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Physics Procedia 65 (2015) 193 – 196

Physics Procedia

27th International Symposium on Superconductivity, ISS 2014

Development of non-destructive evaluation system using an HTS-SQUID gradiometer with an external pickup coil

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Abstract

We are developing a new eddy-current non-destructive evaluation (NDE) system using a high-temperature superconducting quantum interference device (HTS-SQUID) gradiometer with the aim of applying it to power plants. Electric power facilities such as ducts and vessels are generally untransportable because of their size, and thus it is difficult to apply a conventional SQUID NDE system. The new NDE system employs an external Cu pickup coil which is supposed to be driven flexibly by a robot arm at room temperature and an HTS-SQUID chip which is placed in a magnetically shielded vessel. In the present research, we investigated the performance of an HTS-SQUID sensor connected with external pickup coils before mounting them to a robot arm. By varying the Cu coil conditions such as their sizes, the number of turns, and the diameter of wire, we qualitatively evaluated the frequency dependence of the effective area and the cutoff frequency.

Peer-review under responsibility of the ISS 2014 Program Committee

*Keywords:*HTS-SQUID; Non-destructive evaluation; Electric power facilities

1. Introduction

SQUID is one of the most sensitive magnetic sensors. We previously developed an eddy-current NDE system using an HTS-SQUID sensor and investigated its performance with the aim of applying it to electric power facilities [1]. Use of SQUID as a magnetic sensor gives us the highest sensitivity even at low frequencies. Therefore eddy current induced at low frequencies on a conductive material can penetrate it deeply. In the past research, we demonstrated that slit-like flaws located in the lower layer of multilayer test samples consisting of aluminum and resin plates which simulated ducts could be detected by using our conventional SQUID NDE system [2-3].

Since our previous SQUID NDE system had a simple structure with a moving stage, only flat test samples or transportable small samples could be mounted and examined [1]. As the next step, we decided to develop a new SQUID NDE system which can be applied to a real field, or evaluation of untransportable large equipment. For that purpose, measurement using a moving sensor is indispensable.

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Peer-review under responsibility of the ISS 2014 Program Committee
doi:10.1016/j.phpro.2015.05.112

Another requirement for the new NDE system is capability of measuring practical materials with magnetization. In the SQUID NDE system we employed an external pickup coil method which was previously reported in several systems [1] ,[4]. This method enables to keep large distance between a SQUID sensor and a measuring material. Moreover, an external pickup can be moved flexibly, while placing a SQUID sensor at a fixed position. Figure 1 shows the conceptual image of our new SQUID NDE system. The new SQUID NDE system employs an external and movable Cu pickup coil and an HTS-SQUID chip placed in a magnetically shielded vessel. A movable Cu pickup coil is supposed to apply to NDE of untransportable test or actual samples with a 3-dimensonal shape. In the present research, we evaluated the performance of external pickup coils as a magnetometer, connected with an HTS-SQUID in a shielded condition, before mounting them to the new SQUID NDE system.

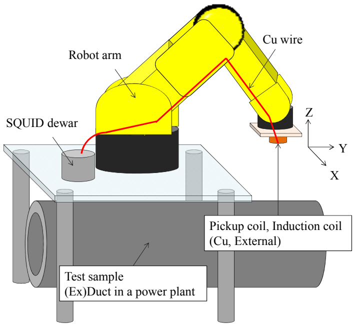

Fig. 1. Conceptual image of new SQUID NDE system.

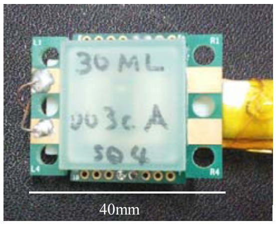

Fig. 2. SQUID sensor module containing thin film SQUID gradiometer and input coil. The electrodes of the input coil on the SQUID module and wires of an external pickup coil were connected by soldering.

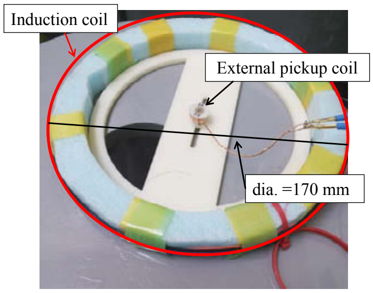

Fig. 3. Configuration of induction coil and pickup coil.

2. Experimental

2.1. Purpose of the research and measurement system

This is the first-step approach of SQUID NDE with a movable external pickup coil. Therefore, evaluation of the basic performance of the external pickup coil system is needed to determine the specification of new SQUID NDE system. The purpose of present research is to evaluate the performance of external pickup coils connected with an HTS-SQUID in a magnetically shielded condition. In the present study, pickup coils with a simple solenoid shape were employed, and the performance as a magnetometer was examined by changing the diameter, length, and the number of turns of the pickup coil.

The measurement system consists of an LN_2 cryostat, a solenoid type induction coil, a FLL circuit (STAR Cryoelectronics), a lock-in amplifier, a PC with interfaces that collect data, and the external pickup coil coupled with a SQUID gradiometer. A planar SQUID gradiometer, with first-order gradiometric pickup coils approximately 5.0 x 5.5 mm^2 in size was fabricated using the HTS multilayer and ramp-edge junction technologies. A 26-turn HTS-thin film input coil fabricated on a different substrate was stacked on the HTS gradiometer with a flip-chip configuration [5]. The effective area A_{eff} of one pickup loop assuming a magnetometer with the same loop size was estimated to be approximately 0.05 mm^2 at 200 Hz. The flux noise level of the SQUID chip without connection to the Cu pickup coil was approximately 8 $\mu\Phi_0/Hz^{1/2}$ at 1 kHz. The SQUID sensor packaged in a form of module has also been used in other SQUID NDE systems [6]. Figure 2 shows the picture of the SQUID module.

2.2. Examined Specimen and Measurement Procedure

Figure 3 shows the configuration of induction coil and pickup coil. A solenoid type induction coil was used. The number of turns and the diameter was 8 and 170 mm, respectively. When an AC current of 0.4 mA (rms value) was applied to the induction coil, the peak-to-peak magnetic field in the center of the induction coil was approximately 0.022 μT. In the present research, five different external pickup coils were evaluated. Figures 4 (a) and 4 (b) are photos of the external pickup coils. Each coil was labeled as shown in Table 1. The number 1-5 in Figs. 4 (a), and 4 (b) is equal to the number of coil in Table 1. The inductance of pickup coil : L_p is given by equation (1). (Here, N_p is the number of turns, a is the radius, l is the length of a solenoid coil, and λ is Nagaoka coefficient.)

$$L_p = 10^{-7}\lambda \frac{(2\pi a N_p)^2}{l} \tag{1}$$

The external pickup coil was set and fixed in the center of the induction coil, as shown in Fig. 3. Magnetic field with a constant magnitude was induced by the induction coil, and the external pickup coil measured the magnitude of magnetic field. Output signals from the lock-in amplifier (R-signals) were collected by PC as a function of induction frequency. The frequency of induction coil current was varied from 35 Hz to 70 kHz. By comparing the magnitude of input and output signals, the effective area A_{eff} of the HTS-SQUID connected with the external pickup coil was estimated.

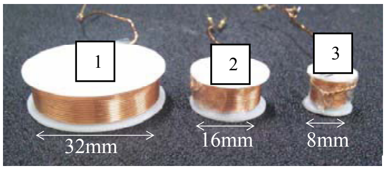

Fig. 4. (a) Pictures of pickup coils 1 -3. Their specifications are described in Table 1.

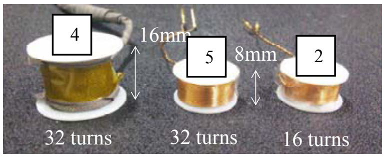

Fig. 4. (b) Pictures of pickup coils 4 -6. Their specifications are described in Table 1.

Table 1. Specifications of pickup coils.

Coil number	1	2	3	4	5
Diameter : $2a$	32mm	16mm	8mm	16mm	16mm
Number of turns : N_p	16	16	16	32	32 (2 layers)
Length : l	8mm	8mm	8mm	16mm	8mm
Inductance : L_p	11.8 μH	4.2 μH	1.4 μH	11.1 μH	17.0 μH

3. Result and discussion

3.1. Size dependence of the system sensitivity and cutoff frequency

Figure 5(a) shows the frequency dependence of the effective area (A_{eff}; mm^2) for the pickup coils 1- 3. The effective area, equal to the system sensitivity, increases with increasing of the induction frequency and the diameter of the pickup coil. Comparing the result of the measurement, the effective area for the small coil (diameter of 8 mm) is equal to approximately 1/2.6 - 1/2.7 of that for the middle-size coil (diameter of 16 mm). The effective area of the middle-size coil is equal to approximately 1/2.7 of that for the large coil (diameter of 32 mm). The effective area is given by the following equation (2), and the equation is considered to be approximately equation (2)' for the case of higher induction frequency ($\omega >> R_p/(L_p + L_i)$) [7]. (Here, M is the mutual inductance, R_p is the resistance of the pickup coil including the wire to the SQUID module, and L_i is the inductance of the input coil.) Considering the estimated inductance for the input coil of 17 μH [5], the ratios of A_{eff} between coil 2 and coil 1, and between coil 3 and coil 2 are expected to be 1/3.0 and 1/3.5, respectively, from equation (2)'. The deviation from the observed results may be explained by inhomogeneity of the applied field because we used a relatively small solenoid-type induction coil in the present study. Use of a large or Helmholtz type induction coil is needed to precisely evaluate A_{eff} in a homogeneous field.

The effective area decreases with decreasing the frequency as shown in Fig. 5(a). A_{eff} decreased at induction frequencies lower than 4 kHz and the cutoff frequency is estimated to be about 2-3 kHz. The cutoff frequency (f_{cutoff}) is given by the following equation (3) [7]. Here, R_p is the resistance of pickup coil Equation (3) indicates that, a small R_p, and/or a large L_p of pickup coil is needed to obtain a lower cutoff frequency. The measurement results shown in Fig. 5(a) indicate that there is no significant difference in the cutoff frequency in spite of the expected difference in R_p. In the case of solenoid coil, L_p increases with increasing of radius of pickup coil as shown in equation (1). Since both R_p and L_p simultaneously increased, less difference in the cutoff frequency was probably observed in Fig. 5(a).

$$A_{eff} = \frac{MN_p a^2 \pi\omega}{\left(\left(R_p^2 + \left(\omega\left(L_p + L_i\right)\right)^2\right)^{1/2}\right)} \quad (2) \qquad A_{eff} = \frac{MN_p a^2 \pi}{L_p + L_i} \quad (2)'$$

$$f_{cutoff} = \frac{R_p}{2\pi(L_p + L_i)} \quad (3)$$

3.2. Structure dependence of the system sensitivity and cutoff frequency

As described above, the sensitivity of the pickup coil strongly depended on its size. The size of the pickup coil is an important factor for the design of NDE systems, because both high spatial resolution and small size of detecting probe are needed especially in a practical use. A high sensitivity with small pickup coil is strongly needed.

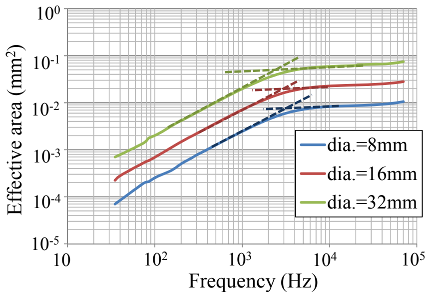

Fig. 5. (a) Frequency dependence of effective area for coils 1-3 (with the diameter of 8, 16, and 32 mm, respectively) connected to the SQUID. Dotted lines are guides to the eye.

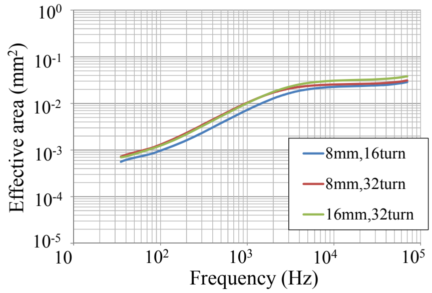

Fig. 5. (b) Frequency dependence of effective area for coils 2, 4, and 5 (with different ways of winding) connected to the SQUID.

Figure 5(b) shows the frequency dependence of the effective area for the coils 2, 4, and 5. The coil 2 is the standard one, and its effective area was plotted by the blue line in the figure. The number of turns is 16 (1 layer), and the length is 8 mm. The coils 4 and 5 have twice number of turns (32 turns). The coil 4 has single layer of winding, therefore the length of the coil is 16 mm. The coil 5 has double layer of winding, therefore the length of the coil is 8 mm. The effective area of the coils 4 and 5 are plotted by the red and green lines, respectively.

Comparing the results for the coils 2 and 5, their sensitivity seems almost equal in the high frequency region over 10^4 Hz. However, the coil 2 has less sensitivity in the lower frequency region. This result means that the cutoff frequency is slightly decreased or improved by employing the stratified pickup coil (coil 5). The equation (3) for the cutoff frequency shows the correlation with L_p and R_p. Here, R_p of the coil 5 is approximately twice larger than R_p of the coil 2, because total length of Cu wire is twice longer. On the other hand, L_p of coil 5 is four times larger, which should lead to a substantial decrease of the cutoff frequency. The only slight decrease observed in Fig. 5(b) could be explained by the situation that L_p and L_i have the same order of magnitude for coil 5.

Comparing the result for coil 4 with that for coil 2, no improvement of cutoff frequency is observed, while A_{eff} at higher frequencies slightly increases. R_p of coil 4 is approximately twice larger than that of coil 2. On the other hand, coil 4 has two or three times larger L_p. Thus the observed almost the same cutoff frequency could be understood. Although it seems difficult to understand straightforward the slightly larger A_{eff} for coil 4, use of a longer coil with the same number of turns suppress a large increase in the inductance, and thus is favorable to obtain larger A_{eff}.

The results of Figs. 5(a) and 5(b) indicate that to obtain a large effective area, use of pickup coils with larger diameter is the most effective and use of longer coil has some positive effects. To improve the cutoff frequency, use of stratifying pickup coil is effective.

4. Conclusion

Before determining the specification of the new SQUID NDE system with a movable normal-metal pickup coil, we fabricated some pickup coils with different parameters and evaluated the performance of the coils connected an HTS-SQUID module. It was found that use of a lengthened or stratified coil slightly improved the system performance in the present experimental conditions. The sensitivity of the pickup coils connected with SQUID is mostly determined by the area of pickup coil, and the increase in the number of turns DOES NOT improve the sensitivity for the case of employing a solenoid type coil. For practical use in NDE, a magnetometer detects unnecessary signals, such as induction field and external magnetic noise. Therefore, the structure of magnetometer has less advantage than gradiometer. The performance of NDE system using a gradiometric external pickup coil must be evaluated at the next step.

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