Eddy current testing probe with dual half-cylindrical coils

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We have developed a new eddy current probe composed of a dual half-cylindrical (2HC) coil as an exciting coil and a sensing coil that is placed in the small gap of the 2HC coil. The 2HC coil induces a linear eddy current on the narrow region within the target medium. The magnitude of eddy current has a maximum peak with the narrow width, underneath the center of the exciting 2HC coil. Because of the linear eddy current, the probe can be used to detect not only the existence of a crack but also its direction in conducting materials. Using specimen with a machined crack, and varying the exciting frequency from 0.5 to 100 kHz, we investigated the relationships between the direction of crack and the output voltage of the sensing coil.

I. INTRODUCTION

Eddy current testing (ECT) is an effective nondestructive technique for detecting defects in conducting materials, such as metallic pipes and structural frames. 1, 2 Various types of ECT probes have been developed for many applications, for example, multifrequency probe, 3 superconducting probe, 4 rotation magnetic flux sensor, 5 planar coils, 6 and meander-mesh coils, etc. 7 ECT probes commonly use a circular coil in order to induce eddy currents in a metallic structure under test. The eddy current distribution generated by the circular coil has an axial symmetry and no eddy current at the center. Due to the axial symmetry, the circular coil cannot detect the anisotropic properties of target material. Besides, not having eddy current at the center, the circular coil suffers a loss of spatial resolution of measurement.

This article presents a new design of anisotropic ECT probe simply composed of a dual half-cylindrical (2HC) coil as an exciting coil and a sensing coil that is placed in the small gap of the 2HC coil. The 2HC coil induces the linearized and maximized eddy current within a test structure underneath the center of the probe. The sensing coil detects the induced voltage generated by the secondary magnetic field due to the eddy current. Because of the linearized eddy current, the probe can be used to detect not only the existence of a crack but also the direction in conducting materials. In this article, we present the construction, numerical analysis, and experimental results of the probe. Using a conducting specimen (duralumin) with a machined crack, and varying the exciting frequency from 0.5 to 100 kHz, the relationships between the direction of crack and the output voltage of the sensing coil were investigated.

II. DESIGN OF DUAL HALF-CYLINDRICAL TYPE ECT PROBE

Figure 1 shows the photograph and the architecture of the ECT probe. The probe consists of 2HC coil and sensing coil as shown in Fig. 1(b). The 2HC coil generates a time varying magnetic field in order to induce an eddy current on a target medium and the sensing coil detects the secondary magnetic fields generated by the eddy currents. The 2HC coil has 47 turns made of 0.32 mm diam copper wire at each half cylinder. The winding direction of the 2HC coil is opposite each other. The bold square in Fig. 1(b) represents the receiver coil of square type with 300 turns of 80 μm diam copper wire. Note the receiver coil is placed in the small gap of the 2HC coil.

In order to show these features, we calculated numerically the magnetic field and the eddy current generated by the 2HC coil and the secondary magnetic field around the sensing coil. The magnetic field distribution by the applica-

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FIG. 1. Eddy current probe composed of a 2HC coil. (a) Photograph of the probe with a holder. The holder was made of nonconducting material in order to prevent undesirable electromagnetic couplings between the exciting 2HC coil and the holder. (b) The architecture of the probe. Arrows indicate the winding directions of the 2HC coil. The bold square represents the sensing coil.
tation of the Biot–Savart law to the geometry of the 2HC coil is calculated in the quasistatic limit.

Figure 2 shows the magnetic fields both around the exciting coil and at the plane of the sensing coil. The magnetic field in Fig. 2(b) is enlarged 1000× for a detailed view. The magnetic field is minimized at the position of the receiver coil as shown in Fig. 2(a). In Fig. 2(b), although the magnetic field exists over the region of the sensing coil, the fields at the upper region in it are exactly equal and opposite to those at the lower region, leading to no net magnetic flux linkage through the sensing coil. Therefore, this setup of the sensing coil can minimize the undesirable magnetic coupling between the 2HC coil and the sensing coil. Figure 3 shows the experimental measurement of the null property of the probe in open air. The 2HC coil is driven by the 1 kHz sinusoidal voltage of 10 V amplitude. The induced voltage amplitude of the sensing coil is directly recorded by the oscilloscope. The position of the sensing coil was manually adjusted in order to minimize the flux linkage between the sensing coil and the 2HC coil.

When the exciting 2HC coil is placed on a conducting medium, the time varying magnetic field generates the eddy currents in the medium. Figure 4(a) shows the calculated current density vectors over the conducting medium of 6 cm×6 cm×1 cm size. In Fig. 4, the bottom of the 2HC coil is placed at z = 1 cm and the upper plane of the conducting medium.
medium at $z = 0$ cm. Figure 4(b) shows the contour plot and the three dimensional (3D) surface plot of the eddy current density at the upper plane ($z = 0$ cm) of the conducting medium, and more clearly shows the distribution of the current.

Note that the current density has the maximal peak and linear shape with the narrow width, right below the center of the exciting 2HC coil. The narrower peak implies better spatial resolution in the measurement of conductivity because the secondary magnetic fields are proportional to the current intensity. More importantly, due to the linear shape of the maximum current, the anisotropic properties such as the direction of crack in the target material can be measurable.

Figure 4(c) shows the calculated secondary magnetic field around the sensing coil. Because the secondary magnetic field is mainly generated by the linear eddy current, the sensing coil can pick up the net flux.

III. EXPERIMENTAL RESULTS

Figure 5 shows the experimental setup. The internal oscillator of a lock-in amplifier (Stanford Research System, SR830) produces a sinusoidal wave. This signal drives the 2HC coil after being amplified to 15 V amplitude by the power amplifier. The voltage signal from the sensing coil is amplified and then fed into the phase sensitive detector (PSD) of the lock-in amplifier. The PSD output is passed through a low pass filter (internal filter of the lock-in amplifier). Finally, the signal is converted to digital value by an analog to digital converter and then transferred to the PC for data storage and postsignal processing.
The bottom of Fig. 5 shows a duralumin specimen, and ECT probe’s location. The machined crack has a depth of 0.5 mm and a width of 0.5 mm. By rotating the probe from 0° to 360° with an increasing step of 1°, we recorded the output voltage at each angle and then subtracted the voltage at an angle of 90° from all data sequence in order to enhance the voltage difference according to the rotation angle.

Figure 6 shows the relation between the rotation angle and the output voltage when the exciting frequency is 1 kHz. The output voltage oscillates with the rotation angle. The sensing coil output voltage at the parallel direction (0°, 180°) to the crack is bigger than that at the perpendicular directions (90°, 270°). The polar representation in Fig. 6(b) clearly shows the angular dependence of the sensed voltage. These experimental results demonstrate that the output voltage of the probe give some indication of the crack’s direction.

The frequency dependence of the output voltage is shown in Figs. 7 and 8. Varying the exciting frequency from 0.5 to 100 kHz, and rotating the probe from 0° to 360° with an increasing step of 1° at each frequency, we recorded the output voltage and then normalized those signals in order to compare the wave forms with each other. In all ranges of various exciting frequencies, the angular dependence is similar. However, when the crack direction is close to the direction of the sensing coil (0°, 180°), the wave form of the output signal depends on the exciting frequency. In the frequency range between 0.5 and 5 kHz, the depth of valley at the angle of 180° or 0° is deeper when the exciting frequency is increased as shown in Fig. 7(b). On the other hand, in the frequency between 10 and 100 kHz, the valley at the angle of 180° is flatter when the exciting frequency is increased as shown in Fig. 8(b). It is supposed that this property may be highly dependent on the crack geometry, electrical parameters of material, probe geometry, etc.