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Prototype of Multi-Channel High-Tc SQUID Metallic Contaminant Detector for Large Sized Packaged Food

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SUMMARY We report on the fabrication of a magnetic metallic contaminant detector using multi-channel high-Tc RF-SQUIDs (superconducting quantum interference devices) for large packaged food. For food safety finding small metallic contaminants is an important issue for a food manufacturer. Hence, a detection method for small sized contaminants is required. Some detection systems for food inspection using high-Tc SQUIDs have been reported to date. The system described here is different from the previous systems in its permitted size for inspection, being larger at 150 mm in height × 300 mm in width. For inspection of large sized food packages, improvement of the signal to noise ratio (SNR) is an important issue because the signal intensity is inversely proportional to the cube of the distance between the SQUID sensor and the object. Therefore a digital filter was introduced and its parameters were optimized. As a result, a steel ball as small as 0.5 mm in diameter at a stand-off distance of 167 mm was successfully detected with more than SNR = 3.3.

key words: *SQUID, detection, food contaminant digital filter*

1. Introduction

In the area of food safety, the mixing of contaminants with food is a serious problem for not only consumers but also manufacturers. Although great efforts are made to prevent contamination during the processing of food, there remains the possibility of small metallic contaminants being mixed in with food. Examples of such contaminants are small metal screws, or fine wires from processing machinery. Several detection methods currently exist, such as X-ray imaging, and eddy current detection systems. The X-ray radiation method is a useful technique and is becoming increasingly popular in food factories. However, the lower detection limit for practical X-ray usage is in the order of 1 mm. Moreover, X-ray radiation sometimes causes ionization of the food, which damages good bacteria and degrades the taste. For instance, the X-ray method cannot be applied for food that has lactic acid bacteria. The eddy current method is widely used for food inspection. However, its sensitivity is highly affected by the conductivity of the contaminants and the food. Thus, definition of the threshold for food such as frozen meals is difficult. In recent years, detection systems based on superconducting quantum interference devices (SQUIDs) have been proposed and developed. This detection technique is based on recording the remnant magnetic field of a contaminant using SQUID sensors [1]–[5].

We designed and realized a prototype system using rf-SQUIDs for practical use. This system permits a food package with a height of 150 mm and a width of 300 mm, which is large enough for food inspection in a factory. The acceptable weight is strengthened and is 10 kg/m by utilizing a durable belt conveyor.

The most important thing is obtaining a better signal to noise ratio (SNR) because the signal is reduced if the distance between the sensor and the object (stand-off distance) becomes as large as 167 mm. Thus we considered the use of a digital filter. A steel ball with a diameter of 0.5 mm is a standard detection target size for metal contaminants and is generally accepted by food manufacturing plants. Thus our target size of the metallic contaminant in food with a stand-off distance of 167 mm was decided as ϕ0.5 mm with SNR > 3.0 (corresponding to a food product height of about 150 mm).

We describe the detail of the detection system including the optimization of the parameter of the digital filter and evaluation results.

2. System Design

2.1 General Specification

A schematic diagram and a picture of the developed system are shown in Fig. 1. Three RF SQUIDs are installed in three individual glass dewar for each, where they are surrounded by an aluminum electromagnetic shield. The SQUIDs are cooled at 77 K by liquid nitrogen, which can be filled automatically from an external reservoir by a pump. The detection region is surrounded by a 3-layered mu-metal magnetic shield for attenuation of environmental noise. A strong permanent magnet is installed outside a magnetic shield. Two conveyors are employed, one for detection and the other for magnetization. The split conveyors prevent the generation of false signals by magnetized contaminants on the conveyor. The food for inspection moves from left to right and passes through a permanent magnet before detection. After magnetization, the remnant magnetic field from metallic contaminants is detected by the RF SQUID magnetometers when it passes below the sensor. The size of the whole system (W × D × H) is 3310 mm × 896 mm × 1665 mm and is covered with a stainless steel panel. In the newest version, a feature of front loading system is employed as shown in the inset of Fig. 1 (b). The aluminum electromag-

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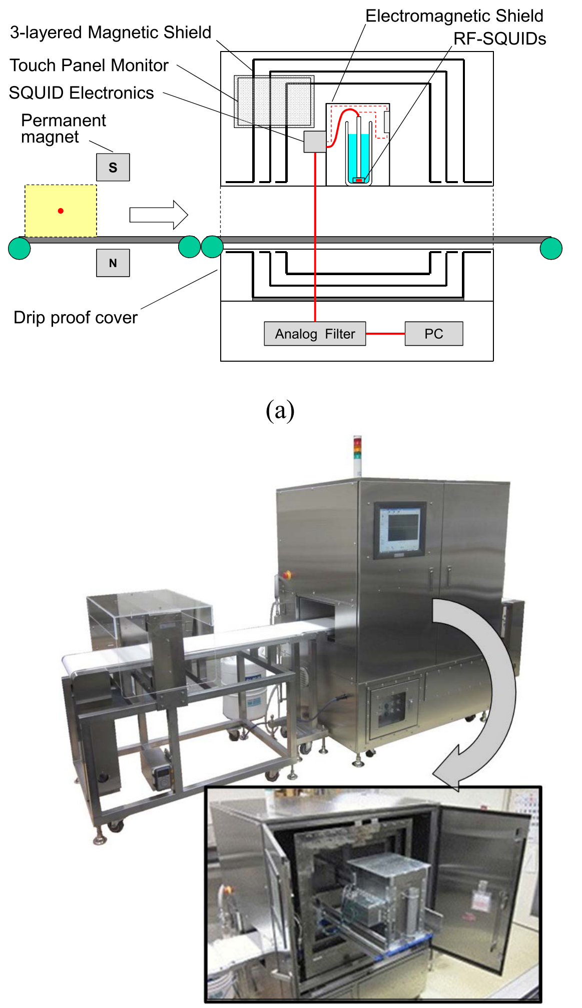

Fig. 1 A schematic diagram (a) and a picture (b) of the developed system. Inset shows the appearance of the electromagnetic shield with SQUID electronics when the front door is open.

netic shield box including RF-SQUIDs, which is on the rails of the drawer at the bottom can be easily pulled out for major maintenance after opening the front doors and the front lid of the magnetic shield box.

2.2 Details of the Detection System

The permanent magnet is made of an *Nd*-based alloy. The magnetic flux density at the center is 236 mT and remains over 218 mT along the conveyor width of 300 mm.

The SQUID and its driving electronics were specially designed for this system and manufactured by Juelicher SQUID GmbH (JSQ). The rf-SQUID magnetometer is mounted in a capsule made of resin, with an outer diameter of 29 mm, and connected to a fiber rod with a pin and a socket system. The noise of each SQUID magnetometer in the system during operation is shown in Fig. 2. It is 300 - 600 fT/Hz$^{1/2}$ at 10 Hz and 120 - 180 fT/Hz$^{1/2}$ at 1 kHz. One

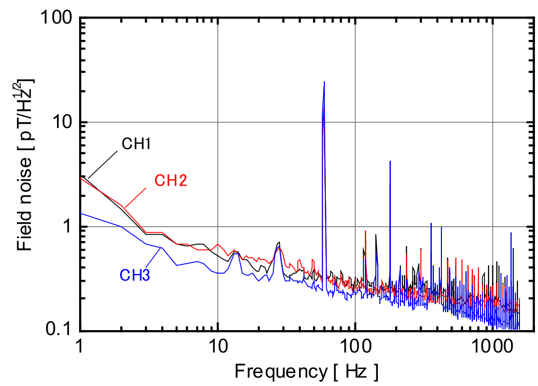

Fig. 2 Magnetic field noise of the each RF-SQUID.

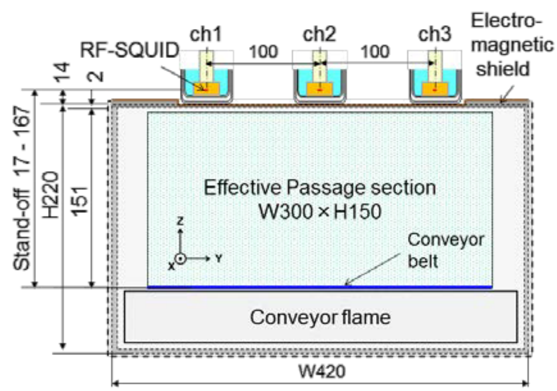

Fig. 3 Detailed cross-sectional view of the detection region.

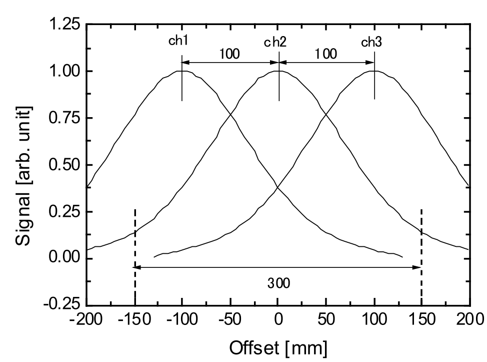

Fig. 4 Profile of sensitivity with SQUID separation of 100 mm.

large peak is due to the 60 Hz of the power line. Small peaks at around 12 Hz and 28 Hz are from the conveyor motor and the inherent noise of the laboratory, respectively. Figure 3 shows the detailed cross-sectional view around the SQUID magnetometers. The effective passage section is (W × H) 300 mm × 150 mm and the standoff, which is the distance between the SQUID and an object is 17 - 167 mm. The separation of each SQUID is defined as 100 mm by calculation. A profile of the sensitivity for each SQUID was calculated based on the assumptions that a magnetic dipole is on the conveyor belt and that the separation is 100 mm [6]. As shown in Fig. 4 the points of minimum sensitivity, where

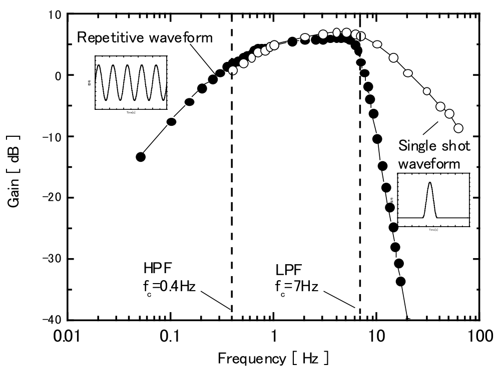

Fig. 5 Experimentally measured gain characteristics for frequency of the analog filters.

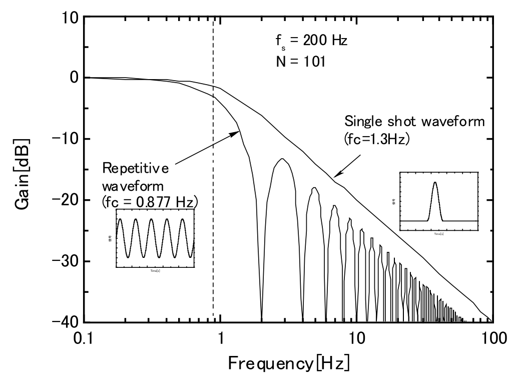

Fig. 6 Gain characteristic for frequency f of the digital filter with f_s of 200 Hz and $N = 101$ for repetitive waveform. Experimentally measured gain characteristics for single shot waveform is also shown for comparison.

the sensitivity profiles cross each other correspond to 75% of the maximum value in the 300 mm width. Thus, if the SNR of 4.0 at a maximum point can be realized, the SNR more than 3.0 can be obtained in the range of 300 mm width.

The magnetic shield covering the sensors is a crucial part of the system for practical use [7]. A three-layer structure was used with the following dimensions of the outer shield: (W × D × H) 862 mm × 729 mm × 972 mm. There are two openings (W × H) 420 mm × 220 mm on both sides of the magnetic shield as shown in Fig. 1 and Fig. 3. The thickness of the permeable metallic material is 1.0 mm. The shielding factor SF in z direction is over 2,600 at 1 Hz.

Signals from the SQUID electronics passed through an analog filter set and were then sent to an A/D converter. In this system, a digital filtering technique was introduced to improve the SNR. The details of the digital filter will be described in the next section.

2.3 Analog Filter and Digital Filter

The contaminant signal frequencies were calculated for conditions in which the standard conveyor speed of the system was 333 mm/s and the height at which contaminant samples could pass through the system was the stand-off distance of 17–167 mm (with a food product height of 150 mm). We calculated an expected single shot waveform observed by the SQUID sensor from a distant object using a dipole model. After calculation for different distances, the obtained waveforms and the actual contaminant signals were compared and then the signal frequency for each distance was obtained by the period. As a result, the contaminant signal frequency f was predicted as $f = 0.71 - 6.94$ Hz. Because the signal frequency of contaminant is proportional to transfer velocity, an analog filter with wide margins was prepared. A high-pass filter (HPF) (−6 dB/oct, f_c: 0.4 Hz) and a higher-order low-pass filter (LPF) (−30 dB/oct, f_c: 7 Hz) were selected. Total gain of the analog filter was designed as × 2. Figure 5 shows the experimentally measured gain characteristic for frequency of the analog filters. The results of the repetitive waveform follow the design but the cutoff frequency f_c of LPF for the single shot waveform, which is similar to the real detection signal is 13 Hz. The decay for it is more gentle than that of the repetitive waveform and −8 dB/oct. Thus, in order to obtain a steeper decay and improve the SNR, introduction of a digital filter was considered. We used past finite data for our filter calculations and a finite impulse response (FIR) type LPF with a rectangular window with which the processing operation can be stabilized [8], [9]. The transfer function of the FIR filter is expressed by

$$y[n] = \sum_{i=0}^{N-1} bix[n-i] \tag{1}$$

The weighting of b_i (window function) was multiplied by the input signal $x[n]$ at time n, and the average value for the N pieces of data is the output $y[n]$. In the case of a rectangular window, we have $b_i = 1/N$. The amplitude characteristic (gain) is expressed by

$$G = (1/2\pi f\tau)\sqrt{2(1-\cos 2\pi f\tau)} \tag{2}$$

$$\tau = N\Delta t \tag{3}$$

$$\Delta t = 1/fs \tag{4}$$

where f in (2) is the signal frequency. N in (3) is the number of data, and Δt is the sampling interval. f_s in (4) is sampling frequency. These equations provide the cutoff frequency f_c, which is derived as $G = -3$ dB ($G = 1/\sqrt{2}$). f_c for the repetitive waveform is expressed as

$$fc = 0.443/\tau \tag{5}$$

Figure 6 shows the gain characteristics of the digital filter for frequency f with f_s of 200 Hz and $N = 101$ when a rectangular window is applied. As shown in the figure, the decays for both the repetitive waveform and the single shot waveform are the same as the −6 dB/oct in the calculation. The cutoff frequency f_c of the single shot waveform is a little higher than that of the repetitive waveform and is 1.3 Hz. As described above, the contaminant signal frequency f is predicted as $f = 0.71 - 6.94$ Hz. The lowest and the highest frequency corresponds to the stand-off distance of 167 mm and 17 mm, respectively. Since the signal intensity is inversely proportional to the cube of the stand-off

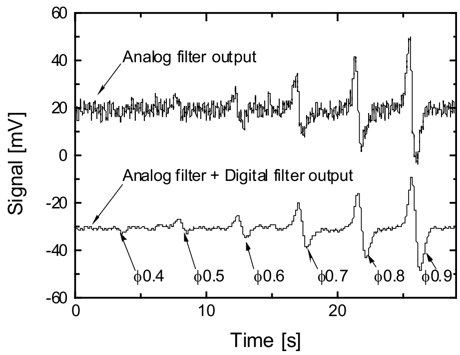

Fig. 7 Time traces of signals from steel balls with different diameters. The upper section shows the trace prior to the digital filtering process, and the lower section shows the trace after the digital filtering process.

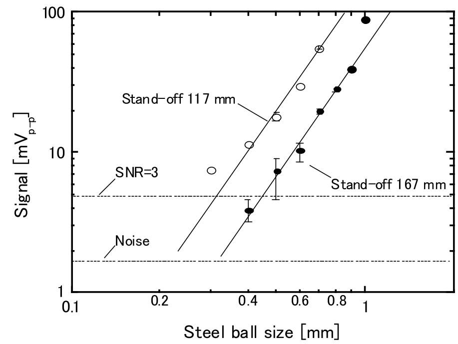

Fig. 8 Dependence of the signal intensity (peak-to peak value) on the diameter after digital filtering process. Both solid lines give the slope of 10^3 per decade.

distance, the critical SNR depends on the largest stand-off distance of 167 mm. Therefore, the cutoff frequency f_c of the digital filter should be selected according to the lowest signal frequency of 0.71 Hz. Finally, the cutoff frequency f_c of 1.3 Hz for the single shot waveform has been decided from this point of view. That is, the sampling frequency f_s = 200 Hz and the number of data N = 101 was selected.

3. Evaluation of the System

To test the system, small steel balls (SUJ-2, high carbon chromium-bearing steel) with a diameter of from 0.4 mm to 0.9 mm were prepared. The stand-off distance was 167 mm, which means the sample object was placed on the surface of the conveyor belt with velocity of 333 mm/s. The object was passed under one of the three channels, ch2. The magnetic field voltage transformation coefficient of the SQUID electronics output signal was 4.14 nT/V (Coefficient after analog filters: 2.07 nT/V). The parameters of the digital filter were set as f_s = 200 Hz and N = 101. Time traces of the signals from steel balls with different diameters are shown in Fig. 7. The upper section of Fig. 7 shows the trace prior to the digital filtering process, and the lower section shows the trace after the digital filtering process. The peak-to-peak value attenuated with 30% after the digital filtering process, but the noise is dramatically suppressed to one fifth of that without digital filtering and becomes 1.65 mV_{p-p}. The dependence of the signal intensity (peak-to peak value) on the diameter after digital filtering process is shown in Fig. 8. The signal responded considerably well in proportion to the cubic of diameter of the object, indicating that the signal was proportional to the volume of the object. The signal intensity of a steel ball of 0.5 mm in diameter with stand-off distance of 167 mm is 7.9 mV_{p-p}, which corresponds to the SNR of 4.4. The SNR at the position in between two SQUIDs decrease 25% smaller than that just below the SQUID as shown in Fig. 4. Even if in the case of a 0.5 mm steel ball, the SNR becomes 3.3, which can be calculated by 4.4 times 0.75, it is over the threshold level of SNR = 3. When the stand-off distance becomes shorter, 117 mm, the SNR of the signal of the steel ball with a diameter 0.5 mm is improved to more than 10 and is large enough.

4. Conclusions

We designed and constructed a prototype of multi-channel high-Tc RF-SQUID metallic contaminant detector for large sized packaged food. The detection technique is based on recording the remnant magnetic field of a contaminant using SQUID sensors. The detection system successfully detected a steel ball as small as 0.5 mm in diameter at a stand-off distance of 167 mm with more than SNR = 3.3. The SNR could be improved to more than 10 when the stand-off distance was shortened and was 117 mm.

A contaminant detection system permitting a food package with a height of 150 mm and a width of 300 mm was realized. These results suggest the system is a promising tool for the detection of contaminants in practical applications.

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References

[1] S. Tanaka, M. Natsume, M. Uchida, N. Hotta, T. Matsuda, Z.A. Spanut, and Y. Hatsukade, "Measurement of metallic contaminants in food with a high-T_c SQUID," Supercond. Sci. Technol., vol.17, no.4, pp.620–623, 2004.

[2] H.-J. Krause, G.I. Panaitov, Y. Zhang, and M. Bick, "Appearance of sign reversal in geophysical transient electromagnetics with SQUID due to stacking," IEEE Trans. Applied Superconductivity, vol.15, no.2, pp.745–748, 2005.

[3] M. Bick, P. Sullivan, D.L. Tilbrook, J. Du, S. Gnanarajan, K.E. Leslie, and C.P. Foley, "A SQUID-based metal detector—comparison to coil and X-ray systems," Supercond. Sci. Technol., vol.18, no.3, pp.346–351, 2005.

[4] S. Tanaka, H. Fujita, Y. Hatsukade, T. Nagaishi, K. Nishi, H. Ota, T. Otani, and S. Suzuki, "A food contaminant detection system based on high-T_c SQUIDs," Supercond. Sci. Technol., vol.19, no.5, pp.S280–S283, 2006.

[5] S. Tanaka, T. Ohtani, Y. Narita, Y. Hatsukade, and S. Suzuki, "Development of Metallic Contaminant Detection System Using RF High-Tc

SQUIDs for Food Inspection," IEEE Trans. Appl. Supercond., vol.25, no.3, pp.1–4, 2015.

[6] S. Tanaka, S. Kudo, Y. Hatsukade, T. Nagaishi, K. Nishi, H. Ota, S. Suzuki, "High-T_c SQUID Metal Detection System for Food and Pharmaceutical Contaminants," IEICE Trans. Electronics, vol.E88-C, no.2, pp.175–179, 2005.

[7] S. Tanaka, H. Fujita, Y. Hatsukade, T. Otani, S. Suzuki, and T. Nagaishi, "A High-T_c SQUID Micro-detector with a high performance magnetic shield for contaminant detection industrial products," Supercond. Sci. Technol., vol.20, no.11, pp.S385–S388, 2007.

[8] L.J. Karam and J.H. McClellan, "IV digital filtering," in The Digital SIGNAL PROCESSING HANDBOOK, pp.228–318, IEEE Press, 1999.

[9] T. Ohtani, S. Tanaka, Y. Narita, S. Ariyoshi, and S. Suzuki, "Development of Contaminant Detection System using HTS SQUIDs," Progress in Superconductivity and Cryogenics, vol.17, no.4, pp.38–42, 2015.

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