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Detection of a Moving Object by Multi-channel SQUID Magnetometer System

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다중채널 고온초전도 양자간섭소자 자력계 시스템을 이용한 이동 물체 탐지

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Abstract

We have constructed a multi-channel SQUID magnetometer system for localization and classification of magnetic targets. Ten SQUID magnetometers were arranged to measure 5 independent components of 3 x 3 magnetic field gradient tensor. To get gradient from the difference of magnetic field measurements, we carefully balanced magnetometers. SQUIDs with slotted washer were used for operation in an unshielded laboratory environment, and noise characteristic in the laboratory was measured. With the multi-channel SQUID magnetometer system, we have successfully traced the motion of a bar magnet moving around it at a distance of about 1 m. In the urban environment, the drift of uniform magnetic field due to the irregular motion of a large magnetic body at distance and earth field causes an error in the position calculation, and this results in the distortion of the calculated trajectory. In this paper, we present the architecture and the performance of the system.

Keywords: SQUID, multi-channel, magnetometer, gradient

I. Introduction

Magnetic anomaly detection using various magnetic sensors has long been used for the localization and classification of magnetic sources such as unexploded ordinances (UXO) or submarines[1]. Here one obtains two or three dimensional magnetic anomaly map by measuring magnetic field strengths over specified area and locates magnetic sources by analyzing the map. But this method has several drawbacks. First, the detection capability strongly depends on the relative orientation between earth's magnetic field and magnetic moment of the source. Furthermore, one can get the results only after the whole area was

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explored. In 1970's methods using all three components of the magnetic field vector rather than total field was developed, and magnetic field gradients were introduced to eliminate the effect of uniform background magnetic fields such as earth's field. Fluxgate sensors were widely used[2], but to detect far removed sources, more sensitive SQUID magnetometer is needed[3],[4].

In this paper, we describe construction of the multi-channel SQUID magnetometer system developed for magnetic source detection and demonstrate the source tracking capability of the system.

II. System

Hardware Fig. 1 is the photograph of the magnetometer system, and the details of the construction were reported previously[5]. In each liquid Nitrogen Dewar sits a probe containing ten-SQUID magnetometers. We developed SQUID control electronics that can manipulate four sets of such magnetometer systems simultaneously (Only three Dewars are shown in Fig. 1.), so that we could pinpoint multiple sources by deploying multiple probes in the array type. We used multi-drop serial communication protocol RS-485 between control electronics and flux-locked loops (FLL) situated on top of each Dewar to prevent the possible loss of command, and to check the current status of FLLs. Uninterruptible Power Supply (UPS) with large battery capacity is employed for outdoor test.

For proper operation of SQUID, use of metal should be minimized. We fabricated FRP liquid Nitrogen Dewar with coolant capacity of six liters and evaporation rate of 0.3 liters per day without any heat load. When the probe with full wiring is inserted, the boiling rate increases to 0.5 liters per day which enables more than ten days of operation before recharging the coolant.

Our system was intended for operation in unshielded environment, and we designed the SQUIDs with slots and holes in the washer[6]. Fig. 2 shows the noise characteristic of our laboratory measured by the fabricated SQUID.

Tracking algorithm When a magnetic dipole of moment $\vec{m}$ is at the origin, magnetic field at location $\vec{r}$ is given by

$$\vec{H} = \frac{3(\vec{m}\cdot\vec{r})\vec{r}}{r^5} - \frac{\vec{m}}{r^3} \qquad (1)$$

and the filed gradient is

$$\frac{\partial H_k}{\partial x_j} = -5(\vec{M}\cdot\hat{n})n_j n_k + \vec{M}\cdot\hat{n}\delta_{jk} + M_j n_k + M_k n_j \qquad (2)$$

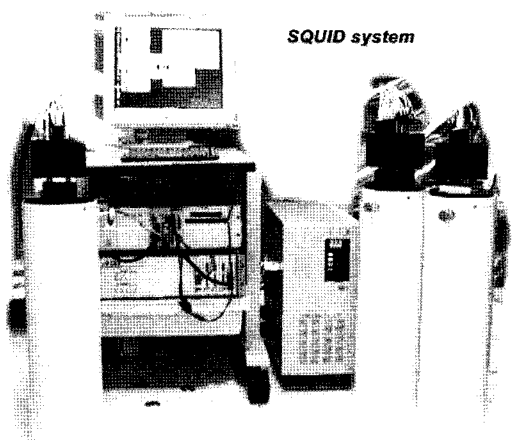

Fig. 1. Photograph of multi-channel SQUID magnetometer system. There is one Dewar at the left and two on the right. At the center are control electronics and UPS.

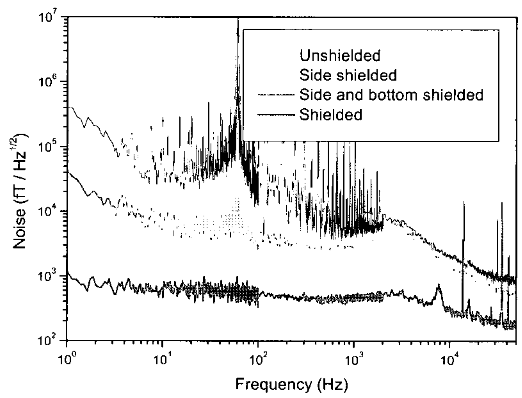

Fig. 2. Noise characteristic of the laboratory measured by the fabricated SQUID. Side shielded means cylindrical mu-metal shield with neither the top nor the bottom cap.

where $\vec{M} \equiv \frac{3\vec{m}}{r^4}$ is the reduced moment, $\hat{n} \equiv \frac{\vec{r}}{r}$ is the bearing vector. If we introduce

$$N_{ijk} \equiv 5n_i n_j n_k - \left(\delta_{ij} n_k + \delta_{jk} n_i + \delta_{ki} n_j\right) \quad (3)$$

and its "inverse"

$$\tilde{N}_{jkl} \equiv \frac{3}{2} n_j n_k n_l - \frac{1}{2}\left(\delta_{jl} n_k + \delta_{kl} n_j\right) \quad (4)$$

Eq. (2) simplifies to

$$\frac{\partial H_k}{\partial x_j} = \sum_{lmi} \frac{\partial H_m}{\partial x_l} \tilde{N}_{lmi} N_{ijk} \quad (5)$$

We can easily solve Eq. (5) in the principal axis frame of $\frac{\partial H_k}{\partial x_j}$, and by transforming back to the laboratory frame, we get $\vec{M}$ and $\hat{n}$ [7],[8]. Since Eq. (5) is nonlinear there are three ghost solutions in addition to the true one, and we can pick the real one using the measured magnetic field values in addition to the field gradients.

Consider the simple case where source dipole moment has only z component and moves in the xy-plane. We can get the location and moment of the dipole by measuring one field component H_z and two field gradients H_{zx} and H_{zy};

$$x = \frac{-3H_{zx}H_z}{H_{zx}^2 + H_{zy}^2}, y = \frac{-3H_{zy}H_z}{H_{zx}^2 + H_{zy}^2}, M_z = H_x\left(x^2 + y^2\right)^{3/2} \quad (6)$$

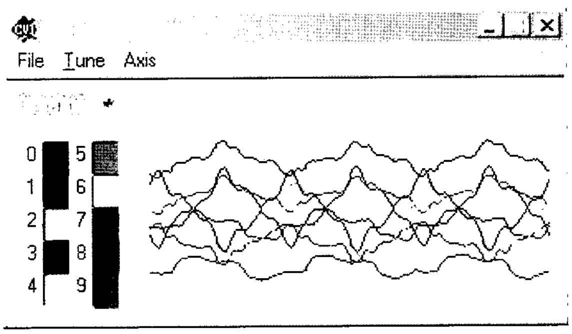

Fig. 3. Panel for displaying SQUID output. Each channel can be selected or deselected for display.

To implement above mentioned algorithm, it is essential to measure the gradients accurately, and two magnetometers comprising the gradiometer should be precisely balanced. In the absence of nearby magnetic sources, we continuously adjusted the gains of SQUIDs until field gradients such as H_{zx}, H_{zy}, H_{xy} remain within specified value in the uniform magnetic field. We use low pass filter, typically 2.5 Hz cutoff, to reduce line noise and other high frequency disturbances.

Operating system Optimum parameters for SQUID operation, e.g. bias current, modulation flux, DC offset, etc. varies according to the environment, and we can set these parameters either manually or by auto-tune algorithm. The auto-tune algorithm is helpful in field operation where fast tuning is needed due to limited capacity of the battery. The working parameters can be saved in the memory of FLL and retrieved at the power up. We can monitor output waveform of single or multiple SQUIDs as we wish. Fig. 3 shows that the SQUIDs remain locked even in an unshielded laboratory environment.

III. Results

To demonstrate the performance of the SQUID magnetometer system, we trace the location of a bar magnet moving on a square trajectory with the

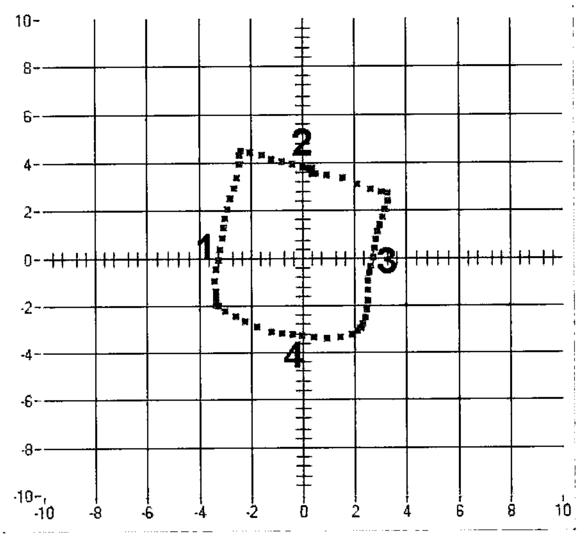

Fig. 4. Tracking result for bar magnet moving on a square trajectory. Axes units are arbitrary.

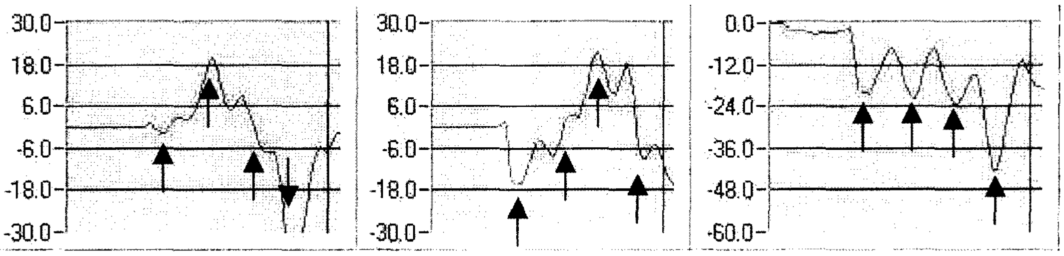

Fig. 5. Real time chart displaying field gradients H_{zx}, H_{zy}, and magnetic field H_z (from left to right) which are used to calculate the dipole location shown in Fig. 4. Four arrows in each plot correspond to points marked by 1, 2, 3 and 4 (from left to right) in Fig. 4.

system at the center of the square. The sides are about one meter. The real time trace result is shown in Fig. 4. Data were taken in about a minute. The sides are not parallel to x or y-axis simply because we didn't align the axes of SQUID system and those of square trajectory. There are several reasons for sides not being straight. Low frequency fluctuation of environmental magnetic field causes deviation from straight line. Also we measure magnetic field "difference", but the algorithm relies on "differential" values of magnetic fields. This has more effect when the source is nearer. Effect from 60 Hz line noise cannot be ignored, either.

Fig. 5 displays real time variation of the field gradients H_{zx}, H_{zy} and magnetic field H_z which are raw data for trace calculation in Fig. 4. We can notice some qualitative features of magnetic dipole tracking: It is easy to understand that magnetic field strength is high when the dipole is near the system (mark 1, 2, 3 and 4 in Fig. 4 and 5). As the dipole approaches x-axis (as y decreases) H_{zy} increases (mark 1 and 3), and the same is true for the perpendicular direction. This can easily be understood from Eq. (6).

Acknowledgments

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References

[1] T. R. Clem, G. J. KeKelis, J. D. Lathrop, D. J. Overway, and W. M. Wynn, "Superconducting magnetic gradiometers for mobile applications with an emphasis on ordnance detection", in *SQUID Sensors: Fundamentals, Fabrication, and Applications*, ed. H. Weinstock, Dordrecht: Kluwer, 517-568 (1996).

[2] G. Allen, R. Koch, and G. Keefe, "Unique man-portable 5 element fluxgate gradiometer system", Proc. SPIE, **2496**, 384-395 (1995).

[3] D. Koelle, R. Kleiner, F. Ludwig, E. Dantsker, and J. Clarke, "High-transition-temperature superconducting quantum interference devices", Rev. Mod. Phys., **71**, 631-686 (1999).

[4] T. R. Clem, D. J. Overway, J. W. Purpura, J. T. Bono, R. H. Koch, J. R. Rozen, G. A. Keefe, S. Willen, and R. A. Mohling, "High-T_C SQUID gradiometer for mobile magnetic anomaly detection", IEEE Trans. Appl. Supercond., **11**, 871-875 (2001).

[5] S. -M. Lee, W. K. Park, H. J. Lee, S. H. Moon, S. H. Lim, D. Y. Kim, and B. Oh, "Construction of HTS multi-channel SQUID system", Progress in Supercond., **2**, 47-50 (2000).

[6] E. Dantsker, S. Tanaka, and John Clarke, "High-Tc super conducting quantum interference devices with slots or holes: Low 1/f noise in ambient magnetic fields", Appl. Phys. Lett., **70**, 2037-2039 (1997).

[7] W. M. Wynn, C. P. Frahm, P. J. Carroll, R. H. Clark, J. Welhoner, and M. J. Wynn, "Advanced Superconducting gradiometer/magnetometer arrays and a novel signal processing technique", IEEE Trans. Magn., **11**, 701-707 (1975).

[8] W. M. Wynn, "Magnetic dipole localization using the gradient rate sensor measured by a five-axis magnetic gradiometer with known velocity", Proc. SPIE, **2496**, 357-367 (1995).