Superconducting Sensors: Instruments & Applications

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Introduction

Magnetic sensing has progressed from the simple magnetized needle used by Vikings for navigation to extremely sophisticated devices used to measure interplanetary regions, the human body and innumerable physical structures. The most sensitive magnetic sensor is the SQUID (an acronym for Superconducting QUantum Interference Device). It has been nearly three decades since SQUID devices have been commercially available. Since then, SQUID sensors have grown from a specialized laboratory instrument measuring exotic quantities as picovolts and nanokelvins to instruments routinely used in such diverse applications as medicine, materials science and oil exploration.

The SQUID as an Amplifier

A SQUID is a device that utilizes superconductivity and the Josephson effect to convert minute changes in current or magnetic field to a measurable room temperature voltage. Four different physical principles are responsible for the ability of a SQUID to act as a magnetic flux transducer.

I) Superconductivity (zero resistance)

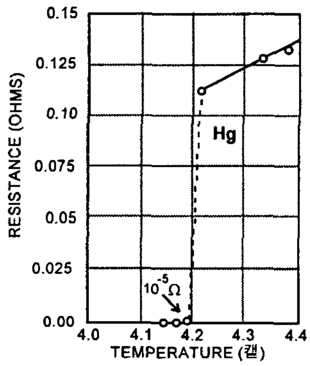

Fig. 1. Resistance vs. Temperature for mercury

Zero resistance means true dc frequency response, flat phase response and no energy losses while superconducting.

II) Meissner Effect (flux expulsion)

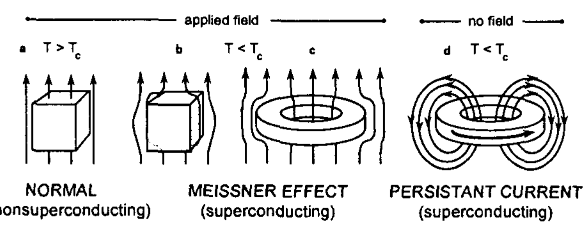

Fig. 2. Flux Expulsion in a superconductor

When a material becomes superconducting, all interior magnetic fields are expelled. If the superconducting material is a loop—and a magnetic field exists within the loop—when the material goes superconducting, any magnetic field inside the loop becomes trapped. Any changes in the magnetic flux penetrating the loop induce a screening current that opposes the external flux changes and keeps the magnetic field within the loop constant. This generation of persistent currents is what allows detection of external magnetic field changes.

III) Flux Quantization (quantum effects)

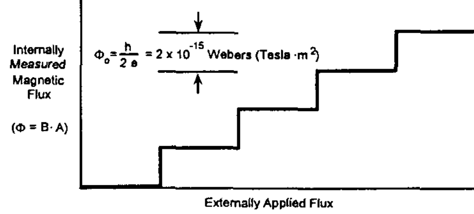

Fig. 3. Internally measured magnetic flux vs. externally applied magnetic flux

Within the loop, flux is quantized in multiples of a quantity known as the magnetic flux quantum, $\phi_0 = h/2e = 2.068 \times 10^{-15}$ webers. The fact that magnetic flux is quantized gives rise to unsurpassed linearity.

IV) *Josephson Effect*
(quantum mechanical tunneling)

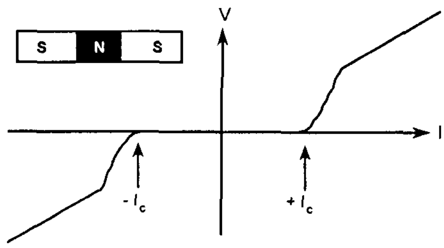

Fig. 4. I-V curve for Josephson junction

If a superconductor (**S**) is broken by a resistive or normal (**N**) region, one would expect the circuit to act as a resistor. However, if the resistive region is thin enough, paired electrons can quantum mechanically tunnel through the resistive region with no voltage drop (the Josephson effect). Above a critical current I_C, however, the circuit acts as a resistive element.

The SQUID Sensor

A SQUID consists of a superconducting loop with one or more Josephson junctions as its active elements. Fig. 5 shows a dc SQUID that uses two matched Josephson junctions (the X≿s 2ɒd the loop) with a dc current ($_c$) applied directly to the SQUID to measure the loop impedance.

The properties of the Josephson junction cause the impedance of the SQUID loop to be a periodic function of the magnetic flux penetrating the loop. Modulation and feedback signals are inductively coupled to the bias current to measure the impedance and keep the output linear. This results in a transducer that converts magnetic flux to voltage. A simple input transformer converts the device into a current-to-voltage amplifier.

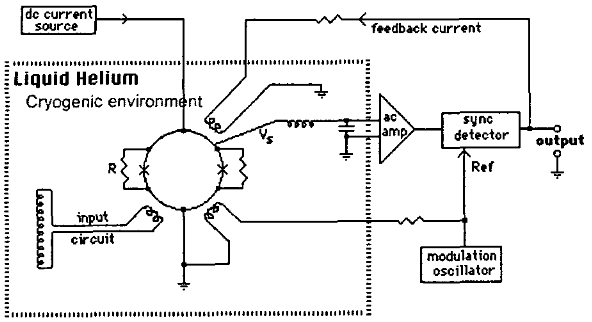

Fig. 5. Block diagram of a typical dc SQUID

SQUIDs offer superb performance: true dc response, wide bandwidth (exceeding MHz frequencies in some devices), zero phase distortion (unlike resistive coils) and energy sensitivity better than 10^{-32} J/Hz. They operate at a very low temperature minimizing Nyquist noise. In most applications, the input circuit is superconducting and thus contributes no additional noise. The periodic nature of SQUID devices—due to flux quantization—coupled with a high degree of negative feedback, is responsible for their superb linearity and high dynamic range (>180 dB in some cases).

The SQUID as a Black Box

When constructing SQUID systems, it is not necessary to be an expert in quantum mechanics or thin film fabrication techniques. In practice, we can think of a SQUID as a black box with one end at cryogenic temperatures and the other end generating an output voltage directly proportional to the input current presented at the superconducting input terminals.

SQUIDs are available in two types: the traditional low temperature (LTS) SQUID that operates at liquid helium temperatures (4.2 K) and the high temperature (HTS) SQUID that can operate at liquid nitrogen temperatures (77 K). LTS SQUIDs can be either rf or dc SQUIDs. HTS SQUIDs are usually dc SQUIDs fabricated from the ceramic oxide $Yba_2Cu_3O_{7-\delta}$.

Measurement Configurations

A SQUID can be configured to measure a wide variety of electromagnetic properties (Fig. 6).

The state of the art in materials processing of high-temperature superconductors limits the variety of superconducting input circuits that can be used with HTS SQUIDs. For example, there is no existing method for making superconducting connections to SQUIDs with HTS wire, and only magnetometers and planar gradiometers are being made in the research environment. As a result, commercially available HTS devices are currently in the form of magnetic sensing rather than current sensing devices.

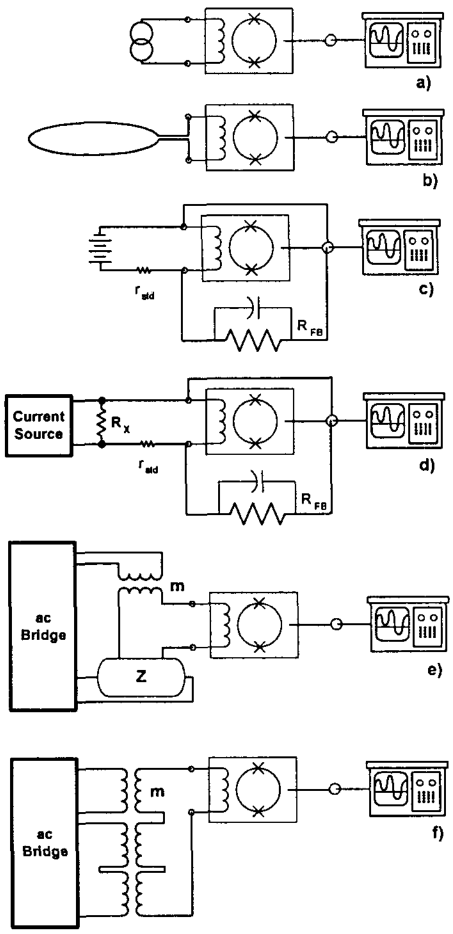

Fig. 6. (a) ac and dc Current, (b) Magnetic Field, (c) dc Voltage, (d) dc Resistance, (e) ac Resistance/Inductance Bridge, (f) ac Mutual Inductance (Susceptibility Bridge)

A large number of applications configure the SQUID as a magnetometer. Fig. 7 shows a typical system. If external magnetic fields are to be measured, the dewar is typically of fiberglass construction

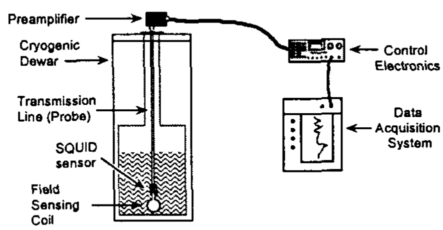

Fig. 7. Typical magnetometer system

Table I shows typical capabilities of SQUID-based instruments. The number in the parenthesis refers to the corresponding figure.

Table I

Measurement	Sensitivity
Current (6a):	10^{-12} ampere/√Hz
Magnetic Fields (6b):	10^{-12} tesla/√Hz
dc Voltage (6c):	10^{-14} volt
dc Resistance (6d):	10^{-12} Ω
Mutual/Self Inductance (6e):	10^{-12} Henry
Magnetic Moment (6f):	10^{-10} emu

For magnetic field measurements, Fig. 8 shows field sensitivities and bandwidths typical of a number of applications of interest.

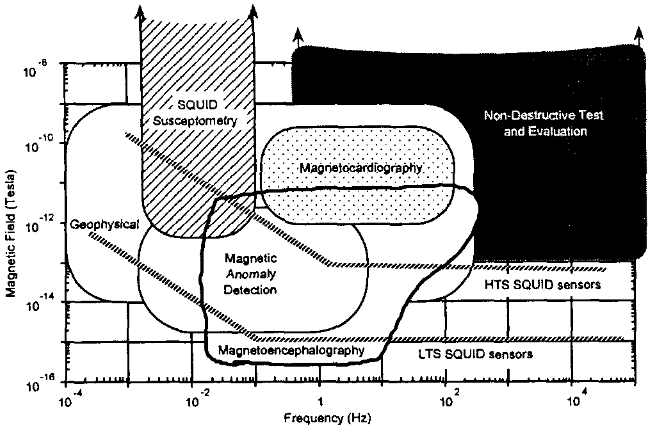

Fig. 8 Field sensitivities and bandwidths typical of various applications. The dashed lines indicate the sensitivity of commercially available SQUIDs

Exotic Applications

Besides the usual laboratory measurements, SQUIDs have been used for more esoteric applications including temperature measurements with resolution near 10^{-12} kelvin. SQUIDs have also been used to measure position for gravity wave detectors with sub Å resolution. Because magnetometers are vector devices, they can detect rotations better than 10^{-3} arc-seconds in the earth's magnetic field. Truly exotic uses of SQUIDs include tests of Einstein's General Theory of Relativity.

Geophysical Applications

One of the first commercial uses for SQUID magnetometers was in the search for oil. A technique known as magnetotellurics can be used to determine the electrical resistivity of the earth's crust by measuring the earth's electric and magnetic field. In particular, magnetotellurics has been used for oil exploration in the overthrust belts of the western United States and deep sediments of the Gulf Coast region. HTS-based SQUID magnetometers can be made small enough to fit into boreholes. Other geophysical applications for SQUID magnetometers include the tracking of surfactants in pressurized oil (well) recovery systems, airborne measurements of magnetic field gradients and measurements of internal ocean waves. A type of SQUID susceptometer known as a rock magnetometer is used to determine the magnetic field orientation of rock samples, yielding information on the strength and orientation of the earth's magnetic field when the rock was formed.

Medical Applications

SQUID magnetometers have been shown to provide diagnostic capabilities in areas where there is no other measurement technique. The use of bioelectric signals as a diagnostic tool is well known in medicine, *e.g.*, the electrocardiogram (EKG) for the heart and the electroencephalogram (EEG) for the brain. The electrical activity that produces the electrical activity measured by EEG and EKG also produces magnetic fields. The analogous magnetic measurements are known as the magnetocardiogram (MCG) and the magnetoencephalogram (MEG).

SQUID magnetometers passively measure functional activity, rather than supply structural information as is done in MRI and CT imaging with external magnetic fields or x-rays. By mapping neural activity, it is possible to localize electrically active regions in the brain to a within a few millimeters. This offers the possibility of detection and diagnosis of a number of neurological disorders. One such application may be in the localization of brain tissue that is responsible for epileptic seizures.

In addition, magnetic measurements can be made for which there are no electrical analogs. These are measurements of static magnetic fields produced by ferromagnetic materials ingested in the body, and measurements of the magnetic susceptibility of iron storage levels in the liver. Table II gives some of the areas in which SQUID magnetometers are currently being used in medical research.

Table II

Studies of the Brain—Neuromagnetism
- Epilepsy
- Presurgical Cortical Function Mapping
- Drug Development and Testing
- Stroke
- Alzheimer's
- Neuromuscular Disorders
- Prenatal Brain Disorders

Studies of the Heart—Magnetocardiography
- arrhythmia
- heart muscle damage
- fetal cardiography

Other Medical Applications
- Studies of the Stomach—Gastroenterology
- Intestinal Ischemia
- Non-invasive in-vivo Magnetic Liver Biopsies
- Lung Function and Clearance Studies
- Nerve Damage (peripheral and spinal cord)

It is only since the development of the SQUID that measurements of biomagnetic fields have become a reality. Today there are biomagnetic SQUID systems that will allow measurements of the magnetic field of the brain over the entire surface of the head (>100 positions simultaneously). There are dozens of sites actively pursuing medical research using SQUID magnetometers. The ability to map electrical activity in the brain has created a market that could exceed a billion dollars. As the medical applications grow, we may see the term SQUID become as commonplace as MRI or CAT scanner.

Non-Destructive Testing

Magnetic sensing techniques such as eddy current testing have been used for many years to detect flaws in structures. A major limitation on their sensitivity is the skin depth of metallic materials. Because SQUID sensors have true dc response and superior sensitivity, they can see "deeper" into metallic structures. dc response also means that they can detect remnant magnetization—without the need for externally applied magnetic fields. Their flat frequency response and zero phase distortion allows for a wide range of applications. Table III shows some of the measurement techniques that can be used.

Table III

Imaging:
- intrinsic currents
- remnant magnetization
- flaw-induced perturbations in applied currents
- Johnson noise in metals
- eddy currents in an applied ac field (flaws)

Hysteretic magnetization due to:
- cyclic stress (strain)
- simultaneous dc & ac magnetic fields

Magnetization of paramagnetic, diamagnetic and ferromagnetic materials in dc magnetic fields

A particular advantage of magnetic sensing is in examining cladded pipes. For example, a pipe with asbestos lagging can be quickly examined because the insulating barriers are virtually invisible to magnetic detection—the asbestos need not be removed or cut into.

Another potential application of SQUIDs is in detection of stress or corrosion in reinforcing rods used in bridges, aircraft runways or buildings. Fig. 9 shows magnetic field maps of an embedded strain sensor that takes on an increasing magnetic dipole character as it is strained.

Fig. 9 Magnetic field maps of an embedded strain sensor under a 4 cm thick concrete overcoating. **A** - bare sensor showing dipole characteristics, **B** - sensor under concrete, **C** - bare concrete. Image **D** = **B** – **C** is a digital subtraction of B and C showing that it is possible to image objects deep underneath magnetically complex coverings. The scans cover a 6 cm x 6 cm area.

Since the initial development of the magnetic microscope in 1988, progress has been made towards improved spatial resolution. A LTS SQUID microscope was able to achieve spatial resolution of 2 μm. This required samples to be at cryogenic temperatures. Present day HTS microscopes are able to image room temperature samples with resolutions approaching 10 μm.

Applications include non-contact measurements of timing and clocking circuits. Instruments with potentially micron resolution at MHz bandwidths could be used for circuit board and IC mapping and on a larger scale—LAN signal propagation. Magnetic Structure Mapping could improve process control, metrology and QA.

The Future Challenge

SQUID-based instrumentation offers superior performance and capabilities compared to conventional measurement techniques. It took nearly a decade after the discovery of Josephson effect before the first commercial SQUID device was available. It has taken another two decades to find commercially significant applications. Today, SQUIDs are routinely used in physics and materials science laboratories. Clinical applications in medicine are rapidly emerging. The introduction of high-temperature SQUIDs has opened up the possibility for increased commercialization of SQUID technology, particularly in applications where portability and convenience are important. Thus uses in geophysics, environmental cleanup and non-destructive testing have become more attractive along with a broader variety of medical applications. As these applications mature, SQUID technology is emerging from one primarily found in laboratories and becoming a significant sensor technology in multiple industries.

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