ABSTRACT

The electromagnetic numerical calculations were performed in order to comprehend differences in sizing characteristics of defect length by eddy current testing on non-magnetic and ferromagnetic materials. While changing the relative permeability of the material and the defect geometry, eddy current density and magnetic flux density distributions were estimated. From these estimated results, the defect lengths were estimated based on the Japanese guideline. The estimated 12 dB drop lengths of both the non-magnetic and the ferromagnetic were closer to the true values than the signal loss lengths. The signal loss lengths in the ferromagnetic were longer than those in the non-magnetic because the eddy current on the ferromagnetic spread on the surface layer. The distributions of the difference of the interlinkage magnetic flux density were independent of the depth of the rectangle defect in both the non-magnetic and the ferromagnetic. On the other hand, those were influenced by the depth of the circular arc defect in the non-magnetic. The estimated lengths in the rectangle defects showed a tendency to be longer than in the circular arc-like defects.

1. INTRODUCTION

Japanese nuclear regulation authority required an eddy current testing for a component made of a low-alloy steel (ferromagnetic material) in a boiling water reactor as one of special inspections for more than 40 years of operating period extension of a nuclear power plant in 2013. Japanese guideline of an eddy current testing (ECT) for components of a nuclear power plant which describes procedures of both a defect detection and its length estimation targets only non-magnetic materials such as an austenitic stainless steel and a high nickel alloy. And, characteristics of both a defect detection and its length estimation were estimated, experimentally. We focused on differences in sizing characteristics of defect length on surfaces of non-magnetic and ferromagnetic materials and started to perform electromagnetic numerical calculations in order to comprehend sizing characteristics. While changing a relative permeability of an inspected object and a defect geometry as parameters in this step, distributions of eddy current densities on inspected objects and magnetic flux densities around coils were calculated. We estimated changes of ECT output signals from those of interlinkage magnetic flux (IMF) densities of coils and measured defect lengths based on the changes of ECT output signals. In this paper, new insights of defect length sizing characteristics on non-magnetic and ferromagnetic materials were described.

2. DEFECT LENGTH SIZING PROCEDURE IN GUIDELINE

A defect length sizing procedure which was described in Japanese guideline of an ECT for components of a nuclear power plant is defined as follows. When a coil of an ECT probe is moved along a defect on a metallic material as shown in Fig. 1, an amplitude of an ECT output signal is changing as shown in Fig. 2. A width of an amplitude chart at a value dropped 12 dB from a peak value of an amplitude and a width at a base line are defined as the 12 dB drop length and the signal loss length, respectively. These defined lengths should be selected depending on a purpose of use, property of coil and measurement accuracy.

Figure 1 - Relationship between defect and movement of coil
3. ELECTROMAGNETIC NUMERICAL CALCULATION PROCEDURE

A two-dimensional electromagnetic numerical calculation model is shown in Fig. 3\textsuperscript{4}). A coil and a defect were given on a surface of a metallic material. An outer diameter, an inner diameter and a height of the coil are 3.2 mm, 1.2 mm and 1 mm, respectively. A lift-off which means a distance between the coil and the surface of the metallic material is 0.4 mm. An initial position of the coil center is at a point of 20 mm from an edge of the defect. Electromagnetic numerical calculations were performed by the finite element method using a dominant equation of the magnetic vector potential and side elements. The dominant equation is

\[ \nabla \times \mu^{-1} \nabla \times A = J_0 - j\omega \sigma A \]

where $\mu$ is the permeability, $A$ is the magnetic vector potential, $J_0$ is the current density, $\omega$ is the angular frequency, and $\sigma$ is the conductivity. The input parameters are the permeability $\mu$, the current density $J_0$, the frequency $f (=\omega/(2\pi))$, and the conductivity $\sigma$. A ferromagnetic material was approximated by a linear. The boundary conditions were symmetric.

Distributions of eddy current densities on the metallic material and magnetic flux densities around coil were calculated while changing the coil center position from the initial one to the defect center in 2 mm interval. A relative permeability of the metallic material and the defect geometry (Cross-sectional shape, length and depth) are parameters in these calculations. Calculation conditions are shown in Table 1.
Table 1 - Calculation conditions

<table>
<thead>
<tr>
<th>No.</th>
<th>Cross-sectional shape</th>
<th>Length (mm)</th>
<th>Depth (mm)</th>
<th>Relative permeability $\mu_r$</th>
<th>Conductivity (S/m)</th>
<th>Frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rectangle</td>
<td>40</td>
<td>0.5</td>
<td>1 (Non-magnetic)</td>
<td></td>
<td>1×10^6</td>
</tr>
<tr>
<td>2</td>
<td>Rectangle</td>
<td>20</td>
<td>1</td>
<td></td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>3</td>
<td>Circular arc</td>
<td>28</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Circular arc</td>
<td>40</td>
<td>10</td>
<td>1000 (Ferromagnetic)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. CALCULATED RESULTS

4.1 Eddy current density distribution

Calculated results of eddy current density imaginary part distribution in the non-magnetic and the ferromagnetic material at a coil center position X of −26 mm in the defect No. 2 are shown in Fig. 4. A scale of Y axis is 1.5 times longer than that of X axis in Fig. 4. In the case of the ferromagnetic, the eddy current concentrated on the metallic material surface layer of approximately 0.1 mm and spread to the X axis direction to the defect because the eddy current on the ferromagnetic was affected by the skin effect.

Calculated results of eddy current density absolute distribution on the non-magnetic and the ferromagnetic material (Y=−0.1 mm) at a coil center position X of −26 mm in the defect No. 2 are shown in Fig. 5. In the case of the ferromagnetic, it is confirmed that the eddy current spread approximately twofold to the X axis direction compared with non-magnetic at the normalized eddy current density of 0.1. This phenomenon means that the eddy current is easily influenced by the defect on the ferromagnetic even if the coil is away from the defect. In other words, an amplitude of an ECT output signal tend to change at a coil center position more distant from a defect on a ferromagnetic than on a non-magnetic. Therefore, we can predict that at least the signal loss length in a ferromagnetic material will be larger than that in a non-magnetic.

Figure 4 - Calculated results of eddy current density imaginary part distribution (Defect No. 2)
4.2 Magnetic flux density distribution

Calculated results of the magnetic flux density real part Y axial component distribution in the non-magnetic and the ferromagnetic material at the coil center position X of −26 mm in the defect No. 2 are shown in Fig. 6. The scale of Y axis is same as that of X axis in Fig. 6. In the case of the ferromagnetic, the magnetic flux density was denser around the coil and more spread to the X and Y axis directions than that of the non-magnetic because the magnetic flux was affected by the eddy current which concentrated and spread on the ferromagnetic material surface layer.

An ECT probe detects a difference between an induced voltage of a coil at a reference point without a defect and that on a defect as a signal from a defect. The induced voltage of the coil is proportional to the temporal differentiation of the IMF of the coil. The induced voltage of the coil is described in the following equation

\[ V = -N \frac{d\phi}{dt}, \]  

Where \( N \) is the number of coil turns, and \( \phi \) is the IMF of the coil. Because the coil geometry and the frequency are constant in the one case of calculations, we assumed that the induced voltage of the coil \( V \) is approximately proportional to the IMF density of the coil. The average of the magnetic flux density real part Y axial component inside the coil on Y axis of 0.9 mm as shown in Fig. 6 was calculated as the IMF density of the coil at the arbitrary coil position. The initial coil center position was defined as the reference point in this calculation. For example, the initial coil center position X is −40 mm in the defect No. 2.

We calculated the difference between the IMF density at the initial coil center position and that at each coil center position as simulated amplitude of an ECT output signal while changing the coil position X from the initial coil center position to the defect center in 2 mm interval. Calculated result of the difference of the IMF density in the non-magnetic and the ferromagnetic material in the defect No. 2 is shown in Fig. 7. The difference of the IMF density in each material was normalized by each peak value in Fig. 7. We estimated the 12 dB drop and the signal loss length as shown in Fig. 7. We defined the signal loss point as the point of less than 1×10^-3. Calculated results of the difference of the IMF density in the vicinity of the defect edge in the non-magnetic and the ferromagnetic material in all the defects are shown in Fig. 8. In Fig. 8, the horizontal axis means the distance from the defect edge. In the case of the rectangle defects (Defect No. 1 to No. 4), the distributions of difference of the IMF density were independent of the defect depths in both the non-magnetic and the ferromagnetic material. On the other hand, in the case of the circular arc defects (Defect No. 5 to No. 7), those were influenced by the defect depths in the non-magnetic (the 12 dB drop length increased with increasing the defect depth).
Figure 6 - Calculated results of magnetic flux density real part Y axial component distribution
(Defect No. 2)

Figure 7 - Calculated difference of IMF density (Y=0.9 mm, Defect No. 2)
5. ESTIMATION OF DEFECT LENGTH

Estimated results of 12 dB drop and signal loss lengths of all the calculated defects (the defect No. 1 to No. 7) using the calculated differences of the IMF density of the coil for all the defects like Fig. 7 for the defect No. 2. All the 12 dB drop lengths of both the non-magnetic and the ferromagnetic material were closer to the true values than the signal loss lengths. As predicted, the signal loss lengths in the ferromagnetic material were longer than those in the non-magnetic because the eddy current on the ferromagnetic material spread to the X axis direction compared with non-magnetic material. In the case of the rectangle defects (the defects whose edges are deeper), the estimated results of both the 12 dB drop and signal loss lengths showed a tendency to be longer than in the circular arc-like defects.
6. CONCLUSION

We focused on differences in sizing characteristics of defect length by ECT on surfaces of non-magnetic and ferromagnetic materials and performed the electromagnetic numerical calculations in order to comprehend sizing characteristics. From calculated results, we confirmed the following. The estimated 12 dB drop lengths of both the non-magnetic and the ferromagnetic material were closer to the true values than the signal loss lengths.

The signal loss lengths in the ferromagnetic material were longer than those in the non-magnetic because the eddy current on the ferromagnetic material spread to the X axis direction compared with non-magnetic material. In the case of the rectangle defect, the distributions of the difference of the IMF density were independent of the defect depth in both the non-magnetic and the ferromagnetic material. On the other hand, in the case of the circular arc defects, those were influenced by the defect depth in the non-magnetic. The 12 dB drop and signal loss lengths in the rectangle defects showed a tendency to be longer than in the circular arc-like defects.

REFERENCES