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Application of a superconductor to the shield of a remote field eddy current testing probe

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Abstract. This paper proposes the application of a superconductor to a remote field eddy current testing probe in order to shorten the probe length and then overcome many of the disadvantages of the remote field eddy current testing, such as the small signal amplitude and the difficulty in handling the probes. Numerical simulations were carried out to confirm that a superconductor located between the exciter and the detector of a remote field eddy current testing probe inhibits the magnetic flux from coming directly from the exciters. Then, a remote field eddy current testing probe equipped with a superconducting shield was designed and fabricated. Experimental results confirmed that a superconducting shield can shorten the probe length and provide clearer signals due to artificial wall thinnings machined on the outside surface of a ferromagnetic tube.

Keywords: Remote field eddy current testing, superconductor, magnetic shield, non-destructive testing

1. Introduction

Superconductors show very different behaviors from ordinary conductors in electromagnetic fields. For instance, no magnetic flux can penetrate a superconductor and thus a superconductor can be used as an ideal magnetic shield. While ordinary metals also work as magnetic shields, the superiority of a superconducting shield over ordinary metal shields is that a superconducting shield works effectively, regardless of the amplitude or the frequency of the magnetic field.

The characteristics of superconductors imply that they have a large potential in enhancing electromagnetic non-destructive testing (NDT) methods that utilizes magnetic flux, such as the eddy current testing and the magnetic flux leakage testing. This is because locating a superconductor in an appropriate position prevents unnecessary flux from reaching detectors and thus leads to detect only desired flux that carries necessary information concerning the target.

Among many possibilities, this paper proposes a superconducting shield of a remote field eddy current testing probe as a new application of a superconductor to an electromagnetic NDT. One of the most essential drawbacks of the remote field eddy current testing, which is stated below, would be overcome by this application.

Remote field eddy current testing is a non-destructive testing method that utilizes AC magnetic field like ordinary eddy current testing [1–3]. However, the remote field eddy current testing is usually applied to the inspection of ferromagnetic tubes such as gas or oil pipe lines. This is because the remote field

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eddy current testing can detect both inner (i.e., on the inner surface of tubes) and outer (on the outer surface of tubes) defects with almost the same sensitivities.

The principle of the remote field eddy current testing is to detect a flux that once penetrates a specimen and diffuses back (indirect flux). Because of its path, this indirect flux contains information about both inner and outer surface of the specimen. Therefore, the remote field eddy current testing has the same sensitivity to inner and outer defects.

The principle requires the detectors to be located in a region where the indirect flux is captured well. In the case of the inspection of tubes, the indirect flux is dominant in the regions far from the exciter because the eddy currents induced inside the tube wall attenuate the flux that directly reaches the detector from the exciter by propagating inside the tube (direct flux). Usually, the distance between the exciter and the detector needs to be more than twice tube diameter.

The long distance between the exciter and the detector leads to several disadvantages, including, for instance, a very weak signal amplitude, and a long probe length that sometimes causes difficulty in the inspection of non-straight targets such as curved or U-bend tubes. While the application of high-performance amplifiers or other signal processing techniques can enhance the detectability of the remote field eddy current testing, shortening the distance between the exciter and the detector without losing the characteristics of the remote field eddy current testing is one of the most essential solutions to the drawbacks.

For this purpose, several studies have proposed the application of a magnetic shield made of conductive materials such as copper [4]. Locating a shield between the exciters and detectors attenuates the direct flux because of the eddy currents induced inside the shield. However, a conductive shield is not always effective when the induced eddy currents are not sufficiently strong. Since a superconductor can work as an ideal magnetic shield, it is very possible that a superconducting shield of a remote field eddy current testing probe can significantly shorten the distance between an exciter and the detectors even when conductive shields do not work well, and enhance the ability of the probe.

2. Numerical simulations

In order to confirm the effectiveness of a superconducting shield and avoid unnecessary experiments, simulations whose configuration is shown in Fig. 1 were carried out in advance of the design of the probe. The configuration models the inspection of a ferromagnetic tube by means of the remote field eddy current testing. In the simulations, no defect is present in the tube and unflawed remote field eddy current signals were computed to provide the relationship between the signal amplitude and the distance between the exciter and the detector, L. This is because such a relationship quantifies well the effect of the shields. Figure 2 illustrates a typical dependency of the amplitude of the remote field eddy current testing signal on L. While the figure shows that the amplitude of the signals exponentially decays with L, a valley is observed at the point circled in the figure. The valley is caused by the difference in the characteristics between the signals dominated by the direct flux and those dominated by the indirect flux. Therefore, if a shield attenuates direct flux well, then the valley (or sometimes just a bend) approaches L=0.

In the simulations, the electromagnetic characteristics of all materials including the superconducting shield were assumed to be linear and isotropic, and therefore the simulations were performed as a quasi-static problem as ordinary eddy current testing simulations. A superconductor, modeled as a material with a conductivity of 1.0×10^6 S/m and a relative permeability of 1.0×10^{-8}, is located between the exciter and the detector of the probe so that it prevents the direct flux from the exciter. Since the amplitude of the

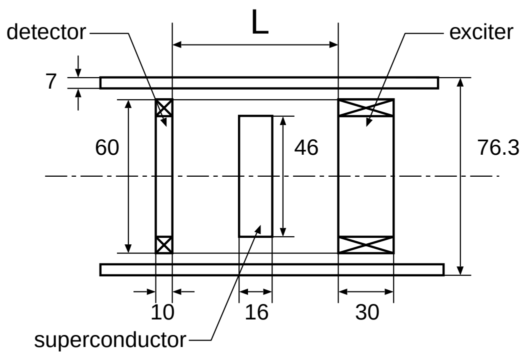

Fig. 1. Configuration of numerical simulations, and the definition of distance L. The dimensions of the tube, probe, and superconductor in the experiments are the same as these.

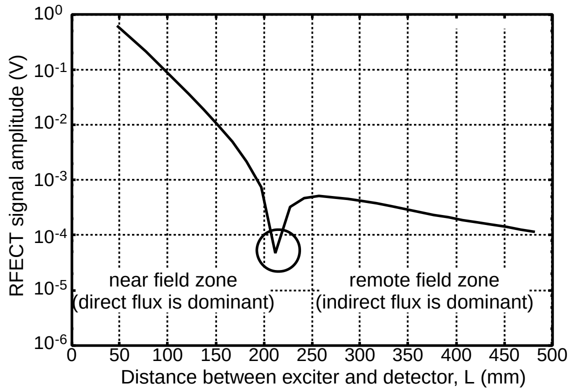

Fig. 2. A typical relationship between the amplitude of remote field eddy current signals and the coil distance L.

magnetic field around the superconductor is sufficiently small compared with critical magnetic field of a superconductor, it is reasonable to neglect the nonlinearity of the superconductor. The dimension of the ferromagnetic tube tested is the same as that of the one utilized in the experiments described in the next section. Because the configuration is axisymmetric, simulations were carried out using axisymmetric two-dimensional eddy current analysis code based upon the finite element method [5–8].

The results of the simulations are shown in Fig. 3. One can observe the clear difference in the signals between with and without the superconducting shield, i.e., the valleys (or bend) in the figure approach L=0 when the shields are used. These results indicate that the length of a remote field eddy current testing can be shortened with the use of a superconducting shield located between the exciter and the detector.

In order to clarify the advantage of a superconducting shield, the effect of a shield made of copper, whose conductivity and relative permeability are 6.0×10^7 S/m and 1.0, was also computed. The diameter and the thickness of the copper shield are same as those of the superconducting shield. While a copper shield also shows effectiveness in preventing direct flux when the exciter is driven at a frequency of as high as 500 Hz, the effect of the copper shield is not clear at low frequencies. At 20 Hz, almost no difference is observed in the signals between with and without copper shield. In contrast, the superconducting shield shows a good shielding effect, regardless of the exciting frequency.

3. Experiment

Then, experiments were carried out to confirm the effectiveness of a superconducting shield. Figure 4 shows a photograph of the remote field eddy current testing probe fabricated. The probe consists of an exciter and a detector unit so that a shield can be located between the two units. In the following experiments with a superconducting shield, a superconducting bulk was situated in an insulator cup made of expanded polystyrene, and then the cup was located between the two units after the cup had been filled with liquid nitrogen. The superconductor utilized as the shield is a YBCO bulk of 46 mm in diameter and 16 mm in thickness (the same dimensions as the ones used in the simulations). While a larger diameter of the bulk would be desirable to achieve a higher shielding effect, the necessary thickness of the insulator cup restricted the largest diameter to this size.

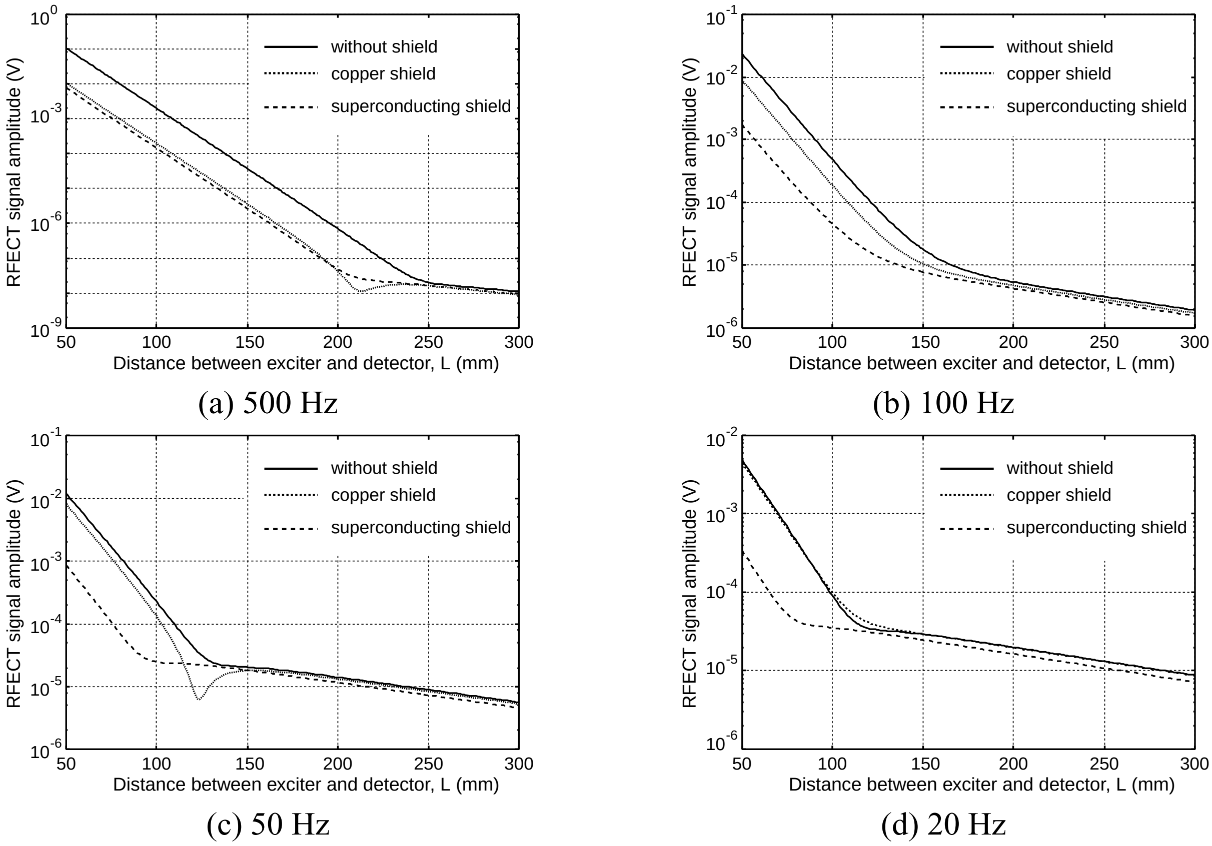

Fig. 3. Results of numerical simulations. A superconducting shield shows efficiency, regardless of the exciting frequency.

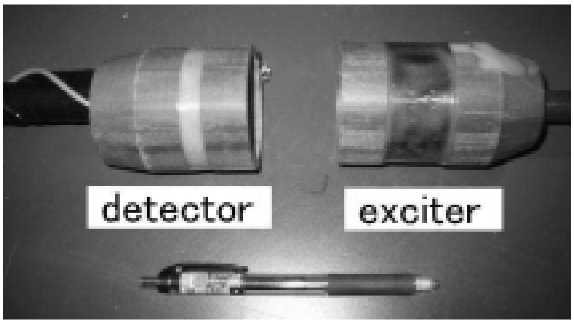

Fig. 4. Remote field eddy current testing probe for superconducting shield experiments.

The effectiveness of the superconducting shield was verified by the inspection of a ferromagnetic tube. The tube has two artificial outer wall thinnings of 10 mm in axial length. The depths of the wall thinnings are 30 and 40% in wall thickness. The outer diameter and wall thickness of the tube were 76.3 and 7 mm, respectively (they are also the same as the ones in the simulations).

In the experiments, an AC current controlled by a function synthesizer was supplied to the exciter via an amplifier; signals of the detector were measured with the use of a lock-in amplifier. The amplitude of

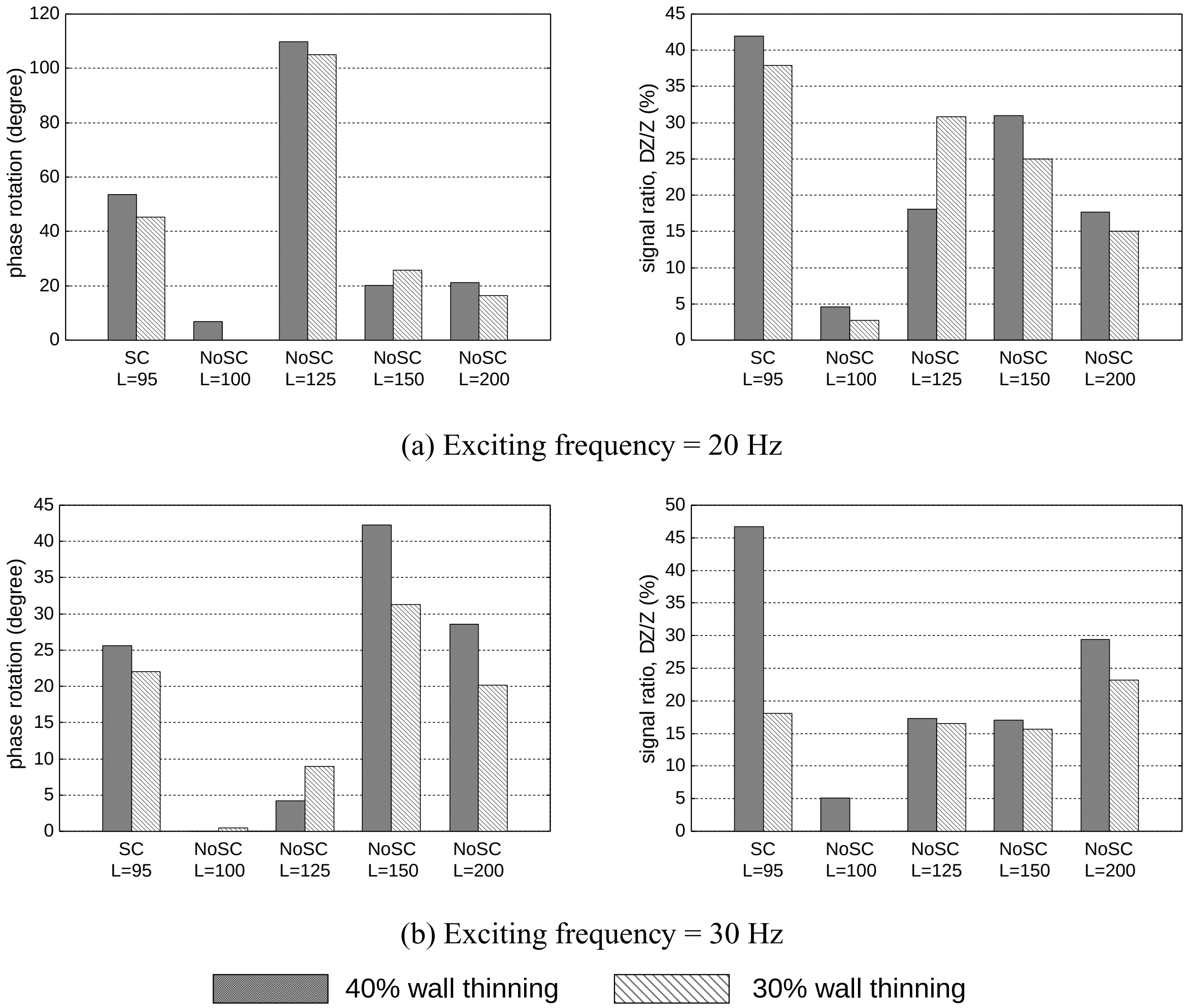

Fig. 5. Experimental results. Phase rotation (left-hand) and normalized amplitude (right-hand) of wall thinning signals. In the legend of the right-hand figures, Z and ΔZ, respectively, refer to the amplitude of the unflawed signals and the change in signal amplitude caused by the presence of the wall thinnings.

the currents supplied to the exciter was monitored by an ammeter to consider a possible change in the amplitude caused by a temperature change due to the liquid nitrogen. Then the signals due to the wall thinnings were measured for cases with and without a superconduting shield.

The results of the measurements are shown in Fig. 5. The measurements were carried out with exciting frequencies of 20 and 30 Hz. The left-hand graphs of the figure illustrate the phase rotation of signals due to the 30 and 40% wall thinnings; the right-hand side illustrates the amplitude of the signals in the percentage of that of unflawed signals. The measurements were carried out with $L = 95$ mm (with superconductor, indicated ‘SC’ in the figure), and $L = 100, 125, 150, 200$ mm (without superconductor, indicated ‘NoSC’).

Note that usually signal amplitude is utilized to characterize defects in remote field eddy current testing and phase rotation is not always useful for this purpose, unlike ordinary eddy current testing. It is sufficient to obtain observable phase rotation due to defects from the viewpoint of remote field eddy current inspection, and to obtain larger phase rotation due to defects is not so demanded. Thus, the left-hand graphs of the figures are presented to show that remote field eddy current signals are clearly obtained, and quantitative discussion hereafter are performed on the basis of the right-hand graphs of the figures.

Signals due to the thinning were very clear when a superconducting shield was applied and L was set to 95 mm. In contrast, almost no signal due to thinning was obtained when no shield was utilized and L was set to 100 mm. While signals with L =125 mm are quite clear, the signals under this condition are not suitable for the quantitative estimation of wall thinning depth [9] because either the amplitude (at 30 Hz) or phase rotation (at 20 Hz) does not increase with wall thinning depth. This is because the detector was located in at transient zone where the direct flux has approximately the same amplitude as the indirect flux. The signals measured in this region exhibit a complex behavior because of the two signal sources, i.e., the direct and indirect fluxes. Signals with $L = 150$ mm also show similar tendencies.

The results with $L = 200$ mm, without the superconductor, exhibit reasonable signals as remote field eddy current testing signals, as well as the ones with $L = 95$ mm, with the superconducting shield. However, the amplitude of the wall thinning signals with $L = 200$ mm were 60-40% of that of $L = 95$ mm with the shield, which confirms the effectiveness of the shield.

4. Conclusion

The application of a superconductor to the magnetic shield of a remote field eddy current testing probe was proposed in this paper. Numerical simulations and experimental verifications showed that a superconducting shield allows the exciter and detector to be located closely, without losing the characteristics of the remote field eddy current testing. Experimental results confirmed that a remote field eddy current testing probe equipped with a superconducting shield realizes much shorter distance between exciter and detector than a probe without shield, and provides larger defect signals, even when the exciter is driven at a frequency as low as 20 Hz.

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