Multipoint measurements of a Pipe Using HTS-SQUID and Magnetostriction-Based Ultrasonic Guided Wave

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Abstract. This paper describes study on remote inspection technology for pipes by using magnetostriction-based ultrasonic guided wave and high temperature superconductor (HTS) superconducting quantum interference device (SQUID) gradiometer. Magnetized nickel plates were adhered on an aluminium pipe sample, in order to use them as magnetostriction-based guided wave transceivers. A pair of 10mm-wide nickel plate with different angle arrangement were used to transceive uniformly distributed guided waves at all angles. A field coil was wound around one set of the nickel plates as a transmitter, while the other was used as a receiver. T (0, 1) mode guided wave was generated on the pipe by supplying a burst sine wave current of one cycle at several tens kHz to the coil. Multipoint measurements of the T (0, 1) mode guided waves around the pipe’s circumference were carried out by setting the HTS-SQUID gradiometer above the receiver with lift-off of about 9 mm and rotating the pipe for 360 degrees. Signal of reflected wave from an artificial slit on the sample was well detected. We simulated the distribution of the guided wave propagating on the pipe with the slit using an ultrasonic simulator and compared the distribution with the experiment result. The guided wave signal distributions including the defect signal obtained by experiment and simulation agreed well.

1. Introduction

Recently, ultrasonic guided wave testing have been applied to long distance structures in chemical plants and electric power facilities [1-3]. Although various modes exist in the ultrasonic guided waves, T (0, 1) mode guided wave, in which group velocity is constant and mode conversion does not occur, is often used for pipes in the testing [4]. We have studied remote non-contact guided wave testing technology combining magnetostriction-based T (0, 1) mode guided waves [5] and high-temperature superconductor (HTS) SQUID gradiometer [6-8]. Typical HTS-SQUID has two to three orders of magnitude higher sensitivity than conventional semiconductor sensors and the sensitivity ranges from DC to MHz, including bandwidth of the guided wave from 10 to 100 kHz. In the magnetostriction-based guided wave testing using the conventional induction coil, since guided waves are transmitted and received by the coil wound around the entire circumference of the pipe, axial position of defect in a pipe can be detected. However, it is difficult to localize its circumferential position (see Figure 1 (a)). On the other hand, since a HTS-SQUID is used as a very high sensitive point sensor with small pickup area, by replacing the receiver coil of the conventional method with HTS-SQUID, it is possible to measure the magnetic signal distribution derived from the guided waves around the pipe circumference (see Figure 1 (b)). In this study, we applied our HTS-SQUID-based guided wave testing system to an aluminium
pipe with an artificial slit and performed multipoint measurements of the T (0, 1) mode guided waves by rotating the pipe for 360 degrees. We analysed signal distribution of the guided waves including reflected wave from the slit using an ultrasonic simulator and compared simulated result with the experimental results.

2. Sample and measurement system

2.1. Sample
An aluminium pipe of 3.0 mm in thickness, 90 mm in outer diameter, and 1500 mm in length was used. At positions of 300 mm and 600 mm away from the left end of the pipe, a pair of nickel plates of 0.2 mm in thickness, 10 mm in width and 283 mm in length were wound around circumference of the pipe and firmly adhered by resin bond. In order to disperse edge effect in magnetization of the nickel plates and generate the guided wave as uniform as possible on the entire circumference, the magnetized nickel plates were adhered as one set with shifting angles as illustrated in the left of Figure 2. Face-to-face parts of the nickel plates were aligned at 0 and 180 degrees. Before the adhesion, the nickel plates were magnetized using a solenoid coil, inside which the plates were exposed by a DC magnetic field of about 10 kA/m toward its longitudinal direction. The nickel plates at 300 mm away from the left end of the pipe was wound with a field coil of 30 turn using Litz wire to reduce the skin effect and used as a transmitter of the T (0, 1) mode guided waves. The other nickel plates at 600 mm was used to receive the T (0, 1) mode guided waves by converting the vibration to magnetic signals oscillating toward pipe’s axial direction. Firstly, the sample without defect was measured using after-mentioned HTS-SQUID-based guided wave testing system. Secondary, a circumferential slit of 40 mm in width, 5 mm in the length was fabricated at 0 degree and 1050 mm away from the left end (see Figure 2) and measured in the same manner as the first measurement.

2.2. HTS-SQUID-based guided wave testing system
We have constructed the HTS-SQUID-based guided wave testing system for pipes based on the magnetostrictive effects and a HTS-SQUID gradiometer. Figure 2 shows the schematic diagram of the system. The function generator supplies burst wave voltage to the power amplifier, in order to feed burst wave current into the transmitter to generate magnetic field on the nickel plates of the transmitter on the pipe. The T (0, 1) mode guided wave is generated by the magnetostrictive effect in the nickel plates on the entire circumference of the pipe, and it propagates through the pipe’s wall. The guided wave is converted into a magnetic signal by the inverse magnetostrictive effect of the receiver and measured by the HTS-SQUID gradiometer located above the plate. The HTS-SQUID gradiometer with ramp-edge Josephson junctions and a planar first-order differential pickup coil made by SUSTERA was used in this work [9]. The gradiometer was cooled at about 73.5 K by a coaxial pulse-tube cryocooler [10]. Flux noise level of the SQUID operated in the normal environment using a commercial SQUID electronics

![Figure 1. Schematic image of conventional magnetostriction-based T (0, 1) mode guided wave testing on a pipe. (a) Magnetostrictive sensors (MsS). (b) High temperature superconductor superconducting quantum interference device (HTS-SQUID).](image-url)
is about 15 $\mu\Phi_0/\text{Hz}^{1/2}$ in a range from 10 Hz to 30 kHz. The voltage from the SQUID electronics is averaged 256 times to increase signal-to-noise ratio (SNR) and measured by a digital oscilloscope.

3. Experiments and results

3.1. Multipoint measurements around pipe’s circumference

One cycle burst currents of $0.3A_{pp}$ @ 60 kHz were repeatedly applied to the coil of the transmitter to generate the T (0, 1) mode guided waves on the sample pipe. Magnetic signals due to the guided waves above the nickel plates were measured by the HTS-SQUID gradiometer, which was set to measure $dB_x/dz$ with a lift-off distance of about 9 mm. At first, the sample without defect was measured. Based on this method, multipoint measurement was performed while rotating the pipe from -180 to +180 degrees at every 45 degrees. Next, a penetrating slit of 40 mm in width in the circumferential direction and 5 mm in length was artificially made on the pipe at 0 degree and 1050 mm from the left end of the pipe. The same multipoint measurement was performed on the defected sample pipe.

Figure 3 shows the magnetic flux signals measured at 0 degree of the pipe. In all the results, a signal was measured from around 0 µs. It is thought that the electrical signals probably originated from the supplied current to the transmitter were mixed in the measuring equipment. Magnetic signals labelled as “T1” and “T2” were measured from about 97 µs and 290 µs, respectively. These signals are the incident wave and reflected wave from the left edge, which propagated toward the both sides of the transmitter after their generation. In the case of the pipe with the slit, a signal “D1” was measured from about 390 µs, which was a reflected wave from the slit. The magnetic signals “T1”, “T2”, and “D1” were measured at all angles, although the waveforms of “D1” were different at angles. The experimentally obtained group velocity for the guided wave is 3102 mm/ms in aluminum.

Figure 4 (a), and (b) show contour maps of the measured signals, which was draw on a plane of the time and angle, using all measured waveforms around the entire circumference of the pipe without and with the slit. The magnetic signals of the incident waves and reflected waves from the left end of the pipe were detected from about 97 µs and 290 µs, respectively. The peak amplitudes of these waves were approximately uniform at all angles. In Figure 4 (b), the reflected wave from the slit was measured from 390-430 µs at entire angles. The distribution of the reflection wave from the slit looks approximately symmetric about 0 degree, where the centre of the slit located. Next, we analysed the distribution of the measured guided waves on the sample pipe using the 2D ultrasonic simulator SWAN21 [11].

In the bottom, estimated waveform, which will be measured by the HTS-SQUID gradiometer above the receiving nickel plates on the sample pipe, is shown with measured times of T (0, 1) mode guided waves propagating at velocity of about 3100 mm/ms on aluminium.
3.2. Simulation of guided wave on plate model with slit

We performed simulation, which was aimed to emulate multipoint measurement on the pipe with the slit using ultrasonic propagation analysis simulator SWAN 21. The contour maps obtained in the experiments were projection of the three dimensional distribution of the magnetic signals above and around the pipe’s circumference into a two-dimensional map. Here, we used the simulator SWAN21 to analyze ultrasonic guided wave on a two-dimensional thickless plate model. We note that the difference between the experiment and this simulation is that the edges (or boundaries) at ±180 degrees on the pipe were connected, thus the guided wave can go through the edges from +180 to -180, and vice versa in the experiment, while the edges at ±180 are not connected and the guided waves reflect at the both edges in the simulation. To emulate the T (0, 1) mode guided wave in the plate model, we used SH guided waves, which are transverse waves and have the group velocity of about 3100 mm/ms in aluminum, which is the same as the T (0, 1) mode guided waves on the pipe [3]. Figure 5 shows the schematic illustration of the simulation model with the virtually opened sample pipe. The model in the simulation aims to emulate the experiments with the sample pipe opened at ±180 degrees (the position of the slit is 0 degree). The width and the length of the model are 283 mm and 1200 mm, corresponding to the distance from the transmitter to the right end of the pipe. The probe position was determined due to limit that the probe can only set on the boundary of the model. A measurement line for the guided wave was set at 300 mm away from the left end of the model.

Figure 6 shows the contour map obtained by the simulation. Since the simulation model is made with the length of 1200 mm, the reflected wave "T2" from the left end of the pipe does not appear. The magnetic signals as “T1” and “D1” were measured from about 104 µs and 395 µs, respectively. The time differences between the experiments and the simulation were about 7 µs and 8 µs for “T1” and “D1”, respectively. Although the generation times of the signals “T1” and “D1” obtained by the simulation slightly differs from those obtained by the experiments, the distribution of the simulated guided waves well agreed with that in experiment. The slight delay is due to the probe and receiver in the simulation do not have width, while the transmitter and the receiver in the experiment has the widths of 20 mm in total. Comparing the defect signal distributions of Figure 4 (b) and Figure 6, they resemble well especially around 400 µs, where the SNR in the experimental result is good. These results shows that the defect signal distribution can be accurately obtained by multipoint measurements using the HTS-SQUID gradiometer. The axial position and the center position of the defect should be localized from the symmetric distribution. In order to analyze defect signal distribution in more detail, it is necessary to increase the SNR of the experiment result. The SNR is partly due to the lift-off distance of about 9 mm, which is limited due to leakage flux from the magnetized nickel plates below the gradiometer. We are trying to suppress this flux utilizing active magnetic shield technique, which is described in ref. [12].

Figure 3. Magnetic flux signals measured at 0 degree of the pipe.
(a) Pipe without slit. (b) Pipe with slit.
4. Conclusion

In this study, we performed the multipoint measurements around the aluminium pipe without and with the slit using the magnetostriction-based T (0, 1) mode guided waves and HTS-SQUID-based system. The pair of 10 mm-wide nickel plates with the different angle arrangement resulted in the uniform distributions of the incident waves and reflected waves from the left pipe edge at all angles. The reflection wave due to the artificially-made slit was measured at all angles with different waveforms.
and the distribution of the defect signal was axisymmetric. The incident and defect signal distributions obtained by the experiment and the 2D simulation agreed well. These result demonstrates that defect signal distribution around pipe can be accurately obtained by multipoint measurement using HTS-SQUID.

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