A Novel Eddy Current Method for Magnetic Plate Identification with Elimination of Lift-off Effect

Kunihisa TASHIRO*1(Mem.), Hiroyuki WAKIWAKA*1(Mem.), Kaiko MINAKATA*1
Toichiro KIMURA*1 and Yoshihiro NAKAMURA*2

A novel eddy current method for magnetic plate identification is presented. This method uses the magnetic property in low frequency and conductive property in high frequency of the magnetic plates. The frequency profiles are measured with a conventional impedance analyzer, as a function of lift-off, which represents the distance between the coil and magnetic plate. If a coil is placed to a magnetic plate, there is a cross frequency at which the measured value is as same as inductance of coil only. The measured value of cross frequency depends on the coil diameter, placed magnetic plate, not strongly depends on the liftoff. In this paper, identification of iron and nickel plates are successfully demonstrated.

A discussion with an iron plate with nickel plating of 40 μm is also mentioned.

Keywords: Cross frequency, magnetic plate, identification, nickel plating.

1. Introduction

Magnetic permeability and electric conductivity are significant parameters to evaluate metal plates in quality and security control. Eddy current method is a well-known tool as non-contact and relatively inexpensive. These features are suitable and acceptable for industrial applications. If a core coil is placed to face a magnetic plate, the changes in the frequency profile of inductance contain both the conductivity and permeability information. It is well-known that the analytical solutions of eddy-current probe-coil problems were given by C. V. Dodd and W. E. Deeds in 1968 [1]. The purpose of this study is to propose the simple and fast identification method.

In previous reports, a suitable air-core coil size was considered [2-3]. The same values in inductance were designed for four coils which had different diameter to generate same magnetic flux at a constant current. The frequency profiles were measured with a conventional impedance analyzer, as a function of distance between the coil and metal plate. When the coils were placed to face an iron plate, a decrease in lift off produced an in-crease in inductance at low frequency, and a decrease in inductance at high frequency. There was a cross frequency at which the measured value was as same as inductance of coil only. It was reported that the value of cross frequency seems to be defined by the coil diameter, be not defined by the lift-off. This measurement technique is known as the swept-frequency eddy current method. In terms of cross frequency, the relationship between the both the conductivity and permeability was discussed with the analytical solutions by Cheng-Chi Tai in 2000[4].

Correspondence: Kunihisa Tashiro, Department of Electrical and Computer Engineering, Faculty of Engineering, Shinshu University, 4-17-1 Wakasato, Nagano, 380-8553, Japan
email: tashiro@shinshu-u.ac.jp

*1 Shinshu University *2 Fuji Electric Corporation

be noted that the conventional consideration usually focused on the constant magnetomotive force \( F = ni \) given by the product of the number of winding and current. In contrast, the coils having same inductance can achieve the constant magnetic flux \( \Phi = Li \). It could be provided another insight when the use of a magnetic core [5].

The lift-off effect is a well-known problem in practical use. To reduce the lift off effects, there are some propositions given by several researches. H. Hosikawa and K. Koyama proposed a new eddy current probe for flaw depth evaluation with minimal lift-off noise [6]. The key point was to use both excitation and detection coil which arranged in orthogonal position. W. Yin and A. J. Peton proposed a ferrite-cored U-shaped sensor for non-magnetic plates [7]. It mentioned the peak frequency at which the imaginary part of the inductance becomes minimum was relatively independent of lift-off variations. C. S. Angani et al. proposed a classification method for wall-tinning evaluation in stainless steel [8]. Using the peak amplitude and its frequency in frequency domain as features, the variation of the thickness and lift-off were detected by Support Vector Machine (SVM).

This paper proposes a novel eddy current method for magnetic plate identification. First of all, experimental setup and the definition of cross frequency are explained. To confirm the proposed method, identification of iron and nickel are demonstrated with several lift-off condition. An iron plate with a nickel plating of 40 μm are prepared for a discussion. By using a conventional optical inspection, it may be identified as a nickel plate. In contrast, the proposed method can identify it as an iron plate without removing the nickel plating.

2. Cross frequency

Fig. 1 shows the setup for eddy current method with an impedance analyzer, Agilent 4294A. The values of series inductance \( Ls \) and resistance \( Rs \) were evaluated in the frequency range from 1 kHz to 1000 kHz. The condition
of evaluation was current constant of 20 mA. The distance between air-core coil and magnetic metal plate defines the liftoff as shown in Fig. 2. A non-metal spacer was used to keep the lift-off. When the coils are placed to face the metal, a decrease in lift off produces an increase in inductance at low frequency, and a decrease in inductance at high frequency. In our previous reports, suitable air-coil size was studied for both magnetic [2] and non-magnetic [3] plate identification.

To generate same magnetic flux at a constant current, four air-core coils were designed and prepared whose value of inductance was as same as 0.2 mH. Fig. 3 shows the photo of coils. The values of mean diameter are 97, 48.2, 24.2 and 12.2 mm, respectively. The specifications were summarized in Table 1. It should be noted that the coils had self-resonance frequency around 2 MHz due to the stray capacitance.

Fig. 4 shows an experimental result for explaining the definition of the cross frequency. Fe represents the magnetic plate made of iron, and Al represents the non-magnetic plate, respectively. If a coil was placed to a magnetic plate, there was a cross frequency at which the measured value was as same as inductance of coil only. If a coil was placed to a non-magnetic plate, there was no cross frequency.

### 3. Identification of iron and nickel plate

Fig. 5 shows an example of experimental results. The material of plate was iron, the mean diameter of coil was 97 mm, and the values of lift-off were 5, 10 and 15 mm, respectively. Because the iron plate has relatively large permeability, the values of inductance was increased at 1 kHz as 10 % when the lift off was 5 mm. Due to the eddy current in the iron plate, the value of inductance was de-
creased at 200 kHz as 30 % with the lift off was 5 mm. Although the differences in lift-off varied the profile of inductance, it was found that the differences in cross frequency were small.

Fig. 6 shows the highlight data of this paper. Two magnetic plates were evaluated with the four coils. The values of cross frequency were plotted as a function of mean diameter of coils, as a parameter of lift-off. When the cross frequency was lower than 1 kHz, the measured frequency range was from 40 to 1 kHz. Values of lift-off decreased the values of fc. When the values of lift-off were 10 and 15 mm for coil1(D=97mm) placed Fe plate, the values of fc were as same as 3.4 kHz. If the values of lift-off were 10 and 15 mm for coil3(D=24.2mm) placed Ni plate, the values of fc were as same as 2.24 kHz. From this experimental result, it was confirmed that the iron and nickel plate were clearly distinguished by the differences in cross frequency. If the diameter of coil was small as 12.2 which was placed to the nickel plate, there were no cross frequency when the lift-off was larger than 5 mm. In other words, this is the limit condition for nickel plate identification with this mean diameter of coil.

4. Discussion

Fig. 7 shows the prepared magnetic plates. Fe and Ni represent the iron and nickel plate which evaluated in the previous chapter. Fe+Ni40um represents the iron plate with nickel plating of 40 μm for the discussion. By using an optical inspection, it may be identified as a nickel plate.

Fig. 8 shows a comparison of the measured values of cross frequency between Ni, Fe and Fe+Ni40um plate. In order to confirm the identification method, the values of lift-off were changed as 7, 12 and 17 mm. As expected before, the iron and nickel plates were clearly distinguished by the differences in cross frequency. From this experiment, the limit values of lift-off were confirmed. If the diameter of coil was small as 12.2, limit values of lift-off were 7 mm and 15 mm for nickel and iron plates, respectively. In contrast, the iron plate with nickel plating was successfully identified as Fe plate. However, the effect of nickel plating on the differences in cross frequency was negligible. It should be mentioned that the nonmagnetic coatings on magnetic base metal and the magnetic coatings on nonmagnetic base metal were demonstrated by Cheng-Chi Tai in 2000[4]. The experimental results were good in agree with the analytical results based on the analytical solution given by Dodd and Deeds. The experimental results in this paper could be explained by the same analytical results.

In our previous reports, identification of several metal plates was demonstrated using a coil of 9 mm in diameter with a ferrite core [9]. The size of plates was as same as this experiment. The magnetic plates were made of iron and nickel, the non-magnetic plates were made of copper and brass, respectively. It should be noted that existing of the plating of nickel or copper were also identified from the frequency profile of the measured inductance. However, the change in the lift-off produced the differences
in frequency profile. With a well-designed magnetic core, a smaller size of coil could identify several magnetic plates using the proposed method. This simple and robust method is also acceptable for classification with a machine learning such as SVM.

5. Conclusion

This paper presented a novel eddy current method for magnetic plate identification with elimination of lift-off effect. The main points were summarized as follows:

1. Definition of cross frequency was explained. It depends on both the coil diameter and placed magnetic plate, not strongly depends on the liftoff.
2. Identification of iron and nickel plates were successfully demonstrated. The values of lift-off were confirmed between 5 mm and 17 mm.
3. The limit values of liftoff were confirmed for the smallest coil having diameter of 12.2 mm. The limit values were 7 mm and 15 mm for nickel and iron plates, respectively.
4. For a discussion, an iron plate with a nickel plating of 40 μm was evaluated with the proposed method. Without removing the nickel plating, it was identified as an iron plate.

Acknowledgment

The authors would like to thank Mr. Ryuji FUJITA who studied at our laboratory until 2018 March. Some of experimental results were based on his master thesis.

References


