Noise characteristics of high-$T_c$ YBa$_2$Cu$_3$O$_y$ SQUID gradiometers

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Abstract

We studied the field noise of high-$T_c$ YBa$_2$Cu$_3$O$_y$ SQUID gradiometers in moving environments. The superconducting quantum interference devices (SQUID) magnetometers were in planar and axial configurations. In shielded environment, the magnetometer shows a gradient noise of $\sim 0.17 \text{ pT/cm Hz}^{1/2}$ at 1 Hz and $\sim 5.1 \text{ fT/cm Hz}^{1/2}$ at 1 kHz. In unshielded environments, a gradient noise of $6.9 \text{ pT/cm Hz}^{1/2}$ was detected in our laboratory. The gradient noise at 1 Hz was increased to $0.38 \text{ nT/cm Hz}^{1/2}$ when the gradiometer system is moving at a speed of 20 mm/s. A moving gradiometer nondestructive evaluation system was set up to detect deep flaws. It was found there is a linear dependence between the phase of the differential field and the depth of flaws. The results are consistent with the SQUID magnetometer NDE system in which the SQUID magnetometer system is fixed and the samples were scanned under the system. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: SQUID magnetometer; Electronic gradiometer; Nondestructive evaluation; Field noise

1. Introduction

Superconducting quantum interference devices (SQUIDs) is the most sensitive sensors in detecting magnetic fields. Compared with the conventional eddy current method, SQUID sensors offer high sensitivity at low excitation frequency and permit us to detect deeper flaws. The SQUID systems have widely been used to detect flaws in steel pipe [1], buried flaws in aluminum plate [2], the plastic deformation gradients in steel [3], and the reconstruction of the defect shapes [4] and the testing of the aging aircraft structures [5] etc.

For some practical applications the SQUID cryostat has been made mobile and capable to operate in unshielded environments as the case of testing of the aging aircraft [5]. The problem with SQUID in unshielded environments is that small magnetic field has to be resolved in the presence of large ambient magnetic fields. Gradiometers are greatly helpful to resolve these problems. In a uniform magnetic field, the shielding current flows around the SQUID loop cancel each other, so the magnetic field coupled to the SQUID can be eliminated. For an inhomogeneous field, the shielding currents cannot be canceled, and the signal is proportional to the gradient fields. In the mobile
SQUID systems the vibration coupling to SQUID can affect SQUID performance. In this work we studied noise spectrum of high-$T_c$ YBa$_2$Cu$_3$O$_y$ SQUID gradiometers in planar or axial configurations and in unshielded and moving environments. Furthermore, we further constructed an electronic SQUID gradiometer system [6] with a baseline of 11.7 cm to detect artificial deep metal flaws.

2. Experiments

The noises of two gradiometers in shielded, unshielded, and moving conditions were studied. One is the electronic gradiometer with a base line of 11.7 mm while the other is the planar gradiometer with a base line of 3.6 mm. Both the rf SQUID magnetometers and gradiometers were commercial sensors (Jülich SQUID company, Germany) and show low SQUID noises. The layout of the SQUID gradiometer system along with the wooden cart carrying the cryostat is shown in Fig. 1. The cart was pushed at different driving speeds using a computer controlled $x$–$y$ stage. In the electronic gradiometer one sensing SQUID was located close to the source while the other sensing SQUID was oriented at a baseline distance of 11.7 mm. Magnetic field or gradient noise spectrum of an electronic gradiometer system in shielded, unshielded and moving conditions in our laboratory were measured. In the electronic gradiometer the difference electronics (Jülich SQUID company, Germany) adjusted to minimize the output of two SQUID magnetometer sensors. The output was fed to a spectrum analyzer to analyze the noise spectrum.

3. Results and discussion

In Fig. 2 we show the noises of a first order rf SQUID electronic gradiometer in shielded, unshielded and moving situations. The noise spectrum labeled “shielded” and “unshielded” was taken when the gradiometer system was stationary. The noise spectrum label with “moving” was measured when the SQUID gradiometer system was moving. The electronic gradiometer system was constructed with two rf magnetometers arranged along the $z$-direction with a baseline distance of 11.7 cm. The gain of a magnetometer is calibrated to be 50 nT/V. The value of $S^1_B (1 \text{ Hz})$ is $2 \text{ pT/Hz}^{1/2}$ (this corresponds a gradient noise of 0.17 pT/cm Hz$^{1/2}$) and the value of $S^1_B (1 \text{ kHz})$ is $60 \text{ fT/Hz}^{1/2}$ (a gradient noise of $\sim 5.1 \text{ fT/cm Hz}^{1/2}$) at 1 kHz in shielded environments. In unshielded environments the value of $S^1_B (1 \text{ Hz})$ is $80 \text{ pT/Hz}^{1/2}$ (a gradient noise of 6.9 pT/Hz$^{1/2}$ cm) in our laboratory. It was found that the $S^1_B (1 \text{ Hz})$ is increased to about $10 \text{ nT/Hz}^{1/2}$ (a gradient noise of 0.86 nT/cm Hz$^{1/2}$) when the gradiometer system moved in a speed of 20 mm/s. We attribute the

![Fig. 1. Measuring setup of a moving gradiometer system.](image1)

![Fig. 2. The $S^1_B$ and the gradient field noise spectrum of an electronic gradiometer system in shielded, unshielded and moving situations.](image2)
increased low frequency noise to the changing of gradient field.

In Fig. 3 we show $S_B^{1/2}$ (and gradient noise) spectrum of a moving SQUID gradiometer system at different moving speeds. Two situations were investigated: (1) the field noise of a stationary gradiometer system due to the quivering of the $x$–$y$ stage; and (2) the field noise of gradiometer system due to the gradiometer system moved at different speeds. In the first case, the measured noise was labeled with “quivering” shown in Fig. 3. It was found the field noise coupled to the gradiometer system due to the quivering of motor is small compared with the noise of a moving gradiometer system. For example, at a speed of 5 mm/s, the noise level is 1.8 nT/Hz$^{1/2}$ (a gradient noise of 0.15 nT/cm Hz$^{1/2}$) while at a moving speed of 20 mm/s the field noise level is increased to about 4.5 nT/Hz$^{1/2}$ (a gradient noise of 0.38 nT/cm Hz$^{1/2}$). For higher speed the noise data are not taken because a limitation of space in which the cart can move.

In Fig. 4 we show the gradient field noise of a planar rf SQUID gradiometer moving with different speeds in shielded, unshielded and moving conditions. The cart carrying the SQUID moved along the $x$-direction. The noise level is 20 pT/Hz$^{1/2}$ cm at 1 Hz measured in shielded environment. The gain of the SQUID electronics with the planar gradiometer is calibrated to be 63 nT/cm V by using a gradient coil.

In Fig. 5 we show the gradient field noise of a moving planar SQUID gradiometer moved with different speeds. The symbol + represents the gradient noise with the base line along the $x$-direction while the symbol $\Delta$ represents the gradient noise
with the base line along the \( y \)-direction (the cart still moved along the \( x \)-direction while the baseline is along the \( y \)-direction). The data labeled with quivering was due to the vibration of the motorized stage. It was found the gradient noise of the gradiometer system is greatly enhanced at higher moving speed when the baseline of the gradiometer is along the \( x \)-direction. Besides, the noise of a stationary gradiometer system only slightly increased as a result of quivering induced by the motorized stage. We attribute the higher gradient noise to the rapid increase of the gradient field \( dB_z/dz \) along the \( x \)-direction in space when the cart moved. To confirm this we measured the gradient field in space along which the cart moved in our laboratory and plotted the data in Fig. 6. A rapid change of \( dB/dx \) was observed as \( x \) was increased. The rapid increasing of \( dB_z/dx \) along the \( x \)-direction, we believe, induces the higher gradient noise shown in Fig. 4a. Besides, since the spatial variation of \( dB_z/dy \) was smaller than that of \( dB_z/dx \), therefore we expect a smaller gradient noise along the \( y \)-axis oriented planar gradiometer. This is indeed demonstrated in the data shown in Fig. 4. Therefore we concluded that the changing rate of the gradient field entering the gradiometers controls mainly the noise behavior in moving gradiometer system. The

![Fig. 6. Spatial variation of the gradient magnetic field.](image)

higher rate the gradient field threading SQUIDs, the greater the gradient noise it induces.

Finally, we used a moving electronic gradiometer system to detect the deep flaws in conducting metals. The setup of the NDE system was the same as the reported one [2] with the dc SQUID magnetometer replaced by the rf SQUID gradiometer. The excitation frequency was 400 Hz. The flaws (two slots) with depth 2 and 5 mm respectively were buried inside the aluminum plate. The cart moved with a speed of 0.5 cm/s. In Fig. 7a we show the detected in-phase and quadrature fields as a function of the position, \( x \). In Fig. 7b, we show the phase of the detected differential field, \( dB/dx \), as a function of \( x \) due to the excited eddy current. In Fig. 7c the phase of the differential field is correlated to the depth of flaws. In Fig. 7c it was found that there is a linear relationship between the phase and the depth of flaws. The present results show consistent results with data detected with a magnetometer NDE system [7] in which the SQUID magnetometer was fixed and the samples

![Fig. 7. (a) The in-phase and quadrature fields induced from the eddy current measured with a moving SQUID gradiometer system; (b) the phase of \( dB/dx \) as a function of the scanned distance, \( x \); and (c) a linear relationship between the phase of the differential field and the depth of flaws. The moving speed is 0.5 cm/s.](image)
were scanned under the SQUID. Besides, the present system offers advantages over the magnetometer system, for instance, in the field sensitivity in unshielded environments.

4. Conclusion

In this work we studied the noise characteristics of moving electronic and planar rf SQUID gradiometers systems. It was found that the low frequency gradient field noise is enhanced when the gradiometer system were operated in moving conditions. Besides, a higher changing rate of the gradient field coupled to gradiometer system induces higher gradient noises. The SQUID NDE gradiometer system was successfully applied to detect deep flaws in conducting metals. The present gradiometer system offers advantages in the field sensitivity over the magnetometer system in unshielded environments.

References