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Robot-arm-based NDE of hydrogen fuel tank using a 3D-movable HTS-SQUID gradiometer

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Abstract. In this study, we constructed a robot-arm-based SQUID-NDE system utilizing a novel HTS-SQUID gradiometer with ramp-edge Josephson junctions for hydrogen fuel tank inspection, and developed an automatic 3D-scanning program. A cylindrical hydrogen fuel tank with a double-layer structure, in which a 3mm-thick Al liner was reinforced by a 3mm-thick carbon-fibre reinforced plastic (CFRP) cover, was prepared. The tank had a 10-mm-long through crack in the Al liner made by pressure cycle test. To inspect the tank using the SQUID-NDE system, we adopted a low-frequency eddy current technique that enables to excite deep part in the Al liner. By applying an excitation field of 7.5μT at 0.4 to 10 kHz to the tank from a double-D coil, the tank was scanned by the system while moving the HTS-SQUID gradiometer along curved surface of the tank in magnetically unshielded environment. Magnetic responses from the deep-lying crack in the tank were successfully detected by the system.

1. Introduction
Effectiveness and potential of non-destructive evaluation (NDE) using HTS-SQUIDs to detect tiny or deep-lying defects in metallic and composite materials and structures have been demonstrated mainly in laboratories and rarely in actual sites [1-4]. However, there seems to be some difficulties remained not perfectly unsolved such as the increase in 1/f noise arising from cooling of HTS-SQUIDs in unshielded environment including the Earth’s field (about 50 μT), and the occurrence of penetration and hopping of flux vortices when HTS-SQUIDs were moved in unshielded environment, resulting in the increase of 1/f noise also. So far, many researches were devoted to solve such problems [5-8]. Recently, S. Adachi and et. al. have developed novel HTS-dc-SQUID gradiometers using ramp-edge Josephson junctions (JJs) with multilayer structure of base-electrode of SmBa₂Cu₃O₇ (SmBCO) and counter-electrode of La₁₀Er₀.95Ba₁.95Cu₃O₇ (L₁ErBCO) [9]. Because the ramp-edge JJs can be located at arbitrary positions, the novel HTS-SQUID gradiometers have no grain boundary (GB) in their differential pickup coils, while conventional HTS-SQUID gradiometers with bicrystal GB JJs usually have large GBs in their pickup coils, where flux vortices has high mobility, which is caused, for example, by the field change due to motion or rotation of the gradiometer in unshielded environment. In addition, since the ramp-edge JJs are sandwiched by the base- and counter-electrodes with an angle of 30 degrees against the substrate plane, it has been shown that the occurrence of penetration of flux vortices in the ramp-edge JJs tends to be significantly less than the bicrystal JJs and step-edge JJs,
whose angles against their substrate planes are 90 degrees or near 90 degrees. These two features enable the novel HTS-SQUID gradiometers to be cooled and moved three-dimensionally (3D) in unshielded environment without the increase of the 1/f noise [10].

In this study, we constructed a practical robot-arm-based SQUID-NDE system utilizing the novel HTS-SQUID gradiometer for advanced materials and structures, which only SQUID-NDE technique can inspect well. We chose a cylindrical hydrogen fuel tank with thick multilayer structure as a subject, since conventional NDE techniques such as eddy current testing and ultrasonic testing can hardly be applied to detect deep-lying defects in the tank due to the structure. Detection of deep-lying crack in the tank using the SQUID-NDE system based on a low-frequency eddy current technique was demonstrated while moving the gradiometer three-dimensionally around curved surface of the cylindrical tank in unshielded environment.

2. SQUID-NDE system based on robot-arm for 3D-structure

For safety inspection of advanced materials and structures such as the hydrogen fuel tank with thick multilayer structure, we have selected the SQUID-NDE method based on the low-frequency eddy current technique [3, 10]. Additionally, for the whole body inspection of the cylindrical tank, the HTS-SQUID must be moved 3D around curved surface of the tank in unshielded environment while crossing the Earth’s field. Thus, we constructed the practical robot-arm-based SQUID-NDE system utilizing the novel HTS-SQUID gradiometer that has high stability for operation and motion in unshielded environment. The schematic diagram and photograph of the system is shown in Figure 1 (a) and (b), respectively. The system consists of the robot-arm (FANUC LR Mate 200iB) with a controller box and an operation panel, a compact FRP cryostat, the HTS-SQUID gradiometer, a SQUID electronics, a double-D excitation coil, a function generator, a lock-in amplifier, a spectrum analyzer and a PC. The robot-arm is a six-axis general-purpose automation robot composed of iron parts and six motors. The robot-arm can be controlled manually with the operation panel and automatically with robot program running on the panel. Through the controller box, the connected PC can control the robot program by a LabVIEW control software, and record the 3D coordinates of the robot-arm tip through the software CIMPLICITY. The movable extent and maximum velocity of the robot-arm are 700 mm in radius and 2000 mm/s, respectively. The repeatable accuracy is ±0.04 mm, while the attachable load is 5 kg. The HTS-SQUID gradiometer was mounted on a tip of a sapphire rod in the cryostat and cooled at about 78.3 K [10]. The FRP container in the cryostat is stuffed with high-polymer absorbent, which absorbs and maintains liquid nitrogen, for 3D motion and rotation. It maintains 200cc liquid nitrogen for 6 hours.

**Figure 1.** Robot-arm-based SQUID NDE system for 3D advanced structure. (a) Schematic diagram. (b) Photograph.
In this system, the HTS-SQUID gradiometer with ramp-edge JJs that have multilayer structures of base-electrode of SmBCO and counter-electrode of L1ErBCO was employed [9]. Because of its structure of 5μm-wide SQUID ring with the ramp-edge JJs and differential 3mm-by-3mm square pickup coils without long GB, the gradiometer can be cooled and operated without any magnetic shielding with the flux noise levels of about 10 μφ0/Hz1/2 in the white noise region and about 120 μφ0/Hz1/2 at 1 Hz in flux locked loop (FLL) operation with DC bias, where φ0 is the flux quantum. The baseline length of the gradiometer is 3 mm. Since the gradiometer can be operated stably until it was exposed in an AC magnetic field of 1.5 mT at 100 Hz, it was successfully moved and rotated in unshielded environment by the robot-arm at a velocity of at least 10 mm/s without increase of 1/f noise [10]. The flux noise spectra of the gradiometer cooled and operated in a moderate magnetically shielded room (shown as the dotted line) and moved in the horizontal plane by the robot-arm in unshielded environment (solid line) are shown in Figure 2. The operating condition in the unshielded environment was similar to that in the reference [11]. Although the 1/f noise increased due to the slow motion in the Earth’s field during the motion and some peak noise appeared at power line 60 Hz and its harmonies, the white noise levels were the same. After the motion, it was confirmed that the 1/f noise of the gradiometer at 1 Hz got back to the original value 120 μφ0/Hz1/2 while keeping the FLL in closed mode. On the bottom plane of the cryostat, a 30mm-diameter double-D excitation coil was set to electromagnetically excite the subject under test at relatively low frequency. The cryostat is moved around the subject and the gradiometer measures the distribution of the field gradient of the secondary inductive field from the excited subject. With the program developed using LabVIEW that runs in the PC, the SQUID output is recorded through the lock-in amplifier in the PC with the corresponding 3D coordinates of the SQUID integrated with the robot-arm, to make a contour map of the field gradient in post process. From the contour map, a defective area in the subject is localized.

3. Experimental setup and measurements

3.1. Hydrogen fuel tank with a crack in Al liner

As a sample, the hydrogen fuel tank with a crack was prepared. The tank is composed of an ellipsoidal dome-shaped cylindrical Al liner wrapped in a CFRP cover with total a length of 420 mm and outer diameter of 168 mm as shown in Figure 3. The thicknesses of the Al liner and the CFRP cover are 3 mm each. The tank was damaged by a pressure cycle test using oil filled in the tank. It has a crack in the Al liner, which extended roughly parallel to the circumference of the tank that was cut along to the axis of the tank. The length of the crack on the inner surface of the Al liner was about 10 mm (See the inset in Figure 3). From the oil leak, it was confirmed that the crack penetrated through the Al liner during the cycle test, although the aperture of the crack on the outer surface of the Al liner was invisible because of the CFRP cover. No damage was observed in the CFRP cover.

![Figure 2. Flux noise spectra of the HTS-SQUID gradiometer cooled and operated in a moderate magnetically shielded room (MSR) (dotted line) and cooled and moved by robot-arm in unshielded environment (solid line).](image-url)
3.2. Measurements using the robot-arm-based SQUID-NDE system

We inspected the defected tank from the outside of the tank to detect the internal crack in the Al liner using the robot-arm-based SQUID-NDE system. At first, we made a robot program to move the SQUID on the robot-arm so that the SQUID moves 3D around the curved surface of the cylindrical tank smoothly and continuously while keeping the lift-off distance between the SQUID and the outer surface of the tank at 5 mm, and tilting the SQUID plane to be normal to the radial direction of the tank as shown in Figure 4. We employed the raster scanning method for the track of the SQUID motion as shown in the same figure. The SQUID was moved at 2 mm/s in the y-w curved surface, where the y direction was parallel to the axis of the tank, and w was the rotation angle around the axis. In the measurement, the measured extend in the y and the w directions were 52 mm and 60 degrees, and the sampling intervals were 4 mm and 2.8 degrees, respectively. During the move of the SQUID gradiometer, the baseline of the gradiometer was kept parallel to the y direction. Consequently, the SQUID gradiometer measured the field gradient of \( \frac{dB_r}{dy} \), where \( B_r \) is the radial field component that was normal to the surface of the tank. During the SQUID motion, the double-D excitation coil, which was set under the gradiometer, moved together with the gradiometer, while generating an AC excitation field to induce an eddy current in the Al liner and a secondary magnetic field from the liner. The excitation frequency from 400 Hz to 10 kHz was used in this work. The corresponding penetration depth into Al in the frequency region ranges from about 4.1 mm to 0.8 mm. The amplitude of the excitation field was constant at 7.5 \( \mu \)T at the centre of the single-D coil. Before the measurement, the position of the excitation coil was carefully adjusted so that the minimum leakage flux coupled to the SQUID gradiometer. In this experiment, since the resistivity of the CFRP cover must be considerably higher than that of the Al liner, it is thought that the induced field from the cover was negligibly weak. The total time to finish one measurement at one frequency was about 10 minutes. Further improvement of the robot program and LabVIEW program will shorten the consuming time, since the gradiometer can be moved at much faster velocity with the FLL operation in closed mode.

4. Results and discussions

The measurement result with the excitation frequency at 1 kHz is shown in Figure 5 (a). The contour map shows the distribution of the SQUID output voltage, which is proportional to the field gradient \( \frac{dB_r}{dy} \) around the tank surface (the y-w surface in Figure 4). In the figure, the horizontal axis is the position y, and the vertical axis is the rotation angle w. Around the position of the internal crack, there is a stronger quadruple signal that was surrounded by a weaker wider quadruple signal. The eight-pole-like signal around the crack is due to the double-D excitation coil, which was set near the outer surface of the tank. The outer quadruple peaks are originated in the eddy current induced mainly by

![Figure 3. Hydrogen fuel tank damaged by pressure cycle test. There is a 10mm-long through crack on the inner surface of the Al liner of the cut tank as shown in the inset.](image)

![Figure 4. Schematic illustration of measurement setup. The HTS-SQUID gradiometer measured the field gradient \( \frac{dB_r}{dy} \) around the curved surface of the tank, which was excited by the double-D excitation coil.](image)
the circle of the double-D coil, while the inner quadruple peaks are originated in the eddy current induced mainly by the straight parts of the coil, where 2 times stronger current flowed than the circle. The relationship between the absolute peak-to-peak amplitude of the inner quadruple signal and the excitation frequency was extracted as shown in Figure 5 (b). The upper horizontal axis shows the corresponding penetration depth $\delta$ into Al while the lower shows the excitation frequency. The signal amplitude has a maximum value at around 1 kHz, where the penetration depth is about 2.6 mm roughly identical to the thickness of the Al liner. This peak frequency should be determined by the shape of the crack, whose aperture must be wider on the inner surface of the Al liner than on the outer surface, and the distribution of the induced current, whose amplitude increases with the frequency but penetration depth decreases with the frequency by contrast.

5. Conclusions

We demonstrated that the robot-arm-based SQUID-NDE system based on the novel HTS-SQUID gradiometer with ramp-edge JJs and the low-frequency eddy current technique enabled us to inspect the 3D advanced structure such as the cylindrical hydrogen fuel tank, and to detect the internal deep-lying crack, which other conventional technique must have difficulties to detect. The robot and LabVIEW programs will be improved for more practical use to shorten the inspection time.

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Figure 5. Experimental results. (a) Iso-field contour map of SQUID output voltage at 1 kHz. (b) Signal peak-to-peak amplitude due to the crack vs. excitation frequency.
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