteria are recommended. In addition, estimated crack length with the RPC data should be reviewed to the real crack length. Because of this complexity, theoretical or experimental approaches have been applied for the investigation of eddy current phenomena. A theoretical approach can be divided as the analytical method, which is to get a solution from well-known Maxwell's equations with particular boundary conditions, and the numerical method, which is to calculate the electromagnetic phenomena in the region of interest with finite element method, finite difference method, or boundary element method etc. [1-4]. Results from theoretical analysis can be useful for understanding eddy current phenomena and interpreting experimental data. Since theoretical analysis is only possible for a case with simplified geometry with symmetry and several assumptions, actual application of the solution is limited. Although the experimental results can be applied directly to the analysis of field eddy current testing, it has also limitations, since it requires lots of specimens and it is difficult to fabricate realistic specimens.

This paper attempts to determine the detectability and sizing ability of RPC technique for detecting both axial and circumferential cracks at the tube expansion region. Detectability and sizing ability for cracks is not a simple concept. Complex factors of crack length, depth, width as well as the overall inspection condition, such as the characteristics of the coil, material characteristics of the test piece, and testing instrument should be considered. Therefore, it is not easy to deal with all the factors and to establish a universal rule at once. In order to get useful results for actual steam generator inspection, crack dimension has been looked at under the same condition of the actual inspection. Specimens including the electro-discharge machined (EDM) artificial cracks with various dimensions were fabricated. Using the RPC technique, detectability and sizing ability for cracks are determined from the eddy current signals of artificial cracks. The experimental results are discussed with theoretical eddy current impedance by a volume integral model, which is modified from the analytical approach.

2. A Volume Integral Approach for Eddy Current Signal

As shown in Fig. 1, the rotating pancake coil rotates helically inside the tube. Since the diameter of the rotating pancake coil is quite small (typically 3 mm) compared to those of the tube, we can ignore the effect of curvature of the tube. Therefore the situation is similar to the case of pancake coil above a flat conductor plate, and the analytical solutions for pancake coil above the conductor plate [5,6] can be applied for this condition.

The analytical approach is somewhat successful in calculations of the impedance from the

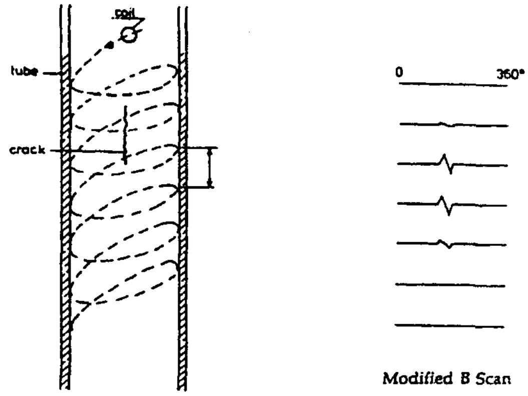

Fig. 1. Principle of the Helical Scan Rotating Pancake Coil and Display

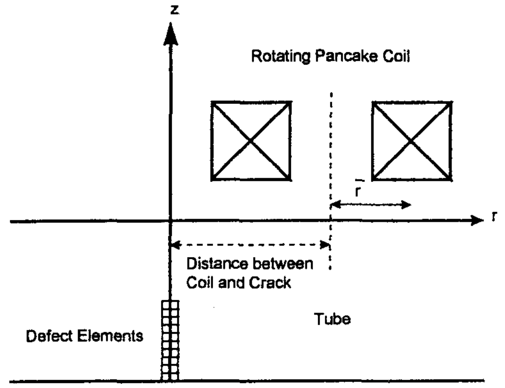

Fig. 2. Configuration of the Defect Elements and Rotating Pancake Coil[7]

simplified and volumetric defect, i.e. spherical or elliptical defect inside semi-infinite conductor plate. However, because we are interested in cracks, which can be characterized as a non-volumetric defect, it gives little meaningful result for the rotating pancake coil in the steam generator inspection. In order to understand the eddy current phenomena by the RPC technique, a volume integral approach is used. Based on the original analytical solution, the volume integral method was developed for more realistic crack response.[7] Basic concept of the volume integral method is that the overall impedance due to a crack can be calculated by the sum of each impedance due to the small defect elements.

A defect can be a sum of small defect element, namely,

$$D = \sum_{i=1}^{n} d_i \tag{1}$$

,where D is defect size, d_i is defect element size, and n is the number of defect elements. Correspondingly, the impedance can be a sum of impedance due to defect elements and the interaction between the small defect elements.

$$Z = \sum_{i=1}^{n} Z_i^{(1)} + \sum_{i,j=1, i\neq j}^{n} Z_{ij}^{(2)} \tag{2}$$

, where Z is impedance due to a crack, $Z_i^{(1)}$ is impedance due to defect elements, and $Z_{ij}^{(2)}$ is the interaction between the i-th defect element and j-th defect element. The second term in the equation (2) should be considered if the distance between the two defect elements is close, but could be neglected if the distance is far. Since the calculation of the interaction term is quite complicated and the model calculation without the interaction term shows a similar pattern to the actual eddy current signal from cracks in the steam generator tubes[7] , the interaction term might be ignored. Fig. 2 shows the configuration of the defect elements and rotating pancake coil for the volume integral method.

A computer program was developed to calculate eddy current response from the crack using rotating pancake coil [7]. The impedance of each individual defect element, $Z_i^{(1)}$ is calculated using the following equation [6]:

$$Z_i^{(1)} = \frac{j\omega\pi\mu n}{(l_2 - l_1)^2 (r_2 - r_1)^2} \int_{l_1}^{l_2} \int_{r_1}^{r_2} rA(r,z)\,dr\,dz \tag{3}$$

, where $A(r, z)$ is magnetic vector potential at the defect location (r, z), l_1. l_2 are length of the

Table 1. Dimensions of Eddy Current Coil and Material Properties of Inconel 600 Tube.

Eddy Current	Outer Diameter	Inner Diameter	Height	Nominal Radius
Coil	3.0mm	1.0mm	1.0mm	1.0mm
Inconel 600 Tube	Wall Thickness	Electrical Conductivity	Magnetic Permeability	
	1.27mm	1.0194×10^6 mho/m	$4\pi\times10^{-7}$ H/M	

coil, r_1. r_2 are inner and outer radius of coil, ω is angular frequency, μ is magnetic permeability of the conductor, and n is the number of turns respectively. The impedance due to a crack is calculated by the sum of equation (3), $Z_i^{(1)}$. Detail calculation of magnetic vector potential for the geometry is described in elsewhere[5,6].

As the coil approaches to a crack, the coil begins to sense the presence of defect and results in the impedance loci, or signal amplitude. The crack length can be determined as the region that signal amplitude is higher than a certain threshold level. In order to characterize the crack length by RPC technique, the effect of eddy current signal amplitude to the relative distance between coil and crack was calculated using the volume integral approach. The relative distance between coil and crack is normalized to the nominal diameter of the coil, $\bar{r}$. Input parameters for the calculations, dimensions of eddy current coil and material properties of Inconel 600 tube, are summarized in Table 1. Theoretical estimation of eddy current signal amplitude to the normalized distance is shown in Fig. 3. When the distance is $3\bar{r}$, the coil begins to sense a crack. The impedance, or signal amplitude increases as the distance decreases and reaches to the peak value at the distance, $\bar{r}$. And the impedance decreases again at the distance of less than $\bar{r}$, which means crack is inside the coil.

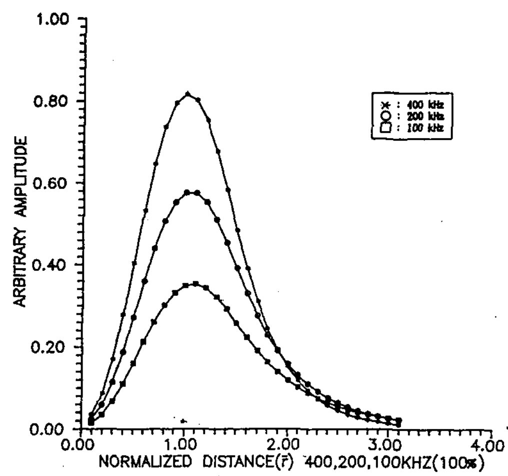

Fig. 3. Eddy Current Signal Amplitude Versus Distance Between the Coil and Crack

3. Experimental Method

The specimens were the same material as in the Westinghouse steam generator series 51 tube, Inconel 600. The dimensions of the specimens were outer diameter of 22.225 mm (0.875 inch) and wall thickness of 1.27 mm (0.05 inch). The specimens were expanded to outer diameter of 22.733 mm (0.895 inch) with mechanical rolling and various size of artificial cracks were fabricated with electro-discharge machining (EDM) method (see Fig. 4). The width of cracks was 0.2 mm, which is the narrowest limit obtainable in fabricating the crack by EDM method.

Table 2. Eddy Current Measurements of the Axial Cracks **(unit : mm)**

Actual crack length	400 kHz	300 kHz	200 kHz	100 kHz	Depth (%)
8	12.32	12.85	11.79	12.07	100%
6	9.40	9.68	9.40	9.40	
4	6.86	7.11	7.11	7.11	
2	4.90	5.44	5.44	5.16	
8	9.42	9.42	7.82	5.69	75%
6	6.85	6.85	5.79	4.69	
4	4.16	4.97	5.23	4.70	
2	2.82	3.07	3.07	2.82	
8	5.69	7.04	7.29	5.69	50%
6	5.21	5.72	4.97	5.44	
4	4.20	4.45	4.75	3.73	
2	3.50	3.35	3.10	*	
8	*	*	*	*	25%
6	*	*	*	*	
4	*	*	*	*	
2	*	*	*	*	

* Unable to measure the crack length

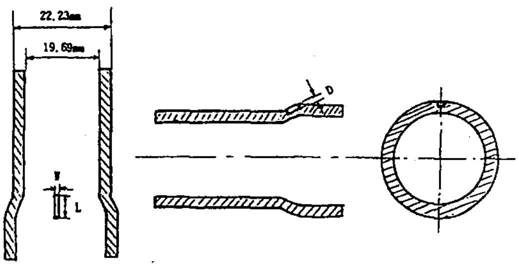

Fig. 4. Schematic Drawings of Roll Expansion of the Tube

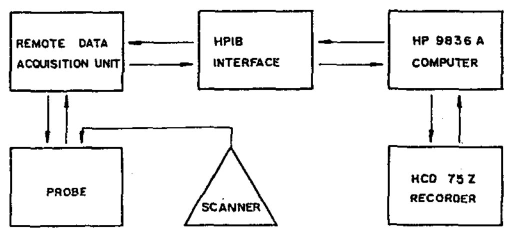

Fig. 5. Block Diagram of the Experimental Set-up

Fig. 5 shows the block diagram of the experimental set-up. The MIZ-18 digital data acquisition system and the DDA-4 digital data analysis system were used as the eddy current testing instruments, which is the same system used in the actual field inspection of steam generator tubes. The rotating pancake coil was MRPC-720-3C/7PH made by the Zetec, which has inner diameter of 1 mm, outer diameter of 3 mm, height of 1 mm, and ferrite bar was used as an inside core. The standard tubes, (ASME standard, TSP (Tube Support Plate) standard, and EDM notch standard) were used for the system calibration.

Table 3. Eddy Current Measurements of the Circumferential Cracks (unit : mm)

Actual crack length	400 kHz	300 kHz	200 kHz	100 kHz	Depth (%)
8	11.79	12.32	13.39	12.60	100%
6	9.68	11.00	11.79	10.21	
4	6.48	7.54	7.82	7.54	
2	4.70	3.91	4.17	4.45	
8	9.40	9.14	8.61	8.61	75%
6	6.32	7.11	7.11	7.67	
4	4.37	5.97	6.76	7.82	
2	4.09	4.09	5.16	4.62	
8	6.58	7.39	7.67	8.46	50%
6	6.22	6.76	6.86	7.93	
4	4.32	5.08	6.22	6.86	
2	*	*	*	*	
8	*	*	*	*	25%
6	*	*	*	*	
4	*	*	*	*	
2	*	*	*	*	

* Unable to measure the crack length

4. Results and Discussion

4.1. Detectability of RPC Technique

The results of eddy current analysis are listed in Table 2 for axial cracks and Table 3 for circumferential cracks. It was not able to detect cracks or measure the length for cracks with depth of 25% of tube wall thickness for both axial and circumferential cracks. Some cracks with depth of 50% of tube wall thickness and length of 2 mm cannot be detected.

Eddy current signal amplitude depends mainly on the crack size. Detectability is defined as the minimum size of the crack by eddy current signal analysis. The factors of detectability are length and depth of the crack in this case. From the Tables 2 and 3, the detectability for crack with this experimental condition seems to be higher than 25% of tube wall thickness regardless of the length. Even though we tried to simulate realistic cracks by fabricating the artificial defect as narrow as possible (0.2 mm width), the defect still contains a finite volume, which means the detectability would be different from the experimental results. Since the crack has ideally no width, the

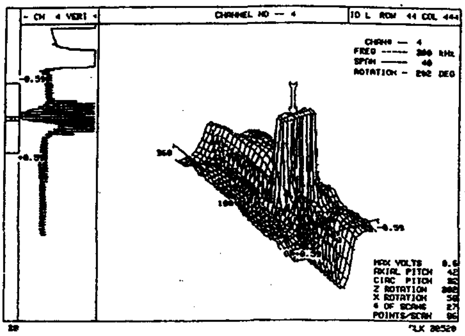

Fig. 6. C-scan Display of the Axial Crack. Dimensions of Crack are Width of 0.2mm, Length of 8 mm, Depth of 100 % Tube Wall Thickness

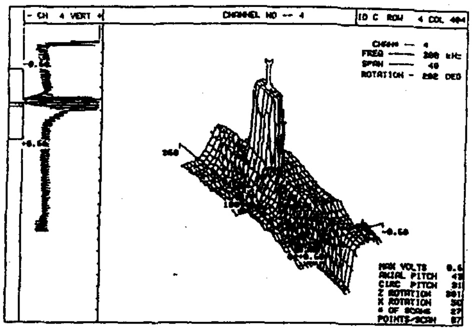

Fig. 7. C-scan Display of the Circumferential Crack. Dimensions of Crack are Width of 0.2 mm, Length of 8 mm, Depth of 100 % Tube Wall Thickness

detectability of actual field inspection would be higher than those from the experimental results.

Typical C-scan displays are shown in Fig. 6 for an axial crack and Fig. 7 for a circumferential crack. The orientation of the crack, axial or circumferential, can be clearly distinguished.

4.2. Sizing Ability of RPC Technique

From the Tables 2 and 3, estimated crack length by RPC method can be compared with its actual length. For the cracks with the depth of 100 % wall thickness, the crack length is over-estimated regardless to the orientation or length. However, as the crack depth decreases, the amount of over-estimation decreases and the differences between the actual length and estimated length become small. Some cracks with depth of 50% of wall thickness show even tendency of under-estimation. It was also not able to determine the length of all cracks with depth of 25 % of wall thickness, which is beyond of the detectable limit.

When we estimate crack length by RPC technique, two factors, namely the sensing distance and the crack depth should be considered simultaneously. If the eddy current signal appears some distance ahead of a crack, estimated crack length might be longer than the actual length, which means over-estimation. The effect of sensing distance between the coil and crack is explained using the volume integral approach. As shown in Fig. 3 for 100% depth of wall thickness, the coil begins to sense a crack at the distance of $3\bar{r}$. As the distance decreases, impedance increases, and reaches to a maximum value at the distance of $\bar{r}$. The impedance decreases again at the distance of less than $\bar{r}$, which means inside the coil. Since the signal amplitude appears at some distance ahead of the crack tip, i. e. distance of $3\bar{r}$, the amount of over-estimation could be expected as 2 mm after taking into account the coil radius, $\bar{r}$ itself ($\bar{r}$ = 1 mm for this case). From the Tables 2 and 3 and Figs. 8 and 9, the amount of over-estimation might be in the range of 2 - 4 mm for the cracks with 100% depth of wall thickness.

On the other hand, as the crack is located deep inside, the eddy current signal decreases exponentially, which is known as the skin effect. The amount of over-estimation can be reduced as the crack depth decreases. Tables 2 and 3 show that the amount of over-estimation is reduced as the crack depth decreases from 100% through 50% of wall thickness. Some cracks with depth of 50% of wall thickness show that estimated length was smaller than actual length, which means under-estimation.

Experimental results are taken from the specimens with the width of 0.2 mm, which means crack with finite width. If we consider an actual crack with approximately zero width, eddy current signal would decrease and the amount of over-estimation could be reduced. In the field inspection, the eddy current analyst should understand the errors in crack length estimation and influencing factors, such as orientation of crack, threshold level, signal shape, degradation mechanism of tube materials, operating history,

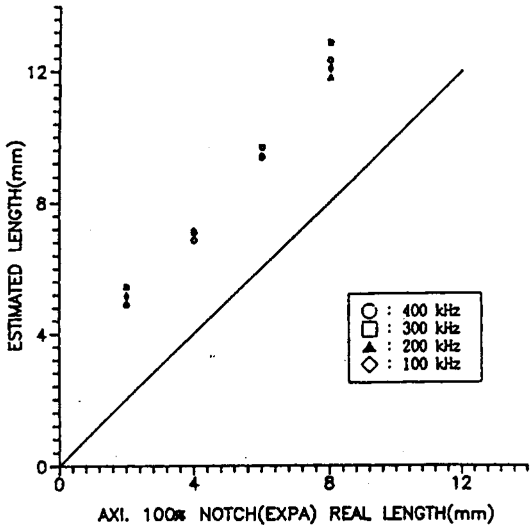

Fig. 8. Length Measurement of Axial Crack with Roll Expansion. The Depths of the Cracks are 100% of Tube wall Thickness

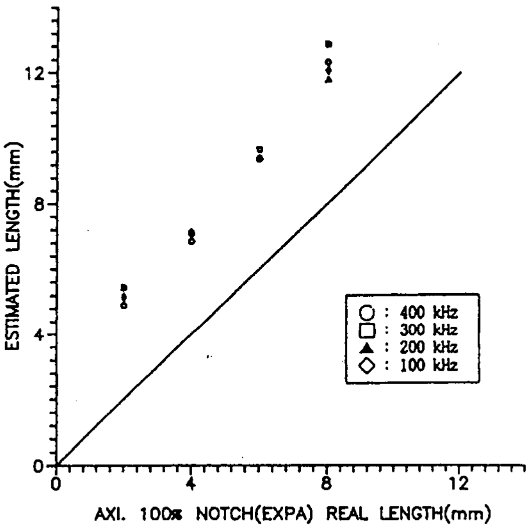

Fig. 9. Length Measurement of Axial Crack Without Roll Expansion. The Depths of the Cracks are 100% of Tube Wall Thickness

and even water chemistry of the steam generator.

4.3. Effect of Roll Expansion on the Eddy Current Signal

Estimated length of axial cracks with 100% wall thickness is shown in Fig. 8 (with roll expansion) and Fig. 9 (without roll expansion). There are few differences in the eddy current measurements between the cases with and without roll expansion. Because the rotating pancake coil is a surface riding type and the spring inside coil could maintain contact to the inner surface in the expansion region, signals due to lift-off might be negligible. This is a great advantage compared to the conventional bobbin coil technique, which shows a high signal amplitude in the region of expansion due to the lift-off effect.

5. Summary

1. It was not able to detect or evaluate the length of the cracks with depth of 25% of wall thickness and some cracks with depth of 50% wall thickness and 2 mm long. Considering the differences between the artificial cracks and actual cracks, the detectability limit in the field inspection would be greater than the depth of 25% of wall thickness.
2. The error in the crack length estimation has been explained with the model calculations by a volume integral method. The crack length for the depth of 100% of wall thickness was estimated greater than the actual length, which is over-estimation. However, as the depth decreases, the amount of over-estimation decreases, and some crack with depth of 50% of wall thickness were estimated as even less than the actual length, which is under-estimation. The eddy current analyst should consider the complex factors for accurate

length estimation.

3. The effect of roll expansion was negligible when the rotating pancake coil is used for the steam generator tube inspection.

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