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Nondestructive Evaluation of Cracks with High-T_C SQUIDs and Perspective

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The eddy-current non-destruction evaluation (NDE) of cracks in conducting materials by using HTS SQUID magnetometers and gradiometers for quantitative non-destructive evaluation are investigated in this work. In the first part of the research, the main effort was devoted to understanding the characteristic of the environmental magnetic noise and the enhancement in the signal-to-noise ratio in conventional unshielded environment. The second portion of the work was related to the quantitative analysis of the phase and the magnitude of the defect signal from the excited eddy-current around the flaw in a conductive specimen. Finally, the optimal design of the eddy-current probes is developed for reducing the cost and preserving the feasibility of the quantitative NDE. The future development of the eddy-current probes using HTS SQUID are proposed and the possible applications are discussed.
Key words: SQUID, NDE

1. INTRODUCTION

Many techniques have been developed in the last decade to reduce the noise level of the SQUID for practical applications. To achieve the best SNR for the HTS SQUID system, one can utilize a costly magnetic shielding. But this is not an adequate solution for many practical applications. The more practical method for suppressing the environmental noise is to use the integrated planar gradiometer or the electronic axial gradiometer for the HTS SQUID system. [3-5]. It was shown that the phase sensitive quantitative planar SQUID gradiometer can detect the depth of a hidden flaw as that detected with an electronic axial SQUID gradiometer. In addition, the integrated planar gradiometer is the simpler in the flux-locked electronics in comparison with the electronic axial gradiometers. [6] However, it is not clear whether the noise performance with the planar gradiometer system would be better or comparable to that with an electronic gradiometer. In addition, the feasibility in the quantitative analysis of the measured results is not shown for the system.

To investigate the quantitative NDE using the planar gradiometer system, the frequency response and the magnetic field map of a conducting specimen with a void were studied. The merits for the quantitative NDE with the planar gradiometer eddy-current probe are demonstrated.

2. EXPERIMENTAL DETAILS

The planar gradiometer used in this work is the high-transition-temperature (HTS) rf SQUID from the Juelicher SQUID company in Germany. To calibrate the gradient-to-voltage transfer function of the planar gradiometer, a long straight wire carrying a current of 7 mA is scanned under the gradiometer along its baseline direction as shown in Fig. 1. The measured magnetic field gradient map was fitting to the analytic formula in order to find the SQUID-to-wire distance h as well as gradient-to-voltage transfer function dG/dV. The best-fit results are h = 4.1 and dG/dV = 2.15 nT/cmV according the magnetic field gradient map shown in the right bottom of Fig. 1. In order to check the validity of the fit result, the experiment results are integrated numerically to give the magnetic map as shown in the right top of Fig. 1. The magnetic field map also shows excellent agreement with the analytic solution by using the same fit parameters obtained in fitting of the gradient map.

The magnetic field map obtained by numerical integration from the gradient map has some figures of merit. Firstly, the uniform ambient noise is rejected by the planar gradiometer. To achieve the similar noise level may require the electronic axial gradiometer, which has two SQUID electrons and the compensation electronics is relatively a complicate SQUID system. Secondly, the integration does actually reduce the remaining noise in the gradient map. Let V_n be the remaining noise (voltage fluctuation) in measuring the gradient map. The magnetic field map is then calculated by using the following formula:

$$B_z(x) = \int \left[\frac{dB_z}{dx'} + V_n \right] dx' \tag{1}$$

Since V_n varies independently with respect to x, the noise in the obtained magnetic field map is greatly reduced.

In the previous work, we concluded that the planar gradiometer eddy-current probe has some advantages over the axial gradiometer eddy-current probe [6-7]. To realize the planar gradiometer eddy-current probe for the quantitative non-destructive evaluation, we further investigated calculation of the defect signal by comparing the results of the numerical simulation with the experimental data.

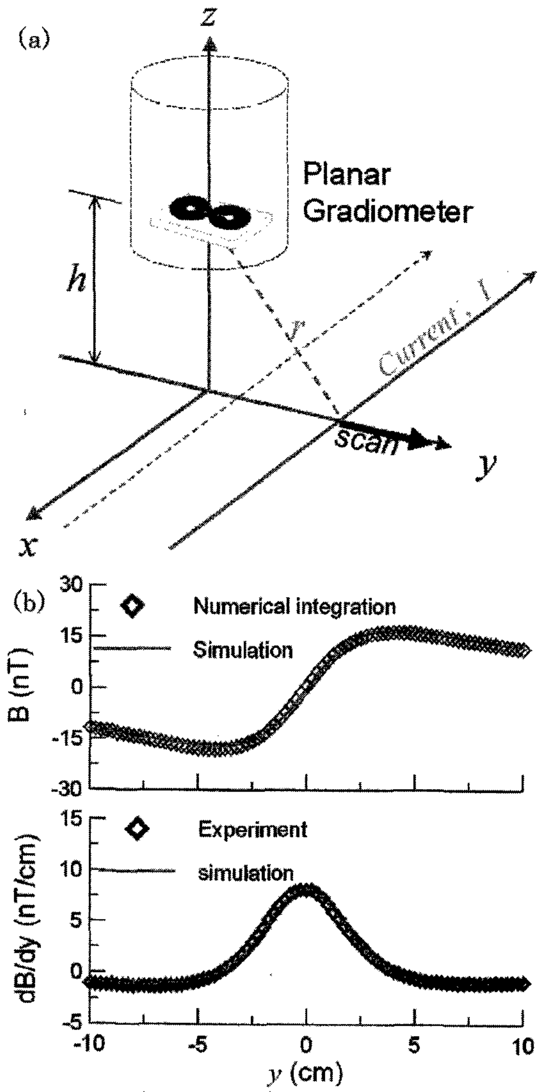

Figure 1 (a) Calibration of the gradient-to-voltage transfer function of the planar gradiometer by measuring the magnetic field gradient map of a long-straight current carrying wire. (b) The magnetic field gradient map measured with the planar gradiometer is transferred into the magnetic field map by means of a numerical integration technique.

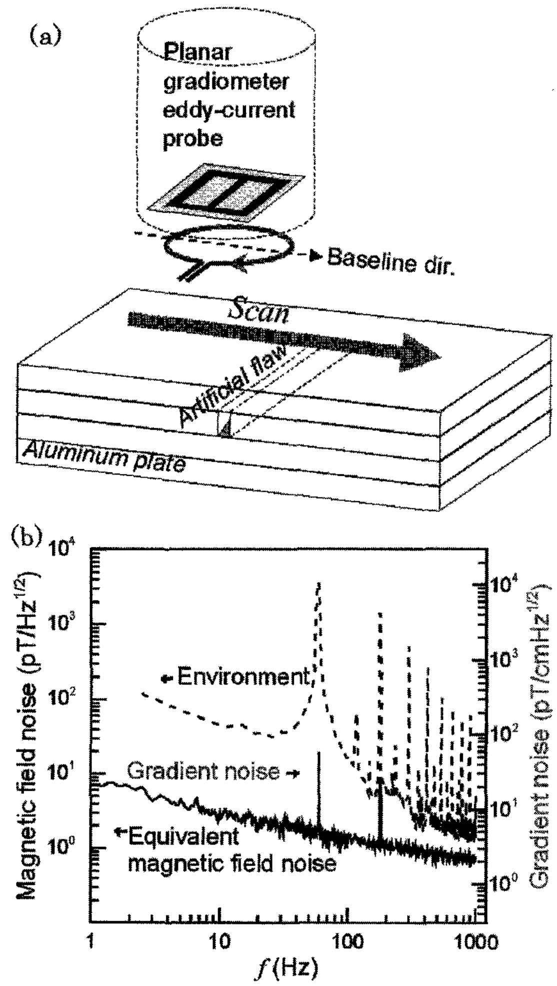

Figure 2 (a) Planar SQUID gradiometer eddy-current probe with a circular excitation coil. (b) The gradient noise and the equivalent magnetic noise of the gradiometer.

3. RESULTS AND DISCUSSIONS

Figure 2 (a) shows schematic diagram of the eddy-current probe studied in this work. The probe is sensitive to the flaws oriented in the direction perpendicular to the baseline of the gradiometer pick-up loop. The noise performance of the planar gradiometer is measured in conventional environment as shown in Fig. 2 (b). The solid curve is the gradient noise referred to the scale on the right of Fig. 2(b). The equivalent magnetic field noise, the same curve, referred to the left scale is obtained by multiplying the gradient noise with the baseline length of the gradiometer. It was found that the equivalent magnetic field noise is less than the environmental noise by a factor 10 at the frequency below 100 Hz, which is about the same as noise performance for the axial electronic gradiometer reported elsewhere. [4]

It has been shown that the eddy-current pattern of an unflawed semi-infinite conductor slab can be calculated analytically. [8] For the hidden flaws with an axial symmetry, we apply the finite-element analysis to find the eddy-current distribution and the defect signal due to the flaw [9]. As the hidden flaw is assumed to be small, the eddy-current distribution does not change greatly form the unflawed case. It is plausible that one can calculate the defect signal form the eddy-current distribution of the unflawed case. To check the validity of this technique, we compared the defect signal by using the unflawed eddy-current with those by using the FEM result of the flawed case. The former source for the defect signal is referred to as the "simple current anti-dipole" and the latter is the "exact current anti-dipole". The defect signals for both cases are shown in Fig. 3 (a) and (b) respectively for the magnitude and the phase. It is clear that the predictions of the simple current anti-dipole deviates form the actual FEM result for both the magnitude and the phase. Although the deviation in the magnitude decreases in the very low frequency (~20 Hz), the deviation in the phase remained. [9] The results implied that the phase of the buried

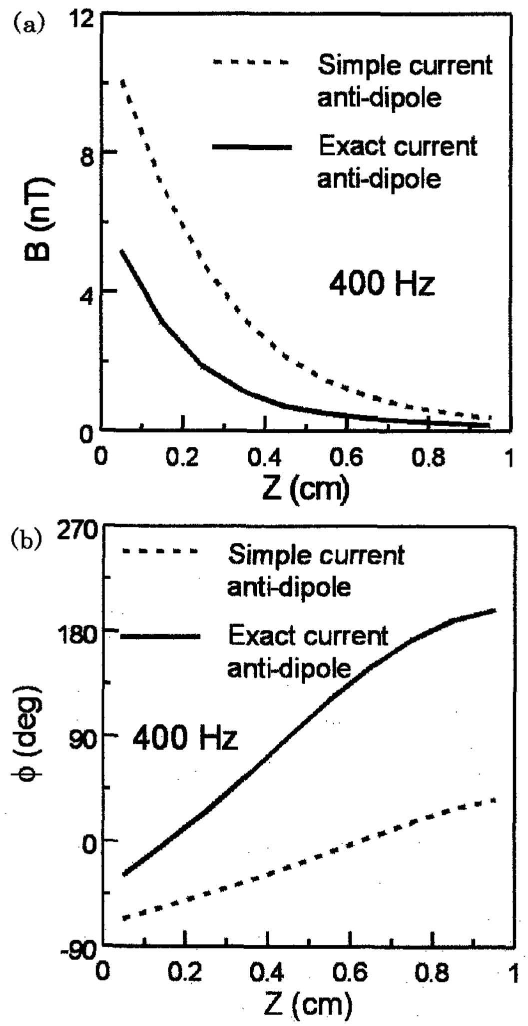

Figure 3 (a) The magnitude, and (b) the phase, of the defect signal of the simple current anti-dipole and the exact current anti-dipole. Z is the depth of the current anti-dipole.

current dipole is always different from the phase of the magnetic field that it generates in the presence of the conductor specimen.

The phase shift of the defect signal is important for the flaw depth evaluation. [9] To predict the phase of the defect signal correctly, one can perform the FEM each time for a distinct frequency, but this is impractical for the routine quantitative NDE. To implement the prediction of the defect signal with the concept of the current-anti-dipole, we suggest the following methods to correct the phase of the defect signal. The phase difference between the buried current dipole and the corresponding magnetic field is measured experimentally by using a SQUID magnetometer as shown in Fig. 4 (a). The data shown is for the frequency of 400 Hz. The phase shift of the magnetic field with respect to the buried current dipole, $\phi_{anti\text{-}dipole}$, is shown in Fig. 4(b) as the curve with the symbol +. The phase of the eddy current for the unflawed case, $\phi_{eddy\ current}$, is the solid curve without a symbol. With the two curves, the resultant phase of the defect signal, ϕ_{defect}, is easily calculated by addition:

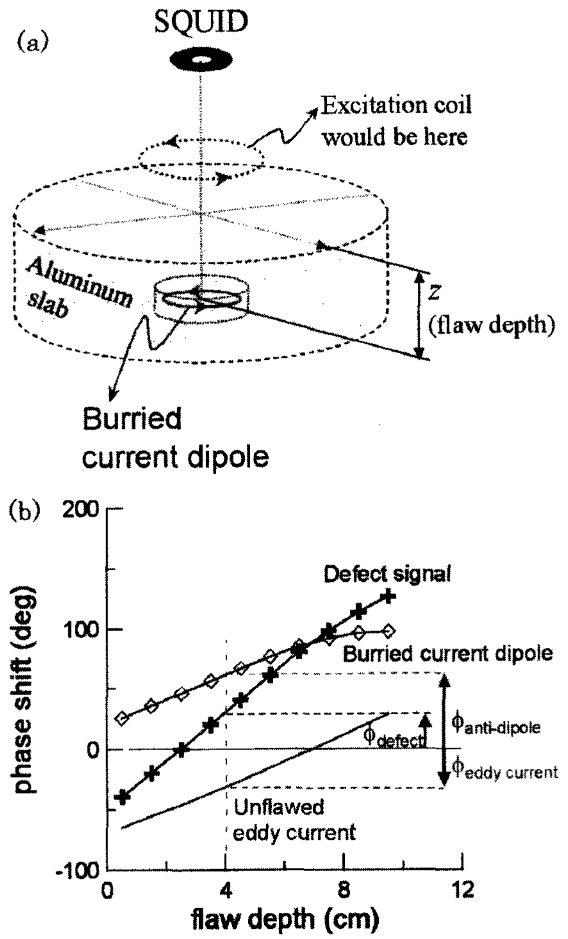

Figure 4 (a) Experimental set-up for measuring the phase shift of the magnetic field for a buried dipole, (b) phase shift of the magnetic field with respect to the buried current dipole (+), phase shift of the unflawed eddy current (solid line), and the phase shift of the defect signal (diamond). The frequency is 400 Hz.

$$\phi_{defect} = \phi_{eddy\ current} + \phi_{anti\text{-}dipole} \quad (2)$$

The obtained defect signal is close to the phase-depth relation we reported before. [7] In other words, one can easily predict the phase of the defect signal according to the analytic solution of eddy currents for the circular excitation coil by using the data similar to that shown in Fig. 4 (b). Therefore, the planar gradiometer eddy-current probe with a circular excitation coil is practical for the quantitative eddy-current NDE.

The eddy current probe shown in Fig. 2(a) can only sense the flaw with a single direction. To release this restriction, we propose the orthogonal planar SQUID gradiometers eddy-current probe with a circular excitation coil as shown in Fig. 5. (a). In order to operate the sensor with a minimal cross talk between the gradiometer channels, a differential modulation coils with orthogonal main current directions was adopted as shown in Fig. 5. (b). The proposed probe could measure the transverse gradient of the magnetic field, dB_z/dx and dB_z/dy, and hence is suitable for the quantitative NDE for flaws with arbitrary orientations.

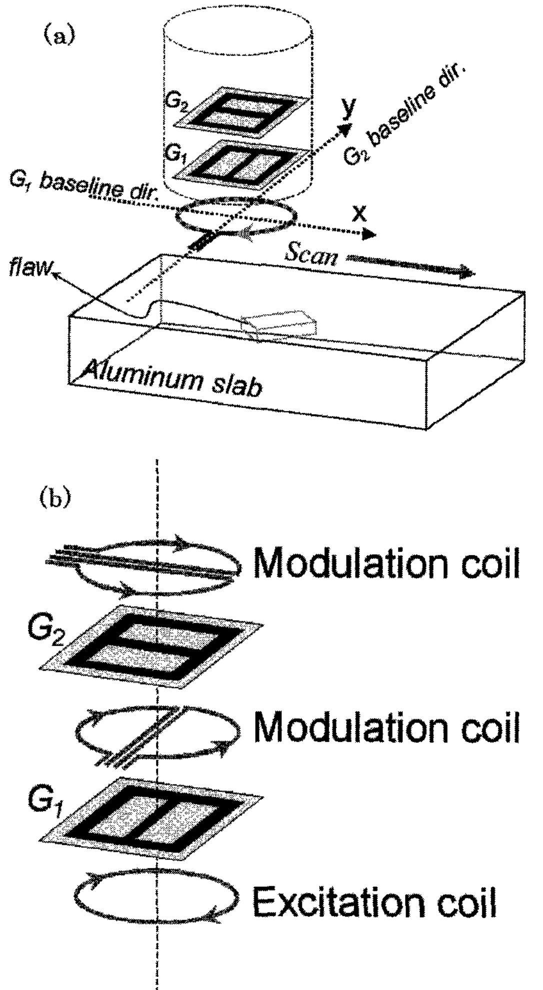

Figure 5 (a) Orthogonal planar SQUID gradiometers eddy-current probe with a circular excitation coil, the probe is sensitive to in-plane oriented flaws. (b) Modulation schemes for the orthogonal planar gradiometer eddy-current probe.

4. CONCLUSIONS

The phase of the defect signal can be easily calculated by adopting the concept of the anti-current dipole. The phase difference of the defect signal is calculated by adding the phase of the anti-current dipole with the phase shift of the buried current dipole. The planar gradiometer eddy-current probe with a circular excitation coil is suitable for quantitative eddy current non-destructive evaluation. In addition, we suggest the orthogonal planar gradiometer eddy-current probe, which is valuable for detecting the flaws with arbitrary orientations.

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