ELSEVIER

Physica C 368 (2002) 105–108

PHYSICA C

www.elsevier.com/locate/physc

High- T_c SQUID magnetometers and gradiometers for NDE application

J.T. Jeng^a, H.E. Horng^b, H.C. Yang^{a,*}

^a Department of Physics, National Taiwan University, Taipei 106, Taiwan, ROC

^b Department of Physics, National Taiwan Normal University, Taipei 116, Taiwan, ROC

Abstract

The performance of the superconducting quantum interference device (SQUID) nondestructive evaluation (NDE) system with a shielded magnetometer and unshielded gradiometers were investigated. In the magnetometer NDE system, the environmental noise was reduced with the SQUID seating inside a μ -metal cylinder, whereas the environmental noise was eliminated with electronic subtraction in the gradiometer NDE system. For the shielded magnetometer NDE system, the signal-to-noise ratio was improved with a higher excitation field to enhance the defect signal. For the gradiometer NDE system, the signal-to-noise ratio was improved as a result of the reduction of environmental noise. The performance of two SQUID NDE systems is compared and the results are discussed. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Magnetometer; Gradiometer; SQUID NDE

1. Introduction

Superconducting quantum interference devices (SQUIDs) are the most sensitive sensor in detecting magnetic flux and have been widely used in many noninvasive applications [1], for instance, in magnetocardiograph [2], or nondestructive evaluation (NDE) of conductive samples [3–7]. For the inducted eddy-current NDE system with high- T_c SQUID, the environmental noise can suppress the usable dynamic range of the SQUID and hence deteriorate the performance of the system. To solve this problem, one may utilize the SQUID magne-

tometer with the electronic gradiometer [4,5] or with a magnetic shield [6,7] in order to reduce the environmental magnetic noise. In this work, the noise characteristics of the shielded SQUID magnetometer and the SQUID gradiometer for NDE systems were investigated. The characteristics of the shielded magnetometer NDE system as well as the gradiometer NDE system were compared, and the performances were discussed.

2. Experimental

The schematic diagrams of the SQUID magnetometer and the electronic SQUID gradiometer for the NDE systems investigated here are shown in Fig. 1(a) and (b) respectively. The SQUID magnetometer was enclosed with a small μ -metal

* Corresponding author. Tel.: +886-2-2362-6937; fax: +886-2-2363-9984.

E-mail address: hcyang@phys.ntu.edu.tw (H.C. Yang).

Fig. 1. Schematics of (a) the shielded SQUID magnetometer and (b) the electronic SQUID gradiometer for NDE systems.

cylinder while the gradiometer consisting of two unshielded SQUID magnetometers was arranged to form an electronic gradiometer with a base line of 12 cm. The sensors used in this study were high- T_c dc SQUID magnetometers (Conductus Inc., USA). The maximum bandwidth of the dc SQUID systems was 100 kHz, and the slew rate was measured to be 0.3 mT/s. In the μ -metal shielded SQUID magnetometer, the outer diameter of the μ -metal cylinder is 2.5 cm with a wall thickness of 3 mm and length of 7.2 cm as shown in Fig. 1. The double-D excitation coil was adopted in order to minimize the excitation field in the SQUID for both configurations shown in Fig. 1(a) and (b). In addition, the compensation coil was used to cancel the phase-shifted excitation field, which was due to the eddy-currents induced in the asymmetric metallic objects near the SQUID.

Before performing the NDE work, we first calibrate the shielded SQUID magnetometer. During the calibration, a dipole coil carrying an ac current was moved vertically below the shielded SQUID, and the induced ac magnetic field, B_z , was measured with the shielded SQUID. The location of the SQUID was determined by a linear fit of $B_z^{-1/3}$ with respect to the vertical coordinate. In this way, the cold-to-warm distance found to be 13 mm, and the shielding factor of the μ -metal cylinder was found to be 30 for frequencies between 100 and 400 Hz.

3. Results and discussion

To estimate the performance of the shielded SQUID NDE system in our laboratory, we measured the noise spectrum of the SQUID in unshielded and shielded configurations as shown in Fig. 2. In the unshielded environment, the magnetic field noise, $S_B^{1/2}$, was 0.2 nT/Hz^{1/2} at 10 Hz and 0.07 nT/Hz^{1/2} at 100 Hz while in the shielded situation the magnetic field noise was reduced to 10 pT/Hz^{1/2} at 10 Hz and 2 pT/Hz^{1/2} at 100 Hz. As the slew rate of the SQUID is 0.3 mT/s, the maximum allowed ac field in the SQUID is found to decrease with the frequency as the broken line in the top of Fig. 2. Hence, the slew rate determines the upper limit of the usable dynamic range of the SQUID. The usable dynamic range of the shielded SQUID NDE system was 110 dB at 100 Hz, corresponding to the maximum ac field of 700 nT and the noise level of 2 pT/Hz^{1/2}.

Although the useful dynamic range of the shielded SQUID was increased with the shield, the signal detected by the shielded SQUID was reduced due to the shield. Thus, one must increase the excitation field in order to enhance the signal detected by the shielded SQUID. To see whether this is possible, an aluminum sample 12 cm $\times$ 7 cm $\times$ 1 cm in dimension with a simulated crack 6 cm $\times$ 2 mm $\times$ 1.5 mm in dimension was examined with the shielded SQUID NDE system. In

Fig. 2. Noises of the SQUID magnetometer in μ -metal shielded and unshielded environments. The usable range of the SQUID is between the slew-rate limit and the noise level of the shielded SQUID. The maximum usable range in the noise-free environment is between the slew-rate limit and the intrinsic noise level of the gradiometer.

Fig. 3. Detected signals from the crack and the edge of the sample at the excitation frequency of 100 Hz. The edge signal dominated the detected signal.

Fig. 3, a line scan of the sample with the NDE system was shown. The excitation frequency used was 100 Hz, which is close to the most effective

excitation frequency for the 4 mm deep crack [6]. The excitation field on the surface of the sample was estimated to be 15 μT with the excitation current of 6 mA in the 80-turns, 28 mm double-D excitation coil. With this excitation field, the crack signal was 0.4 nT and the edge signals from the edges of the sample were 12 nT as shown in Fig. 3. In addition, there is shift from zero by 2.2 nT for the crack signal as shown in the middle of Fig. 3. The shift, which may be resulted from the misalignment of the SQUID in the μ -metal shield, is found to depend on the excitation frequency and the conductivity of the sample. Fortunately, the shift is not too much to dominate the detected signal, and it is removable by injecting a suitable amount of current into the compensation coil [6].

By increasing the excitation current, the signals detected by the shielded SQUID can be further enhanced until the signals reach the slew-rate limit of SQUID. As shown in Fig. 2, the slew-rate limit is 700 nT at 100 Hz, which is 60 times greater than the edge signals shown in Fig. 3. Hence, the excitation field must be increased to 900 μT , which corresponds to 360 mA in the excitation coil, in order to utilize the full useable range of the shielded SQUID NDE system. Actually, the excitation current of 360 mA is achievable by using a conventional excitation source. The ultimate usable dynamic range of the shielded SQUID system is limited to the maximum possible dynamic range (140 dB at 100 Hz) determined from the slew-rate limit and the intrinsic noise level of the SQUID.

In Fig. 4 we show the noise spectrum of an electronic dc SQUID gradiometer. The environmental noise was measured by using the sensor SQUID only, while the noise of the first order gradiometer was obtained by subtracting the output of the reference SQUID from that of the sensor SQUID in the unshielded environment. The intrinsic noise of the dc SQUID gradiometer was measured in a well-shielded environment as shown in the bottom of Fig. 4. In the unshielded environment, the electronic gradiometer shows a magnetic filed noise level of 20 $\text{pT}/\text{Hz}^{1/2}$ at 10 Hz and 3 $\text{pT}/\text{Hz}^{1/2}$ at 100 Hz. Namely, at 100 Hz, the usable dynamic range of the electronic gradiometer NDE system is 107 dB, which is close to that the shielded SQUID NDE system in Fig. 2. In

Fig. 4. Noise spectrum of the first order SQUID gradiometer in unshielded environment. The usable range is between the slew-rate limit and the noise level of the dc SQUID gradiometer in the unshielded environment. The ultimate usable range in the noise-free environment is between the slew-rate limit and the intrinsic noise level of the gradiometer.

addition, a low excitation field ($<30 \mu\text{T}$ at 100 Hz) is needed in order to make use of the full usable dynamic range of the gradiometer NDE system. Nevertheless, the electronic SQUID gradiometer is not so stable as the shielded SQUID magnetometer because the sensor and the reference SQUIDs remain noisy. Therefore, the shielded SQUID NDE system offers some advantages over the gradiometer NDE system in simplicity and stability.

We replaced high- T_c dc SQUIDs by high- T_c rf SQUIDs (supplied by the Juelicher SQUID company in Germany) to further increase the usable dynamic range of the gradiometer. The measured slew rate of the rf SQUID was 1 mT/s and the intrinsic noise level was $0.3 \text{ pT/Hz}^{1/2}$ at 100 Hz. With the rf SQUID, the usable dynamic range of the gradiometer NDE system was increased to 118 dB at 100 Hz. In addition, the high- T_c rf SQUID gradiometer system was more stable for the unshielded operation because of the higher slew rate. In Ref. [5], the high- T_c rf SQUID with a slew rate of 2.5 mT/s and an intrinsic noise level of $1 \text{ pT/Hz}^{1/2}$ at 100 Hz was used in their gradiometer

NDE system. Although the SQUID showed a greater intrinsic noise level, the usable dynamic range of 125 dB at 100 Hz is a bit larger than our present results due to the higher slew rate. Nevertheless, the large usable dynamic range (118 dB at 100 Hz) of our rf-SQUID NDE system has made them much better than the conventional eddy-current probe in detecting the deep crack in good conductors [1].

4. Conclusion

In summary, the usable dynamic range of the high- T_c SQUID NDE system can be enhanced with a shielded SQUID or with a SQUID gradiometer. The shielded SQUID NDE system performs well if a higher excitation field is achievable while the SQUID gradiometer works well with a low excitation current. The large usable dynamic range of the SQUID NDE system made them much better than the conventional eddy-current probe in detecting the deep crack in good conductors.

Acknowledgements

The authors thank the Ministry of Education of the ROC for the financial support under the Program for Promoting University Academic Excellence.

References

- [1] W.G. Jenks, S.S.H. Sadeghi, J.P. Wikswo Jr., J. Phys. D: Appl. Phys. 30 (1997) 293.
- [2] J.P. Wikswo Jr., IEEE Trans. Appl. Supercond. 5 (1995) 74.
- [3] H. Weinstock, M. Nisenoff, Proc. SQUID, in: H.D. Hahlbohm, H. Lubbig (Eds.), Proc. I.C. SQUID, West Berlin, New York, 1985, p. 843.
- [4] Y. Yavrin, H.-J. Krause, W. Wolf, V. Glyantsev, J. Schubert, W. Zander, H. Bousack, Cryogenics 36 (1996) 83.
- [5] M.V. Kreutzbruck, J. Tröll, M. Mück, C. Heiden, Y. Zhang, IEEE Trans. Appl. Supercond. 7 (1997) 3279.
- [6] J.T. Jeng, S.Y. Yang, H.E. Horng, H.C. Yang, IEEE Trans. Appl. Supercond. 11 (2001) 1295.
- [7] N. Tralshawala, J.R. Claycomb, J.H. Miller Jr., Appl. Phys. Lett. 71 (1997) 1573.