Devisal of an array type pulsed eddy current probe for monitoring fuel rods

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Abstract

An array type pulsed eddy current (PEC) probe is devised for monitoring fuel rods that does not allow probe scanning. The probe consists of an array of encircling coils located along the rod and the outside of coils is shielded so that magnetic flux from the exciter coil cannot reach the sensor coil. Positions of a pair of exciter and sensor coils are consecutively relocated electronically. Numerical simulation is performed using the backward difference method in time and the finite element method for spatial analysis. At one position of send-receive pairs, the peak value is extracted from a sensor PEC signal. As the defect size gets bigger, the peak value of the PEC signal increases while the peak time reduces. The array type signal proposed in this work is produced by accumulating those peak value data for all probe positions. Simulation results show that the proposed array type signal is excellent in reflecting not only the defect depth and length but also its location within the probe area. Such characteristics of the array type signal would be very helpful for monitoring fuel rods that does not allow probe scanning.

Keywords: Array probe, Array type signal, Pulsed eddy current, Numerical simulation

1 Introduction

Nuclear fuel is the heart of nuclear power plant operation. The nuclear fuel rod is the first defense wall against the radioactive contamination. The fuel rod is accessible only from outside since it houses fuel pellets inside. Almost all eddy current testing (ECT) methods require probe scanning to get meaningful signals. However, certain parts of the fuel rod, such as under spacer grids in the fuel assembly, do not allow probe scanning [1]. For this reason, an encircling send-receive type pulsed eddy current (PEC) probe with array of coils is devised, that does not require probe scanning through consecutive relocation of exciter and sensor coil positions. The array type signal is composed by accumulating peak values of sensor PEC signals for all positions. PEC signal is expected to be rich of information due to its broadband nature [2]. In the send-receive type probe, the sensor coil detects not only the magnetic flux produced by induced eddy currents but also the source magnetic flux from the exciter coil, that is much stronger than those from the eddy currents. In eddy current testing, sensors should detect the magnetic flux produced by eddy currents since they reflect the condition of test specimen [3-5]. Therefore, in this work, all the coils are shielded by ferrite to prevent source magnetic flux from directly affecting sensor signals.

2 Governing Equation and Numerical Analysis Methods

The governing equation for the PEC testing is
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\[ \nabla \times \left( \frac{1}{\mu} \nabla \times \vec{A} \right) = \vec{f}_s - \sigma \left( \nabla V + \frac{\partial \vec{A}}{\partial t} \right) \]  

(1)

where \( \mu, \sigma, \vec{f}_s, \vec{A} \) are permeability, conductivity, coil current density vector, and magnetic vector potential, respectively.

To predict PEC signals, the backward difference method in time and the finite element method for spatial analysis are used. Applying the Galerkin weighted residual method to the governing equation, the following elemental matrix equation is obtained.

\[ [S]\{A\} + [C]\{\frac{\partial A}{\partial t}\} = \{Q\} \]  

(2)

where elements of each matrix can be expressed as follows if axisymmetry of the problem is assumed.

\[ S_{ij} = \int \frac{1}{\mu} \left[ \left( \frac{N_i}{r} + \frac{\partial N_i}{\partial r} \right) \left( \frac{N_j}{r} + \frac{\partial N_j}{\partial r} \right) + \frac{\partial N_i}{\partial z} \frac{\partial N_j}{\partial z} \right] 2\pi r \, dr \, dz \]  

(3)

\[ C_{ij} = \int N_i \sigma N_j 2\pi r \, dr \, dz \]  

(4)

\[ Q_i = \int N_i J_s 2\pi r \, dr \, dz \]  

(5)

where \( N_i \) and \( N_j \) are shape functions at each node point in a quadrilateral element. These elemental matrix equations are summed up to form a global matrix equation and solved for the magnetic vector potential at every node point. To handle the time derivative term, the backward difference method in time is applied.

\[ \{A\}^{n+1} \]  

= \frac{\{A\}^{n+1} - \{A\}^n}{\Delta t} \]  

(6)

where \( \{A\}^n \) is the magnetic potential evaluated at time, \( t^n \).

Rewriting (2) by using (6), the following recursive relation is obtained and the magnetic potential at any time can be calculated.

\[ \left[ \frac{1}{\Delta t} [C] + [S] \right] \{A\}^{n+1} = \{Q\}^{n+1} + \frac{1}{\Delta t} [C]\{A\}^n \]  

(7)

PEC signal can be calculated as follows since it is the electromotive force induced in the sensor coil.
\[ V_{emf} = \frac{\{A\}^{n+1} - \{A\}^n}{\Delta t} \cdot 2\pi r_c \]  

(8)

where \( r_c \) is the centroidal radius of the sensor coil element.

3 PEC Defect Signals from Shielded Probe

Nuclear fuel rod is accessible only from outside so that encircling coils are employed. In the send-
receive type probe, the sensor coil detects not only the magnetic flux produced by induced eddy currents
but also the source magnetic flux from the exciter coil, that is much stronger than those from the eddy
currents. In eddy current testing, sensors should detect the magnetic flux produced by eddy currents
more than those from the exciter coil currents, since the presence of defect is detected by the changing
distribution of induced eddy currents. In this work, therefore, both coils are shielded by ferrite.

Figure 1 shows the pulse current density supplied to the exciter coil. The pulse width is 400 \( \mu \)S and the
time step of 10 \( \mu \)S is used for time marching calculation. The wall thickness and outer diameter (OD)
of the zircaloy fuel rod are 0.635 mm and 9.7 mm, respectively. The conductivity of zircaloy is \( 1.4 \times 10^6 \) S/m.

When the sensor coil is located 19.05 mm (1.96 OD) away from the exciter coil and a 12.7 mm long
OD defect is present between the two coils, PEC signals at the sensor coil are calculated for no, 25%,
50%, and 75% deep OD defects and they are shown in Figure 2. These results show that the peak value
increases and the peak time appears earlier as the defect depth increases. Almost linear relationship
seems to exist between peak value and defect depth as shown in Figure 3.
4 Generation of Array Type Signal from PEC Signals

For continuous monitoring of fuel rods, array of shielded encircling coils are set up along the tube. Exciter and sensor coils are consecutively relocated to the right as shown in Figure 4.
Figure 4: Consecutive relocation of exciter coil.

Let the coil number increase to the right starting from the leftmost coil. Sensor coil is located at no. 6 when the exciter coil is no. 4 as shown in Figure 5. For a defect, wall thinning is used and its length is 50.8 mm which corresponds to the area from coil no. 3.5 to 7.5 in Figure 5. As exciter and sensor locations are moved to the right, relative coil positions to wall thinning area is summarized in Table 1.

Figure 5: A pair of exciter and sensor coil outside of OD wall thinning area.
Table 1: Consecutive change of coil locations

<table>
<thead>
<tr>
<th>Exciter Coil No.</th>
<th>Sensor Coil No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (outside defect)</td>
<td>3 (outside defect)</td>
</tr>
<tr>
<td>2 (outside defect)</td>
<td>4 (inside defect)</td>
</tr>
<tr>
<td>3 (outside defect)</td>
<td>5 (inside defect)</td>
</tr>
<tr>
<td>4 (inside defect)</td>
<td>6 (inside defect)</td>
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<td>9 (outside defect)</td>
</tr>
<tr>
<td>8 (outside defect)</td>
<td>10 (outside defect)</td>
</tr>
</tbody>
</table>

As previously mentioned, the peak value increases as the defect depth increases. When both coil locations are within the wall thinning area as shown in Figure 5, no. 6 sensor coil signal would show the highest peak value. On the contrary, if coil no. 8 acts as an exciter coil, then both coils are outside the defect area so that no. 10 sensor coil signal would show the smallest peak value. Change of PEC sensor signals due to wall thinning is shown in Figure 6 as both coil locations move to the right. From these signals, peak value at each position is extracted to form an array type signal as shown in Figure 7.

Figure 6: Change of PEC sensor signals due to wall thinning.

5 Characteristics of Array Type Signals

To find characteristics of array type signals, defect size and locations are changed and corresponding changes in the array type signal are studied. Figure 7 shows array type peak value signals from 25%, 50%, and 75% deep OD wall thinning. Their axial length is 50.8 mm. Results show that the array type peak value signal increases around defect area and its strength is higher when the defect depth is deeper. Figure 8 shows array type signals as the axial length of defect is increased. The signal difference are clearly noticed so that defect length can easily be estimated. Figure 9 also proves that the location of defect can easily be identified by the array type signal. These results demonstrate that the array type signal is easy to interpret and reflects defect information very well.
Figure 7: Array type signals from 3 different defect depths.

Figure 8: Array type signals from different defect lengths.

Figure 9: Array type signals from different defect locations.
6. Conclusion

To inspect fuel rods that are not accessible from inside and does not allow probe scanning from outside, a shielded, encircling, send-receive type PEC array probe and an array type signal are devised through the use of numerical analysis method. The probe consists of an array of encircling coils along a tube and the outside of coils is shielded by ferrite. Positions of a pair of exciter and sensor coils are consecutively relocated and at each position, the peak value is extracted from a sensor PEC signal. Numerical simulation results show that the peak value of the PEC signal increases while the peak time of the PEC signal reduces as the defect size increases. The array type signals are proposed by accumulating those peak value data for all probe positions. Simulation results show that the proposed array type signal is excellent in reflecting defect location as well as variations in defect depth and length. These characteristics of the array type signal would be very useful for monitoring fuel rods that does not allow probe scanning.

References