Contents:

Feature Article: SQUID Applications •Medical Applications

Top of Superconductivity Web21

Feature Article: SQUID Applications · Medical Applications
- Application of SQUIDs for Minerals Exploration

Tsunehiro Hato, Senior Research Scientist
Electronic Devices Division
SRL/ISTEC

Between 2010 and 2011, the author's group developed a practical SQUID system applicable to minerals exploration under the development of the next generation SQUITEM equipment and SQUID magnetometers, commissioned by Japan Oil, Gas and Metals National Corporation (JOGMEC). With the successful completion of final tests in Australia, a practically designed SQUID system developed for electromagnetic exploration has been delivered to JOGMEC. This project was a joint development between ISTEC, who led the development of a magnetometer comprising of a SQUID sensor, and Mitsui Mineral Development Engineering Co., Ltd., who was responsible for fabricating the receiving apparatus.

In the TEM or electromagnetic method as shown in Figure 1, a copper-wire transmitter is positioned in a 100-200 m square and direct current applied. The current flowing through the transmission loop is abruptly turned off, which induces an underground current. By utilizing a highly sensitive magnetic sensor and measuring changes in the resistance of induced current differentiated by time, allows a distribution of sub-surface resistivity structure to be analyzed. For example, taking measurements every 100m
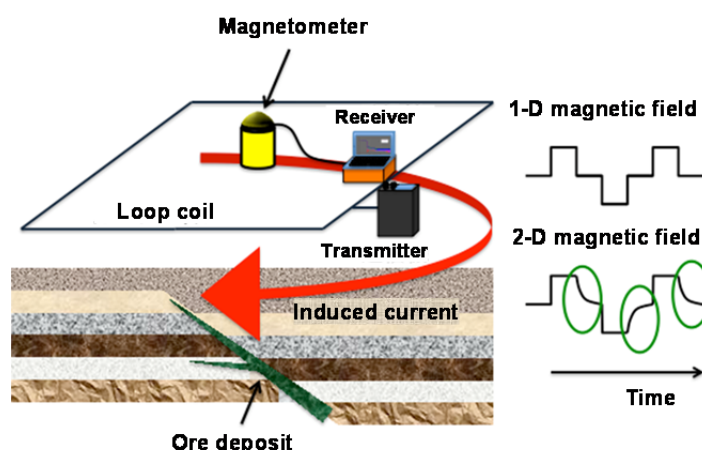

Fig. 1 Diagram showing the principle of the TEM method

builds a 2D picture of specific underground resistances that can be further investigated. SQUIDs are applicable to this methodology because of their high sensitivities, DC operational characteristics and wide frequency bands that range to 100 kHZ. With exploration depths expected to reach 1km, a reliable system is required to handle large currents and the accompanying large magnetic field changes. Key developments to address these areas are dependent upon realizing operational system stability and high slew rates (the maximum rate of magnetic field change per unit time). Minimizing or eliminating RF noise is important to realize operational stability. Additionally, the induced currents generated within the system need to instantaneously attenuate at a rate fast enough so that sub-surface induced currents do not interfere with the magnetic field measurements. The author and his group have selected own materials to solve shield issues whilst researchers around the world continued racking their brains. The efforts have resulted in both operational stability and greater measurement accuracy. Cooling SQUIDs amidst terrestrial magnetism have led to the design of a structure suitable for field use, where the design was prioritized with wire filament technology in order to minimize flux trapping.

December 2013   Date of Issue: December 16, 2013

Superconductivity Web21

Published by International Superconductivity Technology Center
KSP, Kawasaki, Kanagawa 213-0012 Japan   Tel:+81-44-850-1612, Fax:+81-44-850-1613

The system developed has achieved 10.5 mT/s slew rate characteristics, equivalent to 10-times the slew rate compared to conventional JOGMEC systems. The maximum current that can be applied has improved by over 40-times. This compact practical system is shown in Figure 2. The receiver system has a battery source that enables 17-hours of operation. Two attaché cases house the receiver system and magnetometer, including a 30 m-long cable that connects the receiver and magnetometer, which combined weigh a total of only 25.6 kg. Liquid nitrogen can be sustained for 17 hours if kept still and has been confirmed as offering more than required 8 hours of successful field operations, which includes its transportation.
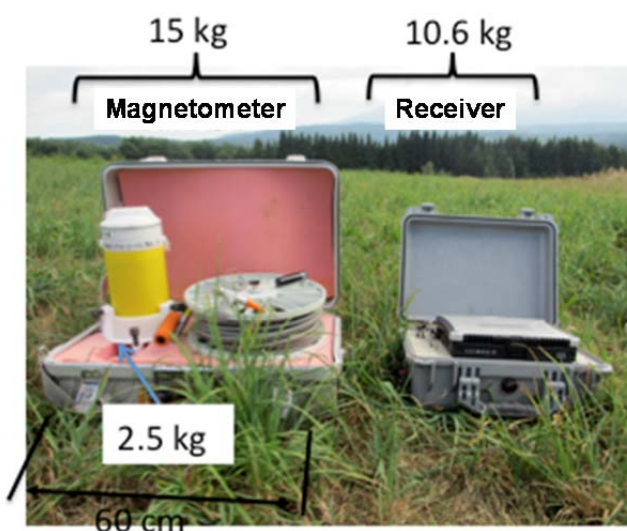

Fig. 2   System outline

Figure 3 shows the comparison between the analyses of testing trials of the distribution of underground resistivity structures measured in Akita. These results have proven that the system developed was able to analyze resistivity structures with greater resolution than systems utilizing induction coils and conventional systems employed by JOGMEC. The near-surface resistivity is greater, and here, the magnetic field attenuates rapidly when the applied magnetic field is artificially shut down.   The induction coil and the system are both able to track the changes. A conventional system has insufficient slew rate and is therefore unable to respond to such changes. The induction coil reaches its detection limits at around an area 500m below the surface, resulting in greater uncertainty of measured resistivity structures. The system developed is clearly able to respond to increases in specific resistivity, overcoming the deficiencies of a conventional system. The reason behind such deficiencies is thought to be due to a disruption of measurements caused by an induced current generated within the system, attributed to the shutdown of the artificial magnetic field. Induced currents generated within a conventional system are not an impediment to analyzing areas exhibiting relatively lower specific resistivity, thereby allowing them to be effectively employed in the field. However, conventional systems are still predicted to influence the analysis of specific resistivity distributions measured in areas having high specific resistivity. The system developed here is expected to benefit measurements in areas where specific resistivity is high. Its high slew rate characteristics and the suppression of induced currents allow the system greater sensitivities and enable a continuous analysis of resistivity structures measurements 1km below the surface.

December 2013   Date of Issue: December 16, 2013

Superconductivity Web21

Published by International Superconductivity Technology Center
KSP, Kawasaki, Kanagawa 213-0012 Japan   Tel:+81-44-850-1612, Fax:+81-44-850-1613
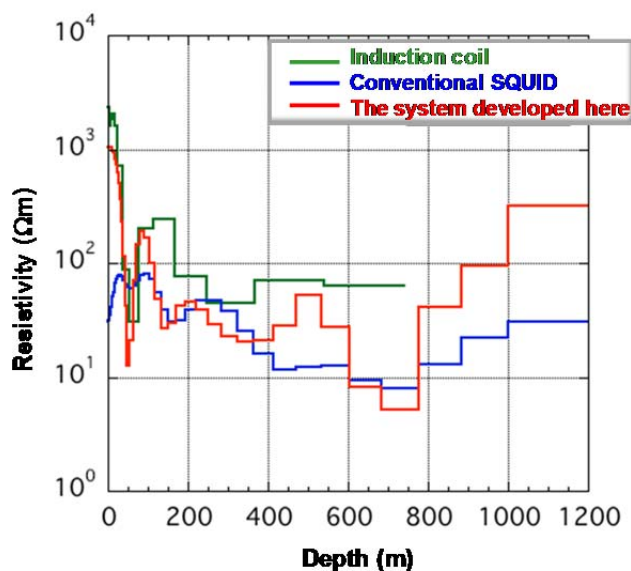
Fig. 3   A comparison between the analysis of sub-surface resistivity structures

Final tests in Australia have analyzed 2D-like resistivity structures, produced by analyzing the data measured every 100m. The system even proved to be satisfactory when operating in environmental surface temperatures exceeding 50℃, providing precise measurements of the depth of low specific resistivity layer, including graphite located close to the surface. Additionally, the system was able to capture strata deeper than boring surveys, which are presumed to be rich in copper and iron. These findings clearly illustrate the significant advantages afforded by the TEM method, providing data from deep underground strata and its practical use in future exploration is highly anticipated.

Top of Superconductivity Web21

Feature Article: SQUID Applications · Medical Applications
- Compact DC and Rotating-sample Magnetometers Utilizing HTS-SQUID

Keiji Tsukada, Professor
Division of Industrial Innovation Sciences
Graduate School of Natural Sciences and Technology
Okayama University

A magnetometer is the fundamental measurement system widely utilized to evaluate the magnetic characteristics of materials. The most common system comprises of a normal-conducting pickup coil measuring material characteristics using a normal-conducting magnet. In particular, industrial uses of this system include evaluating the characteristics of materials that for example exhibit large magnetic susceptibilities. On the other hand, highly sensitive magnetometers utilize low temperature superconducting (LTS) SQUIDs are employed in fundamental physical and chemical research applications to investigate very weak magnetic characteristics of materials such as paramagnetism and diamagnetism. Our R&D has advanced under JST's S-Innovation program. Herewith, the author introduces the development of a novel system offering the sensitivity characteristics equivalent to low temperature superconducting (LTS) SQUIDs, but more compact in design. The research employed a high temperature superconducting (HTS) SQUID developed by ISTEC.

There are basically two types of measurement systems that have been developed. One is the DC magnetometer (Figure 1), which measures variations in magnetic field strengths by oscillating a sample in an increasing DC magnetic field. Another is the rotating-sample magnetometer (Figure 2). Here, the sample to be measured is rotated under a permanent magnet. Measurements using the DC magnetometer entail oscillating a sample on the normal-conducting pickup coil located between electromagnets, and the pickup coil then transmits this signal to the SQUID input coil. In this case, there are 1/f noise characteristics issues associated with HTS-SQUIDs operating at low frequencies. High frequency measurements are therefore necessary to improve sensitivities. However, since mechanical oscillations are limited in vibration speed, the location between the pickup coil and sample required optimization. Enhancements to this have led to the generation of harmonic waves producing high oscillation frequencies signals that are 2 or 3 times greater, and thus able to realize a system with lower noise characteristics. This has enabled the system to not only evaluate basic magnetic characteristics, but also has led to a new application able to measure the materials' moisture content using the diamagnetic characteristics of water in a compound, which exhibits complex magnetic properties. Biochemical studies require prompt analysis of many samples. For this purpose, the author's group has developed the rotating-sample magnetometer. Here, the magnetic characteristics of several samples can be measured simultaneously by placing them onto a rotating disc. This method can easily adapt to increasing rotational speeds and therefore, higher SN ratios become feasible by signal processing ever-increasing numbers of signals. In particular, the novel method by which the system is able to rotate the pickup coil enables measurements of magnetization relaxation phenomena to be observed after applied magnetic field is turned off. Also, improved sensitivities and magnetic response time measurements have enabled the weak magnetization relaxation phenomenon of water to be analyzed.

December 2013   Date of Issue: December 15, 2013

Superconductivity Web21

Published by International Superconductivity Technology Center
KSP, Kawasaki, Kanagawa 213-0012 Japan   Tel:+81-44-850-1612, Fax:+81-44-850-1613

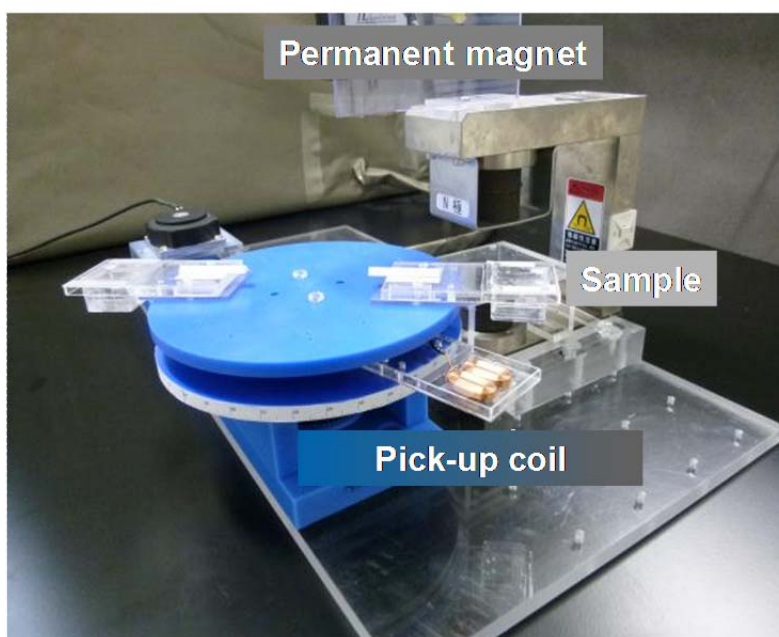Fig.1 A SQUID DC magnetometer (An iPhone is positioned for scale)

Fig. 2 SQUID rotating-sample magnetometer

As mentioned above, the systems evaluate magnetic characteristics using an HTS-SQUID, enabling moisture and magnetization relaxation phenomena to be observed, exploiting the weak diamagnetic characteristics of water in particular. Here, the author has highlighted one particular application. It is anticipated that many novel measurements will emerge in the future since improved sensitivities and system compactness.

Top of Superconductivity Web21

Feature Article: SQUID Applications •Medical Applications
- SQUIDs utilized in Non-destructive Testing of Power Facilities

Joji Kawano, Research Scientist (PhD)
Power System Engineering, Information System and Telecommunications Section.
Energia Economic and Technical Research Institute.
The Chugoku Electric Power Co., Inc.

A Superconducting Quantum Interference Device (SQUID) is a magnetic sensor exhibiting extremely high sensitivity. It is already utilized practically in the medical fields. SQUIDs permit non-invasive measurements in changes of micro-magnetic field signals generated by neuronal activities within the skull. For industrial applications, it is highly anticipated that SQUIDs could potentially be applicable in non-destructive testing applications, able to detect material cracks by measuring fluctuations in magnetic fields. High temperature superconducting SQUIDs are cooled using liquid nitrogen, producing a large temperature-cooling margin. This permits the cooling apparatus to be compact in their designs. Field trials exploring underground natural resources utilizing high temperature superconducting SQUIDs have been conducted over recent years [1].

In a collaborative study between the International Superconductivity Technology Center (ISTEC) and Energia Economic and Technical Research Institute of The Chugoku Electric Power Co., Inc., has led to advanced investigations and studies into non-destructive testing applications employing SQUIDs, and the groups have also explored the potential applicability of this technology in the progressive monitoring of possible degradation in power facilities.

The technology to assess the progression of possible degradation in facilities and machines is desirable in order to ascertain their life spans and to prevent and predict unexpected faults in advance, thereby effectively increasing the utilization of the plant. To address this, the author and his group have explored utilizing SQUIDs for diagnosing possible degradation in power facilities. The findings concluded that a SQUID could potentially be employed for non-destructive diagnosis of power facilities, including the power plant. Here, the author provides a summary of non-destructive testing and implementation contents of the research using SQUIDs, as well as the future direction of R&D.

1. The characteristics of SQUIDs in non-destructive testing

The fundamental principles of SQUIDs in non-destructive testing applications rely upon eddy currents testing (ECT) [2]. Although generic ECT without SQUIDs can be employed in high-speed diagnosis, the sensitivity of the sensor is inadequate. The sensor needs to be placed in close proximity to the sample to be measured in order to achieve high S/N ratios. Improving sensor sensitivity requires excitation at high frequencies. However, at high frequencies there are insufficient eddy currents generated from deep within thick conductors. Therefore, non-destructive tests employing ECT have been utilized to detect surface cracks around conductors. This study has progressed specifically focusing on the applicability of non-destructive testing applied to power facilities, utilizing the technology developed at ISTEC. The non-destructive sensor of the system is a high temperature superconducting SQUID. Figure 1 provides an outline of the sensor. The sample under test does not need to be in close proximity to the highly sensitive SQUID sensor. Additionally, since the sensitivity does not degrade at low frequencies, crack detection in deep areas of a thick metal conductor could be permissible [2]. These characteristics along with previous

measurements results pave the way for future crack detection in SUS and aluminum samples measuring up to 40mm-thick, and also providing potential diagnoses of cracks in ducts equipped with exterior finishes and containing thermal insulating materials as shown in Figure 2. The SQUID-based non-destructive testing system is currently undergoing performance evaluation trials involving detecting signals emanating from a crack made to a test specimen simulating the duct. The ultimate aim is for this system to be applicable to monitoring possible degradation at power facilities.
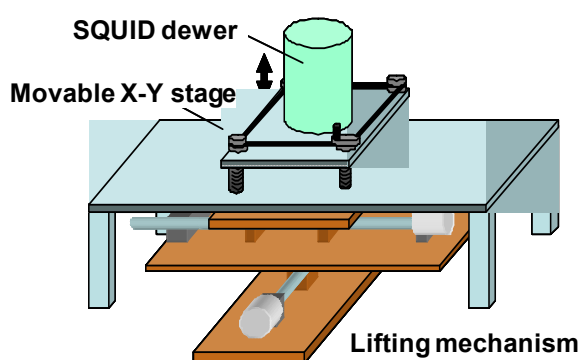
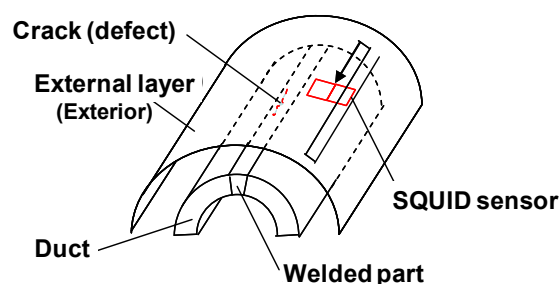Fig. 1 Outline of SQUID measurement system

Fig. 2 An example of a facility that can be diagnosed (Duct equipped with exterior parts)

2. Research Summary

(1) Study of a SQUID-based non-destructive testing system applicable to power facilities

A test sample simulating a duct equipped with exterior parts was fabricated as shown in Figure 2. The current specifications of the measurement system are limited to either a portable or planar-shape type system. The test piece has been fabricated by combining a 2mm-thick aluminum flat plate with a 5mm-thick insulator. It was designed to simulate and study crack growth in a typical metal duct covered with heat insulating materials. Figure 3 shows the location of a 26mm-thick test sample and the SQUID sensor. Figure 4 shows a 2D-image of the signal observed from the test. The aluminum plate is simulated as having a 20mm-long slit-shaped crack through its center, which is termed the defect layer. As the defect layer is positioned in a pre-defined area within the multilayer conductor, it is possible to vary the depth from the exterior parts to the simulated crack. The signal from the crack emanates from deep within the conductor, travelling through the aluminum plate and the resin board, which is designed to correspond to the exterior parts and insulating layer.
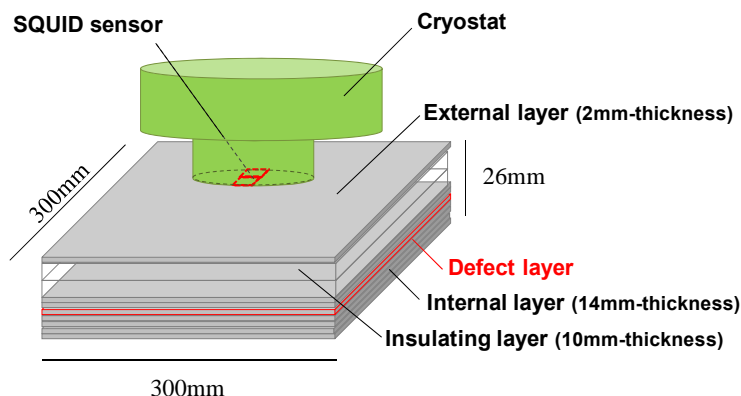
Fig. 3 Location between the test sample and the measurement system

December 2013   Date of Issue: December 15, 2013

Superconductivity Web21

Published by International Superconductivity Technology Center
KSP, Kawasaki,Kanagawa 213-0012 Japan   Tel:+81-44-850-1612, Fax:+81-44-850-1613
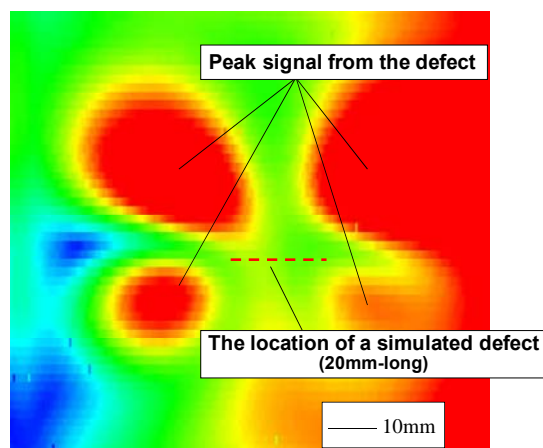
Fig. 4 2D-image of measured signal

(2) Prototype fabrication of new type system

The Energia Economic and Technical Research Institute is currently advancing research activities for the development of a new type of non-destructive detection system, aiming for non-destructive field applications employing SQUIDs. Vibrations of the system during measurements and the accompanying magnetic field changes affect the SQUIDs sensitivity. To address this, the SQUID sensor is affixed to the system as shown in Figure1 and measurements made by placing the sample under test on a movable X-Y stage. This method eliminates the effects of signal variations during measurements due to sensor vibrations. However, the system is limited to measuring samples that are flat and that can be accommodated by the portable apparatus. The fixed sensor approach methodology is therefore not applicable to field measurements involving large-scale structures, including those at power facilities.

The current research aims are to overcome above-mentioned issues. Measurement systems designed for field applications need to measure immovable 3-D shaped structural objects. Figure 5 shows an image of a SQUID-based measurement system designed for such field applications, which is currently planned for development. The SQUID sensor drive system would be housed in a magnetic shield with the pickup coil placed at the edge of a robotic arm. It is anticipated that this system will have minimal interferences due to environmental magnetic fields surrounding the power plant and substation as well as interference effects caused by the measurement target itself. The development of a SQUID sensor drive system for non-destructive testing allowing degradation diagnosis of 3-D structured objects will lead to significant progress in the realization of highly-sensitive apparatus able to be utilized in future power plant facilities.
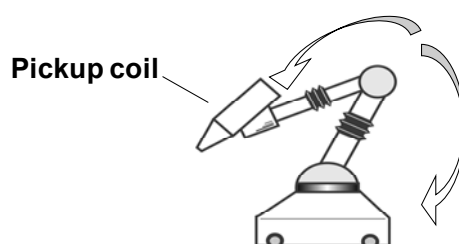

Fig. 5 A new type of non-destructive testing system (in middle of development, image)

Reference:

1. Eiichi Arai: Metals exploration system utilizing high temperature superconducting SQUID (Development of SQUITEM), Journal of Applied Physics

2. Joji Kawano: Non-destructive testing of cracks within magnetized materials using a high temperature superconducting SQUID sensor, Tokyo Institute of Technology, Doctorial Dissertation