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PRINCIPLES OF SUPERCONDUCTOR IMAGING SURFACE GRADIOMETRY*

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Magnetic sources in the vicinity of superconducting surfaces produce images in such a way that a single pick-up coil parallel to the surface acts as a first order gradiometer. The principles will be described, together with specific discussions of the imaging by planar and spherical surfaces. The fact that these surfaces also deflect noise due to remote sources make this concept particularly appealing as a method for detecting extremely weak sources in a hostile environment. Possible applications to neuromagnetometry, corrosion detection and non-destructive evaluation will be discussed.

1. INTRODUCTION

In electrostatic applications, if two or more sets of charge distributions produce an equipotential surface on which $\phi = 0$, the principle of imaging can often be applied. For example, two equal but opposite charges generate a planar surface at the perpendicular bisector that acts as a grounded plane. One speaks, then, of a charge in front of such a surface as having an image plane of equal but opposite charge on the opposite side and obtains the solution by treating the two problems as being equivalent. The principles of electrostatic imaging have been applied successfully in a number of practical situations, a notable example being the propagation of radio waves over a conducting earth.

We have extended the imaging analysis to incorporate currents rather than electric charges, taking advantage of the fact that a superconducting surface is an excellent approximation to a perfect conductor. In our analysis, if a set of current carrying elements give rise to an isomagnetic contour on which the normal component of the magnetic field is zero, the situation is wholly analogous to the electrostatic case. The simplest example is of two parallel wires in which the currents flow in opposite directions. The magnetic field normal to the perpendicular plane half-way between is zero everywhere, so that one can treat the case of a current parallel to a superconducting surface as being equivalent to the two wire problem. Indeed, a wire in the vicinity of the plane will be repelled by its image wire; this behavior is consistent with the Meissner effect.

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2. PLANAR MODELING

In this presentation we shall discuss the simpler problems of current and loop dipoles because of their potential applications to non-destructive evaluation, corrosion studies and magnetoencephalography (MEG), to name a few. The loop dipoles, for which the magnetic moment M is equal to NIA (amp-m²) where N is the number of turns, is well known. Less familiar is the so-called current dipole which is modeled as a short (typically a few millimeters) current-bearing filament. Although this type of dipole is physically perplexing, it does appear to be a good representation of neural currents generated in the brain and the heart. Because of our experience and interest in neuromagnetism, the sources we will discuss will be primarily current dipoles, although it will be convenient to approximate the sensing coils by loop dipoles.

FIGURE 1

The dipole p and the sensing loop are above the superconducting plane; the image dipole is below.

Consider, as a first example, a current dipole oriented parallel to a superconducting plane d cm away (Fig. 1). The image dipole that allows the boundary condition to be satisfied has the same moment 'p', is equidistant on the opposite side and is oriented in the opposite direction (in this example, along the $-y$ axis) from the source. To understand the import of this statement, consider a pick-up coil parallel to the surface at $(0,0, h)$. It senses both the source and its image, so that the average flux density it detects is

$$B_{no} = (\mu/4\pi) p x \{ 1/[x^2 + (d-h)^2]^{1.5} - 1/[x^2 + (d+h)^2]^{1.5} \}$$

Consider, now a different scenario in which the source and the loop are configured the same way but in which the superconducting plane and the image have been removed and a second pick-up coil parallel to the first is placed at $(0,0,-h)$. If the two coils are wound in series opposition as shown in Fig. 2, the net average flux density detected is precisely the same as the result presented in the preceding equation. In other words, for this simple planar case, the single loop in the vicinity of the superconducting plane observes the current dipole in a way that makes the loop magnetometer act like a first order gradiometer.

FIGURE 2

The configuration of Fig 1 is redrawn to show how the equivalent first order gradiometer is achieved.

The implications of this are immense for two reasons. First, the magnetic field produced by neural activity are extremely weak, being typically in the range of 10 -1000 fT. Because the measurements must be made against background noise which is several orders of magnitude greater, commercially available sensing systems rely on first or second order gradiometers which require extremely accurate construction and balancing. The imaging concept indicates that a single coil and planar superconductor will produce the equivalent result. Second, the presence of the superconducting surface in itself provides further magnetic noise reduction by steering or deflecting the undesired noise away from the sensing loop. A numerical example of this will be presented.

The issue of mutual inductance has, so far, not been introduced because, in deriving the equation for the average flux, the current induced in the sensing coil was ignored. In reality such a current must be included and in so doing, the coil itself must be imaged. For purposes of this discussion, the coil and its image will be assumed to be simple loop dipoles. Note that their orientations must be in opposite directions in order to satisfy the boundary condition. Because of the additional contribution from the image loop, the flux density sensed is modified to

$$B_n = B_{no} - (N/4)(2\pi\mu)(M/a^2)(a/2h)^3$$

where a is the radius of the coil. The reduction, which will be of order 10% or less for cases of practical interest, is a result of the mutual inductance between the loop and the superconducting plane.

3. SPHERICAL GEOMETRY

A final point, which is really the essence of the discussion, is that we are pursuing more complicated geometries than the simple plane discussed so far. It is well-known in electrostatics, for instance, that a charge in the vicinity of a conducting sphere has a relatively simple image. It is not surprising that a tangentially oriented current dipole located at a point $(0,0,d)$ on the Z -axis inside a superconducting sphere of radius a produces an image $p' = -(a/d)p$ at $(0,0,a^2/d)$. What is unexpected is that a loop dipole M at the same position produces an image $M' = -(a/d)^3 M$, also at $(0,0,a^2/d)$. The significance of these effects and their implication to gradiometry will be discussed.

The reason for pursuing this course is two-fold. First, a spherical (more realistically a hemispherical) configuration, if practicable, would be ideal for studies of brain neural activity. It is straightforward to envision an array of loops that would permit researchers to obtain all of their data on a single set of measurements, obviating the need to move the dewar from position to position as is now done. Second the noise reduction from distant sources would be far greater in this geometry than in the planar case. In a companion paper, some of the experimental efforts to evaluate the spherical case will be described.

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