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Design and fabrication of eddy current array probe for structural integrity inspection of dry cask storage system

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1. Introduction

As a part of the project for the Development on the Key Technology of Sensor Transport System for Structural Safety Inspection of Dry Cask Storage System, the USERS Corporation and the Chosun University have been conducting researches on the defects such as cracks and corrosion that may occur in the spent fuel cask storage system. An arrayed ECT probe was designed for the application. In the design of the probe, the operating frequency with consideration for the general inspection is used.

2. Methods and Results

This section describes the features and principles of arrayed ECT probes, the design of arrayed probes for structural integrity testing of dry cask storage systems, and coil fabrication and cable selection.

2.1 Features of Arrayed ECT Probe

The advantages of eddy current testing are that less surface preparation is required for the test, which saves time and can save costs associated with removing hazardous chemical waste associated in penetration testing and magnetic particle inspection applications. In addition, eddy current inspection techniques can provide more quantitative information by providing defect depth information that other surface nondestructive inspection techniques can not provide. This ability of the eddy current inspection technique is considered to be a very attractive advantage in the detection of surface defects, the distinction of duct instructions from irrelevant indications, and the defect depth estimation of surface connection defects. In particular, the ECA test is characterized in that the test time is significantly shortened and the reliability is high, as compared to the eddy current test using a single coil as shown in the figure below. In other words, single coil eddy current test is relatively time consuming than ECT because a raster scan has to be applied to inspect specific area as shown in the figure below. In an ECT test the time is shortened and high quality signal is collected, improving the test reliability.

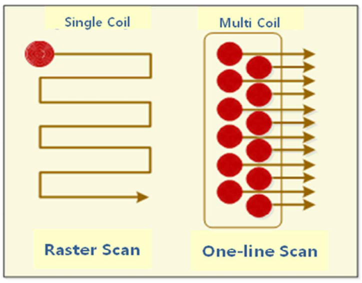

Fig. 1. Eddy current inspection Surface coil scanning method

2.2 Principles of arrayed ECT probe

The multiple array eddy current array (ECA) technique is a technique that can inspect a large area of a test at a time by placing several pancake coil sensors adjacent to each other in a circumferential direction or on a plane. (See Figure 2). The ECA technique can electronically drive several eddy current sensors placed adjacent to each other in the same probe and collect the generated signal in a short time. Such data collection is possible using a multiplexing scheme that can prevent mutual magnetic induction (inductance) between each sensor. The ECA generally applies up to 64 sensor coils in a circumferential (bobbin type) or plane (surface coil type) arrangement in transmit-receive mode (T-R mode), depending on its application. The operating frequency range usually applies from 20 Hz to 1 MHz to non-destructive testing, depending on the multiplexing required setting. ECA transducers are generally composed of 8 to 64 pancake coils according to the application and can be operated in three operating modes: absolute mode, differential mode, and transmit-receive mode. Each of the pancake coils constituting the probe is arranged in two rows at regular intervals in the horizontal and vertical directions as shown in Fig.2.

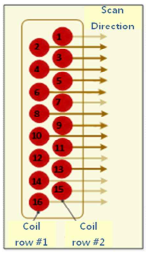

Fig. 2. ECA probe coil placement (16-coil example)

Figure 3 below shows how the coil arrangement and the first axial and circumferential dual channel signals are obtained. In the figure, the first one axial channel is the magnetic field generated from the B1 coil is transmitted to the A1 coil and the A2 coil to detect the signal (axial fault detection channel), and the first one circumferential channel has the magnetic field And transmitted to the B3 coil to detect the signal (circumferential defect detection channel).

The transmit-receive coils are activated with different multiplexing times so that each receive coil can simultaneously detect the signal from a single transmit coil. The other channel increases the coil number by one and generates the signal in the same way. In this case, a total of 16 11.25 degrees circumferential channels are obtained with a total of 32 22.5 degrees axial directions.

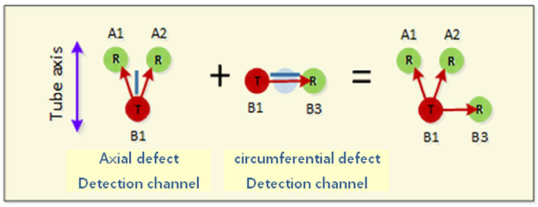

Fig. 3. ECA probe coil signal transmission and reception method for circumferential and axial channel generation.

As described above, three operating modes are generally used in the ECA application: absolute, differential, and transmit-receive modes. In the most commonly used transmit-receive (T-R) mode of operation, the maximum detection sensitivity for defects in the 45 ° and 135 ° diagonal directions is shown. Therefore, the T-R mode can compensate for the differential mode, which indicates the minimum detection sensitivity for defects in the 45 ° and 135 ° directions. (See Figure 4). Coil channel allocation and the number of hardware inputs required are similar to other coil modes. T-R mode requires four data acquisition board inputs including eight coil channels except the last one. Figure 4 shows the T-R mode coil pattern, and each slash indicates a single T-R coil channel.

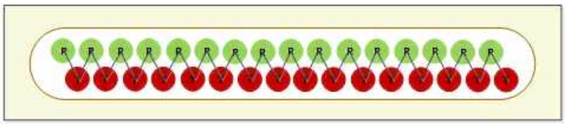

Fig. 4. Coil placement in transmit and receive (T-R) mode.

In the above application, the odd-numbered coil channels are used to detect faults in the 45 ° direction, and the even-numbered coil channels are used to detect faults in the 135 ° direction. A total of two C-scans are thus generated, one for each defect direction. The multiplexing order is the same for both T-R and differential modes, but the number of coils is different. The differential channel is generated by extracting two different coil signals, while in T-R mode the first coil is the transmitter and the second coil is the receiver.

2.3 Array type ECT probe design

The penetration depth of induction eddy currents is very important. If the induced eddy current does not penetrate the tube wall, the defects located on the outside of the tube will be missed. At a standard penetration depth of "1" for a particular material, the eddy current density drops to 37% of the surface eddy current density. According to the formula for obtaining the standard penetration depth, the depth of eddy current penetration is inversely proportional to the square root of the product of the inspection frequency, conductivity, and relative permeability. In conclusion, the higher the frequency, the smaller the penetration depth.

Considerations for general inspection should be that the standard penetration depth at the applied operating frequency be equal to the minimum tube thickness. However, the actual test is carried out at a much higher frequency, where the frequency is used for the ASME calibration specimen at a phase angle of 90° between the 20% tube ID groove (360°) and the 10% OD groove (360 °) Frequency.

In addition, a higher frequency can be applied in addition to the detection frequency. With this frequency, a minimum of 90° phase angle separation occurs between the 100% ASME through hole (TW hole) and the 4-20% flat-bottomed hole signal. This frequency is sometimes called the optimum frequency and is used when phase angle analysis is needed.

The frequency response of the probe is another consideration for selecting the fault detection optimal frequency. Once the required operating frequency is determined, the inspector designs the probe to operate within a certain frequency range. When the transducer is used outside the required frequency range, the sensitivity of detecting the defect is significantly reduced. The probe extension cable also greatly affects the probe frequency response. An approach to minimize this problem is to specify the applicable operating frequency range according to the length of the extension cable expected to be used, and another way is to determine the frequency response by using an impedance meter. In general, the greatest sensitivity of fault detection is obtained near the highest coil impedance, which is about at 380 kHz in the figure. At this point, the phase angle is inverted by 180°. This frequency is called the resonant frequency, and resonance occurs when the inductive reactance of the coil is equal to the capacitive reactance of the extension cable.

For most analog equipment, the probe operates below the resonant frequency. This prevents the frequency drift of the frequency towards the resonance point, thereby avoiding the 180° phase angle inversion from the operating point of the probe. In contrast, digital equipment is more stable, so there are no problems in keeping the probe equilibrium point near the resonant frequency. However, the probe performance is degraded by the reduction of the capacitive reactance when above the resonant frequency. That is, the current flows through the cable rather than the coil. In general, it is desirable to keep the resonant frequency of the probe high in order to guarantee the inductive coupling of the probe in a wide operating frequency range. If a Bode plot is not available, a reference standard can be scanned to determine the optimal frequency based on the signal amplitude of the probe at various frequencies. That is, the largest signal amplitude obtained from the defects of the calibration specimen means the frequency close to the resonant point of the probe.

The defect detection frequency is a frequency close to the resonance point of the probe. Note that the eddy current amplitudes respond to external noise sources (ie tube supports, OD conductive deposits, etc.) when selecting the frequency. Increasing the frequency increases the response to tube ID noise, while reducing the response to external noise sources. Conversely, decreasing the frequency increases the signal from outside the tube wall, but reduces the noise inside the tube (ie, denting, probe motion, etc.).

Unfortunately, amplitudes resulting from noise, such as dent and probe wobble signals, become larger at higher frequencies. Consequently, a secondary frequency must be selected to improve the overall signal-to-noise ratio. After selecting the frequency based on the signal amplitude, the secondary frequency used to complement the detected primary frequency should be selected. The secondary frequency is more clearly illustrated by the phase angle-to-frequency relationship that exists between the various test variables. Since the optimal frequency based on the signal amplitude may not represent the optimal phase angle separation between the various test variables, the secondary frequency is selected such that the phase angle between the defect and the external noise source be optimally separated.

2.4 Arranged ECT probe production

The ECA probe consists of several coils and is made of flexible material so that it can be scanned on a flat, curved surface. The diameter of each coil is approximately 3 ~ 3.5mm, and the diameter of the enamel copper wire used in the winding is about 0.02 ~ 0.05mm, and the winding is wound about 300 ~ 800 times depending on the application. This ECA probe is generally arranged in two rows of eight pancake coils, and the coil winding is made by winding about 350 times assuming general usage as shown in the figure.5 below.

Fig. 5. ECA probe coil winding and arrangement

The cable length of the ECA probe was designed to be about 10.5m, taking into account the on-site inspection conditions of the spent fuel storage canister (see Figure 6). Because the length of the probe is long and consisted of several strands (16 total strands, 8 strands 2) Silver-plated coaxial cables with small cable diameters and high conductivity were used. In addition, the probe case is used in a radiation environment, it was fabricated using PEEK with radiation and abrasion resistance (see Figure 6).

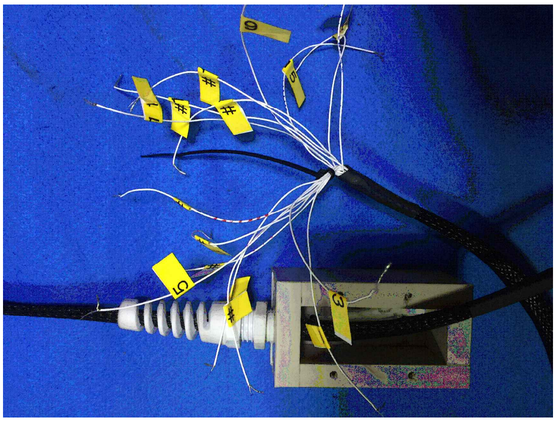

Fig. 6. Probe Cases & Cables.

3. Conclusions

A study on the spent fuel dry cast storage system has been conducted in the USA for several years, mainly by EPRI. Recently, there have been some issues on the dry cast storage system and structural integrity in domestic nuclear power plants. It will be helpful to develop optimized eddy current probes for use in dry cast storage system integrity testing.

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