Defect Detection of Pipes using Guided Wave and HTS-SQUID

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Abstract. In this paper, we investigated ultrasonic guided wave measurements on aluminium pipes with defects using high temperature superconducting (HTS) SQUID gradiometer and magnetostrictive sensors (MsS), which utilized pre-magnetized nickel thin plates. One of the pipes was provided with an axial defect, and the other was provided with a circumferential defect. The MsSs were used by adhering them on circumferences of the pipes to generate ultrasonic guided waves and to receive the waves by converting them into the magnetic signals, which were measured by the HTS-SQUID gradiometer. Guided wave measurements using the MsSs and the gradiometer demonstrated that magnetic signals of about 3.3 mΦ₀ due to reflected waves from both the defects were successfully detected. Reflected wave signals of about 1.4 mΦ₀ from thin nickel plates of the MsS on the pipes were also detected.

1. Introduction

In recent years, in order to maintain the health of pipes in social infrastructures, importance of non-destructive inspection (NDI) is increasing. Ultrasonic guided wave testing is mainly used for NDI of long pipelines, for example, in chemical plants [1-5]. Ultrasonic guided waves used for this inspection are mainly T (0, 1) mode and L (0, 2) mode guided waves. The T (0, 1) mode guided wave is easy to handle because it has no velocity dispersion and its group velocity is constant in a material. Therefore, the T (0, 1) mode guided waves are used as transmission/reception signals. Magnetostrictive method and piezoelectric method are often used in the ultrasonic guided wave testing. In such case, it is necessary to bring the ultrasonic transducers into contact with target pipe. When the pipe is wrapped with insulating materials, it is necessary to peel off the materials at a measuring part. It leads to cost and time.

From these backgrounds, we have introduced high temperature superconductor (HTS) superconducting quantum interference device (SQUID) as a receiver in the magnetostrictive method. HTS-SQUIDs have extremely high sensitivity in a frequency range from DC to a few MHz [6], which includes the frequency range from 10 to 100 kHz of the ultrasonic guided wave. Furthermore, it has the very low intrinsic magnetic noise of about 10 μΦ₀/Hz½ (Φ₀ is the flux quantum). From these characteristics, we thought that a vibration due to the guided wave in a pipe can be measured without contact by a HTS SQUID while converting the vibration into a magnetic signal based on the inverse magnetostrictive effect of the receiving part of the magnetostrictive method. Therefore, we have studied the novel NDI technique to measure magnetic signals due to ultrasonic guided waves on an aluminium pipe combining a HTS-SQUID gradiometer and the magnetostrictive method, which utilizes magnetized
nickel to convert vibration into magnetic signal and vice versa. In the previous study [7, 8], ultrasonic guided waves generated in a target pipe by the magnetostrictive method were successfully detected by the HTS-SQUID gradiometer above a magnetized nickel wound and adhered around the circumference of the pipe. In this study, we demonstrated detection of reflected wave signals due to defects in axial and circumferential directions in sample aluminium pipes using the HTS-SQUID gradiometer and the magnetostrictive method.

2. Samples and measurement system

2.1. Samples
As samples, aluminium pipes of 3.9 mm in thickness, 60 mm in outer diameter, and 2000 mm in length were used. At each position of 200 mm, 750 mm and 1300 mm away from the left end of each pipe, a thin nickel plate of 0.2 mm in thickness, 20 mm in width and 157 mm in length and previously magnetized toward its longitudinal direction by a strong permanent magnet, was wound around the circumference of the pipe and firmly adhered by resin bond. The thin nickel plate at 200 mm was wound with a coil of 25 turn and 60 mm in diameter and was used as a transmitter of T (0, 1) mode guided wave. When ac current of 1 A_pp was fed to the coil, we measured a generated magnetic field of about 0.5 mT just below the coil using a Hall sensor. Another magnetized thin nickel plate of the same dimension at 750 mm was used to receive an ultrasonic guided wave and convert it to a magnetic signal. One of the pipes (labelled as #1) was provided with a penetrating defect of 100 mm in length in the axial direction and 2 mm in width, which was made at 975 mm from the left end of the pipe. The other pipe (labelled as #2) was provided with a penetrating defect of 50 mm in width in the circumferential direction and 2 mm in length, which was made at 1030 mm from the left end. Schematic figures of the defects and pipes are shown in Figure 3 (b) and Figure 4 (b). We noticed that residual magnetization leaked from the magnetized nickels at each face-to-face part of them. When the SQUID gradiometer was brought close to the parts, the SQUID gradiometer could not be locked properly with a commercial flux locked loop circuit. We defined the parts of the nickels was at 0 degree in the circumference of each pipe (see Figures 2-4). In this definition, the centres of the defects were set at 180 degrees.

2.2. SQUID NDI system
We constructed the SQUID NDI system for pipe based on the magnetostrictive effects using the HTS-SQUID gradiometer. Figure 1 shows the schematic diagram of the system. Details of the system are described in refs. [7, 8]. As a sensor, the HTS-SQUID gradiometer with ramp-edge Josephson junctions, which has a planar differential pickup coil that consists of two 1 mm x 1 mm square coils, was used. In the measurement system, the gradiometer was cooled at about 69 K by a coaxial pulse-tube cryocooler [9]. Flux noise level of the HTS-SQUID gradiometer is about 10-15 μΦ_0/Hz^1/2 in a range from 10 Hz to 30 kHz. One cycle of sine wave voltage at 30 kHz from a function generator was amplified into current of 1 A_pp by a power amplifier, and the current was repeatedly applied to the coil of the transmitter with a period of 0.33 s to generate an excitation magnetic field. The T (0, 1) mode ultrasonic guided waves were generated by magnetostrictive effect in the thin nickel plate, and they propagated the opposites directions (+x and −x) through the pipe’s wall. When the guided wave reached the thin nickel plate of the receiver, the vibration due to the guided wave was converted into a magnetic signal by the inverse magnetostrictive effect. The magnetic signal was measured by the HTS-SQUID gradiometer, which was placed above the center of the receiver. The HTS-SQUID gradiometer was set to measure dB/dx above the magnetized nickel thin plate on the sample pipe with a lift-off distance of about 2 mm. Output voltage of the SQUID electronics passed through a high-pass filter (HPF) with cut-off frequency of about 1 kHz and then was amplified using a low-noise amplifier with a gain of 20 dB and noise level of 4 nV/Hz^1/2. The voltage from the SQUID electronics were measured by a digital oscilloscope and the data were averaged 256 times on the oscilloscope.

3. Experiments and results

3.1. Experiment on aluminum pipe without defect
We investigated effects of defects on magnetic signals due to ultrasonic guided waves using the aluminium pipes #1 and #2. Using the pipe #1 with defect, we measured magnetic signals due to the T (0, 1) mode ultrasonic guided wave with the HTS-SQUID gradiometer, which was set above the pipe at 90 degrees (see figure 2 (b)). Figure 2 (a) shows the measurement result. At about 180 µs, a magnetic signal of about 9.1 m∅₀ in peak-peak amplitude labelled as “a” was measured. At about 305 µs, a magnetic signal of about 8.3 m∅₀ labelled as “b” with reversed phase to “a” was measured. After the signal “b” was generated, a series of smaller signals including “c” than the signals “a” and “b” was measured at 440 µs, 560 µs, and 660 µs. The group velocity of a T (0, 1) mode torsional wave propagating in aluminium pipe is known to be about 3100 mm/ms. From the distance between the transmitter and the receiver and the guided wave velocity, start timing of the magnetic signal due to the incident wave measured by the SQUID gradiometer is calculated to be 177 µs, which agrees well with the timing of “a”. The transmitter generated the guided waves propagating to both sides of the transmitter. One wave propagated toward the +x direction and generated the magnetic signal “a” at 177 µs. Meanwhile, the other wave propagated toward the -x direction, and then reflected at the left end of the pipe with the reversed phase, then propagated toward the +x direction to generate a magnetic signal at the thin nickel plate. Start timing of this signal measured by the gradiometer is calculated to be 306 µs, which agrees well with the timing of “b”. After the signal “b” was generated, the small signal “c” was measured. In the previous research, it was reported that the guided waves were partly reflected at a nickel thin plate adhered around the circumference of the pipe, and the reflected waves were detected by means of a magnetostrictive sensor [10]. It means that thickening of the pipe’s wall due to the adhesion of the nickel plate, as well as defects such as thinning of a pipe’s wall, makes a guided wave reflect. Some portion of the wave reflected firstly at the left end of the pipe was reflected again at the nickel plate, and it was again reflected at the left end and some portion of this wave transmitted through the nickel plate to arrive at the nickel plate of the receiver, as shown in figure 2 (b). Start timing of this transmitted wave measured by the gradiometer is calculated to be 435 µs, which agrees well with the timing of “c”. It is considered that the small signals after “c” at 560 µs and 660 µs were originated in the guided waves repeated reflected at the thin nickel plates and also at the ends of the pipe and transmitted through the plates. From these results, in the guided wave measurement using the HTS-SQUID gradiometer, it was found that this method can not only measure the reflected waves from the ends of the pipe but also the reflected waves from the thin nickel plate.

3.2. Experiments on aluminium pipes with defects

3.2.1 In case of axial defect
The penetrating defect toward the axial direction was produced at 975 mm in the x direction and at 180 degrees of the pipe #1, and guided wave measurement was performed under the same conditions as in the experiment in 3.1. Figure 3 (a) shows the measurement result and figure 3 (b) shows the estimated propagation paths of signals “d”, “e”, “e’”, and “f”. As shown in figure 3 (a), the magnetic signal “d” at 169 µs and the signal “e” at 302 µs with reversed phase to “d” were the same incident and reflected
waves as “a” and “b” in figure 2 (a). Comparing the signal “e” in figure 3 (a) with the signal “b” in figure 2 (a), the signal “e” was a slightly wider in time. Comparing the amplitude ratio of the signals “a” over “b” with that of “d” over “e”, the latter is a bit larger. We considered this reason as follows: the incident wave that generated “d” propagated toward the +x direction, and reflect at the axial defect, and the phase of the wave was reversed. This reflected wave is labelled as “e’” in figure 3 (b). From the propagation path of signal “e” and “e’”, they should superpose at around 314 µs. Because the timings of “e” and “e’” are slightly different and some parts of the signals cancelled each other, the signal ratio “d”/“e” become larger than that of “a”/“b”. The signal of about 3.3 mΦ0 labelled as “f”, which was not observed on the same pipe without the defect as shown in figure 2 (a), was measured at 440 µs. The signal “f” was considered to be originated in the wave that generated the signal “e”, which propagated toward the +x direction through the receiver after first reflection at the left end, and reflected by the defect with the reversed phase and returned to the receiver. The start timing of the signal “f” measured by the gradiometer was calculated to be 446 µs, which agrees well with the timing of “f”.

3.2.2 In case of circumferential defect

The penetrating defect toward the circumferential direction was produced at 1030 mm in the x direction and at 180 degrees of the pipe #2, and guided wave measurement was performed under the same conditions as 3.1 and 3.2.1. Figure 4 (a) shows the measurement result and figure 4 (b) shows the estimated propagation paths of the signals “g”, “h”, “i” and “j”. Regarding the signals “g” and “h”, the results were similar to those in figure 2 (a) and figure 3(a). However, just after the signal “h” was measured, a signal of about 4.2 mΦ0 labelled as “i” was measured by the gradiometer. The propagation path of the wave that generated this signal was the same as that of “e’” in figure 3 (a). However, compared with the position of the axial defect, the position of the circumference defect was 35 mm further away from the nickel plate of the receiver. The start timing of the signal “i” is calculated to be 347 µs. Therefore, the signal “i” was measured separately from the signal “h”. The propagation path of the wave that generated the signal “i” was almost the same as the signal “f”. The start timing of “j” is calculated to be 379 µs, which agrees well with the timing of “j”, so “j” was also originated in the wave reflected at the defect. As shown in figure 4 (a), continuous signal was generated after the signal “i”. As shown in ref. [11], it is supposed that standing waves was probably generated due to the relation that the wavelength of the guide wave (about 100 mm at 30 kHz) was twice as long as the length of the defect (about 50 mm in width).

![Figure 2](image1.png)

**Figure 2.** (a) Measurement result of the sample #1 without defect. (b) Propagation paths of the signals “a”, “b” and “c”.

![Figure 3](image2.png)

**Figure 3.** (a) Measurement result of the sample #1 with axial defect. (b) Propagation paths of signals “d”, “e”, “e’”, and “f”.

![Graph](image3.png)
4. Conclusion

In this paper, the SQUID NDI system for pipes based on ultrasonic guided wave testing was firstly applied to the aluminium pipe #1 without defect. The magnetic signals due to the T (0, 1) mode guided waves at about 3100 mm/ms, which included the incident wave and the reflected waves from the sample end and the thin nickel plate of the transmitter, were measured. In the measurements using the aluminium pipe #1 and #2 with the axial and the circumferential defects respectively, the magnetic signals due to the reflected waves from the defects were successfully measured. The standing wave was observed in the latter case and the occurrence of the wave is probably due to the relationship that the wavelength of the guided waves was twice longer than the length of the defect. At the present time, we are developing a new method to generate T (0, 1) mode guided waves without contact to a sample pipe, which does not require magnetized thin nickel plates.

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