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Ultrasonic Guided Wave Testing Based on High Sensitive SQUID Magnetic sensor for Pipes

超高感度 SQUID 磁気センサを用いた超音波ガイド波試験

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1. Introduction

We have investigated nondestructive evaluation (NDE) techniques using high temperature superconductor (HTS) superconducting quantum interference devices (SQUIDs) for conductive materials.[1-3] The HTS-SQUID-based NDE systems have great advantage of extremely high magnetic sensitivity in broad range from DC to about 1 MHz in principle.[4] In this study, we utilized our HTS-SQUID NDE system to ultrasonic guided wave testing[5], in which the HTS-SQUID gradiometer detected magnetic signal due to guided wave without contact to target pipe based on magnetostrictive effects.[6]

2. Sample, System and Experimental method

As a sample, a zinc-plating steel pipe of 2 mm in thickness, 50 mm in diameter, and 1.5 m in length was used. At positions 500 mm away from both ends of the pipe, nickel thin plates of 0.2 mm in thickness, 20 mm in width and 157 mm in length, which were previously magnetized toward its longitudinal direction by a strong permanent magnet, were wound and firmly glued around the circumference of the pipe. One of the nickel plates was surrounded by a wound coil and they were used as a magnetostrictive transmitter. The other was used as a part of a receiver, which receives ultrasonic guided wave and converts it to magnetic signal based on the Villari effect (or inverse magnetostrictive effect).

A HTS-dc-SQUID gradiometer with ramp-edge Josephson junctions was used to measure magnetic signals due to the ultrasonic guide waves above the magnetized nickel of the receiver. The gradiometer has a planar differential pickup coil, which is composed of a pair of a square coil of 1 mm x 1 mm. Magnetic flux sensitivity of the gradiometer, operated by a commercial SQUID electronics is about 10-15 $\mu\Phi_0/\mathrm{Hz}^{1/2}$ in a range from 10 Hz to 20 kHz. Although the sensitivity in the range from 20 kHz to 100 kHz is a bit lower, the almost flat sensitivity of the HTS-SQUID gradiometer well suites the detection of magnetic signals due to the ultrasonic guided waves, which ranges in 10 kHz to 100 kHz.

We utilized our HTS-SQUID NDE system to indirect detection of ultrasonic guided wave as schematically shown in **Fig. 1**. In the system, the HTS-SQUID gradiometer was cooled at about 69 K by a coaxial pulse-tube cryocooler in a cryostat.[1] The SQUID gradiometer was operated with the SQUID electronics in a flux locked loop mode with dc bias and flux modulation schemes. The SQUID gradiometer was set above the magnetized nickel thin plate on the sample pipe with a lift-off distance of about 2 mm, to measure magnetic signals due to ultrasonic guided waves. The gradiometer was set with its baseline parallel to the x axis such that it measured dB_z/dx component. Output voltage of the SQUID electronics passed through a high-pass filter (HPF) and then was amplified using a low-noise amplifier with a gain of 20 dB. The output voltages from the SQUID electronics were measured and recorded by a digital oscilloscope and the data were averaged 256 times on the oscilloscope. **Fig. 2** shows the typical flux noise spectrum of the SQUID NDE system.

Burst sine wave voltage of 1 V_{pp} and 1 cycle at 30 kHz was supplied from a function generator, and the voltage was amplified by a power amplifier

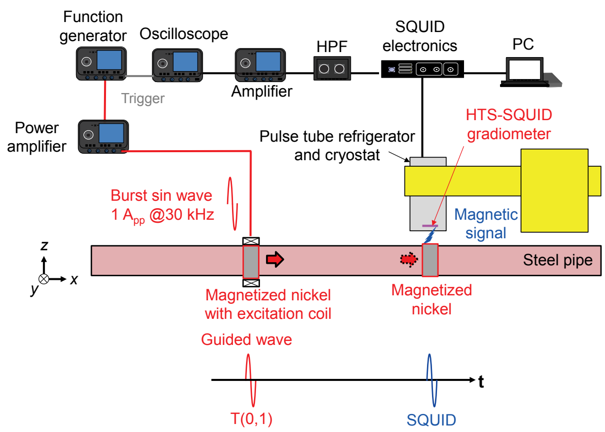

Fig. 1 Schematic diagram of HTS-SQUID NDE system for pipe and image of transmitted guided wave.

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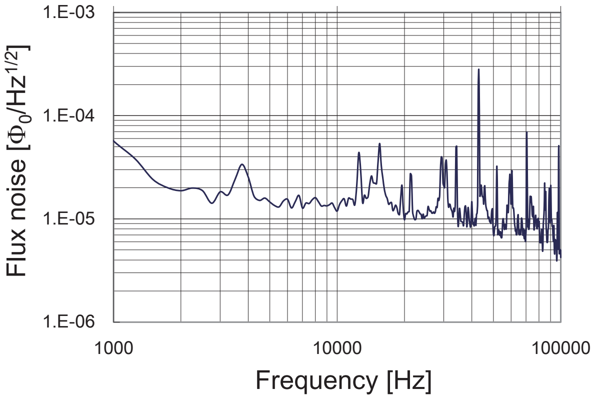

Fig. 2 Flux noise spectrum of HTS-SQUID NDE system from 1 to 100 kHz.

in order to flow 1 A_{pp} burst sine wave current to the transmitter to generate a torsional wave T(0, 1). The current was repeated with duration of 67 ms for time averaging.

3. Results and Discussion

Fig. 3 shows the measurement result. At about 160 μs after the generation timing of the guided wave, a magnetic signal of about 0.24 mΦ_0 in peak-peak amplitude labeled as #1 was measured by the HTS-SQUID gradiometer. At about 320 μs after the start of the signal #1, a magnetic signal #2 of about 0.43 mΦ_0 with reversed phase to #1 was measured. A magnetic signal #3 of about 0.21 mΦ_0 with the same phase as #1 was measured at about 320 μs after the signal #2. Since the group velocity of a torsional wave T (0, 1) propagating in a steel pipe has no frequency dependency, and it is about 3125 mm/s, the measured timing of the signal #1 by the SQUID gradiometer is calculated to be 160 μs, which agreed with the timing of #1.

The transmitter generated the guided waves propagating to both sides of the transmitter. One wave propagated toward +*x* direction and generated the magnetic signal #1 at 160 μs, and then reflected at the right end of the pipe with the reversal phase.[6] Then, it propagated toward –*x* direction to generate a magnetic signal at the receiver nickel plate. Meanwhile, the other wave propagated toward -*x* direction from the transmitter, and then reflected at the left end of the pipe with the reversal phase, then propagated toward +*x* direction to generate a magnetic signal at the nickel plate. The timing of the magnetic signal generated by the former and latter waves at the receiver had to synchronize at 320 μs after the signal #1. This is because the signal #2 had about 2 times larger amplitude than that of #1 with the reversed phase. The signal #3 was generated by the guided wave, which propagated firstly toward -*x* direction, reflected at left end, and then reflected again at right

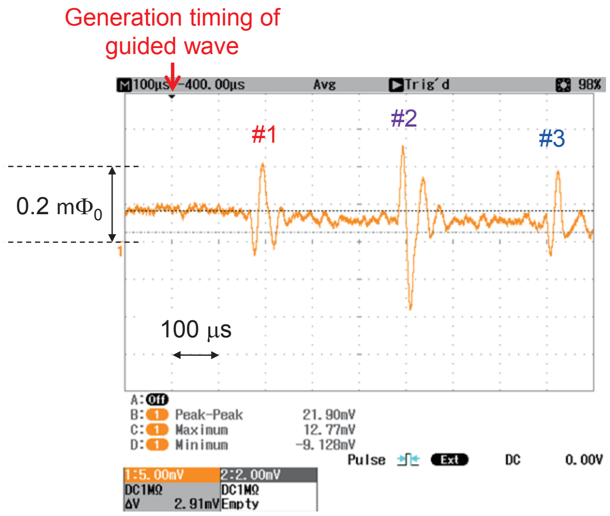

Fig. 3 Flux noise spectrum of HTS-SQUID NDE system from 1 to 100 kHz.

end. The timing of #3 must be at 320 μs after the #2, and it agreed well with the timing of #3. The phase of #3 must be the same as that of #1, and it also agreed well with the experimental result.

4. Conclusion

We successfully detected the magnetic signals due to the ultrasonic guided wave T(0, 1) without contact to the sample pipe based on the magnetostrictive effects by using the high sensitive HTS-SQUID gradiometer.

Acknowledgments

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