Controlling Alternating Current Distribution inside Conductive Material Leads to a Novel Volumetric Examination Method —Experimental Verification*¹

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This paper experimentally demonstrates that controlling alternating current distribution inside conductive material enables one to perform volumetric examinations using electromagnetic phenomena. Several current distributions are superposed to locally realize a unique alternating current distribution having a phase difference of 180 degrees between currents flowing near the surface and those deep inside, while having non-exponential decay in depth direction. Experimental results clearly show that measuring the phase of magnetic field outside the material as a function of the ratio of the superposition provides quantitative information about the depth of defects. In addition, this approach is applicable even though the depth of defects is much deeper than the standard depth of penetration; experimental results show clear differences between signals due to near-side notches of 10, 12, 15, and 20 mm deep, when an exciting frequency of 100 kHz is adopted.
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1. Introduction

Maintaining the integrity of structures is one of the most important issues in recent industries. When a defect is found in an important structure, knowing the profile of the defect, especially its depth, is necessary to take a proper action for the maintenance of the structure. Ultrasonic-based nondestructive testing methods are most often utilized for this purpose. However, they are not always effective, for instance, in the inspection of highly anisotropic or inhomogeneous materials. Recently several studies have proposed the usage of electromagnetic-based nondestructive testing methods to overcome the problem. Since electromagnetic-based nondestructive testing methods are relatively insensitive to the microstructure of materials, one can expect that utilizing them together with ultrasonic-based nondestructive testing methods will lead to a high reliability of structures.

One of the most serious problems concerning the application of present electromagnetic-based nondestructive testing methods is that their signals do not contain explicit information about the depth of defects. Whereas quite a few papers report that computational inversion techniques would solve this problem,^{1,2)} its practical application is difficult because the ill-posedness of the problem is not yet fully evaluated.³⁾

In this paper, the authors propose a novel approach to overcome this problem. The key idea of the approach is to control the distribution of alternating currents flowing inside a conductor to obtain explicit indication concerning the depth of a defect. After the principle of the approach is described, the results of experimental verifications are presented.

2. Principle of the Novel Approach

When alternating currents flow in a conductive material, usually the currents are accompanied by a time delay in accordance with increase in depth. The presence of a defect disturbs the currents and the phase lag of the magnetic field generated by the disturbance depends mainly on the time delay of the currents originally flowing there. Therefore, one can evaluate the depth of the defect from the phase of the magnetic field to some extent. This is the physical background of depth estimation using conventional electromagnetic-based nondestructive methods using alternating currents such as eddy current tests. However, the alternating currents flowing inside conductive material exponentially decay in the depth direction. Measuring the magnetic field generated by the disturbance deeply embedded inside the material is a difficult matter and, therefore, electromagnetic nondestructive testing methods are not very suitable for the evaluation of the depth of a defect.

From another point of view, the discussion above leads to the idea that the difficulty in evaluating the depth of a defect would be solved if alternating currents flowing inside conductive material do not significantly decay and they are accompanied by a large time delay in depth direction. One of the examples of the distribution of alternating currents satisfying these two requirements is

$$J(d) = \begin{cases} J_0 \sin(\omega t) & \cdots d < d_0 \\ J_0 \sin(\omega t + \pi) & \cdots d \geq d_0 \end{cases}, \quad (1)$$

where $J(d)$ is the density of alternating currents flowing at the depth of d , ω is the angular frequency, and J_0 is a constant. It is expected that the depth of defects much deeper than the skin depth at the angular frequency of ω can be evaluated because the distribution does not decay exponentially in depth direction anymore. In addition, the distinctive change implies whether defects are above or below d_0 leads a difference of 180 degree between the magnetic fields generated by the currents.

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Fig. 1 Two AC distributions with different degree of attenuation in depth direction.

The authors have found that superposing several alternating current distributions realizes a distribution locally similar to (1). How alternating currents flowing inside conductive materials decay in the depth direction mainly depends on the frequency of the field and the electromagnetic characteristics of the material; it slightly depends on other parameters. If an alternating magnetic field is utilized to induce alternating currents (eddy currents), the distance from the exciter is not negligible.⁴⁾ In general, currents flowing near an exciter show high current density on the surface and rapidly decay in accordance with increase in depth. In contrast, those far from the exciter are weaker on the surface, but they attenuate less in the depth direction.⁵⁾ The former and the latter are illustrated in Fig. 1 as distribution A and B, respectively. The horizontal axis of Fig. 1 indicates the current density, while the vertical axis shows the depth from the surface. Note that alternating currents flowing in a nonmagnetic material show linearity. Thus, if distributions A and B have the same frequency and 180 degree difference in their phases, superposing them with a ratio of 1 : 1 provides another current distribution similar to (1), as illustrated in Fig. 2(a). The horizontal axis of the figure shows

$$f = \frac{J_A(d) - J_B(d)}{J_A(0)}, \quad (2)$$

where $J(d)$ indicates current density at a depth of d and subscripts A and B represents distribution A and B shown in Fig. 1, respectively. The horizontal dotted line indicates where the phase of currents changes 180 degrees.

It should be noted that the depth of the dotted line depends on the ratio of the super positioning, as shown in Figs. 2. Figures 2(b) and (c) illustrate distributions obtained by superposing distribution A and B with ratios of 1 : 1.4 and 1 : 1.8, respectively. Therefore, measuring the magnetic field with different values of superpositioning would provide an abrupt change of the phase of the field, which would contain the information about the depth of a defect.

Fig. 2 Superposed AC distributions.

3. Experimental Verification

Experimental verifications were conducted to support the idea explained in the previous section. Since the authors have worked for the development of eddy current techniques, the experiments here utilized an eddy current probe developed on the basis of an earlier study of the authors' to induce alternating currents in a conductor. The dimension and profile of the probe is illustrated in Fig. 3. The probe consists of a pancake detector and four coaxial tangential exciters with nine terminals to control the ratio of the superpositioning. The probe has a symmetric structure, and thus no signal is detected when no defect exists.

The difference between the two inner and the two outer exciters in distance from the detector provides two eddy current distributions with the same frequency but with a different degree of decay under the detector as illustrated in Fig. 1. Therefore, superposing eddy currents generated by the inner and outer exciters realizes current distributions similar to those illustrated in Fig. 2. Since all the exciters are connected in series, the terminals of the exciters can control the number of coil windings in which excitation currents flow through and the ratio of the number is identical to the ratio of superpositioning. The number of windings of the exciters is 144; the terminals on the exciters enable one to access every

Fig. 3 Probe utilized in the experimental verification.

Fig. 4 Experimental setup.

96 + 6*n* turns of the inner coils and every 18*n* turns of the outer coils (*n* = 1, 2, ..., 8).

Experimental setup is illustrated in Fig. 4. A function synthesizer and an amplifier were utilized to excite the probe; a lock-in amplifier was used to measure voltage induced at the detector as nondestructive signals. The voltage of the shunt resistance was utilized as a reference signal of the lock-in amplifier so changes of the impedance of the exciter coil do not affect the origin of the phase of measured signals. It should be noted that no dedicated or specialized instruments are necessary for the experiments. All the instruments

(a) side view

(b) top view

Fig. 5 Probe arrangement.

Fig. 6 Experimental results.

utilized in the experiment are generally employed in the conventional eddy current inspection.

The experiments were performed to gather signals due to four artificial rectangular notches machined into an SUS316L steel plate of 25 mm thick. The notches measure 40 mm in length, 0.5 mm in width, and 10, 12, 15, and 20 mm in depth. The probe scanned the notches by running directly above and along a notch, as illustrated in Fig. 5. The exciting frequency was set to 100 kHz, at which the standard depth of penetration is approximately 1 mm.

The results obtained are shown in Fig. 6. The horizontal axis of the figure is the ratio of the superpositioning defined as

$$\frac{\text{exciting currents flowing within the inner coils (Ampere-turns)}}{\text{exciting currents flowing within the outer coils (Ampere-turns)}} = \frac{\text{number of inner coils' windings}}{\text{number of outer coils' windings}}. \quad (3)$$

The vertical axis denotes how the phase of signals rotated. The figure shows that increasing the ratio of superpositioning provides a distinctive change in the phase of signals and the

change is almost 180 degrees, maximum, which is well supported by the physical background stated in the previous section.

Fig. 7 Trajectories of measured signals (ratio of exciting current = 1.0).

It is remarkable that one can clearly distinguish signals due to the four notches, although the shallowest notch is about 10 times as deep as the skin depth. Conventional electromagnetic nondestructive methods utilizing alternating currents, such as eddy current testing and magnetic flux leakage methods, cannot distinguish signals due to deep notches. In contrast, the approach proposed in this paper provides a difference between signals due to notches much deeper than the standard depth of penetration because it realizes current distributions that do not exponentially decay in accordance with increase in depth. Figure 7 shows the signals due to the notches of 10, 15, and 20 mm in depth measured when the value of the ratio defined in eq. (3) is 1.0. Every signal represents quite different trajectories depending on the depth of the notch.

4. Conclusion

This paper has demonstrated that superposing several alternating current distributions would significantly enhance the ability of electromagnetic nondestructive testing methods to measure the depth of a defect. The following lists the

advantages of the approach revealed by the demonstration.

- (1) It provides clear indication.

The parameter that would be utilized to evaluate the depth of a defect is a sudden rotation of signals at X-Y plane, which is easily recognized during inspections.

- (2) It is applicable not only to the inspection of thin structures but also that of thick ones.

The approach would enable one to evaluate the depth of a defect much deeper than the standard depth of penetration. The experiments have demonstrated that the approach provided a clear difference between signals due to 15 mm and 20 mm deep near-surface notches when the depth of penetration is as shallow as 1 mm.

- (3) Its sensitivity to surface breaking cracks is as high as conventional methods

The approach works as a conventional method when the ratio defined in (3) = 0, which ensures that its sensitivity to surface breaking cracks is as high as the conventional methods.

- (4) It does not require special experimental apparatus.

All the experimental apparatus utilized in the experiments are the same as those utilized in conventional eddy current tests. Connecting equipment to the apparatus is the only thing that needs to be changed. Whereas the experiments performed in this study utilized the terminals of the coils to control the ratio of the superpositioning, the linearity of the problem implies that the same results should be obtained by numerically superposing signals obtained when the inner exciters are driven alone and those obtained when the outer exciters are driven separately as well.

The authors have mainly worked for the enhancement of eddy current techniques and thus the experimental verifications in this paper induced alternating currents using electromagnetic induction. Since the key idea of the approach is to realize and control alternating current distribution, one would be able to induce currents directly inside a conductor using terminals and a voltage source, as conventional AC potential drop tests, to perform inspections based on the approach.

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