Enhance the Sensibility of the Eddy Current Testing

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Eddy current testing (ECT) is one of the most representative nondestructive testing methods for metallic materials, parts, structures and so on. Operating principle of ECT is based on the two major properties of magnetic field. One is that alternating magnetic field induces eddy current in all of the conducting materials. Thereby, an input impedance of the magnetic field source, i.e., electric source, depends on the eddy current path. Second is that the magnetic field distribution depends only on the exciting but also the reactive magnetic fields caused by the eddy currents in targets. Former and latter are the impedance sensing and magnetic flux sensing types, respectively.

This paper concerns with an improvement of sensibility of the impedance sensing method. Sensibility of the ECT is improved by means of two steps. One is an optimum exciting frequency selection. We employ the natural parallel resonant frequency of ECT coil. The other is to increase the sharpness of the resonance curve on impedance versus frequency characteristic by changing the coil connection. As a result, we have succeeded in developing the ECT sensor having up to 4 times higher sensibility compared with those of conventional one.

Keywords: Eddy current, Nondestructive testing, Resonant frequency.

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1. Introduction

Modern engineering products such as air-plane, automobile, smart building, high speed train and so on are essentially composed of metallic materials for forming the shape of product, suspending the mechanical stress and constructing the structural frames. In particular, the mass transportation vehicles, e.g. large air plane, high-speed train, express highway bus and so on, carrying a large number of people are required ultimately high safety as well as reliability.

To keep the safety of such vehicles, nondestructive testing to the metallic materials is one of the most important technologies because most of the structure materials are composed of the metallic materials.

Various nondestructive testing methods, such as eddy current testing (ECT), electric potential method, ultrasonic imaging and x-ray tomography, are currently used. Among these methods, ECT does not require complex electronic circuits and direct contact to target. Furthermore, target whose major frame parts are composed of conductive metallic materials can be selectively inspected by ECT [1,3].

Operating principle of ECT is very simple. The ECT is based on the two major properties of magnetic field. One is that exposing the conductive materials to the alternating magnetic fields induces eddy current in all of the conducting materials. Thereby, the input impedance of the magnetic field source, i.e., electric source, can detect the change of the target impedance caused by defects blocking eddy current flowing. The ECT based on this principle is called impedance sensing type. The other type utilizes a separately installed sensor coil to detect the leakage magnetic flux change. The magnetic field of ECT is composed of two components: one is the exciting and the other is the reactive magnetic fields. The reactive magnetic field is caused by the eddy currents in the target so that change of eddy current paths changes the reactive magnetic fields. Thus, the independently installed sensor detects this magnetic field change. This type is called a separately sensing coil type.

This paper concerns with an improvement of sensibility of the impedance sensing method. Improvement of the sensibility is carried out in the two major steps.

The first step is to select the optimum exciting frequency. We select the natural parallel resonant frequency of the ECT coil when facing with a wholesome part of target. A system comprising the ECT facing with the wholesome part of target takes the maximum pure resistive impedance. When the ECT sensor coil meets with a defect of target, this resonance condition is essentially not satisfied. This makes it possible to maximize the deviation between the resonance and not resonance impedances.

The second step is to increase the resonant impedance as well as to sharpen the peaky impedance versus frequency characteristic by changing the coil connection [4]. Since the natural parallel resonant impedance become larger, then the deviation between the resonance and not resonance impedances is essentially larger. This essentially enhances the sensibility of ECT sensor.

2. Enhancement of ECT Sensibility

2.1 Operating Principle of ECT

Let an arbitrary finite length solenoid coil shown in
Fig. 1 (a) be an eddy current sensor coil. When we put on this sensor coil on a copper plate as shown in Fig. 1 (b) and apply an alternating current to the sensor coil, because of the Faraday’s law, eddy current is induced as a reaction of the alternating magnetic fields. By measuring the input impedance of the sensor coil, we are able to diagnose a difference of the target copper plate condition between no defects (Fig. 1 (b)) and 2 mm crack defect (Fig. 1 (c)). This is similar to the secondary impedance change detection from primary input terminal in a conventional single phase transformer.

Thus, it is obvious that a simple finite length solenoid coil can detect the defects of the target conducting materials. This is the operating principle of ECT.

2.2 Natural Resonant Phenomena of ECT Coil

Any of the coils always exhibit an inductive property because of the magnetic fields around them by applying a current into the coil. However, any of the coils have the capacitances among the coils. Even though a simple finite length solenoid coil shown in Fig. 1 (a), it is possible to observe its natural resonance phenomena as shown in Fig. 2. Figs 2 (a) and 2 (b) are the frequency f versus impedance $|Z|$ and the frequency f versus phase $\phi$ characteristics, respectively.

2.3 Optimum Operation Frequency

Decision of ECT operation frequency is of paramount importance, because sensibility and searching depth of ECT are greatly depending on the operation frequency. Theoretically, the operation frequency of ECT can be decided by taking the target conductivity and its skin-depth into account. However, final selection of operation frequency is determined by the past experiences and the practical tests.

In the present paper, we select the natural parallel resonant frequency of the ECT sensor coil when facing with a wholesome part of target. The ECT facing with the wholesome part of target takes the maximum pure resistive impedance. When the ECT sensor coil meets with a defect of target, the resonance condition is essentially not established. Therefore, the input impedance from sensor coil input terminals is also reduced to small in value compared with those of the resonant one. Namely, a deviation between the resonance and not resonance impedances becomes maximum value.

A sensibility $\varepsilon$ of ECT is defined by

$$
\varepsilon = \frac{\text{reference} - \text{measured}}{\text{reference}} \times 100 \%.
$$

where the reference and measured in Eq. (1) refer to the input impedances from the ECT coil terminals when facing the ECT coil with the wholesome and defect parts of target, respectively.

2.4 Enhancement of Quality Factor $Q$

The sensibility of Eq. (1) is greatly depended on the quality factor $Q$ of the parallel resonance defined by

$$
Q = \frac{f_0}{\Delta f},
$$

where and $\Delta f$ are the resonant frequency and the bandwidth, respectively.

The quality factor $Q$ represents a sharpness of the resonant curve on the impedance versus frequency coordinate. So that high $Q$ in Eq. (2) means high sensibility in Eq. (1).
To increase the quality factor $Q$, we employ the resonant connection shown in Fig. 3. Figs. 3 (a) and 3 (b) are the two parallel conductors and their resonant connection, respectively. Denoting $R$, $L$, $M$ as the resistance, self-inductance and mutual inductance, it is possible to draw an equivalent circuit of the resonant connected two conductors as shown in Figs. 3 (c) and 3 (d).

Fig. 4 shows a difference between the normal and resonant coil connection [4]. Practically, the resonant connection is carried out by twisting the two coils to uniform the facing side of both conductors as shown in Fig. 5 [5].

3. Experiment

3.1 Tested Target Peace and Trial ECT Coils

Fig. 6 shows a target peace which is composed of the SUS316. A vertical line shape artificial crack having 10mm length, 0.2 mm width and 0.5 mm depth had been made to the SUS316 by the electrical discharge machining. Fig. 6 shows a 20 mm by 20 mm target area. The ECT sensors measured at the 9 by 9 sampling points with 2.5 mm regular spacing on this 20 mm by 20 mm square area.

We have worked out a lots of ECT coils for comparison. Table 1 lists the representative 6 tested ECT coils. Every tested coil is wound around the Manganese-Zinc type ferrite bar used as an axial core material. No.1 is a normal ECT, No. 2 is a resonance type not employing twisting of coil, No.3 is a resonance type employing 100/m twisting, No.4 is a resonance type employing 150/m twisting, No.5 is a resonance type employing 200/m twisting, and No.6 is a resonance type employing 400/m twisting.

3.2 Conventional ECT Operating at 256 kHz

At first, we evaluated the line shape crack in Fig. 6 by conventional ECT employing 256 kHz operating frequency. Fig. 7 shows the results of defect searching. Observe the results in Fig. 7 suggests that any of the sensor coils are capable of detecting the defect. Further, it is difficult to decide which sensor is the highest sensibility. In the other words, normal ECT defect searching using a particular operating frequency never reflects on the difference of the conductor connection and coil twisting.

3.3 ECT Operating at Resonant Frequency

Any types of ECT coils have their own natural resonant frequency even if they are facing with the target without any defect. No.1, 2, 3, 4, 5 and 6 ECT coils in Table 1 have the natural resonant frequencies, 4650, 4950, 3650, 3300, 3425 and 3475 kHz, respectively. Fig. 8 shows the typical frequency characteristics of the trial ECT coils.
Table 1. Specification of the trial ECT coils.

<table>
<thead>
<tr>
<th>No.</th>
<th>Type</th>
<th>Conductor length: 50cm</th>
<th>Diameter of conductor: 0.1mm</th>
<th>Axis core: Ferrite bar (MnZn)</th>
<th>Coil outer diameter: 2.4mm</th>
<th>Coil inner diameter: 2mm</th>
<th>Coil length: 6mm</th>
<th>Number of twisted turns: 0</th>
<th>Number of coil layers: 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Normal</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Resonant</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Twisting</td>
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<tr>
<td>4</td>
<td>Twisting</td>
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<tr>
<td>5</td>
<td>Twisting</td>
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<tr>
<td>6</td>
<td>Twisting</td>
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</table>

Fig. 7. Defect searching results. Any sensor coils can detect the two different kinds of base metallic materials.
Fig. 8. Frequency $f$ vs. impedance $|Z|$ characteristics of the ECT coils (a) No.1, (b) No.2 and (c) No.4, respectively.

Fig. 9 shows the defect searching result using each of the distinct natural resonant frequencies. Comparison of the results in Fig. 7 with that of Fig. 9 reveals that the resonant frequency operation is far superior sensibility in any ECT coils. In particular, No. 4 in Fig. 9 (d) exhibits nearly 10% deviation. This fact is verified that the quality factor of No.4 in Fig. 9 (b) is far excellent compared with those of No. 1 and of No. 2.

Fig. 10 shows the quality factor of three type coils, Normal Resonant and Twisting. We have gotten two different groups. One is the normal coil having relatively small quality factor 10.67. The other group has the good quality factors 14.05 and 14.40. However, observing the resonant and twisting coils, we can get the difference between them. That is the difference of resonant frequency. Twisting effect reflect on to the decreasing of resonant frequency about 1MHz. We have succeeded in increasing the quality factor and decreasing resonant frequency by changing the coil connection.

Fig. 9. The results of defect searching. Any sensor coils can detect two different kinds of base metallic materials.
4. Conclusion

New innovative idea to enhance the sensibility of ECT sensor has been proposed in this work. Our idea needs not any special tools but requires a consideration of natural resonance phenomena, i.e., utilization of the resonant impedance, frequency and capacitive effect among the coils.

We have selected the natural parallel resonant frequency of the ECT sensor coil when facing with a wholesome part of target. When the ECT sensor coil has met with a defect of target, the resonance condition has not been established. This has led that the impedance has reduced to small value compared with those at resonant condition. As a result, a deviation between the resonant and not resonant impedances has become the maximum. Thus, the sensibility of ECT sensor has been enhanced.

Further, connection of the conductors to be applied a half of the source voltage to adjacent conductors has made it possible to enhance the capacitive effect among the conductors. Practically, this connection has been carried out by twisting the two coils to uniform the facing side of both conductors. Due to this enhancement of the capacitive effects, the resonant frequency has been reduced and succeeded in increasing the sensibility.

References