Three-dimensional (3D) SQUID-NDE system with freely movable operation

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Abstract. A practical robotic three-dimensional (3D) SQUID-NDE system was developed for the first time. A previously developed travelling SQUID-NDE [1], i.e., one that is not stationary but rather the SQUID sensor itself moves or scans along the surface of the object, was improved for 3D access by utilizing an articulated-type (6-axes) robot used in industry. The unique feature of this system is that the SQUID sensor, which is a newly developed ‘quasi’ third-order SQUID gradiometer, can freely move in 3D during evaluation of an object. A computer-aided geometrical interpolation method combined with a laser CCD displacement sensor was also developed to teach the robot about the 3D (xyz) coordinates of the surface of the evaluated object. Without applying any external magnetic field or current, the robotic 3D SQUID-NDE system successfully detected artificial damage in a cylindrical object.

1. Introduction

Demand for practical nondestructive evaluation (NDE) of large-scale objects has prompted applications of Superconducting Quantum Interference Devices (SQUID). Such applications require a SQUID sensor that can freely move three-dimensionally (3D) against a fixed large curved-face and/or complex-shaped object. The signal-to-noise ratio of a SQUID sensor is adversely affected, however, by environmental noise as well as by magnetic noise generated from a servomotor of a mechanically driven propulsion system, for example. Spurious signals frequently appear when a SQUID sensor moves in a non-uniform magnetic field, such as in the ambient environment. With conventional SQUID-NDE systems, therefore, an object is moved under a rigidly fixed SQUID sensor, which is covered by magnetic shielding to suppress undesirable magnetic disturbances. To realize a SQUID sensor that can freely move in the ambient environment, SQUID-based eddy current systems have been designed and tested by independent groups [2-4]. We recently developed a practical system called a traveling SQUID-NDE [1] for evaluating large objects without applying a current or magnetic field to the objects under study. In this traveling system, the key technology to allow the SQUID sensor to move is a newly developed SQUID gradiometer that can “travel” across the surface of an object [5]. However, there is relatively little data on the development of a SQUID-NDE system that can inspect an object in 3D. For a SQUID sensor to manipulate in 3D, the space between the SQUID sensor and the surface of the object must be kept constant, and the SQUID sensor must be tilted with respect to the vertical direction of the surface of the object. A prototype 5-axes robot
SQUID-NDE system was reported [6], although it can not be applied to 3D measurements because one degree-of-freedom in the robot movement is restricted. In this study, a 3D SQUID-NDE system was developed in which a conventional articulated-type (6-axes) robot used in industry is utilized to manipulate the SQUID sensor in 3D to travel across an object. A numerical surface reconstruction procedure that can handle a vast number of points was also developed to teach the robotic system the measurement positions automatically. The capability of the robotic 3D SQUID-NDE system was tested by using it to evaluate artificial damage of a cylindrical object.

2. Construction of a 3D SQUID-NDE system

Three key technologies were developed for the robotic 3D SQUID-NDE system: a ‘quasi’ third-order gradiometer, a numerical interpolation procedure to reconstruct curved surfaces, and an articulated-type (6-axes) robot used as the SQUID sensor manipulator.

2.1. ‘Quasi’ third-order low-Tc SQUID gradiometer

A SQUID sensor that can freely move in 3D is based on a ‘pseudo’ third-order gradiometer fabricated by a multilayer process of low-Tc SQUIDs. The gradiometer contains a DC-SQUID made of Nb/Al-AlOx/Nb Josephson tunneling junctions combined with two coplanar concentric second-order derivative coils connected in series and positioned counterclockwise to each other. As schematically shown in Fig.1, the pickup coil loops are a figure-8-shaped series connection that is geometrically one stroke and are connected to the SQUID body magnetically by using a flux transformer-type coupling. (An example of “geometrically one stroke” is writing a ‘figure-8’ by hand, namely, the figure can be drawn in a single stroke without having to add a line or curve to finish the figure.) Previous comparison between simulations and experimental data [7] showed that the SQUID gradiometer is a “quasi” third-order gradiometer. Based on the parameters of the gradiometer [5], such as mutual inductance, pick-up coil inductance, and on the system noise spectra [8], the magnetic flux density resolution of the robotic 3D SQUID-NDE system is 4.5 nT /Hz^{1/2}cm^3. The fabrication processes for this gradiometer are basically the same as those reported elsewhere [9]. The flux noise spectra measured at an electric power substation by using this gradiometer confirmed that the gradiometer operated normally (a) in the immediate vicinity of the 450MVA transformer, (b) directly under (5.9m) a 275kV transmission line (840A, 50Hz) adjacent to a 275kV electric gas circuit breaker (GCB), and (c) inside a constant-voltage constant-frequency (CVCF) room at the substation building [7]. For practical applications, a high-Tc SQUID is superior because it does not require liquid He, and is therefore easier to handle and more convenient than a low-Tc SQUID. However, a multilayer fabrication process for high-Tc SQUIDs has not been established for achieving flux transformer-type coupling and for achieving a series connection of the pickup coil loop [10].

2.2. Numerical interpolation procedure to reconstruct a curved surface

In the robotic 3D SQUID-NDE system, the robotic system is taught the 3D coordinates (i.e., x, y, and z) without requiring CAD data of the evaluated object as follows. Initially, while maintaining a constant height level above the surface of an object, a laser CCD displacement sensor (LK-502, Keyence, Japan) scans the shape of the object within the evaluation area in the x-y lattice (Fig. 2). After this initial scan, a vertical vector perpendicular to the surface of the object is calculated.
numerically based on the data acquired by the displacement sensor. The simplest method to calculate the vertical vector is nearest neighbour (NN) averaging, although NN averaging is not sufficiently accurate, possibly due to incomplete surface reconstruction of the evaluated object [7]. Thus, the numerical surface reconstruction procedure used by the robotic 3D SQUID-NDE system was improved by using computational-geometry oriented techniques [11], such as B-spline interpolation. Comparison of the B-spline interpolation for reconstructing the surface of an object and experimental data obtained by the displacement sensor revealed that the error of the surface reconstruction is less than 0.1mm. Details of numerical surface reconstruction by B-spline interpolation are reported elsewhere [7].

**Figure 2.** Photograph of laser CCD displacement sensor equipped with a 6-axes robot to measure the xyz-coordinates of an object. The shape of the object in an x-y lattice was measured using the laser CCD displacement sensor while maintaining a constant height level above the surface.

2.3. Articulated-type (6-axes) robot used as a SQUID sensor manipulator

In the robotic 3D SQUID-NDE system, a conventional articulated-type (6-axes) robot uses the numerically obtained 3D coordinates to manipulate the SQUID sensor in 3D to travel across an object. Figure 3 shows a photograph of the robotic 3D SQUID-NDE system. The system is comprised of a ‘quasi’ third-order SQUID gradiometer, electronics for SQUID operation, liquid He cryostat (h300mm x φ100mm), aluminum extension (800mm-long), 6-axes robot, and PC. Prior to evaluating an object by using the SQUID sensor in the SQUID-NDE, the displacement sensor used for reconstructing the surface of the evaluation object is removed and the SQUID sensor is connected as the end-effector of the robot. Table 1 summarizes the specifications of the articulated-type robot (M-16iB, FUNUC) used in the robotic 3D SQUID-NDE system.

**Figure 3.** Photograph of the robotic 3D SQUID-NDE system developed incorporating an articulated-type (6-axes) robot. Prior to the SQUID measurements, the vertical direction is continuously calculated using a numerical surface reconstruction procedure (see section 2.2).

### Table 1. Specifications of articulated-type robot (M-16iB, FUNUC) for 3D SQUID-NDE.

| Item                        | Specifications   |
|-----------------------------|------------------|
| Controlled axes             | 6 axes           |
| Maximum load capacity       | 20 kg            |
| Allowable load inertia      | 0.25 kgm$^2$     |
| Drive method                | Electric servo drive |
| Repeatability               | ±0.08 mm         |
| Maximum speed               | 2,000 mm/s       |
3. Evaluation of a cylindrical object

Applicability of the robotic 3D SQUID-NDE was examined by using the system to detect artificial damage in a cylindrical steel tube (see Fig. 2). The test samples were commercially available STK400 steel tubes with 508mm outer diameter, 500mm length, and 6.4mm thickness. The STK400 was a carbon steel tube typically used for general structural purposes with an average tensile strength of 400N/mm². The measurements were done without applying an external magnetic field or current. A small ferrite magnet (~10mg, 5mm-long) attached under the tube was used as dummy damage. Along with the dummy magnet, a slit (70mm-long x 1mm-wide x 1.5mm-deep) was made as an artificial flaw at the top of the surface of the tube (indicated by oval) by using a tube cutter. The 3D SQUID image obtained from a surface scan of the tube (Fig. 4) shows that the detected signals corresponded to the artificial flaw and dummy magnet, although unidentified minor signals were also detected. The detected SQUID signal was 40 $\Phi_0$ (where $\Phi_0$ is magnetic flux quantum defined as $2.07 \times 10^{-15}$Wb) at the position of the magnet (arrow). Interestingly, SQUID signals corresponded to the position of the weldment as well, as shown in the inset. These data clearly indicate that the 3D SQUID-NDE system has a sufficiently good signal-to-noise ratio.

In conclusion, a practical robotic 3D SQUID-NDE system was developed for large-scale applications. To demonstrate its capability, the system was used to detect artificial damage in a carbon steel (STK400) tube. The system was found capable of 3D NDE measurements with sufficiently good signal-to-noise ratio. Widespread practical use of this robotic 3D SQUID-NDE system is expected.

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