AN RFECT PROBE WITH A SUPERCONDUCTING SHIELD

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ABSTRACT. This paper proposes an RFECT probe equipped with a superconducting shield to shorten the distance between the exciter and the detector of the probe. Numerical simulations are carried out in axisymmetric configurations to clarify the effect of superconducting shield. The results of simulations imply that superconducting shields have advantages over a copper shield in its shield effect especially when the exciter is driven at a low frequency. An RFECT probe equipped with the superconducting shield is designed and fabricated with the aid of the numerical simulations. Experimental results confirm that the presence of superconductor shield shortens the distance between the exciter and the detector of the RFECT probe.

INTRODUCTION

Superconductors have very different behavior in electromagnetic fields from normal conductors. Like the superconducting quantum interface device (SQUID), superconductors have big potential as a mean to enhance electromagnetic non-destructive testings because of the behavior. For instance, the Meissner effect indicates that no magnetic flux can penetrate a superconductor, and therefore a superconductor can be a perfect magnetic shield that works effectively.

Based upon the aspect mentioned above, this paper proposes an application of a superconductor to a shield of a remote field eddy current testing (RFECT)[1] probe. While it is very difficult to inspect outer defects of a magnetic tube from inside with the use of the ordinary eddy current testing, RFECT shows efficiency in the inspection. The principle of RFECT is to detect magnetic flux that once penetrates tube wall and diffuses back. The detector of RFECT must be located far enough from the exciter because the magnetic flux that propagates inside tube directly from the exciter is dominant near the exciter, which leads a long RFECT probe. The length of an RFECT probe causes several problems, e.g. very small signal, difficulty in handling the probe and so on. Several papers have proposed RFECT probes with a shield made of conductive materials such as copper[2]. The shield is located between the exciter and the detector and attenuates the direct flux by the eddy currents induced inside.
Consequently, the remote field zone approaches the exciter. However, the shield is not always effective, especially when the exciter is driven at a low frequency because the eddy currents are not strong enough.

Superconductors are, on the other side, ideal magnetic shields and it is expected that they work effectively even in the cases that the conductive shields do not work well. The biggest problem concerning the application of superconductors is obviously the presence of coolant which is necessary for the emergence of the superconductivity. The purpose of this paper is to clarify the possibility of the application by means of numerical simulations and experiments.

NUMERICAL SIMULATIONS

In order to clarify the shielding effect of superconductors, numerical simulations were carried out before experimental validation. Figure 1 illustrates the configuration of the simulations. The configuration is axisymmetric one.

One can derive governing equations of eddy current analysis with the use of magnetic vector potential $A$ starting from the Maxwell equations\[3\]. In the case of an axisymmetric problem, the potential has only $\theta$ component and the governing equation reduces to

$$\nabla \times \left( \frac{1}{\mu} \times A_\theta \right) = J_\theta - \sigma \frac{\partial A_\theta}{\partial t}, \quad (1)$$

where $A_\theta$, $J_\theta$, $\mu$, and $\sigma$ are the $\theta$ component of magnetic vector potential, current density in exciters, permeability, and conductivity, respectively. Equation 1 is discretized by the nodal-FEM and solved by the ICCG.

First, the distance from the exciter to the beginning of the remote field zone was revealed by numerical simulations. Since the purpose of the simulations was to clarify the shield effect due to a superconductor, specimen was chosen as a straight tube with no cracks. Figure 2 shows a typical response of the RFECT signals as a function of the distance between the exciter and the detector. The direct flux, which directly propagates from the exciter, is dominant near the exciter and is attenuated rapidly.
FIGURE 2. Typical response of RFECT signal with coil distance. The bend (valley in this figure) indicates the boundary between near field zone and remote field zone. Whether the bend becomes valley or not depends on exciting frequency, material properties of tube and so on.

with the distance from the exciter because of the eddy currents induced inside tube wall. On the contrary, the indirect flux, which penetrates tube wall and diffuses back, is not affected by the eddy currents. One can observe a bend highlighted with a circle in the figure, which is caused by the difference in decay ratio between the direct and indirect flux. Therefore, the bend indicates the beginning of the remote field zone, and the detector must be located farther than the bend.

Figure 3 shows simulated RFECT signals with different distances between the exciter and the detector. In order to clarify the effect of superconductor shield, RFECT signals with a shield made of copper and without any shield were also simulated. Superconductors were modeled as a material with $\sigma = 1.0 \times 10^6$ S/m and $\mu_r = 1.0 \times 10^{-20}$; those of copper are $6.0 \times 10^7$ S/m and 1.0. The distance between the exciter and the shield, $d$, and the thickness and the radius of a shield, $t$ and $r$, are 5, 10 and 30 mm, respectively. One can observe the bends appear closer to the exciter when copper shields were located between the exciter and the detector, which indicates that the shields prevented direct flux from the exciter and the remote field zone approaches the exciter. The fact that no bend appeared when a superconductor shield was located means that direct flux was almost completely shielded. Note that the shield effect of the copper shield is not sufficient and there is no difference between with and without a copper shield when the exciting frequency is low, whereas the effect of superconductor shield is evident regardless of the frequency, which implies the efficiency of a superconductor shield.

Since a superconductor shield needs coolant and an insulator, it is very difficult to use a large superconductor shield and there must be a space between the shield and tube wall. Then simulations were carried out to clarify the effect of the dimension of the superconductor shield on its shield effect, whose results are shown in Fig. 4. The results conclude that the shield effect increases with the radius of the shield, and the distance between the exciter and the shield does not affect the effect significantly within the range adopted in the simulations. The thickness of a superconductor shield was fixed to be 10 mm because it does not have large effect on the shield effect if it is larger than the London length.
FIGURE 3. Comparison of RFECT signals with and without superconductor/copper shield ($d = t = 10$ mm, $r = 30$ mm). One can observe that superconductor shield show efficient shield effect regardless of the exciting frequency, while the shield effect of a copper shield is not sufficient when the exciter is driven at low frequency.
FIGURE 4. Effect of the dimension of superconductor shield, t = 10mm

EXPERIMENTAL STUDY

Setup

Figure 5 displays the photographs of a superconductor used as a shield in this study and a specimen. The specimen is a tube made of low carbon steel, whose outer diameter is 76.3 mm and thickness is 7.0 mm. An artificial wall thinning of 40% depth is fabricated in its outer surface. The superconductor is a YBa$_2$Cu$_3$O$_{7+z}$ bulk and measures 17.5 mm in radius and 15 mm in height. Its critical current density is approximately $1.7 \times 10^7$ A/m$^2$, while it is very difficult to measure exact value because the superconductor is not monocrystal.

The dimensions of RFECT probes used in the experiments are illustrated in Fig. 6. The probe shown in Fig. 6(a) consists of two units so that a superconductor shield can be located between the exciter and the detector. The superconductor is placed in a cup filled with liquid nitrogen, and the cup, which is made of expanded polystyrene and plays a role of an insulator, is installed between the units after liquid nitrogen is stabilized. Since the cup did not have a cap, the specimen was vertically located and the probe equipped with the cup was inserted from the top of the specimen when the cup contained liquid nitrogen, which is depicted in Fig. 7. An RFECT probe with variable coil distance, which is shown in Fig. 6(b), was also used in order to measure the effect of the coil distance on RFECT signals. The characteristics of the exciter and the detector of the probe are respectively same as the ones of the two-unit type probe’s ones. The exciting current is controlled by a function synthesizer and
FIGURE 5. Photographs of the superconductor (left) and the specimen (right) that were used in the experiments.

FIGURE 6. RFECT probes used in experiments, (a) Two-unit type RFECT probe for the measurement of effect of shields, (b) Ordinary type RFECT probe with variable coil distance.
RFECT signals are measured with the use of a lock-in amplifier.

**Results and Discussion**

In order to clarify the effect of coil distance on RFECT signals, signals due to the wall thinning were measured using the ordinary type probe, i.e., the one shown Fig. 6(b), with the distance ranging from 60 to 130 mm and exciting frequency of 20 Hz. The plots with solid lines in Figs. 8(a) and (b) indicate the ratio of the amplitude of the wall thinning signal to that of unflaw signal and maximum phase rotation of the signal, respectively. The results revealed that no clear RFECT signals due to the wall thinning can be recognized when the coil distance was shorter than 100 mm.

Then the superconductor was located in the cup and mounted to the two-unit type probe with coolant. Measured signal when the distance between two coils were 90 mm is shown in Figs. 8(a) and (b) with a cross. Note that signal due to the wall thinning was observed, while it could not be at all in the case without the shield when the distance was same. The signal was as distinct as the one obtained with the use of the ordinary type probe whose coil distance was 110-120 mm. One can conclude that the superconductor shield worked effectively.

However, the shield effect due to the superconductor shield was not as great as what the numerical simulations showed. The results of the simulations imply that the biggest reason for that is the radius of the superconductor. While the results shown in Fig. 4 indicate that the radius of a superconductor shield should be as large as possible, we had to use relatively small superconductor since the insulator made of expanded polystyrene was fragile and shrank because of coolant. An insulator made of more rigid materials, such as FRP, will solve this problem.

**CONCLUSION**

In this study, an RFECT probe with a superconducting shield was designed with the aid of numerical simulations. In addition, preliminary experiments to observe the effect of the shield were also carried out. The results of the experiments confirmed that the shield attenuated the direct flux from the exciter and therefore was able to shorten the length of the probe even for an exciting frequency as low as 20Hz.
FIGURE 8. Results of the experiments, left: the ratio of the amplitude of the RFECT signals due to OD40% wall thinning to that of unflaw signals, right: phase rotation of the RFECT signal due to OD40% wall thinning

REFERENCES