Robot-arm-based Mobile HTS SQUID System for NDE of Structures

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Abstract. A robot-arm-based mobile HTS SQUID system was developed for NDE of fixed targets. To realize the system, active magnetic shielding technique using fluxgate as reference sensor for ambient field was applied to a cryocooler-based HTS SQUID gradiometer that was mounted on commercial robot-arm. In this technique, ambient field noise and pulse noise of 550 nT from robot were measured by the fluxgate near the SQUID, and then the fluxgate output was negatively fed back to generate compensation field around the SQUID and fluxgate. The noise from robot was reduced by a factor of about 20 and the shielding technique enabled the HTS SQUID to move in unshielded environment by the robot-arm without flux-trapping or unlocking at 10 mm/s. System noise measurement and inspection of hidden cracks in multi-layer composite-metal structure were demonstrated using the mobile SQUID-NDE system.

1. Introduction

Non-destructive evaluation (NDE) using HTS SQUID has been expected as a new inspection technique for conductive materials and structural parts, because of extremely high sensitivity in the low frequency range and capability of detecting deep-lying defects [1-3]. However, typical HTS SQUIDs, even with gradiometric geometries, become unstable when they are moved in ambient field because of occurrence of unlocking or flux-trapping due to existing magnetic noise. Therefore, the targets of SQUID-NDE are limited in relatively small movable materials and parts such as wires, boards and wheels [4-6]. In order to realize the inspection of larger immovable parts and structures such as aircraft wings and tanks, HTS SQUIDs should have mobility in the unshielded environment [7]. So far, we also successfully moved a HTS SQUID gradiometer by applying an active magnetic shielding (AMS) technique [8]. In this technique, the SQUID was used to measure environmental magnetic noise coupled to the SQUID during the motion and then the SQUID output was fed back to a feedback circuit with a compensation coil, which generated the cancellation field against the noise at the SQUID. For more practical inspection, a programmable robot-arm is suitable to move SQUID three-dimensionally. However, such robot-arms are generally composed of iron parts with strong residual fields, and radiate magnetic field by driving currents. Preliminary experiments, in which we measured the radiated magnetic noise from a commercial robot-arm by a fluxgate, revealed that maximum amplitude of the noise was about 1 μT at a point about 500 mm away from the arm tip. When the HTS SQUID gradiometer, based on YBa$_2$Cu$_3$O$_{7-x}$ (YBCO) and bicrystal SrTiO$_3$ (STO) substrate, was exposed in such noise, flux-trapping or unlocking of SQUID occurred, resulting in unstable operation, although the
SQUID was magnetically shielded by applying the feedback circuit using the SQUID output. Thus, we have been developing new AMS technique, employing the fluxgate, since it can be stably operated in such relative strong magnetic noise and it also has relatively high sensitivity. In the new technique, the fluxgate located near the SQUID is used to measure the environmental field and feed back its output to the feedback circuit with the compensation coil, which surrounds both the SQUID and fluxgate for noise cancellation around them. In this study, we applied the new AMS technique to the HTS SQUID gradiometer mounted on the robot-arm, to develop a mobile SQUID-NDE system in the unshielded environment. The system performances were investigated by measuring the noise during the motion of the SQUID, and by detection of hidden slots in multi-layer composite-metal structures.

2. Sensor-mobile SQUID-NDE system

2.1. System configuration

The mobile SQUID-NDE system developed in this study is composed of following: HTS SQUID gradiometer with electronics, coaxial pulse-tube cryocooler (PTC) with cryostat, robot-arm, excitation coil and function generator, compensation coil, band pass filter, fluxgate with electronics, lock-in amplifier, spectrum analyzer and personal computer (PC). The photograph and schematic diagram of the mobile system are shown in figure 1 (a) and (b), respectively. The HTS SQUID gradiometer is mounted in the PTC and cooled at about 70 K. The PTC is attached on the tip of the robot-arm. The fluxgate is attached on the wall of the cryostat about 40 mm away from the SQUID to measure the ambient field and generated noise from the robot-arm. The fluxgate output is fed back to the compensation coil through the band pass filter to generate compensation field against the noise. To induce eddy current under the sensing SQUID gradiometer, excitation coils are set at both sides of the SQUID. The SQUID output measured through the lock-in-amplifier and the coordinates of the robot-arm tip are recorded in the PC synchronously after each stepwise move of the robot-arm.

2.2. SQUID and cryocooler

The planer-type first-order HTS SQUID gradiometer has differential pickup coils, composed of two rectangular coils with an area of 3.6 mm x 2.9 mm and baseline of 3.6 mm [3, 8, 9]. A STO bicrystal substrate with mis-oriented angle of 30 degrees and YBCO thin film deposited on the substrate with thickness of 200 nm are used. The differential pick-up coils are connected directly to a SQUID ring.

Figure 1. Sensor-mobile SQUID-NDE system based on robot-arm.

(a) Photograph. (b) Schematic diagram of the system.
The magnetic flux white noise of the SQUID cooled at about 70 K by the PTC in unshielded environment was about 70 μΦ₀/Hz⁰.⁵ from 300 Hz to 4 kHz. The HTS-SQUID gradiometer was mounted in the cryostat integrated with the PTC so as to measure the field gradient of vertical component dBₓ/dx or dBᵧ/dy. The distance between the SQUID and robot arm tip is about 600 mm. The minimum lift-off distance between the SQUID and room-temperature is about 1 mm.

2.3. Active magnetic shielding

The major problem encountered when a HTS-SQUID is moved in an ambient field, the SQUID would be unlocked due to coupling of faster field change than the slew rate or flux-trapping in weak parts in the SQUID, e.g. Josephson junctions, resulting in the unstable operation. In addition, the robot-arm composed of iron parts and motors with large driving current radiates a pulse noise with the maximum amplitude of about 1 μT at the start of motion, which also causes the problem. To stabilize the SQUID operation even when exposed in such noisy situation, we have been developing the new AMS technique, which employs the feedback circuit composed of a fluxgate with electronics, compensation coil and band pass filter. The commercial fluxgate (Mag-03 MS 70) is employed since it can measure the magnetic field up to several tens μT and it also has high sensitivity of around 10 pT/Hz⁰.⁵ [10]. The fluxgate is set at a point about 40 mm away from the SQUID to measure the vertical component Bₓ in the ambient field around the SQUID. The square compensation coil (220 mm x 220 mm) is wound around the SQUID so that the compensation coil surrounds both the SQUID and fluxgate to generate cancellation field for both sensors. The turn number of compensation coil is 20. The centers of the compensation coil and the SQUID locates on the same axis. In this AMS technique, the ambient field noise is measured by the fluxgate and the amplified output from fluxgate electronics is filtered through the band pass filter with cut-off frequency between 0.1 Hz and 100 Hz because the flux noise couple to the SQUID during motion is supposed to be mainly composed of low-frequency noise and 60-Hz power line noise. Then, the filtered output is negatively fed back to the compensation coil and the flux noise coupled to the fluxgate and the SQUID is cancelled by the compensation flux. For NDE measurements, frequency range over 100 Hz should be used for excitation to avoid influence of the compensation flux.

2.4. Robot-arm

The robot-arm (Fanuc Robot LR Mate 200iB) is composed of iron parts and six motors, control unit and operation panel [11]. The robot-arm can be operated manually using the operation panel or automatically through software program running on the panel. The maximum velocity of the robot-arm motion is 2000 mm/s and the movable range is 700 mm in radius. The repeatable accuracy is ±0.04 mm and a load which can be attached on the robot arm is 5 kg.

2.5. Program

We developed a measurement and automatic robot-arm motion program for the mobile SQUID-NDE system. The program is developed using LabVIEW incorporating the commercial robot control soft CIMPLICITY™, through which the coordinates of the robot-arm tip can be read by the PC. The program is run on the PC, and is composed of following modules: the first module control the robot-arm to move the SQUID to the initial position for NDE measurement through the operation panel. And then the robot-arm is temporally stopped, thereafter the SQUID measures magnetic field from a specimen under test while applying an excitation field to the specimen. Next module controls the lock-in amplifier to obtain the SQUID output at the same frequency as the excitation frequency, and record the SQUID output in the PC. Simultaneously, the three-dimensional coordinates of the robot-arm tip is also recorded through CIMPLICITY. Then the robot-arm moves the SQUID stepwise, and the measurement procedure is repeated until reaching the final measurement position.

3. Noise measurements and results
We evaluated the noise performance of the system. The HTS SQUID gradiometer was set to measure the field gradient \( \frac{dB_z}{dy} \), and the fluxgate was set to measure \( B_z \) as shown in Figure 1 (b). The robot with the SQUID and fluxgate moved in the \( y \)-direction at 10 mm/s.

3.1. Measurement of robot noise by fluxgate

The AMS technique using the fluxgate should suppress the noises at both the SQUID and fluxgate. At first, the magnetic noise radiated from the robot-arm was measured using only fluxgate with and without the feedback circuit during the motion to study the effectiveness of the suppression. Figure 3 shows typical magnetic noise measured by the fluxgate with the feedback circuit off during the motion at 10 mm/s. In the figure, the motion started at 3.3 s. The sharp magnetic noise of the peak amplitude about 550 nT was measured after the start. This noise made the HTS SQUID operation unstable. Subsequently the oscillating magnetic noise was also observed. On the other hand, the magnetic noise with the feedback circuit on is also presented in the figure for comparison. With the AMS technique, the sharp magnetic noise is well suppressed to be about 1/18 at the peak amplitude, so is the oscillating noise, compared to those with the feedback circuit off. In the latter measurement, the SQUID kept stable operation throughout the motion. It is shown that the magnetic noise radiated from the robot-arm and the ambient field coupled to the SQUID and fluxgate are well suppressed by the AMS technique.

3.2. Noise measurement by SQUID

The system noise during the motion at 10 mm/s was also measured by the HTS SQUID gradiometer. For comparison, the system noises with the feedback circuit off and on before the motion were also measured. Figure 4 shows the noise of the moving SQUID with the feedback circuit on and those of fixed SQUID with the circuit off and on. Compared to the noise of the fixed SQUID with AMS off, the noise of the fixed SQUID with AMS on is almost the same level, while the peak noise at e.g. 28 Hz and 60 Hz are suppressed. Because the SQUID noise level is lower than the fluxgate noise, the white noise level of the SQUID is not changed with this AMS technique. On the other hand, since the amplitudes of the peak noises at 28 Hz and 60 Hz were enough high to be measured by both SQUID and fluxgate, these peak noises were suppressed. The white noise during the motion with the AMS on increased from 70 to 200 \( \mu \Phi_0/\text{Hz}^{1/2} \), while the peak noises were well suppressed as same as the fixed SQUID. It suggests that the magnetic white noise was originated in the robot-arm.

Figure 2. Magnetic noise from robot-arm measured by fluxgate with feedback circuit on or off when the robot arm was moving at 10 mm/s.

Figure 3. Magnetic flux noise during motion of SQUID at 10mm/sec (bold line). Noises of fixed SQUID with and without the AMS (thin line and dotted line) are shown together for comparison.
The peak noises over 100 Hz increased somewhat because it is supposed that the phase of the feedback voltage was varied through the band pass filter (0.1 – 100 Hz) and the feedback voltage was not negatively but positively fed back. Even though the white noise and some peak noises increased, both flux-trapping and unlocking did not occur. It is concluded that the SQUID-NDE system has enough potential for sensor-mobile inspection.

4. Demonstration

Finally, we demonstrated the system performance by inspecting deep-lying defects in thick and multi-layered composite-metal structures that imitated the configuration of multi-layered hydrogen fuel cell tanks [12]. The reason why the structures are adopted in this work is because it is difficult by conventional NDE techniques such as eddy current testing and ultrasonic testing to inspect such thick and complex structures.

4.1. Experimental setup

As specimen, multi-layered composite-aluminium boards were prepared. The structure was rectangular aluminium plate of 240 mm in length, 140 mm in width and 10 mm in thickness, which was covered by same size 3-mm thick carbon fibre reinforced plastic (CFRP) plate. An artificial slot was made in the centre of the surface on aluminium plate, which size was 20 mm in length, 2 mm in width, depth in 5 mm. The specimen was put under the SQUID-NDE system so that the longer direction of the slot was set to be parallel to the x-direction (see figure 1 (b)).

The mobile SQUID-NDE system employs the eddy current technique. A schematic sketch of the inspection principle of the multi-layered composite-Al structure is showed in figure 4. For detection of deep-lying slot, strong and focused excitation field in low frequency range is effective to induce large eddy current in deeper parts of the specimen. As the excitation coil, we used two electromagnets with C-shaped ferrite cores [8, 12]. The excitation coils were symmetrically set at each side of the HTS SQUID gradiometer while aligning the axis of the core perpendicular to the slot as shown in the figure.

4.2. Measurements and results

The inspection of the slot in the multi-layered specimen was carried out using the robot-arm-based SQUID-NDE system. At first, the slot was set to be located on the near surface of the Al plate. In this case, since the slot depth ranged in 0 – 5 mm in the Al plate, we adopted an excitation frequency at 400 Hz, at which the corresponding penetration depths into Al was calculated to be about 4 mm. The amplitude of the excitation field applied to the specimen was about 1 μT. Next, the Al plate was turned upside down so that the slot was located on the far surface. In this case, the slot depth ranged in 5-10 mm in the Al plate, we changed the excitation frequency at 70 Hz, which corresponded to the penetration depth of 10 mm. The cut-off frequency was set to be between 0.1 Hz to 10 Hz for the change.

In the settings of the specimens, the baseline of the gradiometer was aligned to be perpendicular to the longer direction of slot in both cases (see figure 4). This means that the current under the gradiometer mainly flows perpendicular to the slot direction, thus the distribution of field gradient due to a slot becomes the quadrupole-type signal in the vicinity of the slot [8, 12]. The SQUID was moved by the robot-arm in the x-y plane with 5-mm interval spaces toward both x and y direction at the velocity of 10 mm/s and the distribution of field gradient dBz/dy from the specimens were two-dimensionally scanned. The lift-off distance between the SQUID and CFRP surface was set to be about 3 mm.

The measurement result of the specimen with the slot on near surface excited by field at 400 Hz is shown in figure 5. A quadrupole signal was successfully observed around the slot even though right-hand peaks were superposed with the background. The background field gradient may be due to imperfection of the alignment of the SQUID and excitation coils and specimen. The same kind of quadrupole signal was also
detected in the case of the slot located on the far surface. These results indicates the superiority of the robot-arm-based SQUID-NDE system in the inspection of hidden defects in multi-layered structures.

5. Conclusions and perspective
We successfully developed the new SQUID-NDE system with robot-arm by applying the AMS technique using fluxgate, keeping lock of the SQUID during the motion at 10 mm/s. The deep-lying defects in the multi-layered plates imitating the structure of hydrogen fuel cell tank were well detected by the system. In the present system, the SQUID can be moved in only x-y plane due to that the setting direction of the PTC is limited. Therefore, we will develop a handy cryostat storing liquid nitrogen, which will enable the SQUID-NDE system to scan three-dimensionally.

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