Integrated Planar HTS SQUID Gradiometer for NDE Application

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The performance of a SQUID NDE probe with integrated planar SQUID gradiometers was compared to that with an electronic axial SQUID gradiometer. A circular excitation coil was used for the SQUID NDE probe with the planar gradiometer, whereas a differential excitation coil was adopted for the one with the axial gradiometer. These NDE systems are used to detect a buried flaw in aluminum plates, and the phase-depth relations of the buried flaw were found to show similar linear dependences. Overall, the SQUID NDE system with the planar gradiometer is relatively simple and practical for unshielded operations.

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1. INTRODUCTION

The SQUID designed for eddy-current nondestructive evaluation (NDE) has been shown to be a powerful technique for detecting deep lying flaws in conductive materials.¹⁻⁶ Various designs of SQUID NDE probes have been proposed. Among the most promising designs, systems based on the axial SQUID gradiometer or planar gradiometer are particularly useful because of the good noise performance in an unshielded environment.³⁻⁴ For high- T_C SQUIDs, the system with the axial gradiometer utilizes an electronic technique to cancel environmental magnetic noise, while the system with the

Fig. 1. SQUID NDE probes with (a) the electronic axial gradiometer, (b) the planar gradiometer.

planar gradiometer employs a symmetric superconducting pickup loop to reject ambient noise. To date, it is shown that the NDE system with the axial gradiometer can be used to detect the depth of the buried crack.^{2,5} However, it is not clear whether the system with the planar gradiometer can be used to obtain comparable results. Hence, it is interesting to compare the SQUID NDE probe with the planar gradiometer to that with the axial gradiometer on the detection of the flaw depth.

In this work, a comparison study between the SQUID NDE probe using the planar SQUID gradiometer and that using the axial SQUID gradiometer is given. The phase-depth relation of buried flaws with both SQUID NDE probes are investigated and the results are discussed.

2. EXPERIMENTAL DETAILS

The schematics of the SQUID NDE probes with the planar gradiometer and the axial gradiometer are shown in Fig. 1. The sensor shown in Fig. 1 (a) is the axial gradiometer consisting of the reference SQUID magnetometer and the sensor SQUID magnetometer spaced by the baseline length of 120 mm, while the one shown in Fig. 1 (b) is the integrated rf SQUID planar gradiometer with a baseline length of 3.6 mm. The above magnetometers and the planar gradiometer are commercial HTS rf SQUID sensors (Juelicher SQUID company, Germany) and show low magnetic noise.⁷ Owing to the long baseline length of 120 mm, the electronic axial gradiometer acts like a magnetometer with noise levels 80, 3, 0.6, and 0.4 pT/Hz^{1/2} at 1, 10, 100, and 1000 Hz respectively. The planar gradiometer, which senses the tangential spatial derivative of the magnetic field, has a noise level of 20, 8, 3, and 0.7 pT/cmHz^{1/2} at 1, 10, 100, and 1000 Hz respectively.

To prevent the useable dynamic range⁸ being suppressed by the

Fig. 2. Block diagram of the SQUID NDE system with (a) the electronic axial gradiometer, (b) the planar gradiometer.

excitation field in the SQUID, the SQUID NDE probe with the axial gradiometer utilizes a differential excitation coil 28 mm in diameter with the location of the coil carefully adjusted to minimize the excitation field in the sensor SQUID magnetometer. For the SQUID NDE probe with the planar gradiometer, the circular excitation coil 14 mm in diameter was adopted, and the location of the coil was carefully adjusted to minimize the excitation field in the planar gradiometer. The distance from the SQUID to the excitation coil was 20 mm for the SQUID NDE probe with the axial gradiometer, and 18 mm for the one with the planar gradiometer.

Block diagrams of the SQUID NDE electronic systems are shown in Fig. 2 (a) and (b). The SQUID electronics used for the planar gradiometer is identical to that for the electronic axial gradiometer. The SQUID NDE system with the planar gradiometer is simpler since only one SQUID electronics, instead of two, is required. Besides, as the integrated planar gradiometer pickup loop prevents the homogeneous environmental magnetic field from contributing to the output of the SQUID electronics, the integrated planar gradiometer is more stable in the unshielded environment in comparison with the electronic axial gradiometer for which the SQUID magnetometers still respond to the environmental magnetic field.

3. RESULTS AND DISCUSSION

It has been shown the SQUID NDE probe shown in Fig. 1 (a) can be used to evaluate the depth of a buried slot in conductive samples.⁶⁻⁷ It is

Fig. 3. Responses of the eddy-current induced magnetic field from the buried flaw measured with (a) electronic axial gradiometer, (b) planar gradiometer SQUID NDE system. The flaw is a buried slot 0.7 mm in width and 1.5 mm in thickness. The excitation frequencies are 90 Hz.

interesting to know whether a similar result can be obtained with the planar gradiometer NDE probe shown in Fig. 1 (b). To investigate this point, aluminum plates with slot were used to simulate a sample with a buried flaw, and examined with the SQUID NDE probes shown in Fig. 1 (a) and (b) respectively. Fig. 3 (a) shows a line scan across the slot buried 2.9 mm deep measured with the SQUID NDE probe using the axial gradiometer and the differential excitation coil. The orientation of the slot is parallel to the main current direction of the differential excitation coil. The in-phase, B_i , and quadrature phase, B_q , magnetic fields were lock-in detected and recorded as functions of the horizontal position as shown in Fig. 3(a). The differential defect field, dB/dx , calculated with B_i and B_q , is shown in the middle of Fig. 3 (a). The corresponding differential phase, ϕ_{diff} , was then calculated according to the relation $\phi_{diff} = \tan^{-1}[(dB_q/dx)/(dB_i/dx)]$ as shown in the lower part of Fig. 3 (a). Near the buried flaw, the phase varies slowly with the characteristic U shape, which was shown to be valuable for evaluating the flaw depth.⁶

When the planar gradiometer NDE probe was used to examine the buried slot, the orientation of the slot was perpendicular to the baseline direction of the planar gradiometer. The circular excitation coil induces an eddy-current in the sample, and the horizontal gradient of the magnetic field, G , was measured and lock-in detected as shown in Fig. 3 (b). The differential gradient response, dG/dx , was calculated in the way similar to the differential defect field as shown in the middle of Fig. 3 (b). The

Fig. 4. Phase-depth relations of the eddy-current induced magnetic field from the buried flaw measured with (a) electronic axial gradiometer, (b) planar gradiometer SQUID NDE system. The flaw is a buried slot 0.7 mm in width and 1.5 mm in thickness.

corresponding differential phase was then calculated according to the relation $\phi_{\text{diff}} = \tan^{-1}[(dG_q/dx)/(dG_i/dx)]$ as shown in the lower part of Fig. 3 (b). It was found that the profile of the $\phi_{\text{diff}}-x$ curve measured with the planar gradiometer was very similar to that measured with the axial gradiometer. However, the differential phase was shifted by 10-20 degrees near the slot. This suggests that similar, but not identical, phase-depth relations may be obtained with the NDE probes shown in Fig. 1 (a) and (b). Fig. 4 (a) and (b) show the phase-depth relations obtained using the NDE probes shown in Fig. 1 (a) and (b) respectively. It was found that the phase-depth relation measured with the planar gradiometer is very similar to that obtained with the axial gradiometer. This means that the planar gradiometer NDE probe can be used to measure the phase-depth relation of the buried flaw as well as the axial gradiometer NDE probe.

As the field pattern generated by the differential excitation coil imposes a complex eddy-current pattern, it is difficult to obtain theoretical predictions of the NDE results to compare with the experimental data using the axial gradiometer NDE probe. In contrast, the eddy-current problem with the circular excitation coil is much easier⁹, and an analytic solution of the eddy-current distribution is still possible for a flawless conductive sample.¹⁰ Hence, with the planar gradiometer NDE probe, one may hope obtain fruitful experimental results through comparison with theoretical predictions.

4. CONCLUSION

In summary, the SQUID NDE system with the integrated planar gradiometer and the circular excitation coil is simple and practical for unshielded NDE applications. Flaw depth evaluation can be performed with this SQUID NDE system, and the results are similar to that obtained with the system using the axial gradiometer. Therefore, the integrated planar SQUID gradiometer is suitable for quantitative nondestructive evaluation.

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