

HTS-SQUID NDE Technique for Pipes based on Ultrasonic Guided Wave

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Abstract. This article describes research on the novel high-temperature superconductor (HTS) superconducting quantum interference device (SQUID) non-destructive evaluation (NDE) technique for metallic pipes based on ultrasonic guided waves. We constructed HTS-SQUID NDE system for pipes based on ultrasonic guided waves, which were generated and received by means of the magnetostrictive effects. Using the system, we measured magnetic signals due to T (0, 1) mode ultrasonic guided waves that transmitted on aluminium pipe, and investigated influences of measurement parameters to the magnetic signals, such as direction of a HTS-SQUID gradiometer, lift-off distance, and intensity and frequency of input current fed to a magnetostrictive transmitter. With the gradiometer oriented parallel to the pipe axis, more than 10 times larger signals were measured compared with that oriented perpendicular to the pipe axis. Magnetic signals measured by the gradiometer were inverse proportional to the power of the lift-off distance, and proportional to the intensity of the input current up to 1 A_{pp}. Relation between the frequency of the input current and the measured signal was shown and discussed.

1. Introduction

Ultrasonic guided waves refer to elastic waves in ultrasonic frequencies (10 – 100 kHz) that propagate in a bounded medium such as pipes, plates, etc., parallel to the plane of its boundary [1-4]. Properties of the guided waves are very complex. In pipes, the guided waves exist in three different wave modes: longitudinal (L), torsional (T), and flexural (F). Furthermore, each mode has parameters on circumferential direction n and wall thickness direction m , i.e., L (0, m), T (n , m), and F (n , m). In spite of such complexities, with adequate selection and proper control of wave mode and frequency, the ultrasonic guided waves are excellent for globally inspecting a large area of a structure from sensor location [4-8]. In long-range ultrasonic guided wave inspection, defects in pipes are inspected by detecting waves that reflected from the defects. Generally, piezoelectric and magnetostrictive transducers are used in such inspection. In recent years, T (0, 1) and L (0, 2) mode ultrasonic guided waves are mainly used, and especially T (0, 1) mode is easy to handle because it has no velocity dispersion and its group velocity is constant in a material, e.g., about 3.1 km/s in aluminium. Magnetostrictive methods, which utilize magnetostrictive and inverse magnetostrictive effects, has advantage over piezoelectric transducers in that no direct physical contact to pipe surface is required in case that the pipe is ferromagnetic material, and its conversion efficiency from electrical energy to mechanical energy and vice versa is sufficiently good for practical use.



To generate T (0, 1) mode ultrasonic guided waves in ferromagnetic and non-ferromagnetic pipes, magnetostrictive sensors (MsSs) combining a magnetized nickel plate and an induction coil are used [8]. In this case, the thin nickel plate is pre-magnetized toward its longitudinal direction and adhered firmly on a circumference of the pipe surface. The nickel generates ultrasonic guided waves when it is exposed in a magnetic field in the frequency range of 10-100 kHz from the coil, and the waves propagate in the pipe. The MsS can also receive the guided waves, because magnetization in the nickel plate changes when the nickel is deformed (or strained) by the propagated guided waves, leading to generate a magnetic field. The MsS picks up the magnetic field by the induction coil. We have been developing a novel non-destructive evaluation (NDE) technique using a high-temperature superconductor (HTS) superconducting quantum interference device (SQUID) to measure the magnetic field from the magnetized nickel in place of an induction coil [9]. Since the HTS-SQUIDs are superior to induction coil with regard to magnetic field sensitivity, it is expected that smaller defects in pipes will be detected by using the HTS-SQUIDs. In this study, we investigated the novel SQUID NDE technique for pipes while changing parameters in measurements of magnetic signals due to T (0, 1) mode ultrasonic guided waves. Direction of the HTS-SQUID gradiometer, lift-off distance between the SQUID and the pipe surface, and intensity and frequency of input current fed to an MsS on an aluminium pipe were changed in the measurements.

2. SQUID NDE system for pipe inspection

We constructed the HTS-SQUID NDE system for pipes utilizing the MsS as ultrasonic guided wave transmitter and receiver. The schematic diagram of the system including the aluminium sample pipe with two MsSs is shown in Figure 1. Details of the system are described in ref. [9]. A HTS-SQUID gradiometer based on ramp-edge Josephson junctions with two 1mm x 1mm differentially-connected pickup coils was used. The gradiometer was cooled at 69 K by a coaxial pulse tube cryocooler in a cryostat. The flux white noise level of the gradiometer was about 10-15 $\mu\Phi_0/\text{Hz}^{1/2}$ from 10 to 30 kHz. Due to the specification of a commercial SQUID electronics, the flux sensitivity above 30 kHz slightly decreased with increase in the frequency. The single sine wave voltage at a few tens kHz from the function generator is amplified and converted into single sine wave current to generate an excitation field at one MsS, which transmits T (0, 1) mode ultrasonic guided waves on the pipe toward +x and -x

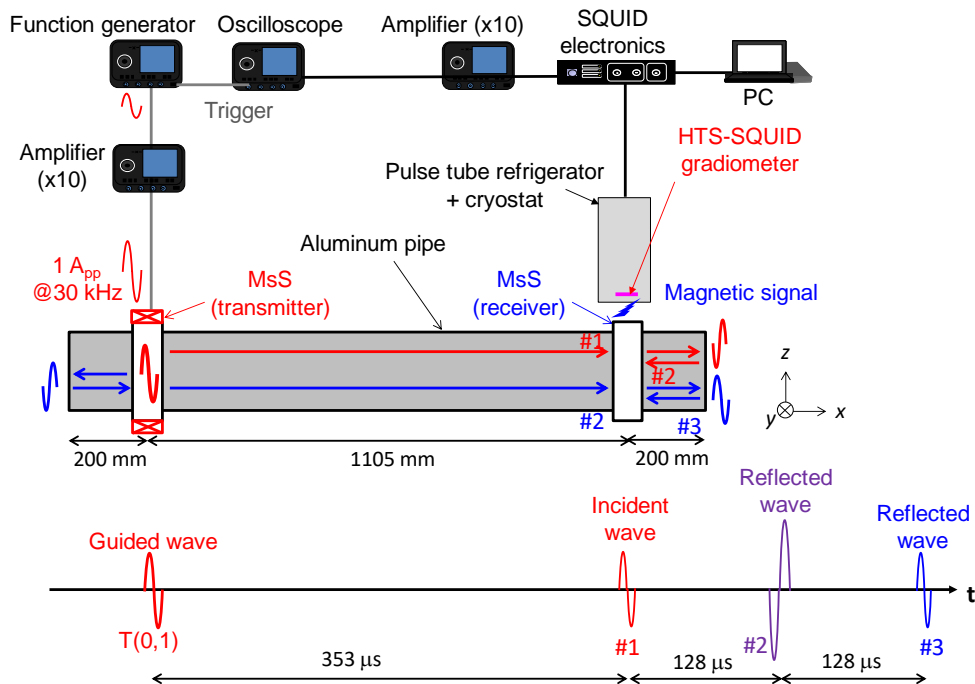


Figure 1. Schematic diagram of HTS-SQUID NDE system for pipes. Length of pipe, positions of MsSs, estimated pathways and time of flight of T (0, 1) mode guided waves are also shown.

directions. The wound coil around the nickel thin plate had 20 turns and the diameter of 50 mm. Under the gradiometer, the other MsS without an induction coil receives and converts the guided waves into magnetic field, which is measured by the gradiometer. Basically, it was set to measure dB_z/dx with a lift-off of about 2 mm and above the pipe axis, although the direction of the gradiometer was occasionally changed in the following measurements. The dimension of the sample aluminium pipe is 3.9 mm in thickness, 60 mm in outer diameter, and 2000 mm in length. Two previously magnetized thin nickel plates of 0.2 mm in thickness, 20 mm in width and 204 mm in length were wound around the circumferences of the pipe and firmly adhered as parts of the MsSs. The positions of the MsS on the pipe are depicted in figure 1. Since the group velocity of T (0, 1) mode guided wave in aluminium is about 3130 mm/ms, time of flight of the transmitted guided waves from transmitter to the receiver can be calculated from the distance between them. The estimated pathways and time of flight of the transmitted waves toward $+x$ and $-x$ directions are also illustrated in figure 1. It is known that the guided waves reflect both at pipe's ends and at defects, including the change of the thickness of the pipe, with reversed phase [10].

3. Experiments and results

In the first experiment, T (0, 1) mode guided waves were generated with the current input of 1 A_{pp} at 30 kHz to the MsS transmitter, and magnetic signals, whose component was dB_z/dx , due to the guided waves at the MsS receiver were measured by the SQUID gradiometer. With the current input of 1 A_{pp}, the applied field was about 0.5 mT_{pp} near the transmitter. Figure 2 shows the experimental result. At 0 μ s, the guided waves were generated and started to propagate toward $+x$ and $-x$ directions. Measured single sine signals at around 350 μ s, 480 μ s, and 600 μ s, which are labelled as #1, #2 and #3, are the incident wave, the reflected wave, in which reflected wave at the left end and reflected wave at the right end were superposed on each other, and the twice reflected wave at the left and the right ends in turn.

Next, we changed the measurement parameters. At first, the direction of the gradiometer was changed to measure dB_z/dy with the same lift-off of 2 mm. The same measurement as above was done and the measurement result is also shown in figure 2, with offset of about -12 m Φ_0 for visibility. Apparently, in the waveform of dB_z/dy , there are the same kinds of signals due to the guided waves, however, the amplitudes of the signals are 20-30 times smaller than those in the waveform of dB_z/dx . The results indicates that the magnetic field generated by means of the inverse magnetostrictive effect of the wound nickel thin plate produces the magnetic field oscillating parallel to the x direction. It can be said that the field change should be axisymmetric. Therefore, the flux coupled to the gradiometer to measure dB_z/dy was cancelled by the differential pickup coil of the gradiometer.

Secondary, the lift-off was changed from 2mm to 20 mm while adopting the same measurement procedure. Relationship between signal peak-peak amplitude of #1 and lift-off distance is shown in figure 3. The amplitude decreased inversely proportional to square of the lift-off distance.

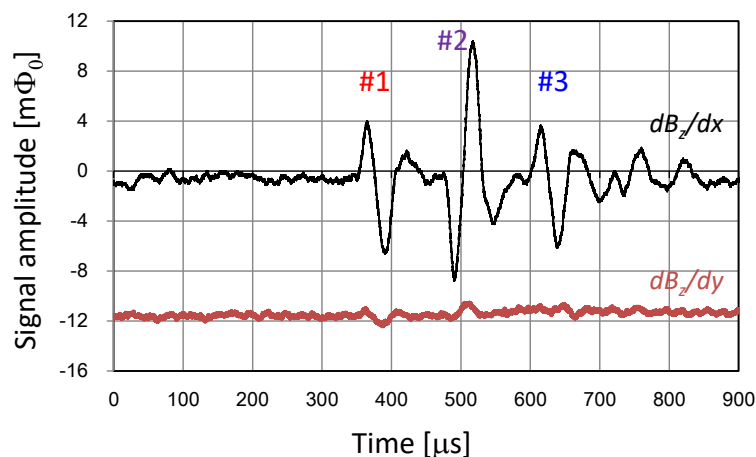


Figure 2. Measurement results of dB_z/dx (upper) and dB_z/dy (lower) above MsS receiver (magnetized nickel thin plate) by HTS-SQUID gradiometer. Offset of about -12 m Φ_0 was added on waveform of dB_z/dy for visibility.

Thirdly, the current amplitude into the MsS transmitter was changed from 0 to 1 A_{pp} at 30 kHz. Relationship between signal peak-peak amplitude of #1 and current peak-peak amplitude is shown in figure 4. As expected, the signal amplitude increased with the current amplitude. However, it is thought that if the excitation field is too strong to disturb the pre-magnetization of the nickel thin plate, the generated guided waves should be also disturbed. Now we are studying this phenomenon while increasing the current amplitude more than 1 A_{pp} up to 12 A_{pp}.

Finally, the frequency of the current into the MsS transmitter was changed from 10 to 100 kHz at 1 A_{pp}. Relationship between signal peak-peak amplitude of #1 and frequency of the input current is shown in figure 5. We corrected the amplitudes according to the sensitivity of the HTS-SQUID gradiometer, which slightly decreases with increase of the frequency [9]. As shown in figure 5, the signal amplitude slightly increased with frequency from 10 to 40 kHz, and it saturated over around 50 kHz. We briefly discuss the results in figure 5. The wave length of T (0, 1) mode guided wave at 40 kHz in aluminium at the group velocity of 3130 mm/ms is calculated to be about 78 mm, and a quarter of the wave length ($\lambda/4$) roughly matches to the width of the nickel thin plate 20 mm, as shown schematically in Fig. 6. We think the relation between the wave length and the width of the nickel thin plate may determine the frequency dependence of the magnetic signals. More profound research is now being studied.

4. Conclusion

In this paper, we investigated the novel SQUID NDE technique for pipes while changing parameters in the measurements of the ultrasonic guided waves on the aluminium pipe. The experimental results showed that the magnetic field change in the MsS receiver occurred toward the x (axis) direction. The magnetic signals due to the guided waves were inversely proportional to the lift-off, and the gradiometer could measure the magnetic signal with even the lift-off of 20 mm. The magnetic signals

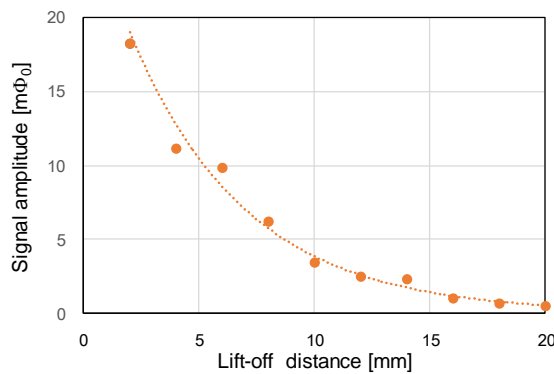


Figure 3. Signal amplitude of guided wave #1 shown in figure 2 vs. lift-off distance.

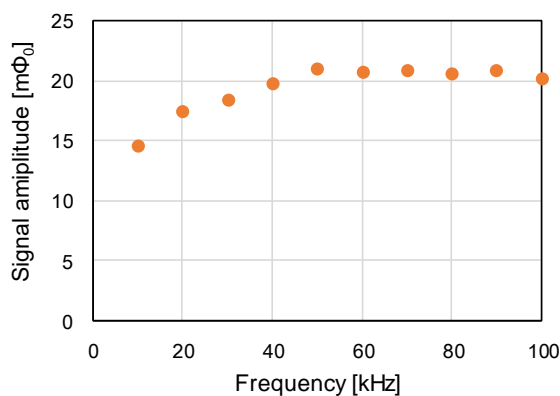


Figure 5. Signal amplitude of guided wave #1 shown in figure 2 vs. frequency of input current.

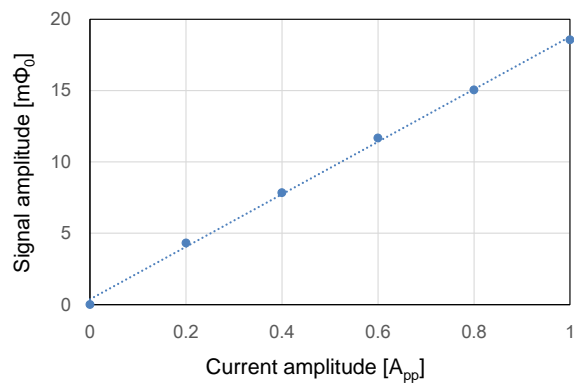


Figure 4. Signal amplitude of guided wave #1 shown in figure 2 vs. input current amplitude.

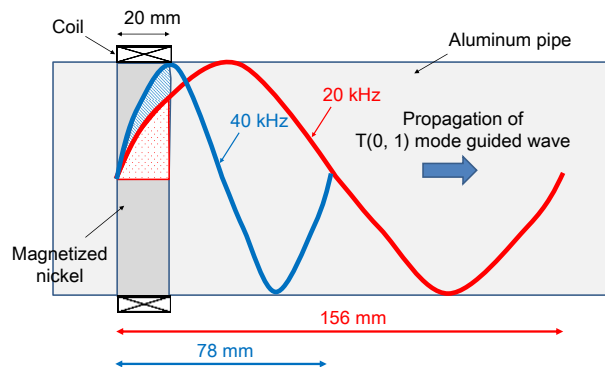


Figure 6. Relationship of width of magnetized nickel of MsS and wave length of guided waves.

due to the guided waves were proportional to the amplitude of the input current up to 1 A_{pp}. The magnetic signal increased with frequency of the input current, but it saturated around 40 -50 kHz, where a quarter of the wave length of the guided wave was roughly the same as the width of the nickel plate of the MsS.

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References

- [1] Graff K F 1975 *Wave Motion in Elastic Solids* (Oxford: Clarendon Press)
- [2] Achenbach J D 1985 *Wave Propagation in Elastic Solids* (Amsterdam: Elsevier Science Publishers B. V.)
- [3] Rose J L 1999 *Ultrasonic Waves in Solid Media* (Cambridge: Cambridge University Press)
- [4] Rose J L 2014 *Ultrasonic Guided Waves in Solid Media* (New York: Cambridge University Press)
- [5] Kwun H and Teller C M 1994 *Mat. Eval.* **52** 503
- [6] Kwun H and Bartels K A 1998 *Mat. Ultrasonics* **36** 171
- [7] Alleyne D N, Pavlakovic B, Lowe M J S and Cawley P 2001 *AIP Conf. Proc.* **557** 180
- [8] Tanaka Y, Tamato E and Fujimoto Y 2010 *International Journal of Applied Electromagnetics and Mechanics* **33** 1237
- [9] Hatsukade Y, Kobayashi T, Nakaie S, Masutani N and Tanaka Y 2017 *IEEE Trans. Appl. Supercond.* **27** 1600104
- [10] Tanaka Y, Ikeda T, Toiyama K, Kuwako S and Fujimoto Y 2006 *Transactions of the Japan Society of Mechanical Engineers* **72** 951 (in Japanese)