INVITED PAPER *Special Section on Superconducting Electronic Devices and Their Applications*

High-T_c SQUID Metal Detection System for Food and Pharmaceutical Contaminants

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SUMMARY There is a possibility that individuals ingest contaminants that have been accidentally mixed with food because processed foods have become very common. Therefore a detection method of small contaminants in food and pharmaceuticals is required. High-T_c SQUID detection systems for metallic contaminants in foods and drugs have been developed for safety purposes. We developed two systems; one large system is for meat blocks and the other small system is for powdered drugs or packaged foods. Both systems consist of SQUID magnetometers, a permanent magnet for magnetization and a belt conveyor. All samples were magnetized before measurements and detected by high T_c SQUIDs. As a result, we successfully detected small syringe needles with a length of 2 mm in a meat block and a stainless steel ball as small as 0.3 mm in diameter.

key words: *SQUID, superconductor, food safety, detection, inspection, contaminant*

1. Introduction

Recently, opportunities for consuming processed foods are increasing in our daily life. Therefore there is a possibility of ingesting unfavorable contaminants, which are accidentally mixed with food. Examples of these contaminants are small chips from processing machines and broken syringe needles used for immunization or hormone injections. Because of the increase in international concern regarding food safety, we should develop a highly sensitive detector to ensure food and drug safety. Although an iron particle detection system has been already developed, there are few reports related to food contaminants and no system for factory use [1]–[3]. Our objective is to fabricate a detection system for factory use. Since the electric conductivity of austenitic stainless steel is low, it is difficult to detect it using the conventional eddy current method. An austenitic stainless steel material is originally nonmagnetic. However, it shows properties similar to those of a ferromagnetic material after martensitic transformation during its fabrication. Therefore it is possible to detect it using a SQUID magnetometer [4]–[8].

In this paper, we describe the systems for small stainless steel contaminants in foods and pharmaceutical drugs using a high-T_c SQUID magnetometer.

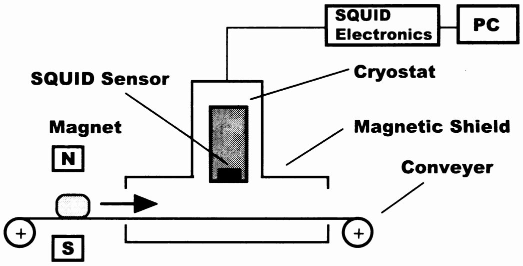

Fig. 1 Block diagram of food contaminant detection system. It consists of a permanent magnet, a conveyor, a magnetically shielded box and SQUIDs.

2. Principles

A block diagram of the detection system is shown in Fig. 1. It consists of a permanent magnet, a conveyor, a magnetically shielded box and SQUIDs. All of the samples move from left to right and pass below the magnet tunnel before the detection. An austenitic stainless steel material is originally nonmagnetic. However, it shows properties similar to those of a ferromagnetic material after martensitic transformation by work hardening during its fabrication [9]. Therefore the magnetization prior to the detection is also effective for austenitic stainless steel contaminants. The magnetic field from a metallic contaminant in food is detected by the SQUID magnetometers when it passes below the magnetometer.

3. System

3.1 Detection System for Meat Block

The target detected by the system is a piece of stainless steel syringe needle $\phi 0.9\,\mathrm{mm} \times 2\,\mathrm{mm}$. The size of a meat block currently processed at a factory in Japan is $640\,\mathrm{L} \times 400\,\mathrm{W} \times 200\,\mathrm{H}$. Thus we decided that the size of the conveyor should meet this requirement. It is fairly large and of 500 mm width. The conveyor speed is also determined by the actual conveyor speed in a factory and is 15 m per minute.

First, we calculated the distribution of the sensitivity of a SQUID sensor to determine the best configuration of the sensors to cover the width of the conveyor. As shown

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$$H_1 = q_m / 4\pi\mu_0 r_1^2$$
$$H_2 = -q_m / 4\pi\mu_0 r_1^2$$
$$r_1 = (r-(L/2))/\cos\theta_1$$
$$r_2 = (r+(L/2))/\cos\theta_2$$
$$\theta_1 = \mathrm{Tan}^{-1}[X/(r-(L/2))]$$
$$\theta_2 = \mathrm{Tan}^{-1}[X/(r+(L/2))]$$
$$H_Z = H_1\cos\theta_1 + H_2\cos\theta_2$$

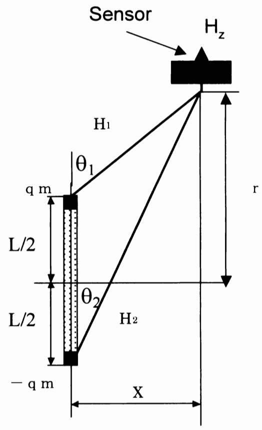


Fig. 2 Calculation of magnetic field from a magnetic dipole. The magnetic field of z-axis H_Z at the position of the sensor was calculated.

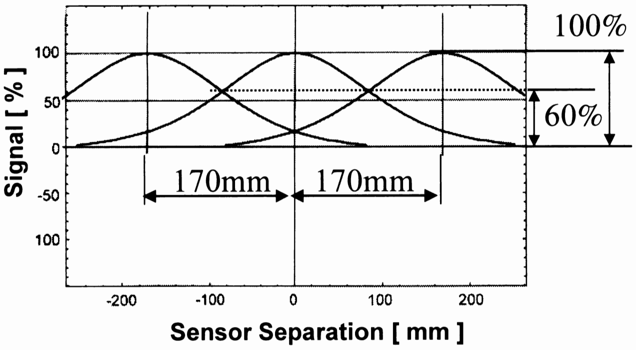


Fig. 3 Distribution of SQUID sensitivity. A sensitivity more than 60% of the maximum value can be obtained at any position on the conveyor of 500 mm width if three SQUIDs are employed.

in Fig. 2, we assumed a magnetic dipole and simulated the magnetic field of z-axis H_Z at the position of the sensor. The distance between the sample and the sensor r was 200 mm. The simulation results are shown in Fig. 3. This shows that if three SQUIDs are positioned with a separation of 170 mm, you can maintain a sensitivity of at least more than 60% of the maximum value at any position on the conveyor with a width of 500 mm. If the distance r becomes smaller than 200 mm, the distribution becomes narrower. However, since the signal intensity is inversely proportional to the cube of the distance, the SQUID can detect the contaminant at any position on the conveyor. In addition, although the contaminant is not vertical but tilted in most cases, we can detect it because there exists the z-component. Therefore, we determined that three SQUIDs are required for this system. The SQUID and its driving electronics employed here were manufactured by Sumitomo Electric Hightechs. The size of the pickup loop is 10 mm × 10 mm square and of high-T_c directly coupled type. The sensitivity of the SQUID is nominally 300 $\mathrm{fT/Hz^{1/2}}$ at 10 Hz. The SQUID driving electronics is of nonmodulation type and its bandwidth is 300 kHz. The details of the SQUID's specifications are shown on the web [10].

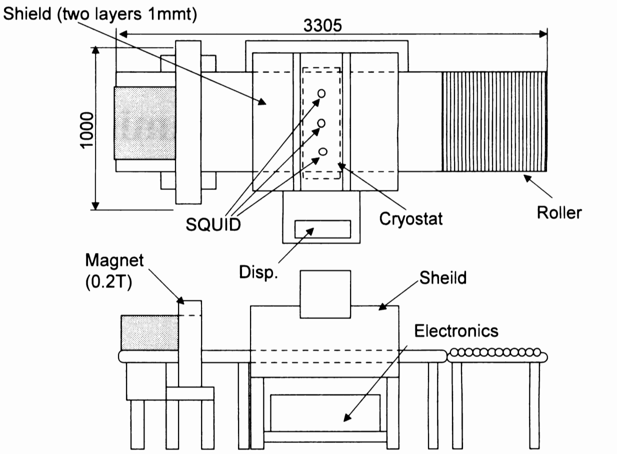


Fig. 4 Design drawing of the large system for meat block. The size is 3305 L × 1290 W × 1610 H.

Figure 4 shows the design drawing of the entire system. The size is 3305 L × 1290 W × 1610 H. The magnet is made of Nd base alloy and its magnetic field is 0.2 T. The LN_2 cryostat used for maintaining the temperature of the SQUIDs at 77 K is made of G-10 glass epoxy resin and its size is 620 W × 200 D × 312 H. The volume of the cryostat is 7 liters and the liquid nitrogen can be maintained for 7 hours without filling. The magnetic shield covering the cryostat consists of two layers of permalloy with a thickness of 1 mm. Most of the frame was made of stainless steel sus304. Although the rollers were originally made of steel, they were replaced with the aluminum alloy to prevent magnetic noise. The system was totally controlled by a PC and you can operate it by touching the display panel in front of the system. All the electronics and the vacuum pump for evacuation of the cryostat were installed underneath the magnetic shield. The signal was passed through a low-pass filter (LPF) at a frequency of 5 Hz or 10 Hz.

We have measured the magnetic field noise of the system without a filter. The signal of the SQUID was measured using dynamic signal analyzer Agilent Technologies 35670A. The noise spectra are shown in Fig. 5. Several peaks around 1 to 5 Hz are due to the environmental noise at the laboratory. It may originate from a voltage stabilizer in the power system. The peak at 60 Hz is from the appliance frequency. The magnetic field noise level at 10 Hz is 300–400 $\mathrm{fT/Hz^{1/2}}$.

For the performance test, a cut stainless steel syringe needle with dimensions of ϕ0.9 mm × 2 mm as a test piece was placed vertically at the center of the conveyor. The distance between the test piece and the SQUID sensor was set at 200 mm. The sample was moved by the conveyor at a speed of 15 m/minute. It was magnetized by the magnet when it passed through the magnet tunnel. Then it was detected when it passed below the SQUID. The time trace of the signal at the center SQUID is shown in Fig. 6. One peak as large as 150 pT can be seen in the middle of the trace. This peak corresponds to the test piece. We could successfully measure the piece of needle as small as 2 mm at a dis-

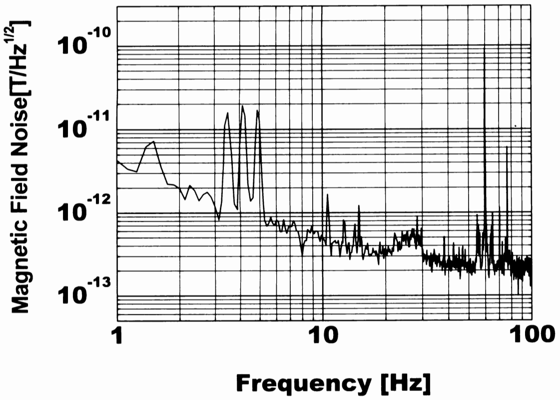


Fig. 5 Noise spectra of the system. Several peaks around 3 to 5 Hz are due to environmental noise at the laboratory. The peak at 60 Hz is from the appliance frequency. The noise at 10 Hz is 300–400 fT/Hz$^{1/2}$.

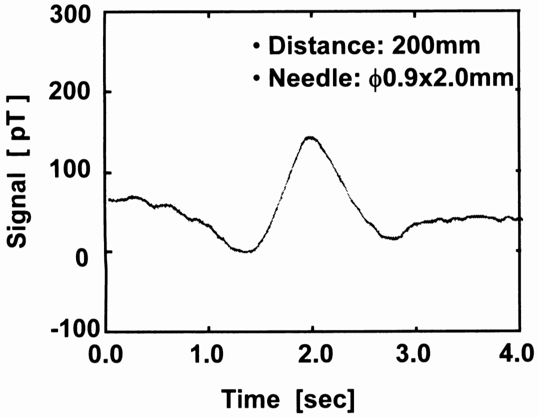
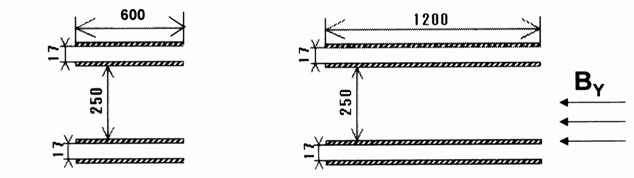


Fig. 6 Time trace of the detected signal. A cut stainless steel syringe needle with dimensions of ϕ0.9 mm × 2 mm was detected. The distance between the test piece and the SQUID sensor was set at 200 mm.

tance of 200 mm.

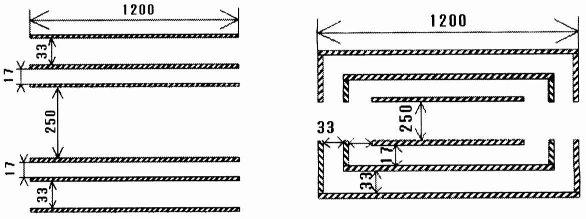
3.2 Detection System for Drug

We also designed a smaller system, which detects contaminants in a drug or a small packaged food. The target to be detected is a stainless steel ball as small as 0.3 mm in diameter. Since the expected dimension of the drug or the packaged food is 150 W × 80 H maximum, the width of the belt conveyor was set at 200 mm and the height from the conveyor to the bottom of the cryostat was 80 mm. The conveyor speed is the same as that of the large system and is 15 m/minute. In the same manner as our large system, we simulated the distribution of the sensing area of the SQUID. As a result, it was found that not one but three SQUIDs are required to have a separation of 35 mm because the sensing area becomes smaller with decreasing the distance.



(a) 2 Layers (short)

(b) 2 layers (long)



(c) 3 layers

(d) 3 layers with flange

Fig. 7 Simulation model of magnetic shield. A magnetic field of 50mT was applied from the Y-direction for each model and the field distribution inside was calculated by FEM.

Table 1 Summary of the simulation.

Applied field: 50μT

Number of layer (Model No.)		Length [mm]	Flux density at Center [μT]	Attenuation [dB]
2	(a)	600	3.20	- 23.9
2	(b)	1200	0.21	- 47.5
3	(c)	1200	0.19	- 48.6
3	(d)	1200 with flange	0.10	- 53.8

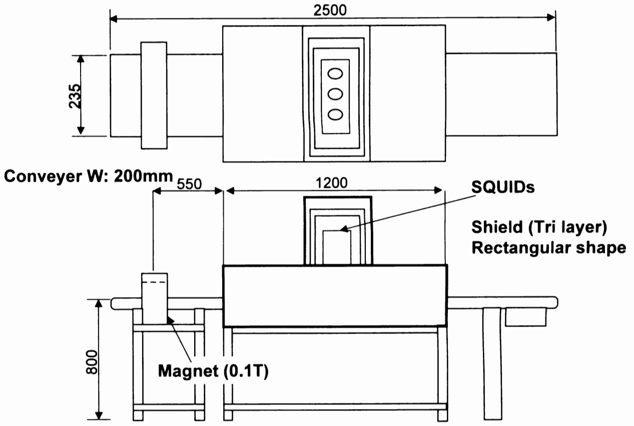


Fig. 8 Design drawing of the small system. The size is 2500 L × 235 W ×800 H.

The magnetic shield is expensive and one of the important components of the detection system because highly sensitive magnetometers are used in a factory where environmental noise is considerably high. Thus, before the design of the system we performed 2D simulation of the magnetic field using four models as shown in Fig. 7. The simulation software *Maxwell* of Ansoft Corporation was used. A magnetic field of 50 μT was applied from the Y-direction for each model and the field distribution inside was calculated by FEM. The thickness of the permalloy layer was 1 mm. A summary of the simulation results is shown in Table 1. The most attenuated result could be obtained using model (d). Thus we employed three layers with a flange as a magnetic shield. Figure 8 shows the design drawing of the small system we constructed. The size is 2500 L × 235 W × 800 H.

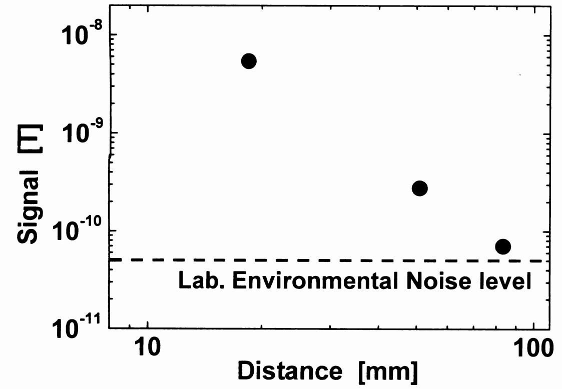


Fig. 9 Magnetic signal vs. distance. The signal intensity is inversely proportional to the cube of the distance.

The magnet is made of Nd base alloy and its magnetic field is 0.1 T, which is half the intensity of the large system. The LN_2 cryostat for maintaining the temperature of the SQUIDs at 77 K is made of G-10 glass epoxy. The system was totally controlled using a PC. The electronic system is almost the same as the large system for meat as described in section 3.1.

We prepared a sus304 stainless steel ball of ϕ0.3 mm. It was magnetized by the permanent magnet and detected by the SQUIDs. The distance dependence of the signal is shown in Fig. 9. It is demonstrated that the signal intensity is inversely proportional to the cube of the distance. The laboratory noise level is also shown for comparison. Although the signal at a distance of 50 mm is six times larger than the noise level, the signal at 80 mm is just 1.5 times larger than the noise. Therefore this system should be used within a distance of 70 mm to obtain a better signal-to-noise ratio.

Detection of a stainless steel ball in an aluminum bag was also performed. The result was the same as that without the bag. This denotes that the aluminum bag is invisible to the SQUID.

4. Conclusion

We have constructed and demonstrated two types of detection systems for metallic contaminants in food or drug. One is for a large meat block and the other is for a pharmaceutical drug or a small packaged food. The former system could successfully detect a stainless steel needle of ϕ0.9 mm × 2 mm and the latter system could detect a stainless steel ball as small as 0.3 mm in diameter. These detection levels are above factoroy requirements.

Acknowledgment

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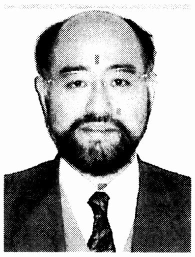

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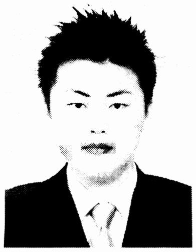

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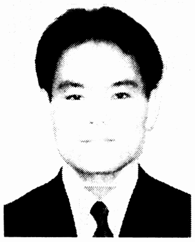

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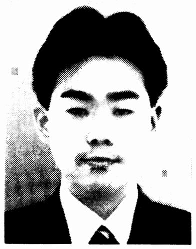

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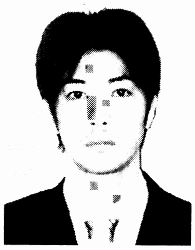

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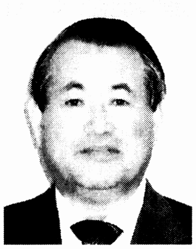

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