DEFECT DETECTION WITH A SQUID MAGNETOMETER

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INTRODUCTION

The development of the Superconducting QUantum Interference Device (or SQUID) as the most sensitive device known for the measurement of changes in magnetic flux has presented new opportunities for the fields of geophysics [1] and biomagnetism [2]. In this paper we report on the use of SQUID instrumentation for nondestructive evaluation of electrically conducting and ferromagnetic specimens [3]. Specifically, we report preliminary experiments on the use of SQUIDs for the detection of defects (such as cracks, holes, weld seams, variations in wall thickness, etc.) in the walls of a hollow pipe, and for monitoring the magnetic state of a ferromagnetic sample under stress-strain loading conditions.

INHOMOGENEITIES IN HOLLOW PIPES

The presence of defects in the walls of a hollow electrically conducting pipe was detected by passing a low frequency current along the length of the pipe and using a second order SQUID gradiometer system [4] to measure the magnetic field contours in the vicinity of the pipe. If there are no defects in the wall of the pipe, the current distribution in the pipe would be uniform, and the magnetic flux pattern around the pipe would be cylindrically symmetric. The variation of the detected signal as the SQUID is moved relative to the pipe is shown in Fig. 1. If the axis of the gradiometer coils intersects the axis of the pipe, the detected signal will be zero. This is so because the magnetic flux lines would be in the plane of the pickup coils of the gradiometer. For all other configurations, the gradiometer coils will intercept a net magnetic flux and a non-zero signal will be obtained.

If there is some type of defect in the wall of the pipe, such as a hole, crack, thickness variation, weld seam, etc., the current distribution in the wall of the pipe would be non-uniform and the magnetic flux contours in the vicinity of the pipe would not be cylindrically symmetric. This is shown in Fig. 2, which presents data taken as the SQUID is moved along the length of a pipe which has a number of defects, always maintaining the gradiometer such that its axis...
Fig. 1. Detected signal as a function of displacement of a horizontal, current-carrying pipe with respect to a SQUID gradiometer with the axis of the gradiometer vertical. The gradiometer was about 23 cm from the center of the 4.4 cm diameter pipe.

Fig. 2. Detected signal from a SQUID gradiometer as a function of displacement of the SQUID along a length of pipe with a circumferential slot at $x = 0$ cm, a longitudinal hole at $x = 28$ cm, and a weld seam at $x < -30$ cm. For most displacement values, there are two data points, one taken when the pipe was displaced in one direction and the other for displacements in the opposite direction.
intersects the axis of the pipe. The peak at X = 0 cm occurred when the SQUID was directly over a circumferential slot in the wall of the pipe, while the signal near X = 28 cm corresponds to a hole in the pipe made by drilling three overlapping holes along an element. The increase in the signal at values of X less than -30 cm was associated with a circumferential weld seam in the pipe just off the scale in the figure. Additional measurements will have to be taken to establish any correlation between the shape of the detected magnetic signal and the geometry of the defect in the wall of the pipe.

The great sensitivity of SQUID instrumentation can be used for the detection and localization of buried pipes. The data shown in Fig. 3 simulates such an experiment in which the SQUID was kept stationary while the pipe was moved. The current through the pipe had an amplitude of about 1 amp at a frequency of about 4 Hz. The separation between the pipe and the sensor was about 1.6 m with the axis of the gradiometer coils tilted at an angle of about 60 degrees relative to the horizontal. (See inset in Fig. 3.) The maximum detected signal was obtained when the pipe was directly below the gradiometer coils while the null signal was obtained when the axis of the gradiometer coils intersected the axis of the pipe. Using trigonometry, the perpendicular separation between the sensor and the pipe, which in this simulation corresponded to the depth of a buried pipe, could be obtained. These measurements were made with the SQUID system operating at reduced sensitivity. If the SQUID were operated at maximum sensitivity and larger currents were used, pipes buried many meters below the surface could be detected. If these measurements were made in a noisy magnetic environment, phase sensitive detection techniques could be used to extract the signal associated with the current flowing along the pipe from the background noise.

![Fig. 3. Signal detected by a SQUID gradiometer as a function of displacement of a pipe below the sensor with the axis of the gradiometer at an angle of 60° to the horizontal.](image-url)
A SQUID system was used to monitor the magnetic state of a steel bar. The changes in the detected signal when a steel bar was subjected to stress were quite large even when the SQUID was about 20 cm from the bar and reduced instrument sensitivity was used. (When a brass bar was substituted for the steel one, if there were any magnetic signal due to the mechanical loading, it was down by at least three orders of magnitude from that seen for the steel bar.) The measured stress-strain curve and the detected magnetic signal for a loading cycle in the linear, reversible regime are shown in Fig. 4(a). The magnetic signal shows an extremal behavior even though the stress-strain curve is linear and reversible over the entire range of loading. As the loading was increased, stress-strain and magnetic traces showed distinctive changes in behavior as shown in Fig. 4(b). With still greater loading, the sample eventually fractured, this being reflected in the magnetic trace as well as in the stress-strain curve (see Fig. 5). For all traces in the region where the stress-strain behavior is linear, the magnetic signal, both on loading and on unloading, shows a characteristic extremal behavior which implies that the magnetoelastic coefficient has changed sign at a value of stress just below the elastic limit. This change in the sign of the magnetoelastic coefficient suggests the possibility of monitoring the stress state of a ferromagnetic structure by applying a cyclic strain transducer to produce a cyclic magnetic response. The phase of the detected magnetic signal relative to the phase of the driving force would indicate whether the average strain value was close to or above the elastic limit or whether the average strain was well below the elastic limit.

Fig. 4. Stress-strain and magnetic signal traces for a steel bar when (a) the sample remained in the reversible regime during the entire loading cycle, and (b) when the maximum loading exceeded the elastic limit and the sample experienced plastic flow.
CONCLUSIONS

These preliminary results suggest the possibility that SQUID magnetometry has the potential to provide innovative techniques for nondestructive evaluation of electrically conducting and of ferromagnetic structures.

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REFERENCES

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DISCUSSION

From the Floor: I understand that the fiber optic magnetometers are approaching the SQUID limit. Could they be applied here?

Mr. Weinstock: In theory one can get any sensitivity one wants by winding a long enough length of fiber. However, my colleague, Dr. Nisenoff,
has calculated that it would take on the order of 100 meters of fiber to provide a sensitivity equal to that of the SQUID. With that much length it would be necessary and perhaps difficult to maintain the temperature and pressure stability required to prevent signal drift. Furthermore, with such a resulting large volume, one probably would have a problem with localization and direction of the magnetic field.

Mr. Sam Marinov: Can you detect corrosion in ferromagnetic metals?

Mr. Weinstock: In fact, the study reported in the first part of our paper involved a steel conduit. Using an ac current through the pipe and monitoring only the ac component of our SQUID output, we can detect purely structural anomalies. The dc component of our output does give information on purely ferromagnetic anomalies. Although not mentioned in the paper, we did file a flat in the steel conduit and were able to detect, at a separation of about 23 cm, the presence of that flat as the pipe was moved longitudinally under the SQUID dewar. Furthermore, if the flat were oriented in the direction closest to the SQUID, the observed signal was less than that for a section of pipe with uniform cross section; but if the flat were oriented 180° away from the tail, the signal was greater.

Mr. Marinov: Are you saying that your method is sensitive to defects such as corrosion?

Mr. Weinstock: We have not looked at a pipe with real corrosion, but the observation I just described seems to indicate that corrosion would be detectable. In addition, we could detect the presence of a weld in the ferromagnetic pipe without applying a current through the pipe.

Mr. John Murphy: I just wanted to make a comment to say that we have been looking at corrosion on buried underground pipe, primarily coated and uncoated pipe, and it is possible, using the technique that the speaker was describing and using either SQUIDs or flux gate magnetometers of selected densities at breaks in pipe coating and to use the same kinds of techniques to do spatial mapping for current distributions both in the near vicinity of the pipe and also in the arc return pattern. This kind of thing is essentially the magnetic analog of the ac impedance method in electrochemistry and provides an opportunity to make quantitative measurements.

Mr. Fred Rothwarf: What spatial resolution do you expect to attain with such a technique?

Mr. Weinstock: In order to obtain good spatial resolution one must map the magnetic field over an area, similar to what is done in neuromagnetometry. There one detects small current sources in the brain 2 to 4 cm below the bottom of the SQUID dewar with a precision of 2 mm. Based on this information, successful operations have been performed on people with severe forms of epilepsy.