

## MAGNETIC FIELD MAPPING WITH A SQUID DEVICE

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### INTRODUCTION

An ability to experimentally determine the magnetic field in the region close to the face of an eddy current coil, the normal location of the work piece, is very desirable. It allows confirmation of the theoretical design of complex coils, offers a potential method for rapid characterization of commercial coils, and may well provide a uniquely direct method of looking at coil/flaw interactions. However, the small size of typical eddy current probes presents some extreme problems in this regard. For the past year we have been attempting to determine the best method to use for measuring the field configuration in the near-field region.

In this paper, results of preliminary measurements using a SQUID (Superconducting Quantum Interference Device) system to determine the magnetic near field of commercial eddy current coils are presented. The SQUID system offers some significant advantages over more conventional techniques in that very small field sensors can be used, and the calibration of the system is tied to the quantum of flux. Unfortunately, there are problems unique to this device and its extreme sensitivity to magnetic disturbances that have had to be addressed along the way. We feel that the solution to many of these problems is now in hand, but certainly a large amount of work remains before such a system can be used with total reliability. However, everything that we have observed to date indicates that this approach is probably the most reasonable for accurate field mapping.

We have also investigated several other potential field mapping devices. One of these is the TEM cell<sup>1</sup> which offers some interesting possibilities, but is more of a far-field device. Others that we have evaluated to a limited extent are: micro Hall probes,<sup>2</sup> and high-permeability disk-reading heads.<sup>3</sup> Fabrication problems are significant in the case of the Hall devices and poor directionality of the tape heads seem to preclude them as mapping devices. In any event, our major experimental effort has been to adapt the SQUID system to our measurement needs. Our approach has been to use a small pickup coil to feed the signal into the SQUID, but there is no reason per se that either a

photolithographed coil or a micro Hall probe or magnetoresistor could not be used as the "front end" for this device.

#### SQUID SYSTEMS FOR NDE APPLICATIONS

Superconducting Quantum Interference Devices (SQUIDs) are relative newcomers to the instrumentation field. The systems are internally complex, but their operation and theory are adequately described in several texts<sup>4,5</sup> and in the manufacturer's literature. In spite of this complexity, SQUID systems are both quite easy to understand conceptually and to use in the laboratory, once the techniques necessary for the handling of liquid helium are mastered. When fitted with a superconducting coil on its input, the SQUID becomes a sensitive detector of magnetic flux. Typical sensitivity with a direct input is in the range  $1.0 \times 10^{-13}$  T. This is excessive for our purposes and is, thus, degraded by several methods described below.

The system, shown in Fig. 1, consists of a SQUID sensor and an input coil, both of which must be kept in liquid helium. The sensor is connected to the room-temperature electronics and the pickup coil is coupled to the input coil by one of several techniques described below. In this configuration, the system can be looked at as a four-terminal device in which the output voltage (at room temperature) is proportional to the input current generated by changing flux through the input coil. In this view, the transfer function can be as high as  $2 \times 10^7$  V/A, or can be switched to as low as  $2 \times 10^5$  V/A.

The problems of magnetic disturbances and rf interference are severe in these systems. Shielding against them is provided by several methods as illustrated in Fig. 2. Superconducting shields, such as the lead can, eliminate most magnetic field effects and provide some rf shielding. Sometimes the entire SQUID system is encased in aluminum foil. Further rf shielding must be provided for the leads which come in from the room temperature region. Additional attenuation of rf is

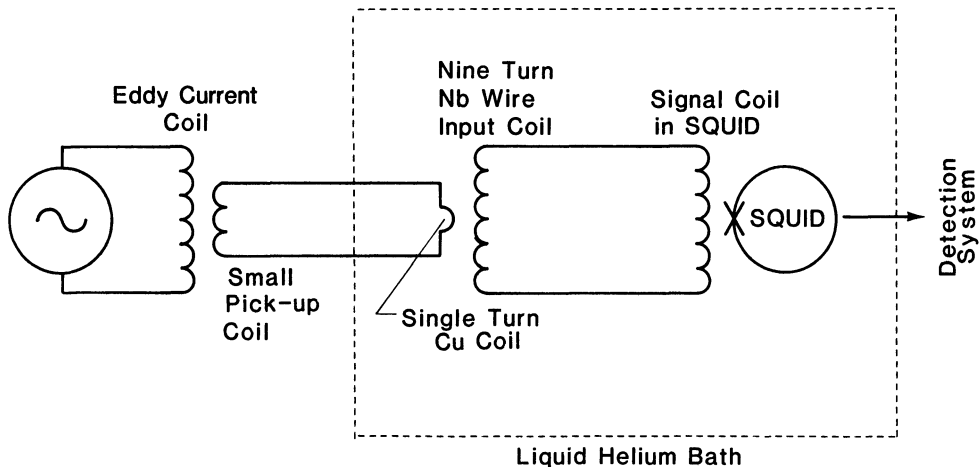


Fig. 1. Electrical schematic diagram of the SQUID detection system.

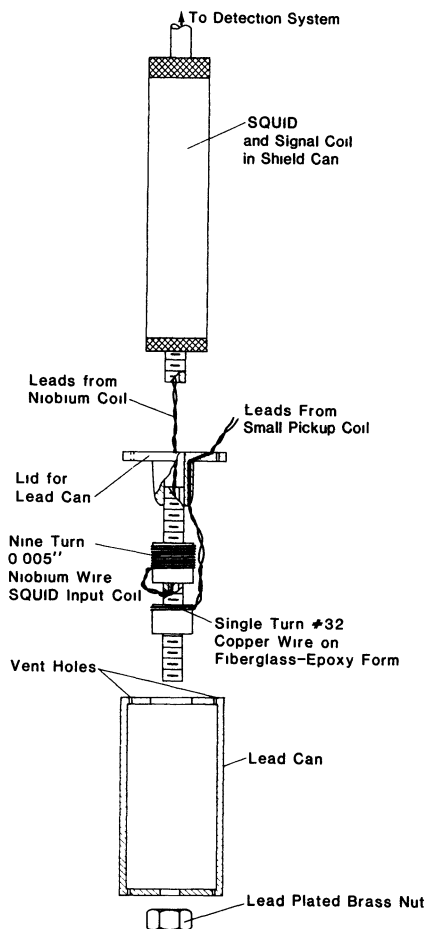


Fig. 2. Diagram of the experimental system. Everything shown is kept at liquid helium temperature. The coils are wound on 12 mm mandrels, which gives the approximate overall scale of the figure.

sometimes provided by filtering the input in the warm region, but this tends to degrade the frequency response of the system.

#### APPARATUS

The apparatus used consists of: the commercial SQUID system described above; the input coil(s) and their coupling system; and the

pickup coils and (sometimes) their impedance matching devices. In addition, an orientation system was developed that allows precise location of the coil under test with respect to the pickup coil. The parts of this device in the vicinity of the coils are nonmetallic.

A small Helmholtz pair was constructed that provides a known test field for determining the area-turns product of the very small pickup coils as well as for finding the magnetic axes<sup>3</sup> of the coils. This coil has a maximum central field of  $2.42 \times 10^{-3}$  T and operates well at frequencies as high as 100 kHz. It is calibrated with a Hall-effect device which, in turn, is calibrated in a standard magnet. This measurement and the calculated field agree within the accuracy of the instrument (1.5%).

A number of pickup coils have been built in the course of the investigation. The one most used in gathering the data reported here is a 115 turn coil wound with #42 copper wire. It has a 0.64 mm inner diameter and a length of 0.76 mm, wound on a plastic form. Several smaller coils (0.30-0.34 mm ID) have been wound using various materials (copper, silicon bronze) and tested. To date the results look promising, but further work on impedance matching and on the production or acquisition of fine wire needs to be done before these coils will be ready for data taking.

A number of different input coil configurations and coupling schemes were used during the course of the investigation. They are shown in Fig. 3. In essence they all provide a method of coupling the flux change seen by the pickup coil into the superconducting flux transformer represented by the detector loop and the coil internal to the SQUID. Sensitivity is not a problem, we have more than we need by several orders of magnitude, but the device is extremely sensitive to rf pickup as well as to external sources of magnetic field, such as moving chairs, etc. Optimization of the signal-to-noise ratio is the driving force in the design. Two excellent papers are available that discuss various aspects of the problem. The first concentrates on the design of room-temperature pickup coil systems<sup>6</sup> and optimization of the S/N ratio, while the second<sup>7</sup> discusses the problems of matching the superconducting flux transformer coil to the SQUID.

Our present solution is shown in Fig. 3c in which the room temperature pickup coil is connected to a cold copper coil contained within a lead shield. This coil is coupled to the input coil of the SQUID flux transformer by being wound coaxially on a nonmetallic form. The actual coupling is capable of being varied by adjustment of the axial displacement of the two coils. The data on the final configuration is as follows:

pickup coil - 115 turns of #42 copper wire,  $L = 4 \mu\text{H}$ ;  
 secondary of pickup coil system - 1 turn of #32 copper  
 wire,  $L = 0.04 \mu\text{H}$ ;  
 superconducting input coil - 9 turns of #36 niobium  
 wire,  $L = 2 \mu\text{H}$ ;

The mutual inductance of the two coils placed as shown in Fig. 3c is approximately 15 nH. The internal coil of the SQUID has an inductance of 2  $\mu\text{H}$ .

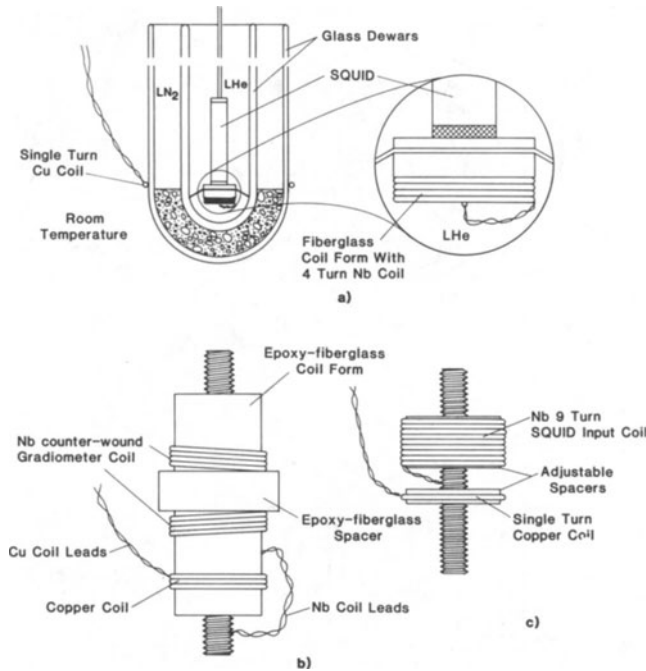
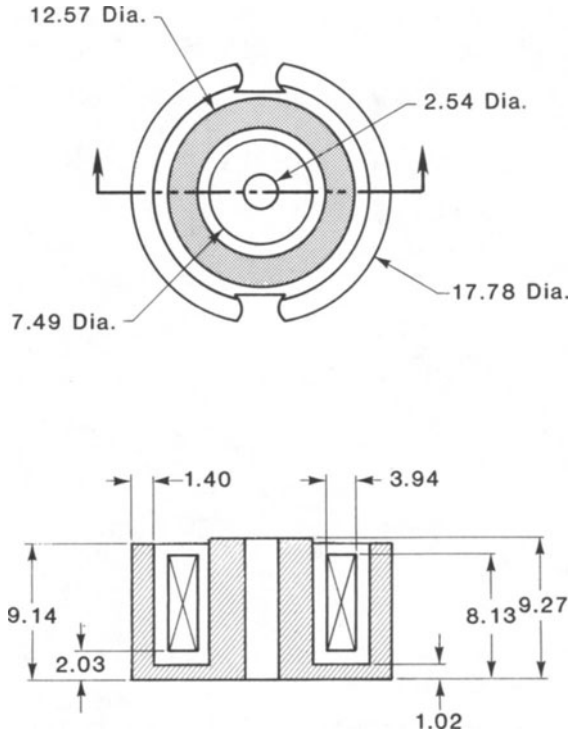


Fig. 3. Coupling configurations used between pickup circuit and SQUID input circuit. In (a) the entire pickup circuit is at room temperature. In (b) and (c) the coupling coil is cold. The gradiometer configuration in (b) minimizes the effect of external fields, but was abandoned in favor of better shielding and the better coupling of configuration (c).

This system has a calibration constant of 1656 V/T (on the X100 sensitivity range), which has proven adequate for our measurements to date. The noise level is typically 0.15-0.45 V (depending on the input filter settings) in our rather electrically noisy laboratory. We feel that it is quite reasonable to expect to be able to increase this sensitivity by at least another order of magnitude while decreasing the noise level by a like amount. We should point out that this noise level is far above the inherent (frequency dependent) noise level of the SQUID device of about 16mV at 100Hz. Clearly there is a lot of room for improvement in the system.

A fairly large commercial eddy current coil (without probe) was chosen for our first set of measurements. Its configuration and dimensions are shown in Fig. 4. The stated operation frequency is 100 Hz and our measurements were made at that frequency. Preliminary measurements have been made on smaller coils to frequencies as high as 40 kHz with this system. The coil inductance was measured to be 70 mH and its resistance is 135  $\Omega$ .



All dimensions in mm

Fig. 4. The test coil. A commercial ferrite-core eddy current coil.

#### MEASUREMENTS AND DATA

Calibration of the system and determination of the magnetic axis of the pickup coils is performed in the small Helmholtz pair described above. A very readable paper on the process and the experimental considerations is available,<sup>8</sup> although it is written primarily for a higher frequency range than that used here. In essence the coil is oriented for maximum signal within the uniform field region of the Helmholtz pair. Since the calibration is done with an ac signal, the earth's field is not a consideration. The coil used for the measurements reported here needed no correction for the magnetic axis; it was along the geometric axis to within two degrees. This was not the case for some of our early smaller coils and, in fact, resulted in a change in our winding practice for those coils.

The field mapping measurements are made with the pickup coil held stationary, either normal, or parallel to the face of the eddy current coil under test. The eddy current coil is mounted on the orienter described above, and moved by the micrometer screws in the base. For our measurements, the coil is driven with a 0.4 mA (p-p) current. Radial field measurement scans are made along the coil face at a predetermined distance from the face. Data are taken at the points indicated in Fig. 5 on the horizontal and normal field components. The actual field vector can then be calculated for each point, and

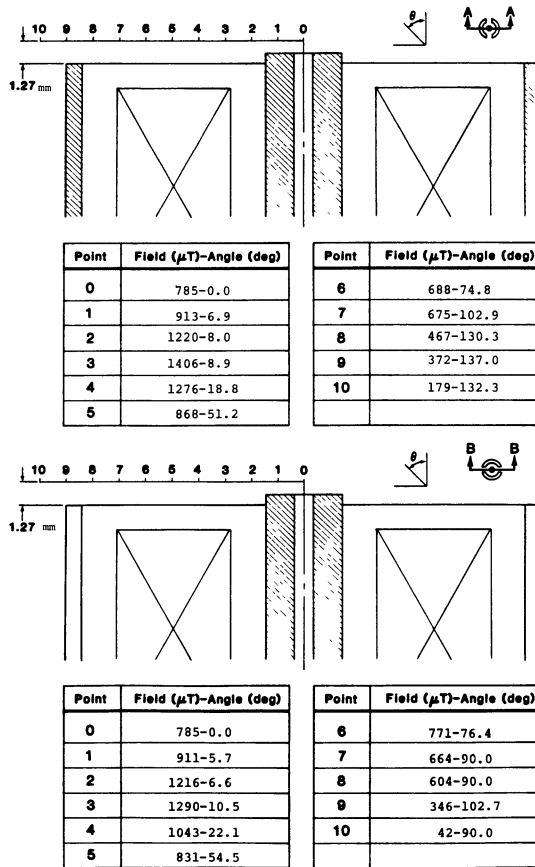


Fig. 5. Location of data point stations for the test coil and field map data.

several are shown in the figure. The output of the SQUID system is read either directly from an oscilloscope display or, for lower values, by a digital voltmeter. The accuracy of the field determination is limited by the noise level of the system and is  $9.1 \times 10^{-8}$  T, the precision is about a third of that.

CONCLUSIONS

It is our conclusion that a SQUID-based system is eminently well suited for field mapping of eddy current coils. The minimum coil size and the fineness of the grid is limited by the dexterity of the coil winder for wire-wound coils. Other techniques, such as photolithography might extend this range somewhat, but eventually the inductance of the leads necessary to transmit the signal down into the liquid helium environment will limit the S/N that can be achieved. Clever techniques for decreasing this distance might well be devised, however.

A major problem at present is the limited frequency range of the commercial SQUID system - now about 50 kHz with a modern hybrid SQUID. However, experimental SQUID systems with a frequency response well into the MHz range have been made<sup>9</sup> and indications are that there will be no insurmountable problems in eventually producing a commercial device.

There is still a great deal to be done in optimizing the present system so as to minimize the noise while maintaining the frequency capability. This includes redesign and better shielding of the lead configuration, aluminum foil shielding between coils in the lead can, filtering, and consideration of large external shields. This is one of the main goals of our continuing research.

The SQUID system appears to offer other potential in the field of NDE. When used with a superconducting pickup, it is a sensitive device for the measurement of dc magnetic flux, which could be of value in flux leakage detection and microscopic magnetic particle inspection as well as techniques using variations in magnetic susceptibility.

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## DISCUSSION

W. Lord (Colorado State University): Were the values of the field that you showed RMS values or peak-to-peak?

F.R. Fickett: Peak-to-peak.

W. Lord: I was intrigued by your statement that it might be possible to use these devices to look at magnetostatic leakage. Is there any way the SQUID itself can be used as a probe in that sense?

F.R. Fickett: Yes. When you start talking dc magnetic fields, which you are in this case, you must use a superconducting pick-up loop. In other words, the second set of coils in our transformer won't be there anymore. You've got the SQUID with an attached superconducting pick-up loop. You must get into the range of your experiment. There-in lies a lot of the problem. You must bring the superconducting loop close enough to the system under test to allow detection. This is not as hopeless as it seems. There are clever techniques using gradiometers and such which have worked in magnetocardiography and magnetoencephalography. We have done these things with SQUIDS. You can look at the magnetic field of brain waves, and you can locate the source position with reasonable accuracy. So it seems to me that some similar sort of clever arrangement should work in this application as well.

W. Lord: How small a probe do you think you could make for looking at leakage flux?

F.R. Fickett: You would wind a coil a couple thousandths of an inch in diameter, maybe. There is a practical limit for the type of detection that we are doing, i.e. using wound coils. There's also a greater limit (probably about five mils) because of the inductance of the pick-up coil has got to be some reasonable fraction of the inductance of the leads that go down into the dewar.

In the dc configuration for flux leakage detection, you can be essentially right at the SQUID, so you don't have the latter restriction. The only requirement for effective use of the SQUID is that the pick-up coils attached to it should have an inductance of around two microhenries. So, it's whatever you can do. If you get into full photolithography you might be able to get well below the sizes I mentioned.

D.O. Thompson (Ames Laboratory): What spatial resolution do you have with this probe?

F.R. Fickett: With this particular probe, it's on the order of the diameter of the coil, about 25 mils. We have also used a short 10 mil diameter coil with no problems. I should have mentioned that the field map that I showed indicating vector fields was made up from two scans, one with the coil axis vertical and one with it horizontal.

D.O. Thompson: What is the upper frequency limit that you have used?

R.F. Fickett: The upper limit that we have used is 40 kilohertz, and that worked okay. The upper limit of the SQUID is about 50 kilohertz, and

that's if you buy the SQUID and don't make it yourself. If you make it yourself, the limit is probably about 5 kilohertz.

D.O. Thompson: What determines that?

F.R. Fickett: It has to do with the way that the SQUID responds to the change in flux. What you are doing is inserting flux quanta into that loop and the system has an effective slew rate that's inherent to the device. If you build an entirely different structure, which is the way they are going for higher-frequency SQUIDs, some sort of stacked thin films or such, then you can get to higher frequencies.

C. Teller (Texas Research Institute, Inc.): Is it possible to use input devices other than coils?

F.R. Fickett: Oh, absolutely, absolutely. One of the things I would like to do is hook the SQUID up to a micron sized Hall probe. It has fantastic current sensitivity--femtoamperes--as in one sense it's just made for that sort of thing, but it is a current device.

From the Floor: What are your main applications? Are they for medical purposes?

F.R. Fickett: We have a group at the Bureau of Standards in Boulder which is doing work on all applications of SQUIDs. In fact, one of the developers of the SQUID, Jim Zimmerman, is in the group. We do medical applications, we do the sort of work described here, and we do very low-level magnetic susceptibility measurements.

From the Floor: But in this case (medical), what resolution would you get on the object? I understood this 25 mils that you mentioned before for the NDE application, but you now have some distance between the coil and the object?

F.R. Fickett: Yes, when you start doing far-distant detection, as with the currents through the brain and so on, your spatial resolution is degraded. I don't know for sure, but I believe that for locations inside the brain, the source of the signal can be determined to within about a centimeter cube.