Application of SUSTERA high-T_c SQUIDs at and under the ground

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Introduction

The biggest advantage of high-T_c SQUIDs as a magnetic sensor is that their ultrahigh sensitivity can be utilized by easy cooling with liquid nitrogen. By employing the thin-film multilayer technology, fabrication of high-T_c SQUID sensors with higher sensitivity or complex structures is expected. Since 2007, multilayer high-T_c SQUIDs using ramp-edge junctions have been developed at ISTEC.[1] Their high field sensitivity of 10 fT/Hz$^{1/2}$ in a white noise region[2] and high tolerance against application of magnetic field were demonstrated. A SQUID module for use with an external pickup coil which enables higher field tolerance and flexible system design was also developed using the same technology.[3] These features of the multilayer high-T_c SQUIDs are suitable for use at the ground without a magnetic shield. Actually a transient electromagnetic (TEM) system using a SQUID magnetometer with an integrated multi-turn input coil for exploration of metal resources was developed.[4] This TEM system with a rather high slew rate has been used in actual exploration. The high-T_c device and SQUID technologies of ISTEC were recently inherited by Superconducting Sensing Technology Research Association (SUSTERA). At SUSTERA we are now developing a variety of systems with multilayer high-T_c SQUID sensors. Here, recent results on the developments of a non-destructive evaluation (NDE) system for social infrastructure and a borehole TEM system for monitoring of an oil reservoir are presented.

NDE system for infrastructure

There are increasing demands for efficient maintenance of infrastructures such as bridges and tunnels in Japan, because many of them are older than fifty years. NDE is one of key technologies to detect deterioration of infrastructures effectively and save the maintenance cost. Eddy current testing (ECT) which is one of popular NDE techniques is mostly used to examine defects located near metallic material surface. Since high-T_c SQUID sensors have ultrahigh sensitivity even at low frequencies which lead to longer penetration depth of eddy current, detection of deep-lying or backside defects for steel plates used in infrastructures is expected by applying them to ECT.

We have been developing an NDE system for a steel plate deck under about 80 mm thick asphaltic pavement which is mostly used in bridges or highways in metropolitan areas. The above-mentioned SQUID module in a compact magnetic shield and a gradiometric pickup coil made of a commercial BSCCO tape were cooled by liquid nitrogen in a glass Dewar, and the cryostat, double-D type excitation coils, and the electronics including a lock-in amplifier were mounted on a hand cart. Prior to a field test, indoor experiments using 6 mm thick simulative test steel plates and a wooden cart moving on rails were performed.[5] Figure 1 shows the magnetic field pattern (real part) near a 50 mm long non-through hole at the backside which was obtained by repeating linear scan along the x-direction with shifts at 30 mm intervals along the y-direction. The excitation frequency was 20 Hz and the lift-off was 80 mm. Clear peaks with alternating polarity are observed near the edges of the non-through hole. Similar peaks were also observed at higher frequencies but large signals due to fluctuation of magnetization in the steel

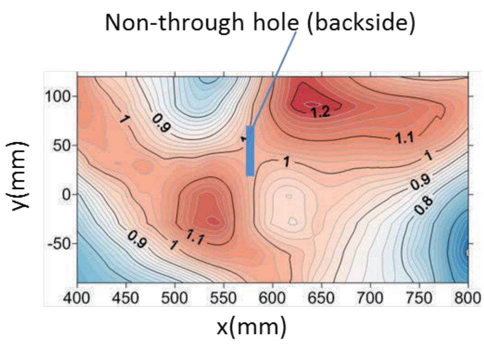

Fig. 1. Magnetic field pattern (real part) of a 6 mm thick steel plate with a backside defect.

plate also appeared. These results suggest that low-frequency ECT using SQUIDs is useful to detect defects in a steel plate deck such as cracks.

Borehole TEM system

Enhanced oil recovery (EOR) utilizing CO_2 is an epoch-making technology for efficient production of oil. To control EOR, it is important to improve accuracy of monitoring technique. The electromagnetic (EM) method is expected to improve the accuracy of monitoring of CO_2 behavior by combining with conventional seismograph and gravity methods. Application of SQUID sensor with frequency-independent ultrahigh sensitivity would enable us to perform cross-hole EM monitoring of a CO_2 injected oil stratum in steel-cased wells with the distance more than 1000 m. Fundamental technology to realize a cross-hole EM system has been developed. A SQUID receiver system consisting of three-component high-T_c SQUID sensors, a liquid-nitrogen Dewar, a SQUID-control circuit, and control and communication electronics which are implemented in an about 2 m long plastic outer vessel with pressure tightness over 70 MPa and temperature resistance below 200 °C has been developed. In a field test, this receiver system was put into a steel-cased well filled with water to the depth of 300 m, as shown in Fig. 2. Evaporated nitrogen gas was released through a plastic tube to the ground and SQUIDs were stably operated with a minimal temperature rise. Observation of magnetic signals generated by a transmitter coil placed in a distant well was successfully confirmed.[6] In another experiment, the receiver system was placed at the depth of 70 m in the same well, and observation of magnetic signals from a transmitter coil on the ground 800 m far from the well was also confirmed.

Fig. 2. SQUID receiver system put into a well at JOGMEC Kashiwazaki test field.

Conclusion

By using high-T_c device process at SUSTERA, multilayer SQUID sensors with high field sensitivity, high tolerance against external magnetic field, and complex design are routinely fabricated. These sensors have been applied to the systems for use at the ground such as metal exploration system and the NDE system for infrastructure, and the borehole TEM system for use under the ground. Although only the ground TEM system has been actually used, these technologies are expected to further extend to various practical systems in the near future.

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Keiichi Tanabe received his M.E. degree in 1979 and Ph.D. in 1988 in applied physics from The University of Tokyo. He worked for Nippon Telegraph and Telephone (Public) Corporation from 1979 to 1995. From 1987 to 1988, he was a visiting researcher at Cornell University, USA. He joined International Superconductivity Technology Center (ISTEC) in 1995. His recent interests include the development of high-T_c SQUID sensors and various application systems with these sensors. He served as the director general of Superconductivity Research Laboratory (SRL) of ISTEC from 2014 until the dissolution of ISTEC in 2016. His current position is the president of Superconducting Sensing Technology Research Association (SUSTERA) which stemmed from the electronic devices division of SRL.