Open access • Journal Article • DOI:10.1109/20.133898

A review of SQUID magnetometry applied to nondestructive evaluation

H. Weinstock

Institutions: United States Department of Energy Office of Science

Published on: 01 Mar 1991 - IEEE Transactions on Magnetics (IEEE)

Topics: Squid

A REVIEW OF SQUID MAGNETOMETRY APPLIED TO NONDESTRUCTIVE EVALUATION

Harold Weinstock

Air Force Office of Scientific Research
Bolling AFB, DC 20332-6448

Abstract

The development of the SQUID as the most sensitive instrument known for the measurement of changes in magnetic flux has presented new opportunities for its use for nondestructive evaluation (NDE) of electrically conducting and ferromagnetic structures. This presentation will review the preliminary studies of this application within the past few years in order to serve as an introduction to those that follow. It will include early work by the author which explored the ability of a SQUID to detect defects in a buried pipe and to detect fatigue in steel structures. Studies designed to find defects in North Sea oil platforms and corrosion currents are covered, as well as more recent work in mapping the magnetic field above a current-carrying circuit board. A discussion of the future for SQUID-based NDE will conclude this discourse.

Introduction

This is the first time the Proceedings of the Applied Superconductivity Conference has had a section whose title deals at least in part with the application of SQUIDs to nondestructive evaluation. This is not surprising since the first published work in this field did not occur until 1985, based upon studies that were begun in late 1982 at the Naval Research Laboratory[1,2] (NRL) and at the University of Strathclyde[3]. Later, it was discovered that there was work done of this type (since the late 1970's) at the Johns Hopkins University Applied Physics Laboratory, but the results of that were not known since there was no publication of it in the open literature. While these early studies were done primarily using SQUID magnetometers or, more precisely, magnetic gradiometers that were built for use in the study of biomagnetism, there are now a growing number of laboratories which have ordered or are already using multisensor systems specifically designed for NDE applications. It will, undoubtedly, be some time before these applications can rival the interest currently shown for biomagnetic and geophysical applications, but at the moment, the future of SQUID-based NDE looks bright. This is especially true because of recent success in the fabrication of low noise HTS SQUIDs and sensing coils operating at 77 K.

When To Use a SQUID

The use of a SQUID for NDE is just another form of magnetic anomaly detection (MAD). Interest in this subject arose because of the similarity with the more mature applications cited above, as well as with the use of SQUID magnetometry for antisubmarine warfare. All applications fall into two categories: detection of magnetic anomalies associated with ferromagnetic material and magnetic field anomalies associated with electric current. The source of a current may have biological origins, be due to induced eddy currents, be due to corrosion, or due to current applied specifically to produce a magnetic environment to help reveal some structural defect. Clearly, it is the unrivaled sensitivity of SQUIDs to small changes in magnetic flux that makes them highly desirable when it is not possible to place a sensing coil or solenoid directly around the object. One should not use a SQUID when a simpler, less expensive technology can provide the required information, although one factor that tends to favor SQUID use is the reliability and ruggedness of SQUID systems in comparison to some other magnetic technologies.

SQUID magnetometry should be used when extra sensitivity is required and nothing else will meet the requirements. In a gradiometer mode SQUIDs are insensitive to large background magnetic fields; they are linear, have wide dynamic range, and can be configured to cancel background noise through the use of a reference magnetometer. Another very important feature is good spatial resolution, i.e., with superior sensitivity, one can make sensing coils relatively small, one of the requirements for improved spatial resolution.

In some NDE and geophysical applications, a magnetometer is relatively far from the magnetic source of interest. In this case, the SQUID's superior sensitivity may be irrelevant if a high ambient noise level renders it no more sensitive than some simpler technology. On the other hand, other applications require placing a sensing coil as close as possible to a field source. In this mode it is invariably advantageous to use a gradiometer coil configuration, ideally keeping the gradiometer baseline large in comparison to the stand-off distance between the bottom of the gradiometer coil and the magnetic field source. With dipole sources falling off inversely as the cube of the stand-off distance, the cryogenic environment sometimes can increase that distance so much that some other technology may be more desirable. To best utilize the SQUID's sensitivity, there should be a commensurability between the stand-off distance and the diameter of the sensing coil. If an array of sensors is used, then this commensurability extends to the spacing between adjacent coils.

Before looking into any NDE application of a SQUID magnetometer, it is important to interrogate those with experience in the area being considered, and to discover whether or not there is a real need for an improved methodology. It may well be that greater sensitivity is irrelevant or that there are some physical limitations which preclude the use of present-day SQUID technology.

Ferromagnetic Materials

Initial State Anomalies

While iron-based alloys (i.e., steels) have been replaced in many applications by lighter weight, yet sturdy alloys, iron-based alloys remain a basic component of buildings, bridges and various means of transportation. When scanning a steel structural element, one may find magnetic field anomalies due to non-uniform geometry which either were original features of that element or features which evolved as a result of strain, deformation, corrosion, etc. Without knowing the magnetic signature of a specific specimen in its virgin state, it is difficult to interpret some anomalous field pattern. This was made clear to me when I found a particularly large anomaly when scanning the length of a 3-meter long iron conduit which appeared at first glance to have a uniform cross section. The mystery was solved when a visitor held the conduit up to a bright light and noted a weld within the interior at just the region for which the anomaly was observed. Figure 1a shows the arrangement of the sensing coil relative to the conduit after longitudinal and

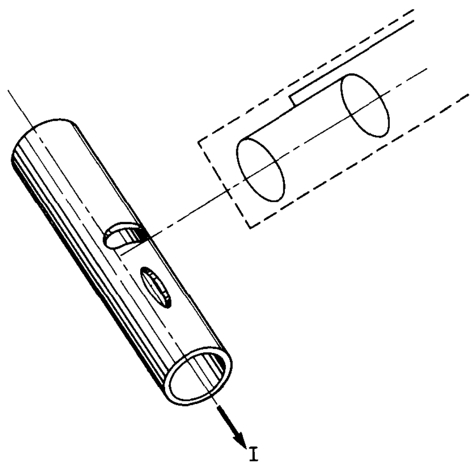

Figure 1a. Schematic of a SQUID magnetic gradiometer aligned normal to the axis of a current-carrying iron conduit with 2 holes.

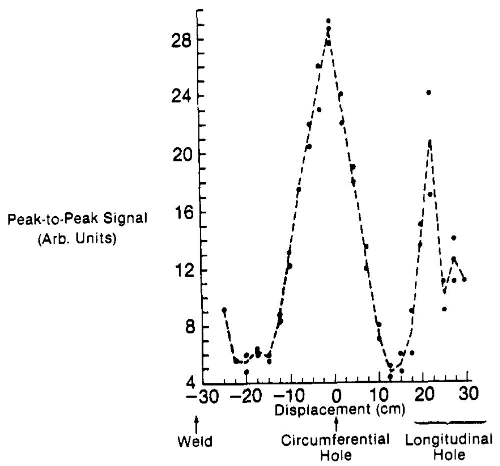

Figure 1b. Output signal from SQUID system when conduit is moved longitudinally under SQUID dewar at a separation of about 20 cm and an applied 4.6 Hz current of about 1 A.

transverse holes were created. Figure 1b shows data taken for this conduit with a SQUID second-order gradiometer separated from the surface of the conduit by about 20 cm. Although these data were obtained with a 4.6 Hz current of about 1 A applied in order to accentuate the effect of the damage created, the welded area produced an easily observable anomaly in the absence of applied current.

Fatigue

Perhaps the most pleasant surprise I received in applying SQUID magnetometry to structural steel occurred when I attempted to observe the magnetic response to stress applied to a steel bar in a tensile testing unit. A schematic of the arrangement is shown in Figure 2a. Because of the geometrical configuration of both the SQUID dewar and the mechanical unit, the tip of the dewar could be placed no closer than 20 cm from the bar, with an

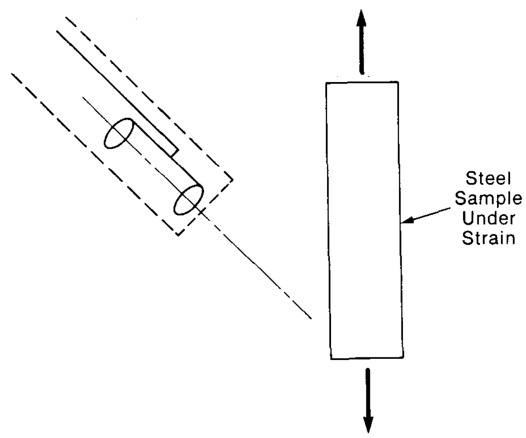

Figure 2a. Schematic of SQUID magnetic gradiometer placed at 45 degrees and 20 cm from a vertical steel bar in a tensile-testing unit.

angle of 45 degrees to the vertical axis of the steel bar. Even at that distance, the change in flux measured by the gradiometer coils was so large, the read-out electronics had to be set for the least

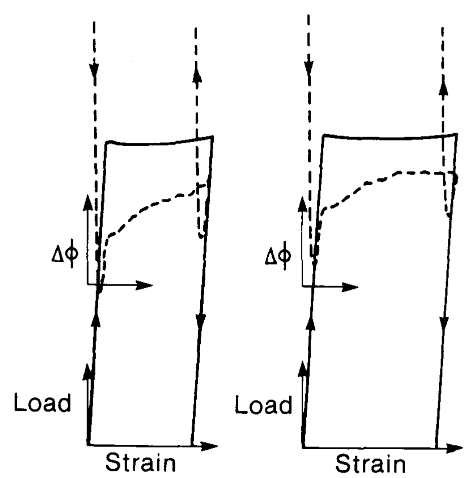

Figure 2b. Response of the SQUID system and stress sensor to applied strain for 2 successive cycles.

sensitive scale. In Figure 2b one can observe the unexpected reversal in the direction of changing magnetic flux as recorded by the gradiometer coils. A 2-pen recorder was used to plot the change in stress and the change in magnetic flux simultaneously as a function of strain. A number of steel specimens, prepared in a variety of ways and cycled many times both below and above the elastic limit, all showed this reversal in changing flux at a stress level about 0.6 of the way to the elastic limit.

The strength of this magnetic response to strain was so great that I suggested it could be observed with an ordinary flux-gate magnetometer placed within a few centimeters of a steel bar. Work by Mignogna nd Chaskelis[4] at NRL has shown this to be so, and it showed also that a SQUID magnetometer could record the same signal-to-noise ratio when placed about an order of magnitude farther from the steel specimen under test. This effort looked for similar behavior in nickel specimens, but no reversal in changing magnetic flux was found.

When a load which does not exceed the elastic limit for steel is applied and then removed, one sees hysteresis only in the magnetic response. This indicates that, even within the limits of elastic behavior, some dissipation occurs. Although I hypothesized that this might be related to a reduction in domain size, it wasn't until a metallurgist told me that phase slip in steel occurs at the same value of stress as that for the reversal in changing flux, that I realized the importance of the reversal phenomenon. Phase slip represents the microscopic origin of fatigue.

This observation of the onset of fatigue in steel can be the basis for a powerful NDE technique that requires only a qualitative determination. If one wants to test a steel structural element for fatigue, all that is required is a periodic mechanical stimulus, possibly with a piezoelectric transducer which produces a small perturbation to the underlying strain. Using phase sensitive detection, the response in changing magnetic flux will be either in phase or 180 degrees out of phase with the mechanical perturbation being applied. In the case of an out-of-phase response, fatigue is present. By scanning the length of the test structure, it also may be possible to find a region of maximum fatigue.

<u>Steel Plates</u>

Donaldson's University of Strathclyde group was engaged in 1982 by the British Petroleum Corportion to investigate the ability of SQUID magnetic gradiometry to detect surface breaking cracks in ferromagnetic steel plates. Figure 3 is a schematic

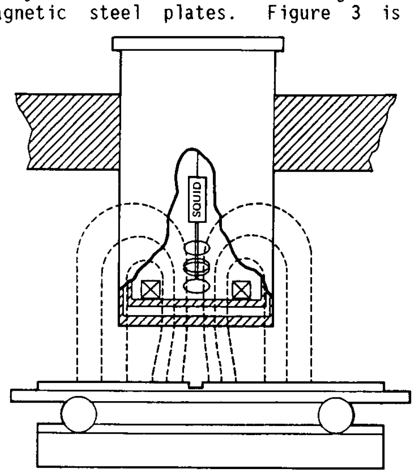

Figure 3. Schematic of test apparatus with SQUID gradiometer and superconducting magnet positioned over cart with machined slot in steel plate. (Reference 4)

diagram of the test apparatus used. A steel cart containing machined notches is moved beneath a stationary dewar containing a superconducting magnet to produce a polarizing field which does not directly produce any changing flux in the gradiometer coils. The actual gradiometer used was not of the axial type as shown, but was in the form of a planar (or "balanced") gradiometer so that there would be relatively small response to changes in the standoff distance due to plate distortions. Figure 4a shows results for the response to a steel plate with slots in both water and air, indicating that detec-

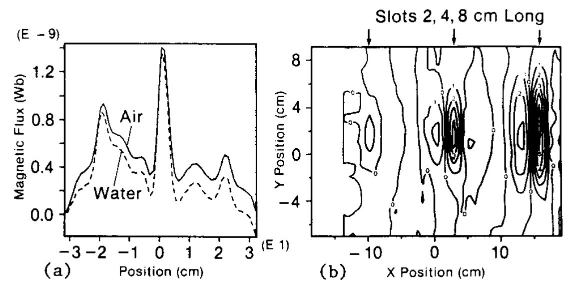

Figure 4. (a) Relative response of SQUID sensor to slotted steel plate in air and under water; (b) magnetic field contour map for plate with 3 slots. (Reference 5)

tion is not much degraded by the presence of water. Figure 4b shows the magnetic field contours associated with these slots. The effect of fatigue beyond the boundaries of a 5-cm long slot is evident in the field contours seen in Figure 5. Unfortunately, it was not possible to distinguish a crack

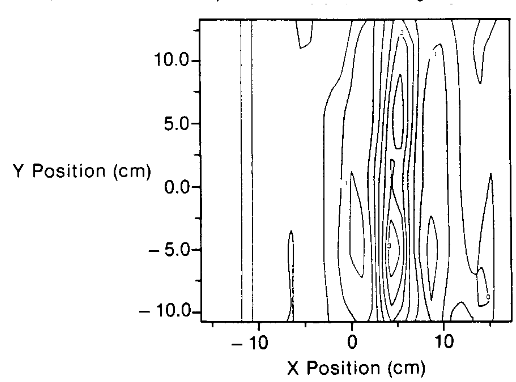

Figure 5. Magnetic field contour map over a fatigued, cracked plate. The effects of fatigued regions well beyond the 5-cm long slot are evident. (Reference 5)

in a weld from the weld itself because of the lack of resolution relating to the larger of either the stand-off distance or gradio- meter coil diameter. A fuller account of this work and a review of related studies may be found in Reference 5.

More recently[6], the Strathclyde group has teamed with a group of Hitachi metallurgists to show that a SQUID-based magnetometry system can detect at a distance features of stainless steel specimens that are characteristic of precipitates due to thermal aging. This same information can be obtained by less sensitive forms of magnetometry, but not (as was the case for the SQUID system) for stand-off distances of up to 9 cm. There may be many practical situations where this becomes important, for example, in power plants where steel pipes are covered with thermal insulation.

Current-Induced Fields

Inherent Currents

In principle, MAD may be applied to any structure that is capable of carrying an electric current. Perhaps the ideal situation is one in which current is present inherently. Such is the case for a corrosion current which, by its very nature, is an indication of a problem requiring remediation. Studies of field patterns associated with corrosion currents have been initiated by a group at MIT[7], and more recent work by this group appears in a following contribution[8].

Eddy Current Techniques

Still another means for studying defects in metallic structures is to induce an eddy current and thereby avoid the need to make physical (electrical) contact with the test object. A SQUID magnetometer was used by a group at the National Bureau of Standards[8] (now NIST) to map magnetic field patterns associated with commercial eddy-current probes, and it was suggested that a SQUID itself could be used to map magnetostatic leakage. However, these studies involved the use of a small copper pick-up coil at room temperature which had to be fed into the cryogenic region for coupling to a superconducting Nb input coil. While adequate for the task at hand, this configuration did not lend itself to a form of SQUID-based eddy current detection.

More recent work by Podney and Czipott[9] has addressed the possibility of using superconducting source, shielding and pick-up coils, arranged concentrically and coplanar, with coupling to a SQUID magnetic sensing unit. Design studies indicate that small near-surface inclusions can be detected if one can construct an array of millimeter-size coils with commensurate center-to-center separation and stand-off distance from the metal surface. Work is progressing on the construction of such an array, and the reader is referred to a fuller account of it elsewhere in this volume.

Applied Currents

While the work of this author[1,2] referred to earlier did involve the attachment of current leads to a conduit under test, the most thorough study of field patterns produced by defects in a current-carrying metallic structure, is that being conducted by Wikswo's group at Vanderbilt University[10]. An update of that group's recent activity is presented in a following paper[11]. The major advantage of the Vanderbilt studies is that they utilize a multi-sensor SQUID system with small, closely spaced sensing coils of relatively small diameter, and with a variable stand-off distance on the order of millimeters. Figure 6a shows a schematic of a typical one-sensor SQUID gradio- meter. Noteworthy features of a typical system include a coil diameter of about 5 cm, a baseline of over 6 cm, and a stand-

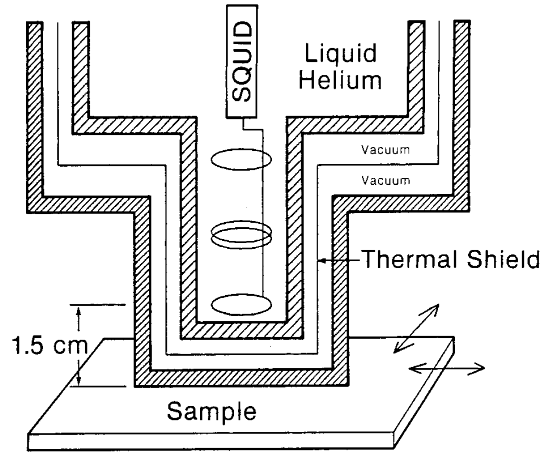

Figure 6a. Schematic of a typical commercial SQUID magnetic gradiometer with a stand-off distance of over one centimeter between the bottom of the sensing coil and room temperature. (Courtesy of J.P. Wikswo, Jr.)

off distance of 1 to 2 cm. In comparison, Figure 6b shows the schematic of what Vanderbilt and BTi, the manufacturer, refer to as the MicroSQUID, a system

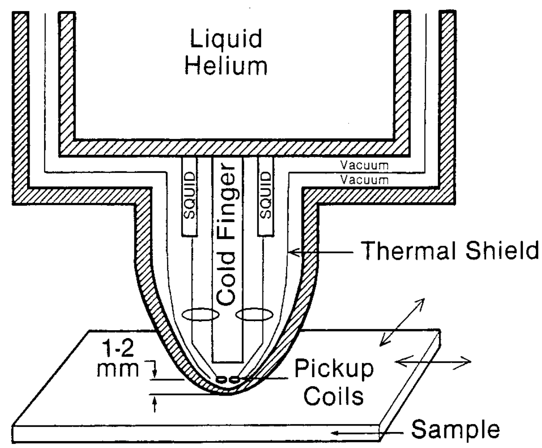

Figure 6b. Schematic of a 4-sensor MicroSQUID with a stand-off distance of one to two millimeters. (Courtesy of J.P. Wikswo, Jr.)

that incorporates four sensing coils located at the corners of a square, 4.4 mm on a side, each with a 3 mm diameter and constructed so that the stand-off distance to room temperature may be varied between 1.4 and 4.0 mm. It is estimated that anomalies due to features less than a millimeter in extent can be resolved.

The ability of the MicroSQUID system to detect the presence of a 0.3 mm diameter hole in a copper plate has been demonstrated[10], but one of the major motivations for construction of this system was its potential use for the tracing of current in a failed integrated circuit chip. As a test of the system's capability to do this, Wikswo and his collaborators constructed a "VU" pattern on a printed circuit board, as illustrated in Figure 7a. When 0.1 mA is passed through this wire configuration, they obtained the magnetic field contour map

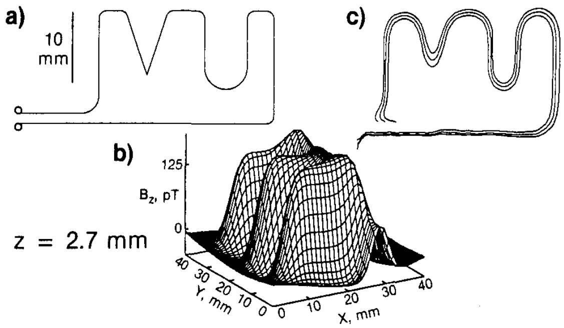

Figure 7. (a)"VU" current pattern with 0.1 mA on printed circuit board; (b) measured magnetic field using MicroSQUID at stand-off of 2.7 mm; (c) reconstructed current image from magnetic field data. (Courtesy of J.P. Wikswo, Jr.)

shown in Figure 7b for a coil stand-off height of 2.7 mm. Figure 7c shows the current image derived from this contour map using a spatial filtering algorithm developed earlier[11].

<u>The Future of SQUID-Based NDE</u>

Much of the early work in this area was done using instrumentation designed for other applications, primarily biomagnetic ones. It is clear, however, that if SQUID-based NDE techniques are to have a major impact, one must construct systems which are specifically responsive to each unique situation. In many cases this will require arrays of millimeter and sub-millimeter size coils with comparable planar separations and stand-off distances. It appears unlikely that such requirements can be met easily using the "conventional low-temperature" superconductors of the past. While such instruments as the MicroSQUID may be tremendously useful in establishing the limits of detectability for certain applications, they may not be practical or cost-effective in their transition from the research laboratory to the commercial world.

The future of SQUID-based NDE is undoubtedly tied to the challenge of making manufacturable, low-noise, ceramic oxide (so-called HTS) SQUIDs and planar sensing coils. The recent work of Koch et al[12,13] is encouraging since it illustrates that planar HTS SQUIDs operating at 77 K have low frequency noise characteristics comparable to that found for commercial Nb SQUIDs operating at 4 K. However, since the method used to produce these Tl-compound HTS dc SQUIDs is not a manufacturable technology, one's enthusiasm must be at at least temporarily restrained.

Not only must one consider specially designed sensing-coil arrays, but one also must consider the construction of unique test beds. At the beginning of this paper I described measurements which showed that it may be relatively simple to determine fatigue in steel structures. In order to exploit this potential more fully, the apparatus shown schematically in Figure 8 was recently constructed. It consists of a (3-axis) vector, first-order SQUID gradiometer mounted vertically over a specially constructed non-magnetic load frame. Specimens under test can be stressed periodically, while the entire frame can be rotated 120 degrees in either direction about its horizontal axis and can be made to travel linearly in an x-y plane. This set up, which is fully automated, will permit mapping of

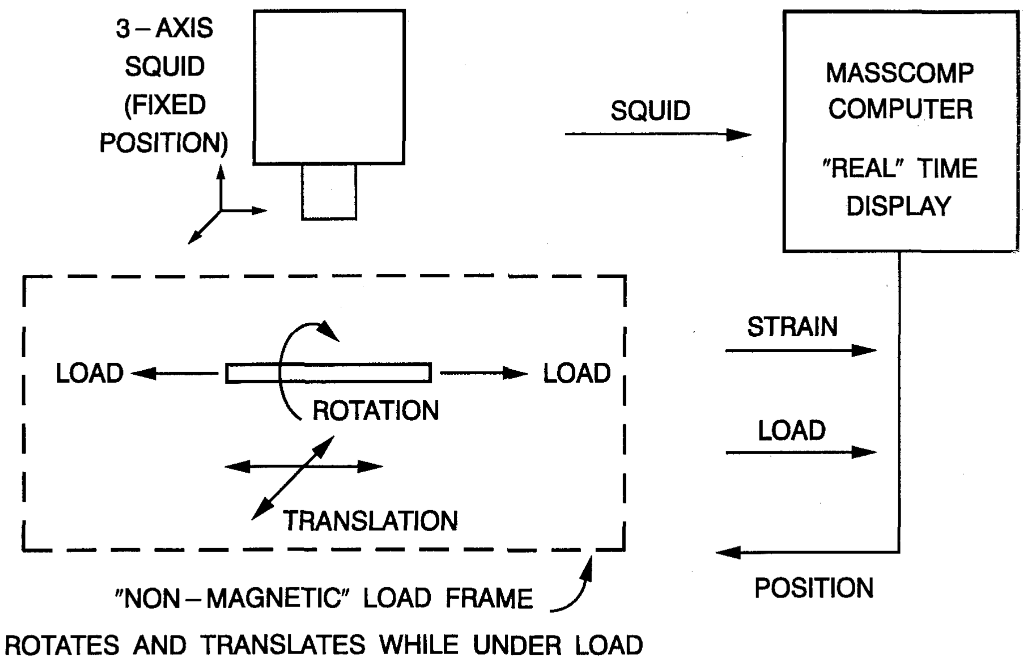

Figure 8. Schematic of non-magnetic load frame, vector SQUID gradiometer and data acquisition system to test for the onset of fatigue and fracture in steel bars. (Courtesy of R.B. Mignogna)

magnetic field contours associated with the onset of fatigue and fracture in steel specimens, and should provide the data needed to verify the potential of SQUID-based units to detect early signs of fatigue in practical steel structures.

In the final analysis, the success of SQUID-based NDE techniques will depend not on what low temperature physicists do in their laboratories, but how well this technology can respond to the real needs of the NDE community, and how well it stacks up against other technologies, some of which may be "moving targets." After learning about the use of SQUIDs in biomagnetism and geophysics, it occurred to me that a modification of these techniques could be applied to NDE. But the first thing I did after entertaining this thought was to contact a major manufacturer of NDE systems which incorporated a variety of technologies. I wanted to know whether there were limits to these existing commercial technologies such that the requirements of their clients, e.g., operators of utility pipe lines and nuclear reactors, were not fully met. It was only after receiving encouragement from this organization that I proceeded further. Although I stated at the beginning of this discourse that the future of SQUID-based NDE appears bright, I am somewhat disturbed by a number of people (within the SQUID community) making even more positive statements in this regard and who have not had any real contact with the NDE community. The true challenge is to present convincing data at NDE meetings, not just at meetings on superconductivity. Success will be assured when acclaim is given during a session on SQUID-based NDE at the annual meeting on Progress in Quantitative NDE. Currently I am not convinced this will occur, but I feel that prospects for it to happen are still favorable.

Acknowledgements

I wish to acknowledge valuable discussions with and data from Professor John Wikswo of Vanderbilt University, Professor Gordon Donaldson of the University of Strathclyde, Dr Walter Podney of SQM Technology, Inc., and Dr Richard Mignogna of the Naval Research Laboratory.

References

1. H. Weinstock and M. Nisenoff, "Defect Identification with a SQUID Magnetometer," Review of Progress in Quantitative Nondestructive Evaluation, D.O. Thompson and D.E. Chimenti, Eds, 6, Plenum, New York, 1986, pp. 669-704.

2. H. Weinstock and M. Nisenoff, "Nondestructive Evaluation of Metallic Structures Using a SQUID Magnetometer," SQUID '85 - Superconducting Quantum Interference Devices and Their Applications, H.D. Hahlbohm and H. Lubbig, Eds., de Gruyter, Berlin, 1985, pp. 853-858.

3. R.J.P. Bain, G.B. Donaldson, S. Evanson and G. Hayward, "SQUID Gradiometric Detection of Defects in Ferromagnetic Structures," SQUID '85 - Superconducting Quantum Interference Devices and Their Applications, H.D. Hahlbohm and H. Lubbig, Eds., de Gruyter, Berlin, 1985, pp. 841-846.

4. R.B. Mignogna and H.H. Chaskelis, "Investigation of Deformation Using SQUID Magnetometry," Review of Progress in Quantitative Nondestructive Evaluation, D.O. Thompson and D.E. Chimenti, Eds., 8, Plenum, New York, 1989, pp. 551-558.

5. G.B. Donaldson, "SQUIDs for Everything Else," Chap. 7 in Superconducting Electronics, H. Weinstock and M. Nisenoff, Eds., Springer, Berlin, 1989.

6. G. Donaldson et al, "Use of SQUID Magnetic Sensor to Detect Aging Effects in Duplex Stainless Steel," Brit. J. of Non-Destructive Testing 32, 238-240, 1990.

7. J.G. Bellingham, M.L.A. Macvicar and M. Nisenoff, "SQUID Technology Applied to the Study of Electrochemical Corrosion," IEEE Transactions on Magnetics, MAG-23, 477-479, (1987).

8. M. Misra, S. Lordi and M.L.A. Macvicar, "NDE Application of SQUID Magnetometry to Electrochemical Systems," IEEE Transactions on Magnetics, MAG-27 (this volume), 1991.

9. W.N. Podney and P.V. Czipott, "An Electromagnetic Microscope for Eddy Current Evaluation of Conductive Materials," IEEE Transactions on Magnetics, MAG-27 (this volume), 1991.

10. J.P. Wikswo, Jr. et al, "Instrumentation and Techniques for High-Resolution Magnetic Imaging," Digital Image Synthesis and Inverse Optics, A.F. Gmitro, P.S. Idell and I.J. LaHaie, Eds., SPIE Proceedings, vol. 1351 (to appear), 1990.

11. D.J. Staton, Y.P. Ma, N.G. Sepulveda and J.P. Wikswo, Jr., "Magnetic Imaging with a High Resolution SQUID Magnetometer Array," IEEE Transactions on Magnetics, MAG-27 (this volume), 1991.

12. R.H. Koch et al, "Low-Noise Thin-Film TlBaCaCuO dc SQUIDs Operated at 77 K," Appl. Phys. Lett. 54, 951-953 (1989).

13. R.H. Koch et al, "Present Status and Future of dc SQUIDs Made from High-T_c Superconductors," Physica B, vols. 165 & 166 (III) (to appear), 1990.