

Detection of Metal Contaminants in Food using High Tc SQUIDs Magnetometer

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Abstract. A PC controlled food contaminant detection system for practical use was designed and constructed. The system we have developed is the High-Tc SQUID based system, which is covered with waterproof stainless steel plates and acceptable to HACCP (Hazard Analysis and Critical Control Point) program. The outer dimension of the system is 1500L mm x 477W mm x 1445H mm and the acceptable object size is 200W mm x 80H mm. This system employed a double-layered permeable metallic shield with thickness of 1 mm as a magnetically shielded box. The distribution of the magnetic field in the box was simulated by FEM; the gap between each shield layer was optimized before fabrication. Then the shielding factor of 732 in Z-component was achieved. This value is good enough to operate the system in a factory. As a result, we successfully detected a steel ball as small as 0.3 mm in diameter with a distance of 75 mm.

Introduction

We are consuming processed foods such as a hamburger in our daily life. There is a possibility that unfavorable contaminants are accidentally mixed with foods even if many efforts have made to exclude such a chance in the factory. Examples of these contaminants are small chips like fine wires of a strainer element of processing machines and broken syringe needles used for immunization or hormone injections to food animals. Because of the increase in international concern regarding food safety, we should develop a highly sensitive detector to ensure food and drug safety. There are some detection methods such as eddy current, X-ray and SQUID (Superconducting Quantum Interference Device) system. The Eddy current method is widely used in the world; however, the sensitivity is much affected by the conductivity of the contaminants and the food itself. Since wires of strainer elements or syringe needles are made of stainless steel, their conductivities are lower than carbon steel. Therefore it is hard to detect stainless steel contaminants by the eddy current method. X-ray method is strong candidate and is getting popular in food factories. It can detect not only metallic but ceramic contaminants. However, the maintenance cost is expensive and its lower detection limit for practical use is in the range of mm order. Several institutes and we have proposed the detection system using a SQUID magnetic sensor to circumvent the difficulties [1-5]. The detection technique is based on recording the remanent magnetic field of contaminant by SQUID sensors. Here we describe a contaminant detection system for food contaminants with a robust magnetically shielded box.

Principle

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 through 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 history during its fabrication. Therefore the magnetization prior to the detection is also effective for austenitic stainless steel contaminants. The remanent magnetic field from a metallic contaminant in food is detected by the SQUID magnetometers when it passes below the magnetometer.

System

General specification. The size of the whole system is 1500L mm x 477W mm x 1445H mm, which is covered with stainless steel, and approvable under the HACCP (Hazard Analysis and Critical Control Point). The magnet is made of Nd base alloy and its magnetic field is 0.1 T. The LN₂ cryostat used for maintaining the temperature of the SQUIDs at 77 K consists of three separated glass dewars. The size of the each dewar is OD 70 mm x ID 50 mm x 300L mm. The total volume of the cryostat is 1.5 liters and the liquid nitrogen can be maintained for 12 hours without filling. An automatic LN₂ supply system is attached. Three high T_c SQUIDs are installed in 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 x 10 mm square and of high-T_c directly coupled type. The sensitivity of the SQUID is nominally 300 fT/Hz^{1/2} at 10 Hz. The SQUID driving electronics is of modulation type and its bandwidth is 10 kHz. The signal was passed through a low-pass filter (LPF) at a cutoff frequency of 5 Hz. 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 except for PC and the glass dewars with SQUIDs were surrounded by aluminum shield panels preventing electromagnetic disturbance outside the system. The appearance of the system is shown in Fig. 2.

Magnetic shield design. Since the magnetic shield covering the sensors is the crucial part of the system for practical use, it was designed in cautious manner. Thus, before the design of the system we performed 3D analysis of the magnetic field distribution inside the magnetic shield.

Firstly, we made a simple tri-layered cylindrical magnetic shield model on a PC for finite element method (FEM) simulation as shown in Fig. 3. The dimension is $\phi 850$ mm x $\phi 750$ mm x $\phi 650$ mm x 1600L mm. The thickness of the material is 2 mm. The simulation software (Ansoft Corporation,

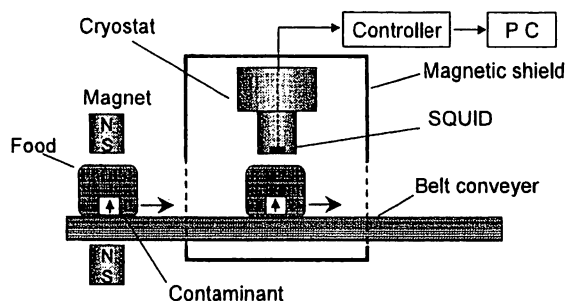


Fig. 1 Block diagram of food contaminant detection system. It consists of a permanent magnet, a conveyor, a magnetically shielded box and SQUIDs.

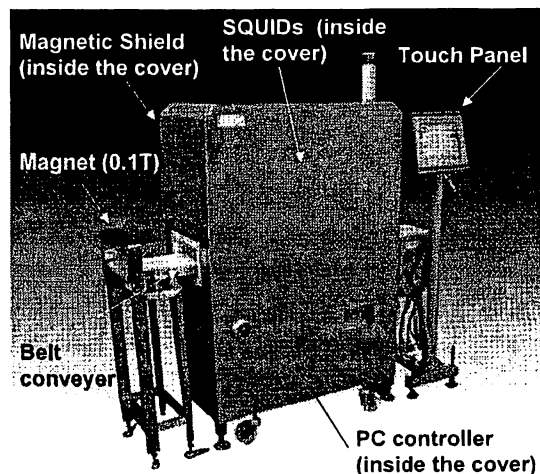


Fig. 2 Appearance of the whole system. The size of the system is 1500L mm x 477W mm x 1445H mm and is covered with stainless steel.

Japan) was used. A dc magnetic field of $5.3 \mu\text{T}$ was given along Z-direction and the field distribution inside was calculated as a function of the relative permeability, μ_s , of the material. The shielding factor (SF) was calculated as a ratio of the imposed external magnetic induction to the value of the magnetic induction at the center of the internal region of the shield. Fig. 4 shows the dependence of the SF on the relative permeability. It indicates that the SF increases linearly along the relative permeability μ_s . Then we made the real tri-layered cylindrical magnetic shield by using permalloy, which has the same dimension as the model above, for comparison. The SF was obtained by applying dc field of $5.3 \mu\text{T}$; the SF was 1250 at the center of the cylinder. Thus we can estimate the relative permeability of the material is about 20000 by comparing the value shown in Fig. 4.

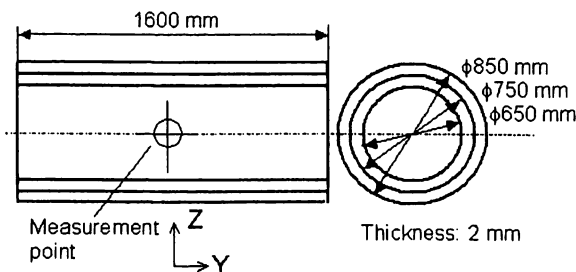


Fig. 3 Simple tri-layered cylindrical magnetic shield model for Finite Element Method (FEM) simulation.

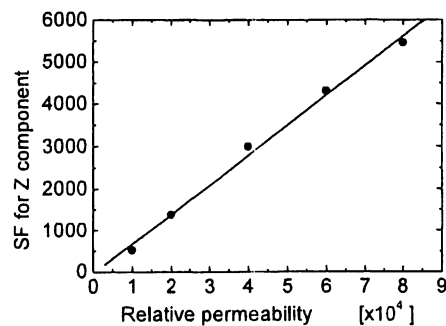


Fig. 4 Dependence of the SF on the relative permeability. It indicates that the SF increases linearly along the relative permeability μ_s .

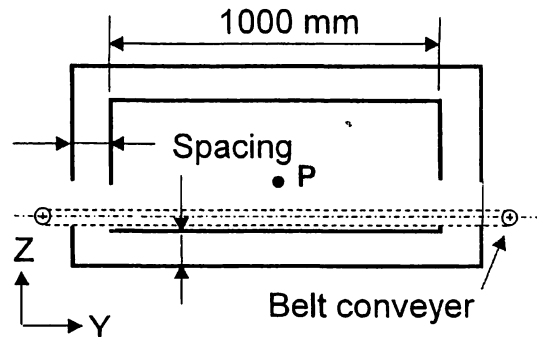


Fig. 5 Rectangular shape model for FEM simulation. This model is more realistic and suitable for the system. The number of the shield layer is two. The size of the inner shield box is fixed as (1000L mm x 252W mm x 482H mm); the spacing between inner and outer box is changed from 10 mm to 400 mm.

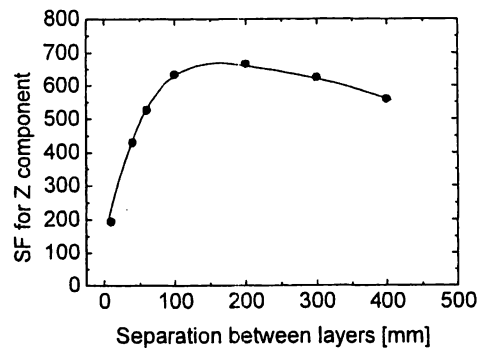


Fig. 6 Shielding factor as a function of layer separation. Shielding factor presents a non-linear behavior and maxima at around the layer separation of 100 to 200 mm.

Secondly, a rectangular shape model as shown in Fig. 5, which is more realistic and suitable for our system was employed for the simulation. The number of the shield layer was two. The same software was used for the FEM simulation. A magnetic field of $50 \mu\text{T}$ was given along Y-direction with angle of 10 degrees. The thickness of the permalloy layer and the relative permeability were supposed as 1 mm and 20000, respectively. The size of the inner shield box was fixed as 1000L mm x 252W mm x 482H mm; the spacing between inner box and outer box was changed from 10 mm to 400 mm. The shielding factor SF was calculated as the same manner as the cylindrical case. Fig. 6 shows the

shielding factor calculated as the ratio between the Z-component of magnetic field outside and at the center of the shield ($z=140$ mm from the bottom of the inner shield box). The shielding factor presents a non-linear behavior and maxima at around the layer separation of 100 to 200 mm. Therefore the separation of 100 mm was used for the design of the shield box by the consideration of its cost of the material. In this model the shielding factor SF of 634 was obtained. Then the dependence of the SF on the length of the inner shield box along the Y direction was investigated. The results are shown in Fig. 7. The Shielding factor SF shows the plateau region around Y length of 700 to 1000 mm. Thus the Y length of 700 mm was employed for real design because of the cost reduction. We also calculated the SF when the height of the inner shield box was extended for 50 mm, which gives more space for electronics in the shield. The shielding factor SF of 523 was obtained at the Y length of 700 mm and the height of 532 mm, which is high enough for practical use. Therefore we finally decided the shield design as inner shield: 700L mm x 252W mm x 532H mm and outer shield: 902L mm x 454W mm x 734H mm.

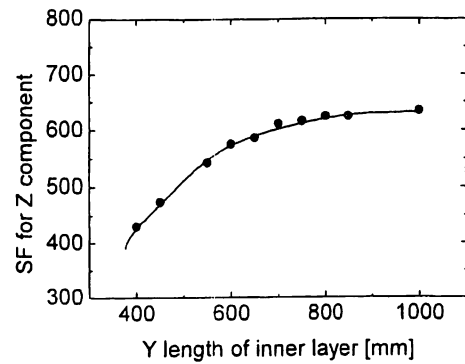


Fig. 7 Dependence of the SF on the length of the inner shield box along the Y direction. The Shielding factor SF shows the plateau region around Y length of 700 to 1000 mm.

Characterization of the system

The double-layered shield box described above was manufactured. Then the actual shielding factor of the shield box was evaluated by applying dc magnetic field; SF of 732 was obtained and it was 40 % larger than the calculated value. This suggests that the relative permeability of the shield materials is better than the value we expected because it is dependent on the annealing conditions. The performances of the total system were tested. Steel balls and stainless steel balls with different diameters were prepared as test samples. The samples were put on the conveyer and magnetized.

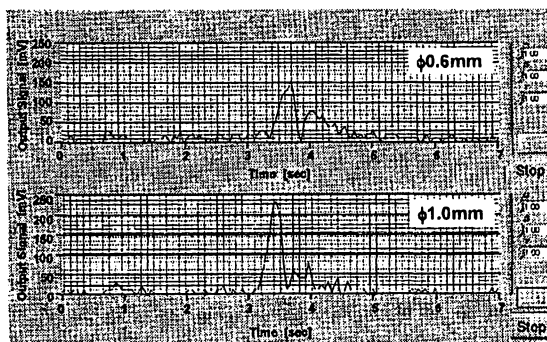


Fig. 8 Time traces of the signals from a SQUID located in the center. They were recorded when each stainless steel ball (sus304) with a diameter of 0.6 mm and 1.0 mm passed through just under the SQUID with separation of 75 mm. Conversion factor of Volt to Tesla is 1.2 nT/V.

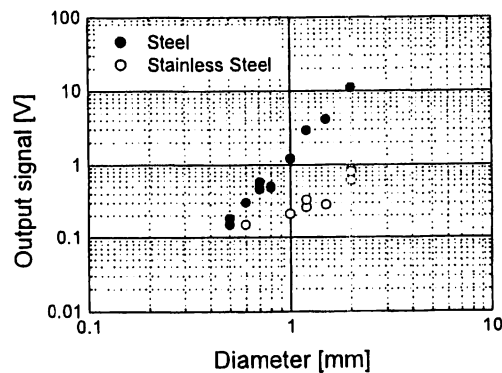


Fig. 9 Dependence of the SQUID output peak signal on the sample diameter. For steel balls (solid circle), signals scale well with the cubic of the diameter. On the contrary, for stainless steel balls (open circle), signals deviate from expected value.

Then they were passed below the SQUIDs with speed of 14 m/min. Fig. 8 shows the time traces of the absolute signal values from a SQUID located in the center. They were recorded when each stainless steel ball (sus304) with a diameter of 0.6 mm and 1.0 mm passed through just under the SQUID with separation of 75 mm. Conversion factor of Volt to Tesla is 1.2 nT/V. The clear signals with S/N of more than 4 were obtained. The signal was not affected by either electromagnetic radiation of a mobile phone or motion of a bulky steel cart near the system. Fig. 9 shows the dependence of the SQUID output peak signal on the sample diameter. For steel balls (solid circle), signals scale well with the cubic of the diameter. It means that signal is proportional to the volume of each sample. On the contrary, for stainless steel balls (open circle), which are nominally austenitic stainless signals deviate from expected value because their magnetism depends on the martensitic phase content which is affected by the mechanical history of the balls.

Summary

We have designed and constructed a food contaminant detection system using high T_c SQUID magnetometers. The detection technique is based on recording the remanent magnetic field of contaminant by SQUID sensors. The magnetic shield which covers the SQUID sensors was designed in cautious manner because it is one of the crucial parts of the system for practical use. After the FEM simulation, the double-layered rectangular magnetic shield using permalloy metal was made; its shielding factor SF of 732 was obtained. Test spherical stainless steel ball as small as 0.3 mm in diameter was successfully detected with more than S/N of 4. The system was robust and not affected by the disturbance of electromagnetic wave from cell phone or motion of an iron-made bulky carrier.

Acknowledgments

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