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SUPERCONDUCTOR IMAGING SURFACE MAGNETOMETRY: PRINCIPLES AND APPLICATIONS*

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ABSTRACT

We present in this paper the principles of superconductor imaging surface magnetometry. This new method should permit MEG and other weak field measurements without the necessity of an expensive magnetically shielded room. We report results showing signal to noise rejection ratios of 1/330,000 with simple apparatus. The goal of 1/1,000,000, seldom achieved by second order gradiometers, should be readily attainable in improved imaging magnetometers.

INTRODUCTION

The insertion of a superconducting body into the magnetic field of a distant source such as the earth's ambient field results in a deflection of the flux lines of the field in the neighborhood of the body. For a long time the processes involved were thought to be either the infinite conductivity or the perfect diamagnetism of the superconductor. Features of both processes were included in London's quantitative analysis [1] of the superconducting sphere more than 40 years ago with this introduction of the famous equation $\text{curl}(\Lambda j) = h$, where j is the internal current density and h is the internal field. Thus, London's equation hold for the interior of the superconductor, while Maxwell's equations still hold for the exterior region [1].

While London considered the superconducting sphere in his analysis, his procedure can be adapted in the study of superconductors having other shapes such as circular rods or plates with circular edges and the interior of hemispheres. Thus, the applications to MEG are blessed with a formal background for the study of the distributions of the ambient magnetic noise fields around the superconducting body. This leads to results for the distribution of flux lines around a plate with circular edges such as we show in Fig. 1.

PRINCIPLES

In Fig. 1 we show how the flux lines of the ambient field due to a distant source at 45° with respect to the plate surface are deflected around the plate. These lines represent lines of constant magnetic potential. They are compressed at the edges and rarified near the center. Since the magnetic field intensity is proportional to the density of the flux lines, the field is larger than H_0 at the plate edges and very much smaller than H_0 near the center where the SQUID pickup coil (A-A' in Fig. 1) is located.

Fig. 1 shows the special symmetry of the flux line distribution with respect to the centerline of the plate. This symmetry is achieved in practice only if the plate itself is

Figure 1. Schematic of one of many configurations of the superconductor imaging surface magnetometer. Pickup loops A-A' and B-B' are a distance d from their near surfaces. Magnetic dipole m is z_0 cm from the front face while image m' is z_0 cm behind the front face. When current dipole p is z_0 cm in front of the front face, the image p' will likewise be z_0 cm behind. Notice that the image rules for m and m' are different from those for p and p' .

designed to be symmetric with respect to the centerline. Thus, our first principle of imaging surface magnetometry is to place the superconducting pickup coil near the center of the plate where the noise field strength is many times smaller than the ambient noise field. In view of the symmetry of the flux distribution, the field in front of the front face at the center of A-A' will be the same behind the back face at B-B'. Accordingly, a coil at B-B' can be connected in series opposition to the coil at A-A'. This principle will further cancel out noise from distant sources.

The objective of imaging surface magnetometry is to detect very weak magnetic dipole sources that are located quite close to the front face of the plate (Fig. 1) while in the presence of the deflected and cancelled noise fields discussed above. Weak sources such as the brain wave sources of MEG and the flaws of materials encountered in NDE (non-destructive evaluation) have intensities only of the order of 10 fT to 1,000 fT. Meanwhile, ambient noise fields fall in the range of 1,000,000 to 10,000,000 fT. Thus, we must be able to reduce by deflection and by cancellation the effective noise field by a factor of about 1,000,000 in order to have a successful imaging surface magnetometer.

SQUID output vs dipole position

Figure 2. Response of the image magnetometer of Fig. 1 to a movable magnetic loop dipole driven at 100 Hz and located 9.7 cm below coil A-A'. The x-position is varied from 12 to 31 cm with the center position being at 21 cm. The peak signal amplitude is $0.045 \Phi_0$.

The final physical principle used in imaging surface magnetometry is that of imaging itself. When a dipole is placed above an infinitely extended surface having infinite electrical conductivity, the image of this dipole appears as shown in Fig. 1. The surface currents induced by the presence of the nearby dipole can be represented by the fictitious image dipole [2]. The field at the pickup coil center becomes the vector sum of that of the source dipole plus that of its image [3]. The finite size of the plate does not seriously affect this vector sum field unless the vertical position of the source is near the plate edge. This image principle led to the naming of the magnetometer as the imaging surface magnetometer.

For a magnetic dipole m oriented according to its direction cosine set (l, m, n) , the image set will be defined by $(l' = l, m' = m, n' = -n)$. For a current dipole oriented according to the same set, however, the corresponding image set will be $(l' = -l, m' = -m, n' = n)$; in all cases, (l, m, n) are referred to the (x, y, z) axes of Fig. 1.

RESPONSE OF A LOOP DIPOLE

The schematic in Fig. 1 indicates a magnetometer comprised of a lead plate with a pickup coil A-A' located a distance d in front of the front face and an identical pickup coil located a distance d behind the back face. In the experiments the pickup coils represented by A-A' and B-B' were made of NbTi wire and were connected in series opposition with common leads connected to an rf SQUID located about 50 cm above. If the ambient noise field at A-A' due to a distant source is reduced by a factor f because of the deflection of the field lines around the plate, there should be an identical reduction of the field at B-B' because of the symmetry. The overall

reduction of the ambient field and its associated noise by this combination should then be proportional to a factor of f^2 .

In experiments in which a Helmholtz coil was used as a simulated noise source, the reduction of the ambient noise field by the above arrangement was an average factor of 330,000. This implies that a single coil system would give a noise reduction of about 580. To achieve a reduction of 1,000,000, a figure desired for typical second-order gradiometers, the coil B-B' would have to be constructed to be more precisely identical to that at A-A'. But such a requirement is easy to accomplish in the construction of the imaging magnetometer. The simplest way is to use a superconducting plate of a larger diameter. On the other hand, second-order gradiometers require elaborate superconducting tab systems and sophisticated trimming arrangements to obtain the 1,000,000 reduction; even then, the system is often susceptible to drifts so that balance is hard to maintain.

We show in Fig. 1 a magnetic dipole m located close to the front face of the lead plate. In the experiments this dipole was a two-turn coil having a diameter of 0.64 cm. It was mounted on a coordinate table and could be moved to arbitrary positions underneath the liquid helium dewar. Its vector magnetic moment could be either vertical (direction cosine $n = 1$) or horizontal ($n = 0, m$ or $l = 1$). We show in Fig. 2 the response of the image magnetometer to a vertically mounted loop dipole mounted 9.7 cm below the plane of the lead plate.

THE CURRENT DIPOLE

The dipole p in Fig. 1 denotes the current dipole. Its field at the center of a coil such as A-A' is determined by the cross product $(p \times r)/r^3$. This is the type of source dipole believed responsible for the signals in MEG. These very weak fields coming from the human brain have small amplitudes in the range of 10 to 1,000 fT. A dipole p defined by its set of direction cosines (l, m, n) will have an image p' defined by the direction cosines set (l', m', n') , as shown in ref. [3]. Notice in Fig. 1 that p' is not the mirror image of p .

SUMMARY

We have reviewed the principles of superconductor imaging surface magnetometry and have discussed experimental results on a prototype magnetometer such as the one shown schematically in Fig. 1. The imaging rules for the loop magnetic dipole and the current dipole are presented.

* Work performed under the auspices of the U.S. Department of Energy

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