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Design and Construction of an HTS DC SQUID Electronic Gradiometer NDE system

*J. Y. Kim, S. G. Han, J. H. Kang, [a]E. H. Lee, [a]I. H. Song
Department of Physics, University of Inchon, Inchon 402-749, Republic of Korea
[a]*Material and Device Sector, Samsung Advanced Institute of Technology P. O. Box 111, Suwon 440-600, Republic of Korea*

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Abstract

We designed and constructed a non-destructive evaluation system using an HTS DC SQUID electronic gradiometer. Our DC SQUID electronic gradiometer is composed of two DC SQUID magnetometers. The system included a non-magnetic stainless steel cryostat and a set of coaxial exciting coils, which were used to induce an eddy current in the test piece. We also have calculated the eddy current density produced by an exciting coil in any direction of the testing object. We could compute the eddy current density distribution in 3D. The SQUIDs were computer controlled and the output data from the electronic gradiometer was obtained by using a Labview software.

Keywords : electronic, gradiometer, DC SQUID, and NDE

I. INTRODUCTION

Applying the SQUIDs to a NDE system, usually requires operating the SQUIDs in a magnetically noisy environment exposed to the earth's magnetic field and other noise sources. Therefore, when designing a SQUID NDE system, it is crucial to design the system so that it may properly operate under the ambient or noisy magnetic field environment. In general, unlike a magnetometer, a gradiometer has the advantage of being easily operated under an ambient or noisy magnetic field [1]. The main goal of this work was to construct a gradiometer system by combining two DC SQUIDs in electronic means, forming an electronic gradiometer and to construct an exciting coil to maximize the sensitivity of the gradiometer to the defects in test pieces.

II. EXPERIMENTAL

We fabricated the two DC SQUID magnetometers, on the basis of a single layer YBCO film as follows. The c-axis YBCO film of 200nm thick was deposited on a $SrTiO_3$ bi-crystal substrate using a pulsed laser deposition method. General photo-lithography with ion etching technique was used to form SQUID

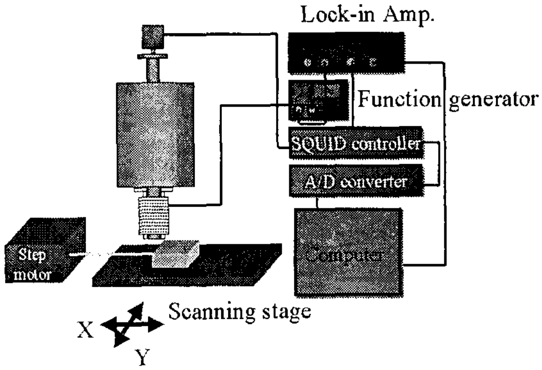

Fig. 1. Diagram of the SQUID NDE system.

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*Corresponding author. Fax: +82 32 766 8018
e-mail : jhkang@lion.inchon.ac.kr

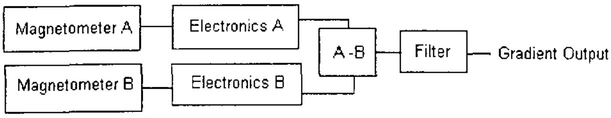

Fig. 2. A block diagram of an electronic gradiometer composed of two SQUID magnetometers.

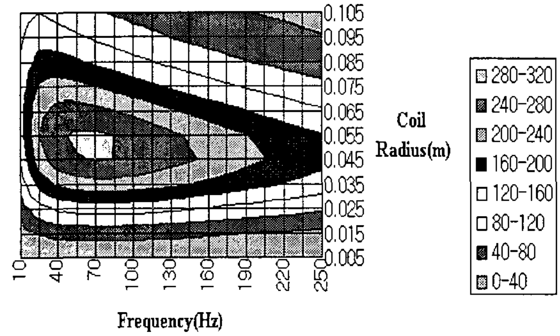

Fig 3. Eddy current distributions on the 2cm thick finit plate. It shows the contour plots of the eddy current densit on the frequency and the coil radius plane.

patterns on YBCO films. The Junction width and the length were 3μm and 6μm, respectively.

The SQUIDs were operated in a non-magnetic stainless steel dewar. Figure 1 shows the diagram of our NDE system which is composed of two SQUIDs and their control electronics [2]. In this work, we have focused to fabricate an electronic gradiometer using two dc magnetometers. Since fabricating an HTS gradiometer with a good balance is difficult, Our approach was to make an electronic gradiometer where two dc SQUID magnetometers are used and an external electronics are used to get a good balance. Figure 2 shows a block diagram of an electronic gradiometer, consisted of two individual SQUID magnetometers and to be used in an ambient field environment [3].

A PCB board was designed and used to mount two SQUIDs on it to work as an electronic gradiometer [4]. And then the board was placed on a probe to be inserted into a non-magnetic liquid nitrogen dewar. To achieve this, we have designed an exciting coil to use in our non-destructive evaluation device. Our cryostat, with a tail made of stainless steel, served as a weak magnetic shield and is a little better in reducing the noise than a plastic one. The coil frame was designed in such a way that the inner and the outer coil radii were 2cm and 4cm, respectively. The wire radius was 0.01mm and the values of each resistance of the inner and the outer coils were 200ohms each.

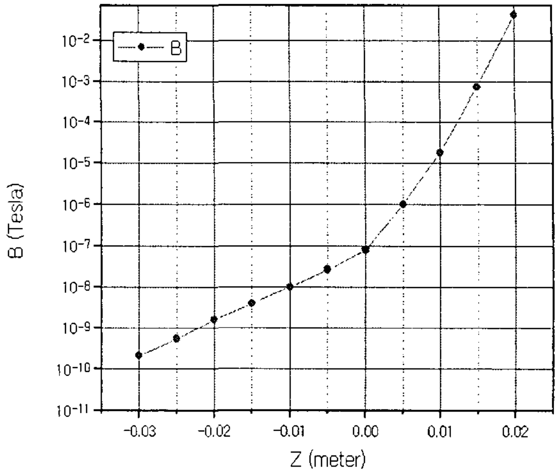

Fig 4. Magnetic field distribution along the z axis.

We also calculated the eddy current density produced by an exciting coil in any direction of the testing object. We could compute the eddy current density distribution in 3D. Each SQUID receives separate control signals and send the data through separate channels. The sample motion stage and the SQUIDs were computer controlled and the output data from the electronic gradiometer was obtained by using a Labview software.

III. Results and Discussion

To optimize the exciting coil design, we calculated the eddy current distribution generated by a circular coil on a finite plate by using the following formula[5];

$$J_{2,\theta}(r,z) = -\frac{ip^2 I}{a^2}\int_0^\infty \{\exp(-kb/a)\} J_1(k) J_1(kr/a)\cdot$$

$$\frac{(k\mu_r+q)\exp\{q(c-z')/a\}-(k\mu_r-q)\exp\{-q(c-z')/a\}}{(k\mu_r+q)^2\exp(qc/a)-(k\mu_r-q)^2\exp(qc/a)}kdk$$

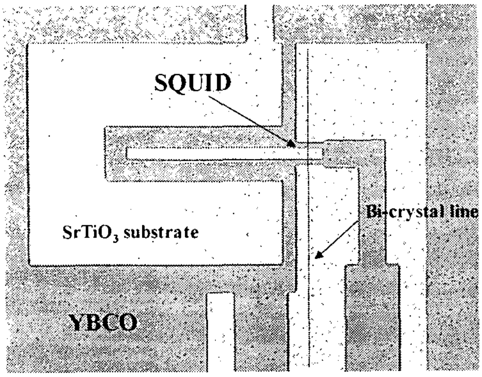

Fig 5. Microphotograph of DC SQUID Junction regio

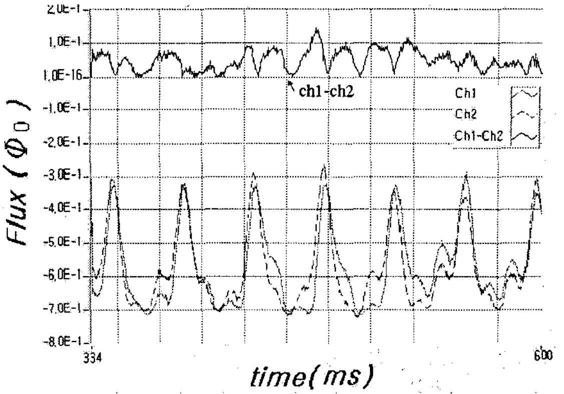

Fig 6. Measurement data of each SQUID channels and th resulting gradiometer output (Ch1-Ch2) at a Mu-meta shielding environment.

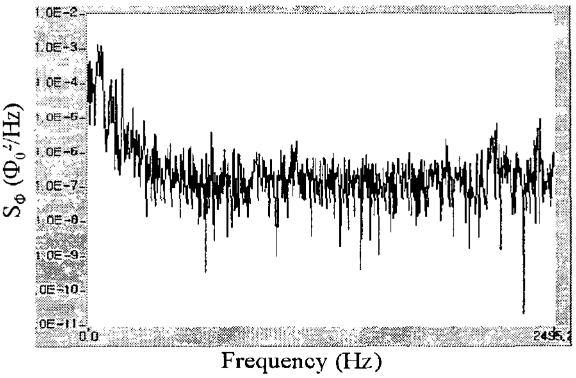

Fig 7. Spectrum analysis of the electronic gradiometer output under a shielded environment.

where $q=(k^2+ip^2)^{1/2}, p=\sqrt{\mu\omega\alpha^2}, \mu=\mu_o\mu_r\cdot\mu_r$ and k are the relative permeability of the medium and the constant of separation, respectively. Results of this calculation are shown in Fig. 3. In this figure, the contour plots of the eddy current density on the frequency and the coil radius plane are shown. In the calculation, we used 10mA as the current flowing in the coil and a 2cm thick finite plate as the test piece where eddy currents are induced. From Fig. 3, we could find that we get the maximum eddy current induced on the plate if we use about 70Hz and the coils with about 5cm in radius.

We also calculated the magnetic field produced by an exciting coil. We placed an 1 inch thick plate under an exciting coil and calculated the magnetic field distribution. This is shown in Fig. 4 where the vertical distance, Z, was measured from the top surface of the plate. From this figure we can see that reducing the distance between the exciting coil and the plate is quite important.

A directly coupled SQUID was designed and fabricated to use in our electronic gradiometer. The microphotograph of the junction region in the fabricated SQUID is shown in Fig. 5. The SQUID noise power level of 13.95 $\mu\Phi_o/\surd$ Hz was observed at the frequency of 10.254 Hz.[4]

To test our gradiometer we used a Conductus PC-1000 SQUID controller to control our SQUIDs and a Labview software to get a good balance. First, we did put a Mu-metal shield around the dewar tail to reduce the ambient field noise and tested the gradiometer. We first obtained the output data from the SQUID controller and fed the data to the Labview sortware to balance the data from the two different channels. The results are shown in Fig. 6. Ch1 denotes the signal from one SQUID and Ch2 from the other SQUID. Ch1-Ch2 is the balanced signal. Spectrum analysis of the balanced output signal, shown in Fig. 7, shows that 60Hz noise is the main source of the noise and the noise floor is about 10^{-7} Φ_o^2/Hz.

We also performed the same experiment without Mu-metal shield and the results are shown in Fig. 8. Spectrum. analysis of the balanced output signal, shown in Fig. 9, shows that our gradiometer is noisier without shield and the noise floor is about 10^{-4} Φ_o^2/Hz which is about 3 orders of magnitude higher than with shield.

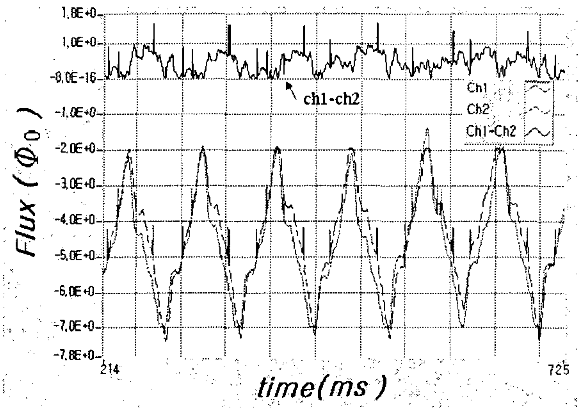

Fig 8. Measurement data of each SQUID channels and the resulting gradiometer output (Ch1-Ch2) at an unshielded environ-ment

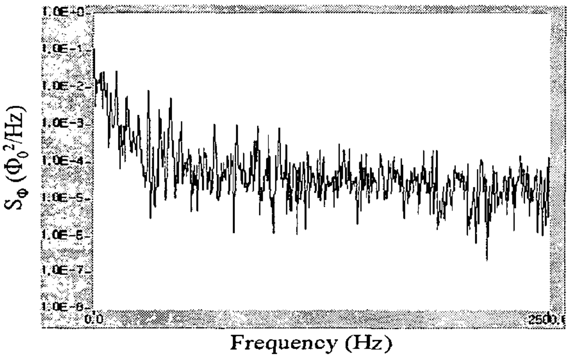

Fig 9. Spectrum analysis of the electronic gradiometer output und-er an unshielded environment

a weak magnet as a test piece. When we placed a Gaussmeter 2cm above the test piece we observed 1.5 Gauss.

We pulled the test piece at the speed of 6cm/s. The vertical distance between the gradiometer and the test piece was 2cm. Part of the resultant output signal is shown is Fig. 10. 15 Hz low pass filter was used to the output signal in Fig. 10. The data in Fig.10 is result averaging 1560 data. The sampling period was 1.0×10^{-4} sec. The inset Fig.10 is the raw data from ch1-ch2.

IV. CONCLUSION

In this work, an electronic gradiometer system has been constructed from two independent channels of YBCO DC SQUIDs. We have fabricated and tested elecronic gradiometers of being scanned test magnet in a magnetically noisy environment. The result is a working NDE system that can be operated in a relatively noisy ambient field environment.

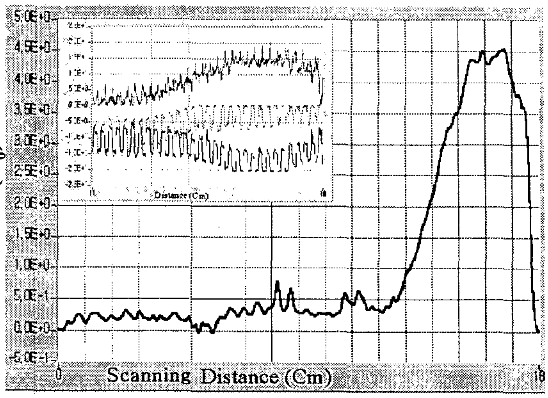

Fig 10. Gradiometer output signal when a magnetic test piece was passed under the gradiometer. Inset shows the raw data of Ch1, Ch2, and Ch1-ch2.

Acknowledgments

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