APSAEM08 Journal of the Japan Society of Applied Electromagnetics and Mechanics Vol.17, Supplement (2009)

A magnetic Contamination Detection System Based on a High Sensitivity Induction Gradiometer

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From a human safety standpoint, metallic contaminant detection systems are necessary in the food and pharmaceutical industries. If products are packaged in metal wrappings, the standard eddy current method should not be used after packaging. Several groups have developed a SQUID based detection system which measures the remanent magnetism of contaminants. Although that system can satisfy requirements, liquid nitrogen maintenance or a cryocooler is needed. Here we present a novel detection system based on an induction gradiometer. This system is free from heavy cooling system, and the magnetic sensor consists of air-cored coils and simple electronics only.

Key Words: food inspection, magnetic contamination detection system, induction gradiometer

1. Introduction

A metal detection system based on eddy current phenomena is inexpensive and easy to use. One of the famous applications is a metallic contamination detection system in the food industry. Although Japanese companies became more sensitive to "food safety" after the promulgation of the Product Liability Law in 1995, we still face such horrible newspaper articles, "iron powder in a juice can" or "a fish hook inside a hamburger" etc. In this system, temperature and water content in an object affect the eddy current property, so that the expected performance is not achieved in practical use. If products are packaged in conductive cans or wrappings, the undesired eddy current which is produced in the conductive material disturbs the inspection.

Most of possible contaminants are fragmented metal with sharp edges caused by degradation of the processing machine. A stainless material is suitable for the processing machine, which has good corrosion resistance and strength characteristics. In particular, the austenitic stainless material SUS304 accounts for over 60 % of all stainless material production. However, the metal contamination detection system based on eddy current phenomena is not suitable for detecting this kind material due to high electrical resistivity.

Several groups have proposed a SQUID based detection system which measures the remanent magnetism of contaminants [1-3]. They focus on the magnetic properties of SUS304. While the austenitic stainless material SUS304 does not have magnetism, stress-induced martensitic transformation makes it a magnetic material. Although that system can satisfy requirements, liquid nitrogen maintenance or a cryocooler is needed.

Here we present a novel detection system based on an induction gradiometer. In order to prevent the eddy current effect, an excitation frequency of less than 1 kHz should be used. The detection principle based on Faraday's law which is used in the standard eddy current method is not suitable for this kind of frequency, because the output voltage is proportional to the frequency. An induction magnetometer, based on the definition of inductance, does not need cryogenic accessories and complicated electronics. In contrast, it has the ability of detecting weak magnetic fields from extremely low frequencies to those is the audible range (0.01 Hz ~ 10 kHz) [4-8]. To demonstrate this system, we show the specifications of a prototype model as well as an experimental result.

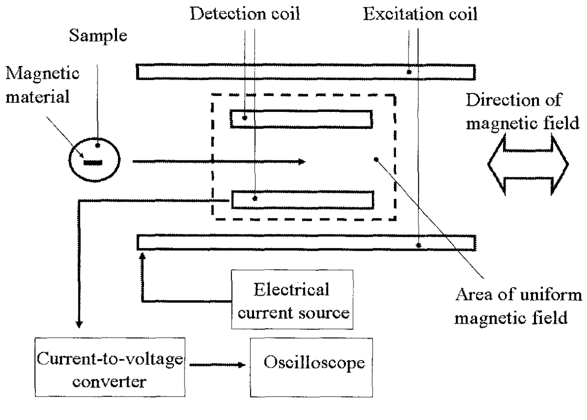

Fig. 1 Schematic diagram of the system

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2. System

2.1 Brief description

Figure 1 shows the schematic diagram of this system. This system has two parts, an excitation coil for generating a uniform magnetic field, and a detection coil having a differential structure. The detection of magnetic field is based on the definition of self inductance instead of traditional Faraday's law. This type of sensor can achieve high sensitivity, comparable to SQUID sensors, at a low frequency [4-8]. When a uniform magnetic flux crosses the differential structured detection coil, a current is not induced. However, an induced current appear in the detection coil if the balance of the magnetic flux is disturbed by a magnetic material. A current-to-voltage converter transforms the weak current into voltage signal.

2.2 Excitation coil

Since the system requires a relatively large, uniform magnetic field, we choose a multi-layer solenoid coil for the excitation. We define the inner diameter D_i as 55 mm and the length l as 165 mm, so that the ratio l/D_i is 3. We calculate the uniformity of the magnetic flux as a function of the normalized outer diameter. It is found that the deviation of the magnetic flux was less than 3 % within 1/3 of the area of normalized length when the ratio of the inner to outer diameter was between 2 and 3. In order to obtain a magnetic flux density of larger than 10 mT while providing a current of 100 mA, we choose the number of turns to be 30,000. Because the capacity of our current source is 1 kW, we decide the diameter of the winding coil is 0.5 mm so that the resistance of the multi-layer solenoid coil becomes less than 1 kΩ. Fig. 2 shows our developed multi-layer solenoid coil, and Table I shows the specifications. The outer diameter became 146 mm. Fig. 3 shows the calculated uniformity of the magnetic flux density.

2.3 Detection coil

In principle, the differential structure of the detection coil should be in good balance. We choose two single-layer solenoid coils for the detection coil. Fig. 4 shows our developed detection coil. The diameter is 35 mm, and the length of each coil is 50 mm. Table II shows the specifications of the detection coil. Fig. 5 shows a schematic diagram of an induction gradiometer.

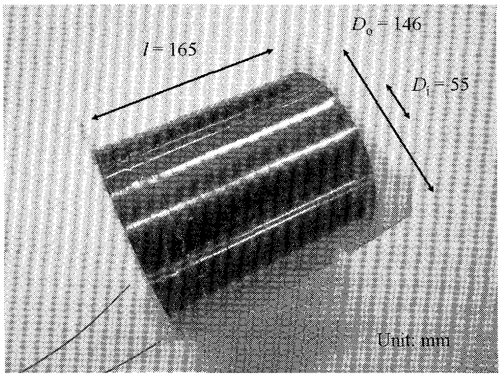

Fig. 2 Our developed excitation coil. The specifications are summarized in Table I

Table I: Specifications of excitation coil

Inner diameter, D_i	55 mm
Outer diameter, D_o	146 mm
Length, l	165 mm
Diameter of winding coil, δ	0.5 mm
Spacing factor, β	0.79
Number of turns, n	30,000 turn
Resistance, R	841 Ω
Inductance, L	30.5 H
Transfer function, B_0 / I *,**	0.20 T/A

* B_0 (T): magnetic flux density at the center

** I (A) : provided electric current

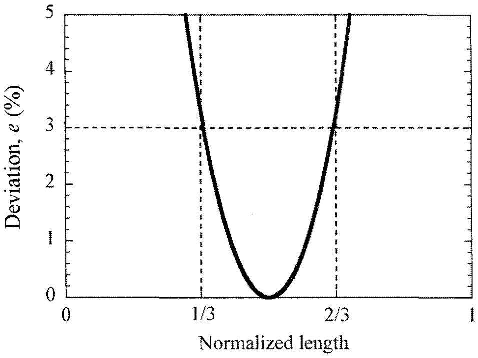

Fig. 3 Deviation of magnetic flux density as a function of normalized length. This result was calculated from Biot-Sarvart's law. The parameters used in this calculation are summarized in Table I

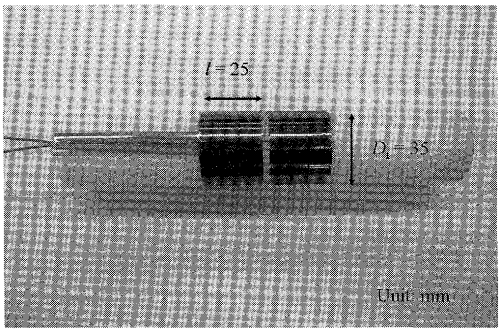

Fig. 4 Our developed detection coil. The specifications are summarized in Table II

Assuming a uniform magnetic flux B (T) crosses one of solenoid coils, the mean cross section area S (m^2) and the number of turns n (turn) lead to the relationship for the flux linkage Φ (Wb) given by

$$\Phi = nSB \text{ (Wb).} \tag{1}$$

From the definition of inductance, the induced current i (A) is proportional to Φ given by

$$\Phi = L_i i \text{ (Wb).} \tag{2}$$

Here, L_i (H) is the self-inductance of a solenoid coil. From Eq. (1) and Eq. (2), the transfer ratio of the magnetic flux to an induced current T_{ib} (A/T) is given by

$$T_{ib} = i / B = ns / L_s \text{ (A/T).} \tag{3}$$

The magnetic flux density produces an equal amount of voltage with a current-to-voltage converter. The induced current is transformed into voltage by an op-amp and a resister R_f (Ω). The sensor output voltage V_{out} (V) is given by

$$V_{out} = -BT_{ib}R_f \text{ (V).} \tag{4}$$

Because the detection coil has a combined inductance L and a combined resistance R, the frequency response of the sensor should also be considered. Since the detection coil is a typical R-L circuit, it behaves as a high-pass filter with a cutoff frequency f_c (Hz) given by

$$f_c = \frac{R}{2\pi L} \text{ (Hz).} \tag{5}$$

Table III shows the specifications of the induction gradiometer.

3. Experiment

Figure 6 shows the experimental setup. A function generator (Wave factory 1941, NF Corp.) and a power amplifier (NF 4510, NF Corp.) are used for the excitation. A uniform magnetic field is generated using the excitation coil. The excitation coil and detection coil are placed coaxially. The electronics (current-to-voltage converter) are shielded by an aluminum box. The output voltage is observed by an oscilloscope (TPS2014, Textronics). The sample is placed inside of the detection coil, at the center of a single-layer solenoid coil. For this experiment, a piece of cheese is used as the sample.

Table II: Specifications of detection coil

Inner diameter, D_i	35 mm
Outer diameter, D_o	36 mm
Length of one coil, l	25 mm × 2
Nunber of turn, n	50 turn × 2
Diameter of winding coil, δ	0.5 mm
Mean cross section area, S	989 mm^2
Self inductance, L_s	74.5 μH
Combined inductance, L	112 μH
Combined resistance, R	1.01 Ω

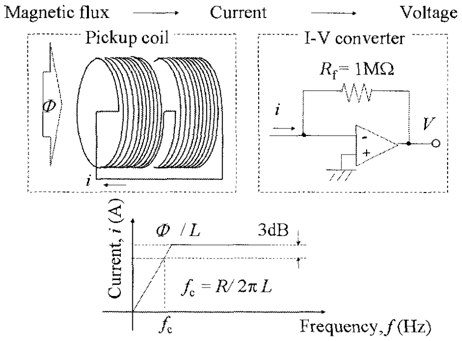

Fig. 5 Schematic diagram of an induction gradiometer with a current-to-voltage converter. If there is an imbalance of magnetic flux density in the detection coil, it is transferred into electric current, and converted into output voltage. The flux-to-current transfer function and the cutoff frequency are defined by the coil properties

Table III: Specifications of induction gradiometer

Power supply*	AA battery × 4
Op-amp	LT1028**
Feedback resistor, R_f	10 MΩ***
Cutoff frequency, f_c	1.71 kHz
Transfer function, T_{ib}	664 A/T
Sensitivity, $R_f \times T_{ib}$	6.64 V/nT

* Ultra low noise DC-DC converter (BR05-I520LB, Bellnix Corp.) is also used for providing suitable voltages of ±15 V.
** Input noise voltage density, 1 nV/Hz$^{1/2}$ at 10 Hz,
Input noise current density, 4.7pA/Hz$^{1/2}$ at 10 Hz
*** High precision resistor; ±1 %, 100ppm/ °C

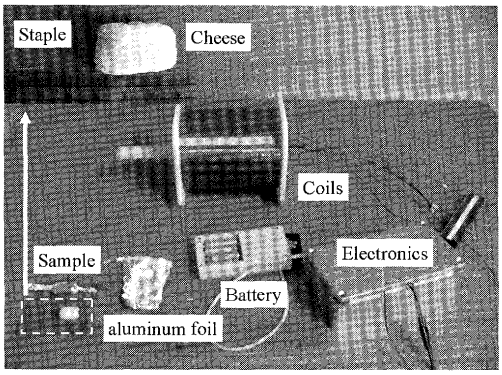

Fig. 6 Experimental setup. The sample, a piece of cheese wrapped in aluminum foil, is to be placed inside of the detection coil, at the center of a single-layer solenoid coil

In order to evaluate the effect of the conductive material on the output voltage, we wrap the cheese in aluminum foil. The thickness of the aluminum lamination is a few mm. To demonstrate the detection system, we embed a staple (width: 0.5 mm, length: 10 mm) into the sample. This kind of stainless material, such as SUS304, is commonly used in production machines, and stress-induced martensitic transformation makes it a magnetic material.

Finally, we decide for the conditions of the excitation field as 10 Hz, 30 $mT_{p\text{-}p}$. This frequency is higher than that of the cutoff frequency of the detection coil. According to principle, the output voltage should be zero when a uniform magnetic flux density is crossed in the detection coil. However, the developed induction gradiometer showed a non-zero signal when the excitation frequency was as high as the cutoff frequency. There are two reasons for this. One is that the valance of the differential structure is imperfect, and the other is that sensitivity is proportional to the frequency below the cutoff frequency.

If no sample was placed in the system, the output voltage was almost zero. It was confirmed that there was no change in output voltage, even if the cheese was wrapped in aluminum foil. In contrast, if a staple was embedded in the sample, the output voltage indicated its existence as shown in Fig. 7.

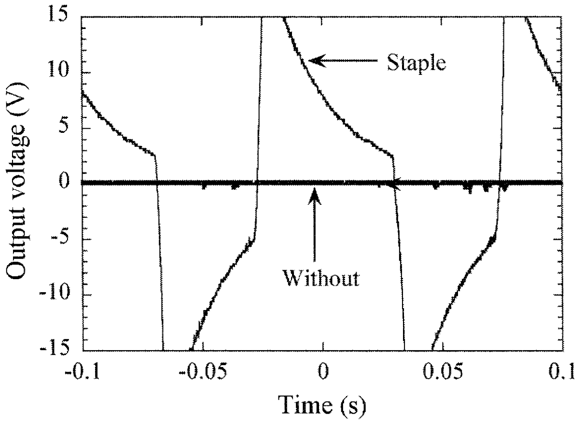

Fig. 7 Experimental results. "Without" represents a sample with no embedded sample. "Staple" represents a sample with an embedded staple

4. Conclusion

We have demonstrated a magnetic contamination detection system using an induction gradiometer. Compared with SQUID based detection systems, this system does not require liquid nitrogen maintenance or a cryocooler. It should be noted that our system is free of lift-off problems which are caused by the finite distance between the sensor and sample. We have chosen air-core solenoid coils for the excitation and the detection. Because samples can be passed through the inside of the coils, it may be suitable for the production line. It is also important to note that this system is compatible with a metal detection system. If we use a high frequency for the excitation, the induction gradiometer can also detect the eddy current signal from the object.

Acknowledgment

This work was supported in part by the Japan Science and Technology Agency, Grant-in-Aid for "SEEDS HAKKUTSU SHIKEN", 2007.

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