Development of Contaminant Detection System using HTS SQUIDs

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Abstract

In terms of food safety,mixture of contaminants in food is a serious problem for not only consumers but also manufacturers. In general, the target size of the metallic contaminant to be removed is 0.5 mm. However, it is a difficult task for manufacturers to achieve this target, because of lower system sensitivity. Therefore, we developed a food contaminant detection system based on high-Tc RF superconducting quantum interference devices (SQUIDs), which are highly sensitive magnetic sensors. This study aims to improve the signal to noise ratio (SNR) of the system and detect a 0.5 mm diameter steel ball. Using a real time digital signal processing technique along with analog band-pass filters, we improved the SNR of the system. Owing to the improved SNR, a steel ball with a diameter as small as 0.3 mm, with stand-off distance of 117 mm was successfully detected. These results suggest that the proposed system is a promising candidate for the detection of metallic contaminants in food products.

Keywords: Josephson junction, SQUID, Detector, Food, Metallic Contaminant

1. INTRODUCTION

Contaminants that mix into food products cause serious problems for not only consumers but also manufacturers. It is very important to be able to detect small metal contaminants to ensure food safety. A contamination incident can lead to substantial losses for the manufacturer because the product then needs to be recalled from the market. Manufacturer losses caused by food contamination can run from one to ten millions of dollars. Metal contaminants can originate from the equipment and contaminate food during the manufacturing process. Further, metal contaminants can be large objects such as bolts or washers, as well as smaller objects such as microscopic chips or minute wires.

Therefore, to detect metal contaminants, food manufacturers have implemented eddy-current inspection systems, x-ray imaging inspection systems, and metal contaminant inspection systems that use superconducting quantum interference devices (SQUIDs)[1-4] in their production lines.

Eddy-current metal detectors are widely used in food manufacturing plants. However, the sensitivity (threshold level) of such systems is unstable because these systems are significantly affected by the electrical conductivity of the contaminant. Other factors that affect the system sensitivity are moisture content, salinity, and temperature.Thus, it is difficult to determine the optimum settings for eddy-current metal detectors used in food inspections.

X-ray imaging inspection systems are efficient systems, and they are used for a variety of purposes in food manufacturing plants and in other industries. However, the detection limit for practical food contaminant inspections conducted using X-rays is on the order of 1 mm. Furthermore, because X-rays often trigger the ionization of food, it occasionally leads to a change in the flavor of the manufactured food products.

We develop and propose a contaminant inspection system that uses the RF SQUIDs to circumvent the reported difficulties[1-4] in metal contaminant detection.

The goal of our study was to detect a steel ball (0.5mm diameter) with an SNR of 5 or greater under the following conditions: Our target was to achieve an SNR of 5 or greater, which is a threshold value with a high safety factor. This would mean that for a food product with a height of 100 mm (stand-off distance of 117 mm), transfer velocity of 333mm/s, and belt width of 150 mm, automatic detection by software was possible and the possibility for erroneous detection was low. A steel ball with a diameter of 0.5 mm is a standard detection target size for metal contaminants and is generally desired by food manufacturing plants.

We therefore considered improving the SNR by using a new method that involved smoothing in the time-series direction by using an analog band-pass filter (BPF) and a real-time digital filter.

We describe the detail of the system and the results of the evaluation.

2. PROPOSED SYSTEM

2.1. Configuration and Specifications of Equipment

A schematic diagram of the developed system is shown in Fig. 1. The system is configured with a permanent magnet, a belt conveyor, a μ-metal magnetic shield box, an electromagnetic shield box made of aluminum, three High-Tc RF-SQUID magnetometers, analog band-pass
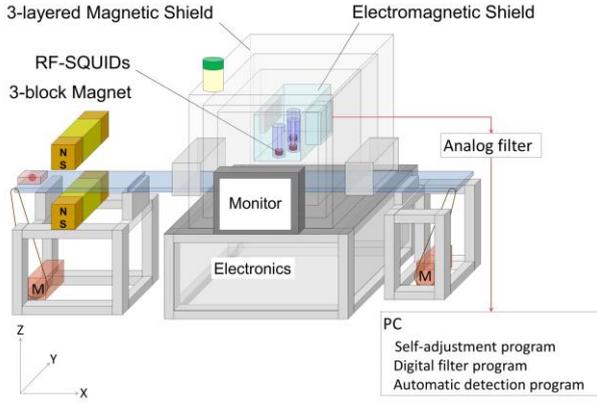
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Fig. 1. Block diagram of the system. As the samples passed through the gate with a pair of permanent magnet, they were magnetized.Then the magnetization of the contaminant is detected by the SQUID.

filters (BPFs), and a computer (with dedicated software installed) for system control. Samples that can pass through the system may be up to 150 mm (W) × 103 mm (H) in size. The stand-off distance between the sample and the sensor was 16-120 mm, and the sensitivity direction of the SQUIDswas in the z-direction. All three SQUIDs were placed near the center of a three-layered permalloy magnetic shield (shielding factor of 1,600 at 1 Hz) and were distributed in 50 mm intervals from the center to the widthwise direction of the belt (y-direction).

As the samples passed through the gate with a pair of permanent magnets facing each other, they were transferred to a belt conveyor and magnetized in the vertical direction. If the food products are contaminated by magnetic metals, their residual magnetization disrupts the magnetic field as they pass under the SQUIDs, and this variation in the magnetic field is detected by the SQUIDs[5].

The RF SQUIDs and their driving electronic equipment were manufactured by Jülicher SQUID GmbH (JSQ). The noise characteristics of individual SQUIDs during system operation are shown in Fig. 2. The noise was 250–450 fT/Hz$^{1/2}$ at 10 Hz, and the noise floor was 100–180 fT/Hz$^{1/2}$ at 1 kHz. The peaks appearing between 25–26 Hz were caused by a standing noise that existed in the research environment. Furthermore, the peaks occurring at 60 Hz were caused by the commercial frequency of 60 Hz. Electromagnetic noises emitted by the environment, the electronics, and the belt conveyor that configure the system were sufficiently shielded by the magnetic shields and an electromagnetic shield made of aluminum.

Signals output from the SQUID electronics were passed through an analog BPF and loaded to the system via an analog-to-digital converter (ADC). The ADC used in our system was AIO-163202F-PE (16-bit), manufactured by CONTEC Co., Ltd.

2.2. Considerations for Filters

In order to derive an appropriate cutoff frequency (f_c) for the analog BPF, we first conducted a two-dimensional simulation based on the sensitivity range characteristics of
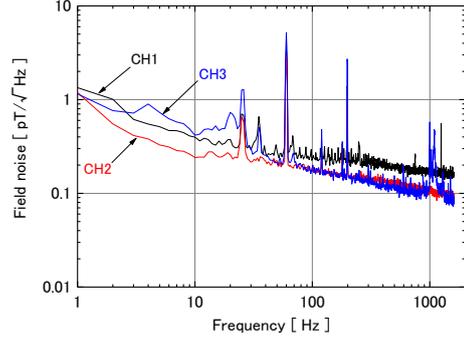
Fig. 2.Magnetic field noise of each RF SQUID in operation.The noise was 250–450 fT/Hz$^{1/2}$ at 10 Hz, and the noise floor was 100–180 fT/Hz$^{1/2}$ at 1 kHz. The peaks appearing between 25−26 Hz were caused by the research environment.

the SQUID. This simulation model has been reported previously[6]. Calculations of the contaminant signal frequencies were performed for conditions in which the standard conveyor velocity of the system was 333 mm/s and the height at which samples could pass through the system was the stand-off distance of 17–120 mm (with a food product height of 103 mm).

The contaminant signal frequency f was predicted as $f =$ 0.98–6 Hz through calculations.Because the signal frequency of contaminant is proportional to the transfer velocity, analog BPFs with ample margins were prepared. The analog BPFs that limit the bandwidth of the signal were the high-pass filter (HPF) (-6 dB/oct,f_c = 0.4 Hz) and the low-pass filter (LPF) (-24 dB/oct, f_c = 11 Hz). The commercial frequency of 60 Hz was sufficiently attenuated. These analog BPFs alsoact as pre-filters for the digital filters.Practical inspection systems need to perform inspections on all products produced at a food manufacturing plant continuously, and therefore, system stability is required. From the perspectives of design and feasibility, 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[7]. The transfer function of the FIR filter is expressed by

$$y[n] = \sum_{i=0}^{N-1} b_i x[n-i] \cdot \quad (1)$$

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

$$G = (f_s / 2\pi f N) \sqrt{2(1 - \cos(2\pi f N / f_s))} \quad (2)$$

andf_c, which is derived as dB ($G = 1/\sqrt{2}$) is expressed as
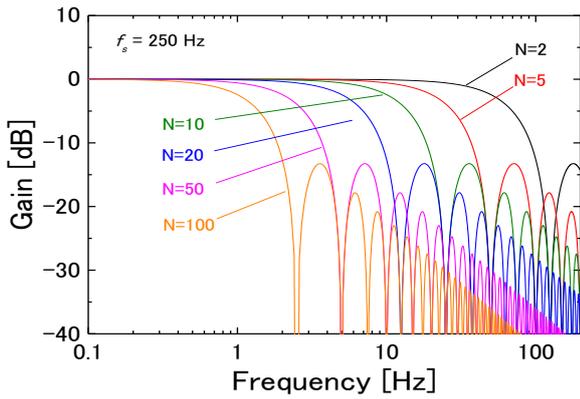
$$f_c = 0.443 f_s / N \quad (3)$$

Fig. 3. Gain characteristics of calculated with number of data points and frequency at sampling frequency of 250Hz. As the number of the data increases, the cut-off frequency lowers.

Fig. 4.Time trace for test sample with a diameter of 0.5 mm. The upper section shows before the digital filtering process, and the lower section shows after the digital filtering process.Noise was attenuated down to 8% by digital filters.

where f in (2) is the signal frequency. N and f_s in (3) is the number of dataand the sampling frequency, respectively.

Figure 3 shows the number of data$N$ and the gain characteristics for frequency f with f_s of 250 Hz when a rectangular window is applied. Gain characteristics can be changed by using different window functions. When building a filter, the f_s generally needs to be oversampled with $2f_c$ or higher in order to prevent aliasing. The real-time digital filter program was therefore incorporated into dedicated software. As described above, the signal frequency of the contaminant is 0.98 to 6 Hz. Therefore, the number of data N was selected as 100,which gives cutoff frequencyf_c = 1.1Hz. This frequency seems to be too low for the signal frequency range of f= 0.98-6 Hz. However, the highest frequency 6 Hz corresponds to the stand-off distance of 17 mm, which is closest position to the sensor. As the signal intensity is inversely proportional to the cube of the stand-off distance, the signal at the position is large enough even after the digital filter at f_c = 1.1 Hz.

Fig. 5.Time trace for test sample with a diameter of 0.3 mm. A steel ball with a diameter of 0.3 mm was detected by the digital filtering process.

3. EVALUTION

3.1. Effect of Digital Filter

Improving the SNR is important because the SNR drops as the distance between a sensor and a contaminant increases. The output signals from the SQUID electronics were passed through the analog BPF and acquired by the ADC. Digital filters then performed a smoothing process in the time direction, and the contaminant detection determinations were made automatically. We used a test sample of the steel ball (SUJ-2, high carbon chromium-bearing steel) with a diameter of 0.5 mm, which was our detection target, to test the effectiveness of the real-time digital filter. The steel ball used as our test sample was an industrial product ordinarily used as a ball bearing. The experiment conditions are described below. The sample was magne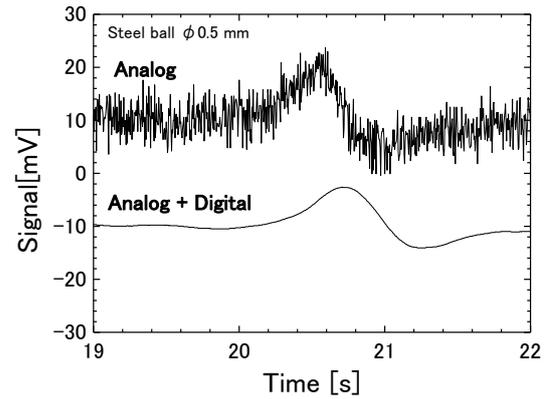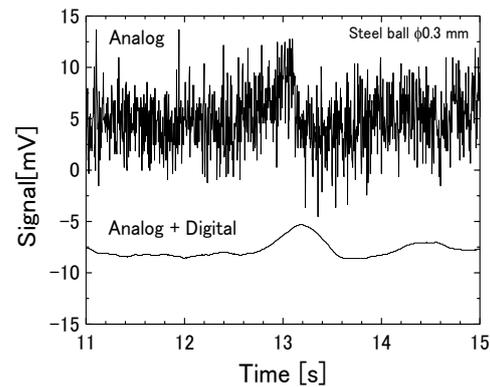tized by the magnets within the system. The stand-off distance was 117 mm. The belt conveyor velocity was 333mm/s. The sample was passed below ch2. The magnetic field voltage transformation coefficient of the SQUID electronics output signal was 4.2 nT/V. f_s was 250 Hz and the number of data$N$ was 100.

The time trace acquired from measuring the test-sample steel ball with a diameter of 0.5 mm is shown in Fig.4. The upper section of Fig.4 shows the trace prior to the digital filtering process, and the lower section shows the trace after the digital filtering process. The trace after the digital filtering process was extremely clean. Noise was attenuated down to 8% by digital filters. The peak-to-peak value attenuated by 20% after the digital filtering process compared with the value before the digital filtering process was performed. This signal attenuation was slightly lower than the gain characteristic but was still a close-enough value. This is considered to have occurred because of the effects of the analog BPF. The SNR improved by more than 10 times using a digital filter. The delay time

associated with the digital signal processing was short, and it was considered acceptable for a practical inspection system.

3.2. Performances

We used steel balls with diameters of 0.3–0.8 mm in our experiment to verify the detection performance of the developed system. The time trace acquired from measuring the steel ball with a diameter of 0.3 mm is shown in Fig.5. The upper section of Fig.5 shows the trace prior to the digital filtering process, and the lower section shows the trace after the digital filtering process. A steel ball with a diameter of 0.3 mm was detected by the digital filtering process. The peak-to-peak value attenuated by 16% after the digital filtering process, compared to the value before the digital filtering process was performed. The attenuation of the signal was lower than the gain characteristic because the signal was extremely small. The SNR was improved greatly, from 0.21 to 2.2.

The relationship between the diameter and signal intensity for steel balls with diameters of 0.3–0.8 mm is shown in Fig.6. We note that the noise level shown is the maximum peak-to peak-noise of the three SQUIDs in operation. The level of noise attenuated to 10% or less, compared with the level of the signal after passing through the analog BPF when digital filters were also used. The signal responded considerably well in proportion to the diameter of the sample, indicating that the signal was proportional to the volume of the sample.

The signal of the steel ball (diameter 0.5 mm) as a concomitant use of digital filters had an SNR of 8.3. The detectable threshold level was at an SNR of 3 or greater. Threshold levels with infrequent erroneous determinations (having high safety factors) are desirable for contaminant inspections at food manufacturing plants. We consider the threshold level at an SNR of 5 or greater to be a high safety factor. The results of the experiment demonstrated that a steel ball with a diameter of 0.5 mm, which was our target for detection, present on a belt conveyor with a width of 150 mm, could definitively be detected automatically. Furthermore, a steel ball with a diameter of 0.4 mm was detected with an SNR of 4.5. However, the signal for the steel ball with a diameter of 0.4 mm did not attain a threshold level with a high safety factor. However, we believe that further improvement of digital filters will enable us to exceed the threshold value of a high safety factor.

Our target (automatically detecting a steel ball with a diameter of 0.5 mm at a stand-off distance of 117 mm) was achieved by using real-time digital filters.

3. CONCLUSIONS

We developed a magnetic metal contaminant inspection system for food products. The system uses three SQUIDs. We verified the detection performance for the real-time automatic detection of a steel ball with a diameter of 0.5 mm being transferred at a velocity of 333mm/s, located at a
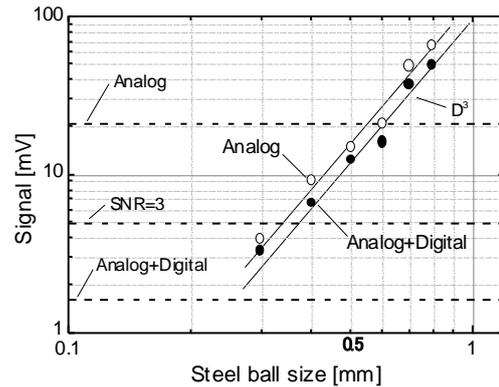

Fig. 6.Dependence of the peak signal on the diameter of the sample.The signal responded considerably well in proportion to the diameter of the sample, indicating that the signal was proportional to the volume of the sample.

sensor-to-contaminant vertical distance (stand-off distance) of 117 mm. We therefore considered an improvement of the SNR by using real-time digital filtering processes.

This resulted in our successful detection of a steel ball with a diameter of 0.5 mm, with an SNR of 8.3, by using an FIR-type LPF with a f_s of 250 Hz and a number of data N 100 points. The steel ball with a diameter of 0.5 mm is a standard detection target size for metal contaminants generally desired by food manufacturing plants. The random noise level was attenuated down to 8% in comparison with the levels prior to implementing the digital filtering process. The SNR improved by at least 10 times by applying digital filters, in comparison with the SNR achieved with an analog BPF. These results indicated that automatic detection was possible within the range of sample passing height of100 mm (stand-off distance of 17–117 mm) on a belt conveyor with a belt width of 150 mm, as the system sufficiently exceeded the SNR of a high safety factor of 5 or greater. We expect the SNR to be improved in the near future to make it possible to have automatic contaminant determination of a steel ball with a diameter smaller than 0.5 mm at threshold levels with high safety factors.

Finally, these results suggest that the system is a promising tool as a practical metal contaminant inspection system.

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