Study on non-destructive evaluation of flaws in multilayer duct using an HTS-SQUID gradiometer

J. Kawano*a, A. Ogawa*a, F. Ishikawa*a, K. Tanabeb

aThe Chugoku Electric Power Co., Inc., 3-9-1 Kagamiyama, Higashi-hiroshima, 739-0046, Japan
bSuperconductivity Research Laboratory - ISTEC, 1-10-13 Shinonome, Koto-ku, Tokyo 135-0062, Japan

Abstract

We have investigated the performance of an eddy-current non-destructive evaluation (NDE) system using an HTS Superconducting quantum interference device (SQUID) gradiometer with the aim of applying it to the equipment in power plants. Use of the SQUID-NDE technique has an advantage, because SQUID has a high sensitivity or low noise characteristics at low frequencies for detecting magnetic signals. In the present research, we have tried to detect flaws in test samples simulating a multilayer duct in a plant, which consists of multilayer aluminum and resin plates. In the test samples, resin plates were sandwiched by aluminum plates. The top aluminum plate and the bottom multilayer aluminum plates were assumed as outer and inner duct layers, and the resin plates were assumed as an insulation layer in a multilayer duct of the plant. A slit-shaped through hole was opened in the bottom layer, and was assumed as a flaw in the duct layer. By using a SQUID-ECT system, we could detect signals from flaws located at more than 10 mm deep positions in the test samples.

Keywords: HTS-SQUID; non-destructive evaluation; multilayer duct

1. Introduction

The influence of system failure which occurs especially in power plants, becomes more serious in these days. Every plant has possibility of undergoing unexpected system failure. To avoid the serious system failure in the plants, periodic inspection and replacement based on the lifetime management will be done. There are some ways of inspection such as Radiation Testing (RT), Ultrasonic Testing (UT), Visual Testing (VT) and Eddy Current Testing (ECT). RT and UT are applied to detection of defects inside of the facilities, and VT and ECT mostly focus on evaluation of surface condition. By applying RT or UT, deeply lying defects can be detected from the surface. However, they need relatively high costs for instrument and/or labor to detect defects.

ECT utilizes the electromagnetic induction phenomenon and is considered as a high speed way of inspection with lower costs [1]. In the past research, we developed and examined the possibilities of an NDE system using an HTS SQUID gradiometer for the purpose of detecting flaws in thick metal plates [2-6]. SQUID is one of the most sensitive magnetic sensors, and has high magnetic sensitivity even at low frequencies. Therefore use of SQUID as an ECT sensor is expected to enable detection of deep-lying defects in conductive materials [5]. We actually demonstrated that slit-like defects located at 30-50 mm deep positions in samples consisting of multilayer aluminum plates could be detected by using our eddy-current SQUID NDE system [4,5].

* Corresponding author. Tel.: +81-82-420-0700; fax: +81-82-420-0706.
E-mail address: 261656@pnet.energia.co.jp
Moreover, the ECT technique has an advantage, because there is no magnetic effect even if there is an insulation layer such as thermal insulator or oxidized layer on the materials under test. In power plants, the most practical and accurate way of inspection at present is considered to be UT. However, the surface condition of measuring objects strongly affects inspectional accuracy. Non-metallic or non-contiguous layer prevents the transmission of ultrasonic waves. Thus the insulation or oxidized metal layer must be removed before the inspection. This means the inspection and evaluation by UT needs much cost. Therefore, a high speed and cost effective way of inspection is required. A high speed and cost effective way of inspection helps us to detect serious defects easily, and thus extend the lifetime of instrument in plants.

In the present research, we have tried to detect flaws in a non-magnetic test samples consisting of multilayer aluminum and resin plates, as the first step. The purpose of this research is to examine the ability of SQUID-ECT to detect flaws in a duct through outer layers. The test sample consisted of three layers. The top aluminum plate was assumed as an outer duct layer in the test stack. The resin plates were assumed as an insulation layer. The bottom aluminum plates were assumed as an inner duct layer. A slit-shaped through hole was opened in one of the bottom aluminum plates, and was assumed as a flaw in the duct layer. We demonstrated that we could detect some defects in the test samples by using the eddy-current SQUID NDE system.

2. Experimental

2.1. NDE system

In the present study we applied an HTS SQUID gradiometer to the NDE system consisting of an LN2 cryostat, a double-D type induction coil, an X-Y stage, a FLL circuit (of STAR Cryoelectronics), a lock-in amplifier, and a PC with interfaces that control stage motion and collect data. Figure 1. shows a picture of the gradiometer. The gradiometer has orthogonally arranged two pairs of pickup loops connected in series. The length of the baseline was 8.5 mm and the effective volume was estimated to be 0.64 - 0.85 mm³, and a typical flux noise of this gradiometer was 10-20 μΦ₀/Hz¹/₂ at 1 kHz. In the experiments, only one pair of pickup loops was used [7].

The gradiometer was cooled by thermal conduction through a sapphire rod from a LN2 bath. As shown in Fig. 2, the SQUID gradiometer was set over the test sample, and the test sample was scanned using an X-Y stage. All the NDE experiments were done without using a magnetic shield. We observed additional noise from the stage-driving motor and the flux noise level at 25-100 Hz was around 200 μΦ₀/Hz¹/₂ [5].

2.2. Examined Specimen and NDE Procedure

Figure 3(a) shows the cross-sectional image of a multilayer duct, and Fig. 3(b) shows the configuration of the test sample. The test sample was formed from three layers. The top aluminum plate was assumed as an outer duct or cladding layer in the test stack. The resin plates were assumed as an insulation layer. The bottom aluminum plates were assumed as an inner duct layer. The through hole with a shape of slit, 30 mm in length and 0.5 mm in width, was opened in one of the bottom aluminum plates, and was assumed as a flaw in the duct layer. Each aluminum and resin plate with a size of 30 cm x 30 cm has a thickness of 2 mm and 5 mm, respectively.

![Fig. 1. Thin film SQUID gradiometer.](image)

![Fig. 2. Configuration of eddy-current SQUID NDE system.](image)

![Fig. 3. (a)Cross-sectional image of multilayer duct; (b) Test sample (Multilayer structure).](image)

![Fig. 4. Configuration and scan procedure.](image)
The stack placed on the X-Y stage was continuously moved at a speed of 6 mm/s, as schematically shown in Fig. 4, and output signals from the lock-in amplifier (R-signals) were collected. The lift-off, or the distance between the gradiometer and the surface of the stack was kept at 4.5 mm. The time constant of the lock-in amplifier was set at 30 ms which seems reasonably short as compared with the moving speed. AC current of 50 mA (rms value) was applied to the induction coil and the peak-to-peak magnetic field just below one D-shape induction coil (70 mm in diameter and 150 turn) for 10 mA current was approximately 26 μT. The frequency of induction coil current was varied from 75 to 275 Hz.

3. Result and discussion

3.1. Evaluation of signal intensity

Figure 5(a) shows a 2D image of the magnitude signal from the lock-in amplifier around the flaw on the aluminum plates. Four peaks are clearly seen around the flaw. Figure 5. (b) shows an example of the profile of the magnitude signal in the Y-direction across the maximum point in the 2D image. (White dot line in Fig.5. (a) ) The profile is asymmetric and the offset increases with the Y position. The existence of the offset signal is probably due to the imbalance of the equipment configuration such as a slight inclination of the coil plane against the sample surface. Here, we define the peak signal intensity as the maximum height of the peak from the offset level. The peak signal intensity in each profile was plotted as a function of the depth of the through hole or slit depth.

3.2. Ability of detecting deep-lying defects

Figure 7(a) shows the schematic illustration of another test sample. Here, the total number of aluminum and resin plates was varied from (1+2+1) to (1+2+7). Only the bottom plate of the inner duct layer had a through hole with the shape of slit. Therefore, in the case of the total number of aluminum and resin plates of (1+2+7), the condition of measurement is the same as the slit depth.
depth of 12 mm in Fig. 6(b), for example. And the frequency of induction coil current was varied from 75 to 275 Hz. Figure 7(b) shows the dependence of the peak signal intensity on the slit depth. The signal decays nearly exponentially with the decay length of approximately 5.2 mm (@75 Hz) and 2.8 mm (@275 Hz). These values are about one half of the skin depth of the eddy current \( \delta = \frac{1}{\pi \mu_0 \sigma f} \), where \( \mu = 1.25 \times 10^{-6} \text{H m}^{-1} \), \( \sigma = 3.8 \times 10^7 \Omega^{-1} \text{m}^{-1} \), and \( f \) (=75, 275 Hz), are the permeability, electrical conductivity of aluminum, and the frequency of induction current. This result is reasonable, because in our previous NDE study using the same SQUID gradiometer, a similar relationship between the signal decay length and the skin depth was observed. Here we focus on the frequency of induction coil current. In the case of AC frequency is 275 Hz, peak signals could not be observed in the 2D image when the thickness of inner duct was 12 mm. And in the case of AC frequency is 75 Hz, peak signals could be observed when the thickness of inner duct was more than 12 mm. Therefore, the system noise including the influence of the offset in this system is estimated to be round 3.0 \( \times 10^{-5} \Phi_0 \). Extrapolation of the fitting curve in Fig. 7(b) implies that we can detect flaws located at 15 mm or deeper in the inner duct by using our NDE system.

3.3. Comparison of signal from inside or backside cracking

Here, we focus on the position of the flaw in the test samples. Figure 8(a) shows the dependence of the peak signal intensity on the slit depth for two cases where the flaw is located inside or backside of the test sample. The signal intensity is normalized at the slit depth of 12 mm which means the same configuration for both the cases. In the case of the flaw located at the bottom of inner duct, the decay length evaluated from the gradient of the fitting curve was nearly equal to the half of the skin depth, as mentioned above. However, in the case of the flaw located inside the inner duct, the intensity of the observed signal decays more slowly. This is probably due to the difference in the distribution of eddy current in the test samples. We assumed these two cases as a cracking backside or inside of a duct, as illustrated in Fig. 8(b). This result indicates that the peak signal from cracking located at the backside of the inner duct is larger when the slit depth and AC frequency are the same. Comparing the two cases, the backside cracking and wall thinning is more seriously leading to a system failure. Thus this result suggests that our NDE system can detect the seriousness of the duct condition non-invasively.

![Fig.8. (a) Dependence of the peak signal intensity on the slit depth for two cases; (b) Illustration of cracking inside or backside of a duct.](image)

4. Conclusion

By using the eddy-current SQUID NDE system, we could detect flaws through the outer and insulation layers. By employing a lower excitation frequency at 75 Hz, a slit-like flaw located at 24 mm and 12 mm deep positions from the surface of the top aluminum plate and the bottom aluminum plates, respectively, could be detected. These results suggest that the eddy-current SQUID NDE provides a cost effective way of inspection, for example, for screening before detecting defects more accurately by UT.

References