Metallic Contaminant detection Systems for Foods and Beverages by High Tc SQUID Magnetic Sensor

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Abstract – A computer controlled contaminant detection systems based on high-Tc Superconducting Quantum Interference Device (SQUID) for food and drink have been designed and constructed. The systems we have developed are the High-Tc SQUID based systems, which are covered with waterproof stainless steel plates and acceptable to HACCP (Hazard Analysis and Critical Control Point) program. One system is for foods and the other is for beverages. The systems employed double-layered permeable metallic shield plates 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 more than 700 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 by ether of the system. We believe that these systems are the fist practical SQUID based metallic contaminant detectors for food and beverages.

Keywords: SQUID, contaminant, detection, food safety, NDE, shield.

1. Introduction

The consumption of processed foods such as a hamburger is a common feature of daily life. There is a possibility that unfavorable contaminants are accidentally mixed with foods although great efforts are 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. Several detection methods currently exist, such as eddy current detector and X-ray imaging. 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 imaging is strong candidate and is getting popular in food factories. It can detect not only metallic but ceramic contaminants. However, maintenance costs for X-ray equipment are high, and the lower detection limit for practical X-ray usage is on the order of 1 mm. Along with others, the authors have proposed the development of a detection system using a SQUID magnetic sensor to circumvent the difficulties outlined above [1]-[5]. The detection technique is based on recording the remanent magnetic field of contaminant by SQUID sensors. Here we describe contaminant detection systems for foods and beverage with a robust magnetically shielded box.

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2. 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 objects 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 sensor.

3. System for Foods

3.1 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 LN_2 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 O.D. 70 mm x I.D. 50 mm x 300 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 LN_2 supply system is attached. Three high Tc 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-Tc directly coupled type. The sensitivity of the SQUID is nominally 300 $fT/Hz^{1/2}$ at 10 Hz. The SQUID driving eletronics is of modulation type with a bandwidth of 10 kHz. The signal is passed through a low-pass filter (LPF) at a cutoff frequency of 5 Hz. The system was totally controlled by a PC and can be operated 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 which prevent electromagnetic disturbance outside the system. The appearance of the system is shown in Fig. 2.

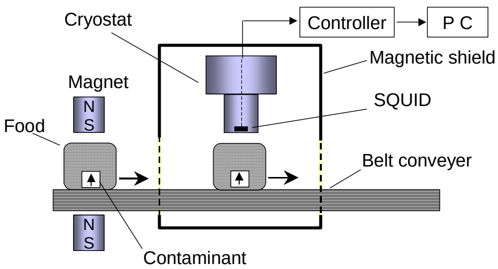

Fig. 1. Block diagram of a contaminant detection system for food.

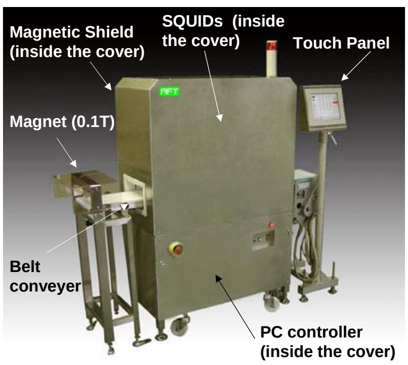

Fig. 2. Appearance of the whole system. The size of the system is 1500L mm x 477W mm x 1445H mm and is covered with stainless steel.

3.2 Magnetic shield design

Since the magnetic shield covering the sensors is the crucial part of the system for practical use, special attention was given to its design. Prior to system design, 3D analyses of the magnetic field distribution inside the magnetic shield were carried out.

Firstly, a Finite Element Model (FEM) simulation was performed on a PC for the simple tri-layered cylindrical magnetic shield model shown in Fig. 3. The model dimensions were ϕ850 mm x ϕ750 mm x ϕ650 mm x 1600L mm. The thickness of the material was 2 mm. The simulation software (*Ansoft Corporation*, Japan) was used. A dc magnetic field of 5.3 μT 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

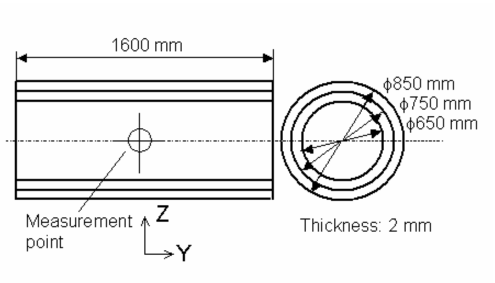

Fig. 3. Simple tri-layered cylindrical magnetic shield model for Finite Element Method (FEM) simulation.

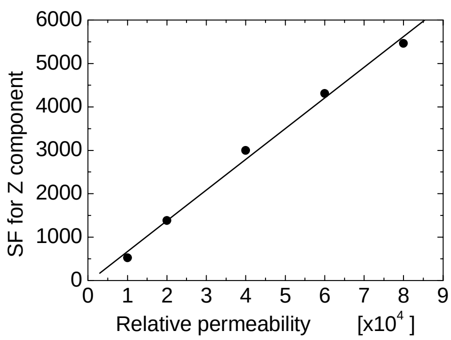

Fig. 4. Dependence of the SF on the relative permeability. It indicates that the SF increases linearly along the relative permeability μ_s.

relative permeability. It indicates that the SF increases linearly along the relative permeability μ_s. An actual tri-layered cylindrical magnetic shield, having the same dimensions as the model described above, was then built using permalloy. The SF of this shield was obtained by applying a dc field of 5.3μT; the SF was found to be 1250 at the center of the cylinder. We thus estimate the relative permeability of the material to be about 20000 by comparing the value shown in Fig. 4.

Secondly, a rectangular shape model as shown in Fig. 5, which is more realistic and suitable for our system was employed for the simulation. Two shield layers were used. The same software was used for the FEM simulation. A magnetic field of 50 μT 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. Figure 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. The final dimensions of the inner shield (L x W x H) were set at 700 mm x 252 mm x 532H mm, while the outer shield was 902 mm x 454 mm x 734 mm..

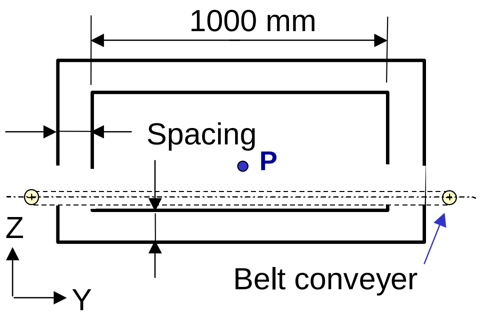

Fig. 5. Rectangular shape model for FEM simulation. This model is more realistic and suitable for the system. The number of the shield layer is two.

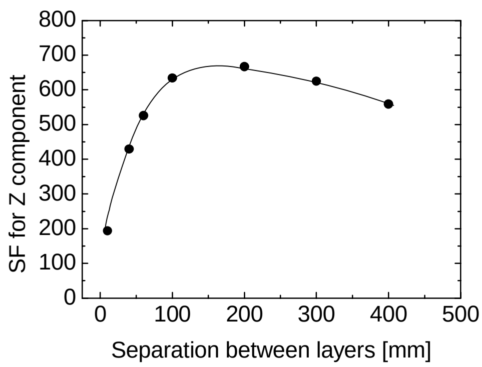

Fig. 6. Shielding factor as a function of layer separation. Shielding factor presents a non-linear behavior and maxima at around the layer separation of 100 to 200 mm.

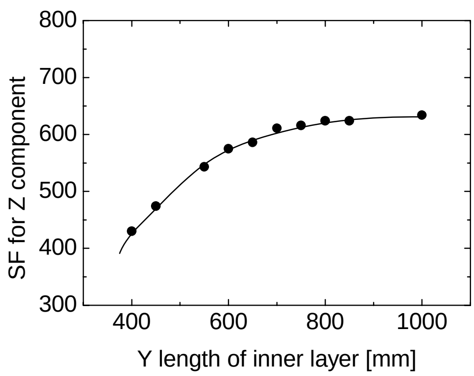

Fig. 7. Dependence of the SF on the length of the inner shield box along the Y direction. The Shielding factor SF shows the plateau region around Y length of 700 to 1000 mm.

3.3 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. Then they were passed below the SQUIDs with speed of 14 m/min. The signal was not affected by either electromagnetic radiation of a nearby mobile phone or the motion of a bulky steel cart near the system. Fig. 8 shows the dependence of the SQUID output peak signal on the sample diameter. Conversion factor of Volt to Tesla is 1.2 nT/V. For steel balls (solid circle), signals scaled well with the cubic of the diameter. This suggests that the signal is proportional to the volume of each sample. On the contrary, stainless steel balls (open circles), which are nominally austenitic stainless, produced signals which deviated from expected values because their magnetism depends on the martensitic phase content which is affected by the mechanical history of the material [6].

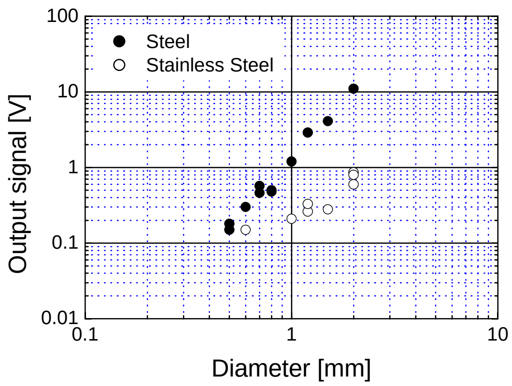

Fig. 8. Dependence of the SQUID output peak signal on the sample diameter. Conversion factor of Volt to Tesla is 1.2 nT/V.

4. System for Beverages

4.1 General Specification

Since the system with a conveyer can not be applied to a liquid material in process, there is a strong demand for detection of metallic contaminants in a beverage such as juice with pulp because a strainer cannot be applied to such a pulpy liquid. Therefore we developed the detection system based on high-Tc SQUID for a beverage. The outer dimensions of the system are 800 mm length x 530 mm width x 1560 mm height. A straight plastic tube with a dimension of 26 x 66 mm, in which a beverage flows is penetrating the system. The two identical SQUIDs were employed so that they can keep the sensitivity over the full width of the tube. The configuration of the SQUIDs is shown in Fig. 9. The separations of the SQUIDs are 40 mm in the direction across the tube and 42 mm in the direction parallel to the flow, respectively. The principle of the detection is the same as that of the detection system for food described above with exception of no belt conveyer. Figure 10 shows the appearance of the system for beverages. A water circulation system with a reservoir tank was prepared for the demonstration. A sample contaminant in the water comes out from the reservoir tank and is magnetized by the magnet. Then it passes below the SQUIDs and finally it is retrieved at the strainer in the reservoir tank.

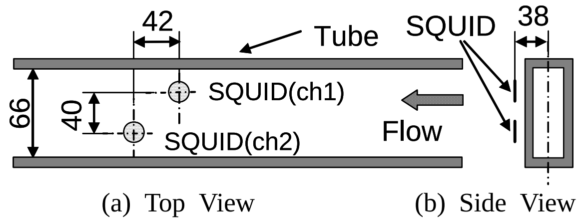

Fig. 9. Configuration of the SQUIDs. Two identical SQUIDs were employed so that they can keep the sensitivity over the full width of the tube.

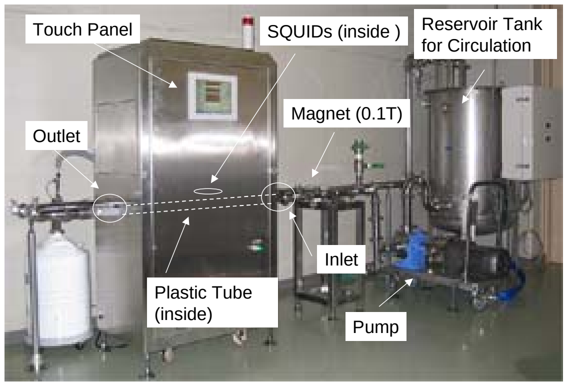

Fig. 10. The appearance of the system for beverages. A water circulation system with a reservoir tank was prepared for the demonstration.

4.2 Characterization of the system

The performances of the system were examined. Stainless steel balls with diameter of 0.3mm were prepared as test samples. The sample was put in a small capsule with some copper weight. Before the measurement, it was confirmed that the copper weight does not affect the output signals. Water with a capsule run in the tube with speed of 0.88 m/s. The signals from the SQUID output were directed to the A/D converter of PC through a band pass filter with frequency of 0. 2 Hz and 100 Hz to eliminate a dc offset and noise. Fig. 11 shows the time trace of signals from the SQUID ch1 and ch2, respectively.

Conversion factor of Volt to Tesla is 30 pT/V. Clear peaks can be seen in the figure. The difference of the peak values between ch1 and ch2 is due to the position of the capsule. In this case, the distance between the capsule and the ch1 must be closer than the ch2. The signal is large enough and S/N ratio is more than 5. This detection level was hard to be achieved by a conventional eddy current or X-ray detection method.

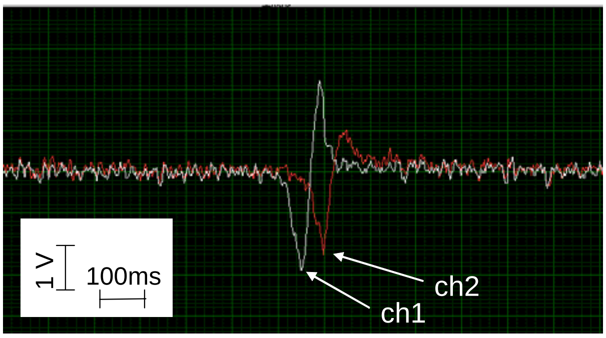

Fig. 11. Time trace of the signals from SQUIDs. Conversion factor of Volt to Tesla is 30 pT/V. Clear peaks can be seen.

5. Conclusion

We have designed and constructed contaminant detection systems for foods and beverages using high Tc 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 more than 700 was obtained. Test spherical stainless steel ball as small as 0.3 mm in diameter was successfully detected with more than S/N of 5. The systems were robust and not affected by the disturbance of electromagnetic wave from cell phone or motion of an iron-made bulky carrier. This detection level was hard to be achieved by a conventional X-ray detection method. We believe that this system is the fist SQUID based metallic contaminant detector for a beverage.

Acknowledgements

This work was supported in part by Ministry of Education, Culture, Sports, Science and Technology

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