Development of Dual-Energy X-ray Inspection System

Hiroaki Watabiki, Toshikazu Takeda, Satoshi Mitani, Takeshi Yamazaki, Manabu Inoue, Hiroyuki Koba, Itaru Miyazaki, Naoya Saito, Syunsuke Wada, Takashi Kanai

[Summary] We have developed a new KD74 Series X-ray inspection system with enhanced sensitivity using a dual-energy method and Anritsu's unique signal process technology. The system detects contaminants inside partly piled-up products, which has been very difficult for conventional systems. Using dual-energy technology from the medical field in our food product inspection system greatly improved contaminant detection. The new machine also has shape detection functions such as package check or missing-product detection to contribute to high quality control in food production.

1 Introduction

Consumer awareness about food safety and security is increasing against the background of recent food safety accidents. In particular, accidents involving contaminants in food products have impacted consumers concerns about damage to health caused by contaminants so food manufacturers are introducing contaminant inspection machines on production lines to prevent mixing of food contaminants in food products as well as production errors.

Previously, detection of contaminants on food production lines depended heavily on metal detection. Metal detectors are designed to detect changes in magnetic field as food passes through a sensor; such changes in magnetic field make it possible to detect metal contaminants. However, food products have a variety of materials and shapes as well as differences in packaging materials that can cause fluctuations in the magnetic field, imposing limits on the minimum detection size for small metal contaminants. Moreover, food contaminants are not limited to metal, and may include stone, plastic, bone, glass, etc., none of which can be detected by a metal detector.

To meet customers requests for a solution to the above problems, Anritsu started developing and selling X-ray inspection equipment about 15 years ago and by about the year 2000, when we started selling the KD72 series, we had increased the performance compared to previous conventional machines fourfold while at the same time halving the cost and reducing the equipment footprint by about one third. Until that time, food production lines mainly used metal detectors for contaminant inspection but deployment of X-ray inspection equipment then started in earnest.

The next model to be released, the KD73 series, expanded the application range and also offered higher sensitivity.

Figure 1 External view of Dual-Energy X-ray Inspection System

This new KD74 series takes the evolution of X-ray inspection systems further with new functions for detecting parts of products caught in the sealed packaging, detecting missing products, detecting broken or deformed products, and of course detecting various types of contaminants.

On the other hand, the performance of inspection systems using X-rays has been improved by advances in image-processing technologies matching the characteristics of the inspected products based on the density gradation of the X-ray transmission. However since it is difficult to control basic X-ray transmission, there are limits to how much more performance can be improved. To solve this problem, we developed the new KD7416DWZ (Figure 1) using a dual-energy method outlined here.

2 Conventional X-ray Inspection System and Problem

In principle, an X-ray inspection system[1] is composed of an X-ray source, conveyor belt, and X-ray detector (Figure 2). Products to be inspected are carried by the conveyor belt past the X-ray source and the differences in the transmission of the inspected product and any contaminants is detected by the X-ray detector to evaluate the presence or absence of contaminants in the inspected product (Figure 3). In actual use, inspected products do not have a simple shape like that shown in Figure 3; surfaces may have concavities and convexities creating differences in product thickness that cause changes in the X-ray transmission, resulting in errors when detecting the presence of contaminants. To solve this problem, image-processing technology has been adopted to help discriminate contaminants even when changes in thickness cause changes in transmission. However, when inspected products are piled-up, and these parts are about the same size and transmission density as the contaminant (Figure 4), even image-processing technology has difficulties identifying whether a contaminant is present or not.

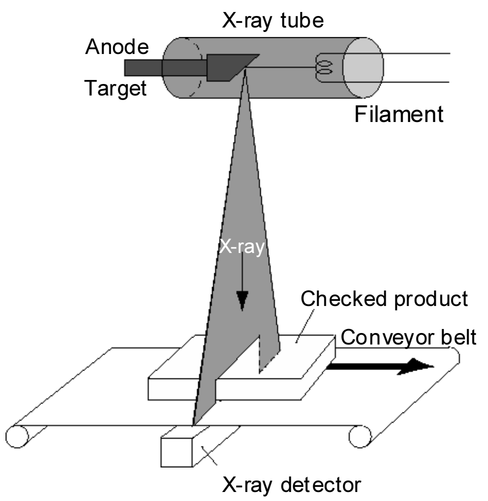


Figure 2 Principle of X-ray inspection system

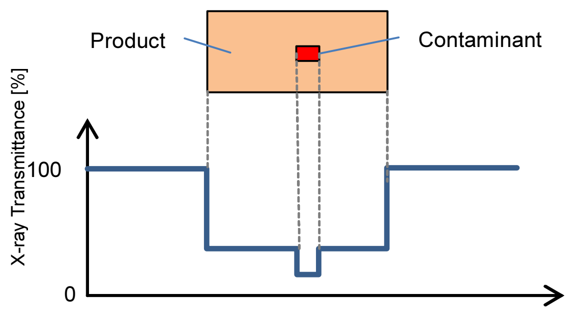


Figure 3 Schematic of X-ray transmission by irradiating product and contaminant

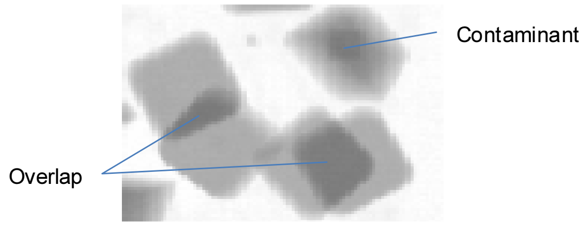


Figure 4 Overlapping product and contaminant in X-ray transmission image

3 Dual-Energy Method

(1) Principle

The dual-energy method is also called the energy subtraction method. It is a detection method using the difference in the X-ray transmission of two energies at different wavelengths.

Assuming the strength of the energy in a material irradiated by a single X-ray source is I_0, the strength I after passage through the material is found from the following equation:

$$I = I_0 \exp(-\mu x)$$

where μ is the total absorption coefficient and x is the material thickness. The respective units are $g^{-1} \cdot cm^{-1}$, and cm. Obtaining the log for both sides, yields the following equation:

$$\ln\left(\frac{I}{I_0}\right) = -\mu x \qquad (1)$$

The transmission on the left side is the product of the absorption coefficient and the thickness. It indicates that the materials cannot be distinguished by simple image contrast.

However, dividing or subtracting the log of the X-ray transmission for two energy sources can remove the effect of thickness. The example for subtraction is shown by the equation below.

$$I_L = I_{0L} \exp(-\mu_L x), \quad I_H = I_{0H} \exp(-\mu_H x),$$

$$\ln\left(\frac{I_L}{I_{0L}}\right) - k \cdot \ln\left(\frac{I_H}{I_{0H}}\right) = 0$$

$$k = \mu_L / \mu_H \qquad (2)$$

Subscripts L and H are the low and high energy sides, respectively. From Eq. (2), applying μ_L / μ_H to the inspected material gives 0 as the result of subtraction. On the other hand, when μ_L / μ_H of the material composing the contaminant is larger or smaller than the inspected material, it becomes possible to distinguish both. As an example, when aluminum contaminant is present in water (inspected food), the ratios of μ_L / μ_H for the absorption coefficients for 25 and 50 keV are respectively 5.4 and 2.4 (Figure 5) making it possible to distinguish them.

If we apply this method to X-ray images, the contrast of the image for overlapping parts appears about the same as non-overlapping parts while parts with contaminants should have a denser contrast, making it possible to improve contaminant detection performance.

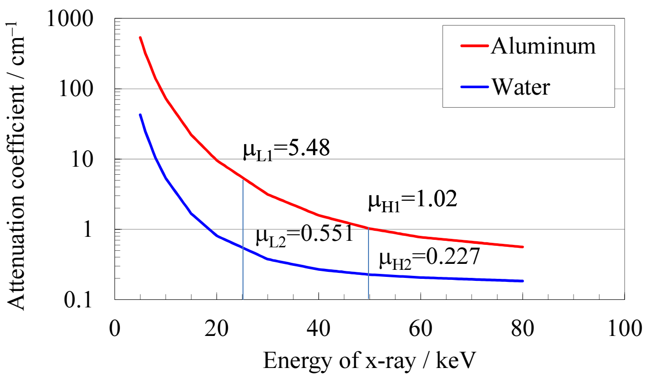


Figure 5 Attenuation coefficients of aluminum and water

(2) Implementation

Implementation of the dual-energy method requires two X-ray sources and consideration of the following two possibilities:

[1] Take X-ray image for different energies using two X-ray sources and X-ray detector.

[2] Take X-ray images with X-ray detector when simultaneously outputting high and low energy images with one X-ray source.

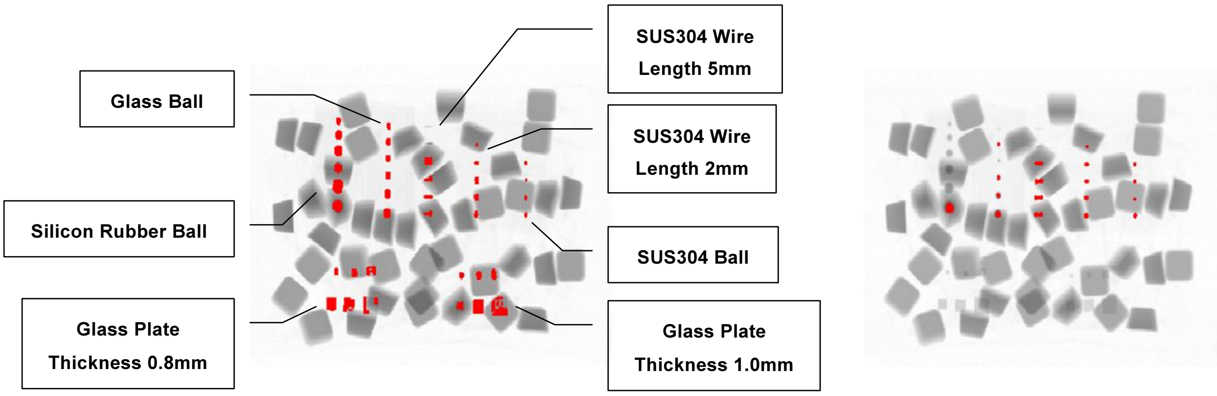
The former method using high dual-energy sources should be effective but care is required about the conveying mechanism required to maintain detection resolution due to the positional accuracy of two shots using two X-ray sources and an image detector. On the other hand, the latter method provides small differences between the low- and high-energy shots compared to the former method and there is a limit on the dual-energy effect but it has the advantage that conveying products has no impact on resolution because one X-ray image is shot. Due to the very large advantage of the latter method, we selected the combination of one X-ray source and X-ray detector (dual-energy sensor) for this development.

4 Sensitivity Compared to Conventional Machines

We compared the effectiveness of the newly developed KD7416DWZ with the dual-energy method to the conventional KD7416DW using a block of chocolate to clarify the importance of the items explained in section 3. Figure 6 shows the contaminant detection results for the new and conventional inspection systems. The red parts in the figure show the detected contaminants in the chocolate. As shown in the figure, the new inspection system has overwhelmingly more red points than the conventional inspection system and detects more contaminants. In particular, it has a higher detection rate for contaminants with relatively low density, such as glass plates and rubber balls, compared to the conventional inspection system. These results confirm that the dual-energy method is very effective in improving the high sensitivity of X-ray inspection systems. Table 1 compares the numeric performance results for the new and conventional systems.

5 Key Design Points

In commercializing the new system, as well as taking maximum advantage of the dual-energy method, we also designed a system that is both easy-to-use and safe for customers. These features are explained below.



(1) KD7416DWZ (2) KD7416DWH

Figure 6 Test sample and contaminant images

Table 1 Sensitivity comparison with conventional machine (Test sample: Chocolate)
(New machine): KD7416DWZ, (Conventional machine): KD7416DWH

Glass plate thickness	Model	Glass plate size (one side length)					
		2.0 mm	3.0 mm	5.0 mm	6.0 mm	7.0 mm	10.0 mm
t = 0.8 mm	KD7416DWZ	100%	60%	100%	80%	90%	100%
	KD7416DWH	0%	0%	0%	0%	0%	0%
t = 1.0 mm	KD7416DWZ	70%	100%	100%	100%	100%	100%
	KD7416DWH	0%	0%	0%	0%	0%	0%

* The above numeric values show the proportion of successful detections when an inspected item with contaminant was passed 10 times through the system.

Model	Test Piece				
	SUS304 ball	SUS304wire × 2 mm	SUS304 wire × 5 mm	Glass ball	Silicon rubber ball
KD7416DWZ	φ0.7 mm	φ0.4 mm × 2 mm	φ0.4 mm × 5 mm	φ1.5 mm	φ4.0 mm
KD7416DWH	φ0.6 mm	φ0.4 mm × 2 mm	φ0.5 mm × 5 mm	φ4.0 mm	>φ8.0 mm

5.1 High-Output X-ray Radiation/Leak Prevention

To make the best advantage of the dual-energy sensor performance, the high and low energy X-rays must be radiated sufficiently well, requiring a high-output X-ray source. The conversion efficiency for X-ray energy is on the order of 1% and 99% of the input energy is radiated as heat so a structure that both radiates heat and prevents leakage of X-rays is required.

On the other hand, many food production lines are incorporating various types of inspection equipment in accordance with recent demands for quality management, so the new system must have the smallest possible space footprint. Consequently, we designed a new thermal converter for the X-ray tube and re-examined the sheet thickness of the cabinet and the surrounding structures in consideration of X-ray leakage, as well as the lead curtains at the entrance and exit, preventing X-ray emissions. As a result of this redesign we were able to keep the length of the inspection system to 800 mm, the same as conventional systems, assuring compatibility with existing production lines to minimize the cost of introducing this new inspection system into a line.

5.2 Achieving Higher Performance

(1) Package Check Function

To maintain the quality of the contents of retort pouches and packaged foods such as ham and sausages, the packaging has a completely airtight vacuum seal. Sometimes, if part of the package contents becomes caught in the vacuum seal, although it does not appear to be a problem, the caught part may lower the seal efficiency, causing major problems with spoilage of the contents. Consequently, food manufacturers conduct visual inspections for this problem. Although automatic inspection using CCD cameras is possible, problem packages may be missed due to different packaging materials with variations in optical transparency, etc.

The caught product detection function finds products with the contents caught in the sealed part as well as products where the shape has been deformed by the caught contents. Inspection using X-rays has is hardly affected by the packaging materials and can detect caught parts than cannot be seen by eye, so it can be used for almost all inspection purposes (Figure 7).

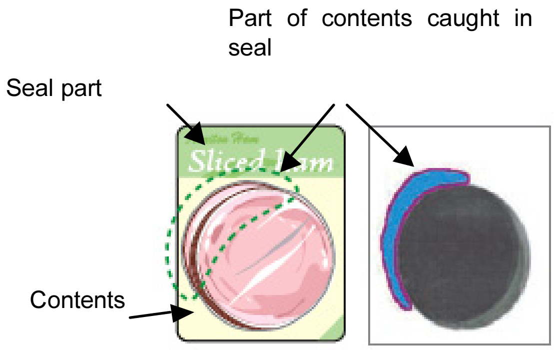


Figure 7 Example of contents caught in sealed parts

(2) Missing Product Detection Function

Similar to food contamination, content shortages or missing items cause many product claims by consumers, so food manufacturers place heavy importance on preventing these types of quality problems. Generally, a line checkweigher is used to check for missing contents, but, as shown in Figure 8, sometimes the product meets the weight requirement but the content count does not. Such problems cannot be detected by checkweighers.

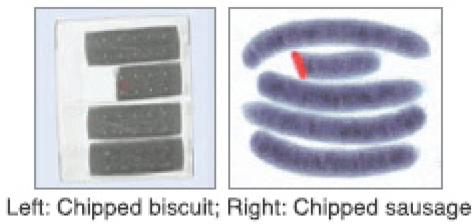


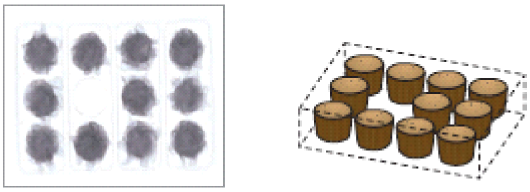
Figure 8 Samples of shape detection function

This function estimates the product weight and count using the density of the X-ray transmittance images to improve quality without requiring hard-to-manage checkweighing using balances.

(3) Shape Detection Function

Consumers also make claims against damaged and broken contents. Misshapen cakes, etc., lower the brand image and value, so shape management is an important item for food manufacturers.

This function uses image processing of the X-ray transmission images to auto-detect deformed, cracked, missing, etc., parts (Figure 9).



・Package of 12 cupcakes
If each cake weighs 20 ±2 g, the total weight of 11 cake each weighing 22 g is 242 g, satisfying the total weight requirement, although the number is incorrect.

Figure 9 Examples of missing-product detection function

5.3 Improved Operability

The dual-image sensor differentiates two images shot simultaneously. The shot is image processed using at least 10 parameters for differential processing. To obtain the best performance from the dual-image sensor, these parameters must be determined in accordance with the characteristics of the inspected product. It is difficult for an operator to make this decision due to the large possible number of combinations. Consequently, we have built an auto-setting function into this inspection system. It automatically sets the parameters simply by feeding the product several times through the system, making it easy for anyone to operate.

5.4 Safety Design

(1) Operator Safety 1—Limiting X-ray Leakage

X-rays can cause serious harm to people and other living things, so machines generating X-rays are regulated in terms of X-ray leakage levels.

The relevant laws in Japan require that if the total leakage of X-rays from a machine exceeds 1.3 mSv in a 3-month period, that machine must be installed in an access-controlled area where X-ray dosages can be monitored.

If a machine leaks less than 1 μSv/h, the total leakage over 3 months will be less than the regulated 1.3 mSv/3 months and the machine does not require any special access restrictions because the operator dose is less than the required standard.

(2) Operator Safety 2—Built-in Safety Mechanisms

Machines on packaged-food production lines must be cleaned several times each day to prevent growth of harmful micro-organisms. To improve the cleaning work efficiency, parts are designed for removal, but if the operator makes a mistake and removes parts designed to prevent leakage of X-rays while the power is still on, there is a risk of X-rays leaking and harming the operator or other people nearby.

To prevent these hazards, we have designed this system to meet the unrestricted Safety Class requirements (<1 μSv/h) and have built-in safety interlocks preventing the ability to generate X-rays when covers, curtains, and parts are removed.

In addition, there are safety emergency switches to stop the conveyor and X-ray radiation in any emergency, such as if products jam inside the system.

We have paid full attention to assuring operator safety in any circumstance by incorporating this extensive range of safety features.

(3) Safety of Inspected Products

X-rays may not only damage living things, including people, but can also have an effect on the inspected products. To guarantee the safety of inspected foodstuffs, Japanese law requires that general packaged and processed foods must not have an absorbed dose of more than 0.10 Gy.

If inspected foods jam inside an X-ray inspection system and the source continues radiating X-rays, there is a risk of exceeding this regulated absorbed dose. To prevent this risk, we have built-in a jam-detection function that displays a message on the system front panel and stops the source radiating X-rays before the standard is exceeded, assuring the safety of the inspected food.

6 Main Specifications

Table 2 shows the main specifications of the KD7416DWZ Dual-Energy X-ray Inspection System.

7 Summary

The KD7416DWZ Dual-Energy X-ray Inspection System can detect contaminants in piled products, something that has been difficult to achieve previously. This feature expands the range of products that can be auto-inspected and has received high evaluation from food manufacturers.

We shall continue development to increase the range of detectable contaminants using X-ray inspection by offering high-performance X-ray inspection systems to ensure safer and more secure food and pharmaceutical products.

References

1. T. Abe, "Development of KD7203AW X-ray Inspection System", Anritsu Technical, No. 80, pp. 81–89 (January 2002), in Japanese.
2. H. Maekoshi (Ed), "Data book for photon absorption coefficients", Japanese Society of Radiological Technology (March 1995), in Japanese.

Authors

Hiroaki Watabiki
Anritsu Industrial Solutions

Project Team Development Dept.
Development Div.

Toshikazu Takeda
Anritsu Industrial Solutions

Project Team Development Dept.
Development Div.

Satoshi Mitani
Anritsu Industrial Solutions

Project Team Development Dept.
Development Div.

Takeshi Yamazaki
Anritsu Industrial Solutions

System Engineering Sec.
Customer Service Engineering
Dept. Development Div.

Manabu Inoue
Anritsu Industrial Solutions

System Engineering Sec.
Customer Service Engineering
Dept. Development Div.

Hiroyuki Koba
Anritsu Industrial Solutions

System Engineering Sec.
Customer Service Engineering
Dept. Development Div.

Naoya Saito
Anritsu Industrial Solutions

Project Team Development Dept.
Development Div.

Itaru Miyazaki
Anritsu Industrial Solutions

Technology Development
Dept.Development Div.

Syunsuke Wada
Anritsu Industrial Solutions

System Engineering Sec.
Customer Service Engineering
Dept.Development Div.

Takashi Kanai
Anritsu Industrial Solutions

Technology Development
Dept.Development Div.

Table 2 Dual-Energy X-ray Inspection System Main Specifications

Model	KD7416DWZ
X-ray Transmission Output	Tube Voltage 25 to 80 kV, Tube Current 0.5 to 1.0 mA, Output 7.5 to 350 W
Safety Class	X-ray Leakage 1 μSv/h max, Leakage prevention using safety equipment
Display Method	15-inch color TFT LCD
Operation Type	Touch Panel
Inspected Product Dimensions	390-mm width max, 150-mm height max. (but some limits on detection range)
Belt Width	420 mm
Number of Product Types	100 max.
Belt Speed and Conveyed Product Mass	5 to 60 m/minute, 5 kg max.
Power Supply/Consumption	100 to 120 Vac or 200 to 240 Vac, 50/60 Hz single phase, 1.0 kVA, 80 A (typical) surge current (5 ms max)
Mass	280 kg
Usage Environment	0° to 35℃, RH 30% to 85%, No condensation
Water Resistance	IP66 (conveyor only), IP40 other parts
External Materials	SUS304