Hitachi 450keV X-ray Computed Tomography System

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Abstract. A 450keV x-ray computed tomography system using silicon semiconductor detectors has been developed for non-destructive inspection testing and digital engineering use. Silicon semiconductor detectors provide good signal-to-noise ratio for measurements with large output current due to incident photons. Circuits for adjusting input bias voltage of preamplifiers are added to realize long term stability of the system by controlling the detector leakage current, changes of which cause quality degradation of the CT image. The system provides high speed scanning of 6 seconds/slice in the rotate-only mode which is sufficient for digital engineering, e.g. only 2 hours are needed to scan 800 slices of a motorcycle cylinder head.

1. Introduction

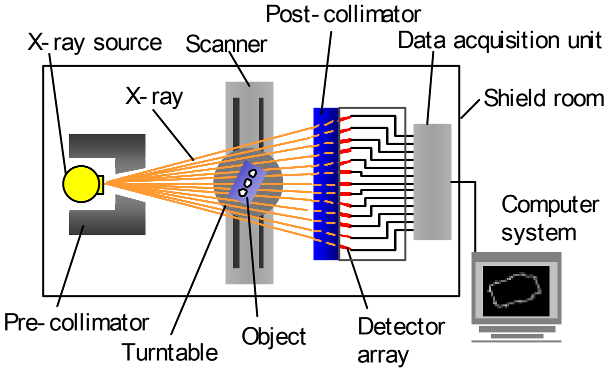
X-ray CT (computed tomography) is a completely nondestructive technique for visualizing features in the interior of opaque solid objects, and for obtaining digital information on their 3-D geometries and properties[1]. Signal currents of industrial x-ray CT systems are small, and the systems are influenced by circuit noise. The object size and density are also large, so the numbers of incident photons often decrease three orders of magnitude. Therefore the S/N (signal-to-noise) ratio of circuits needs to be improved to get good performance of CT images. Silicon semiconductor detectors output a larger current due to incident photons than do the detection pairs of a scintillator and photodiode, and the former have a good S/N ratio for the circuits.

We have developed a high energy x-ray CT system making the most of the favourable features of silicon semiconductor detectors[2]. In this paper, we describe the industrial CT system which realizes high speed scanning by applying the technology of silicon semiconductor detectors and using circuits which stabilize leakage current of the detectors.

2. X-ray CT System

2.1 System Constitution

A schematic diagram, a photo, and specifications of the system are shown in Fig.1 and Table 1. The system consists of x-ray source, pre-collimator, post-collimator, scanner, detectors, amplifier circuits, computer system, and shield room. The system scans automobile parts and aluminium die casts. Medical or low energy x-ray CT systems do not provide good CT images for large scale objects because of decreasing numbers of x-rays in the objects and so cannot be used for industrial systems. Therefore, a 450keV x-ray tube which has the maximum possible energy for a tube is selected for this system. X-rays which are radiated from this x-ray tube can be transmitted through 230mm aluminium or 45mm iron in sufficient numbers.



(a) Schematic diagram.

(b) Photo of the exterior.

Fig.1 X-ray CT system.

Table 1. Specifications of X-ray CT system.

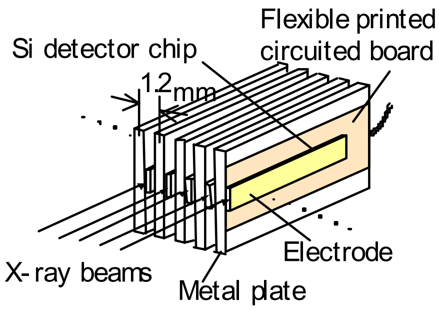
Item	Specification
Max energy of x-rays	450keV
Object size	φ 400mm× H600mm
Scanning mode	3rd generation(rotate-only mode)
Scanning time	Minimum 6s/slice
Pixel size	0.4-0.6mm

2.2 Detectors

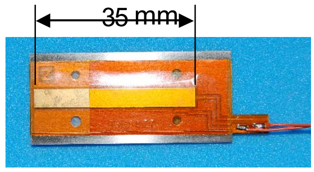
The structure of the detector array is shown in Fig.2. A rectangular silicon detector chip is mounted on the flexible circuit board and this is glued to a metal plate base. The pole of the detector chip is connected to an electrode plane. X-rays are incident on the longer direction of the detector and this improves detection efficiency[3]. The silicon chip length is optimized for the post-collimator structure and the 450keV x-ray beam, so it is 35mm shorter than in a conventional high energy system.

The metal plates shield a detector chip from the other chips to prevent cross talk noise. Cross talk noise is defined as the ratio of the signal quantity due to the scattered radiation from the adjacent detector and the signal quantity due to the directly incident x-rays. The key factor determining the cross talk noise is the Compton process about the first period interaction of the incident x-rays and the silicon chip, and the degradation of the image spatial resolution is caused by this noise[2]. For example, a stainless steel plate which is more than 0.4mm thick effectively reduces cross talk noise to less than 1% of the value which is harmful for the image[3].

Semiconductor detectors such as silicon can detect incident x-rays through direct absorption in the depletion layer and change them to an electronic charge. The charge is proportional to the deposited energy; energy which is required to produce one electron-hole pair in silicon is approximately 3.6eV of absorbed photon energy. Quantum efficiency of silicon is about 30 times larger than that of scintillators such as CWO. Although stopping power of x-ray photons in silicon is smaller than that in scintillators, having a long enough silicon detector to absorb the photons can sufficiently cover the loss of the stopping power. Thus, the S/N ratio of the individual silicon detector to the circuit noise becomes good.



(a) Schematic diagram.



(b) Photo.

Fig.2 Structure of the silicon detector array.

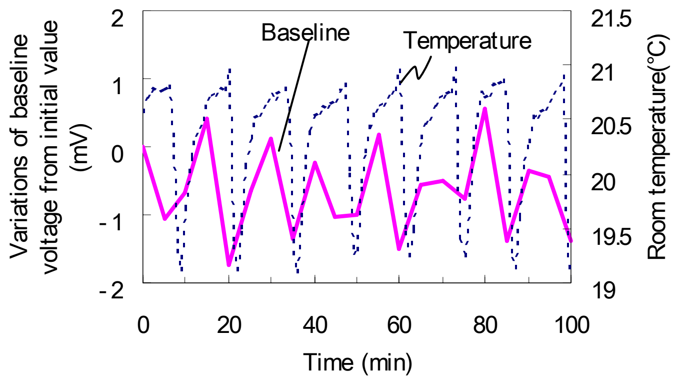
2.3 Signal Conditioning Circuit

Our high energy-x-ray CT system uses a pulsed x-ray accelerator, and each detector and the signal conditioning circuit undergo AC coupling. There is no influence from DC components like leakage current. On the other hand, because the 450keV x-ray tube is a DC x-ray source, each detector and the circuit undergo DC coupling and circuit output is roughly influenced by the leakage current.

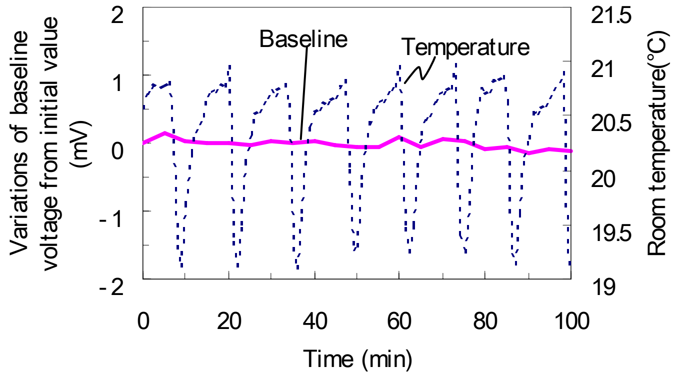
The silicon detectors are like silicon photodiodes and the leakage current is influenced by the ambient temperature and the bias voltage. Moreover, when the volume of a silicon chip exceeds $50mm^3$ as in our detector array, the leakage current becomes picoampere order. If the bias voltage which is applied over each detector is small, the temperature gradient of leakage current can be reduced and it is possible to improve stability of the leakage current.

When the detector is connected with the preamplifier, a current-voltage change is done. Generally, there is an input bias voltage which depends on the unbalance of the inner transistor in the preamplifier. The bias voltage varies as plus or minus by individual preamplifier and has a deviation of about $\sigma = 0.5$ mV. When connecting a detector and preamplifier, this input bias voltage increases the leakage current of the detector and enlarges the temperature gradient of the leakage current. The change of leakage current causes quality degradation of the CT image.

To solve this problem, we controlled the bias voltage by an infinitesimal bias voltage correction circuit and applying the voltage to cancel the input bias voltage on the detector. The correction effect is shown in Fig.3. We measured the variation from the original value of baseline voltage when changing the room temperature of the system periodically. When there is no bias voltage revision, the baseline voltage is synchronized with the change of the room temperature and changes accordingly. The baseline variation is about ⊿ V=2.3 mV for a temperature change ⊿ t=2°C. When implementing the bias voltage revision, the baseline voltage change quantity ⊿ V is equal to or less than 0.15 mV which is a reduction equal to or less than 1/10.



(a) Without bias voltage collection.



(b) With bias voltage collection.

Fig.3 Results obtained with the infinitesimal bias voltage correction circuit.

3. Image Quality Stability

We measured long term stability of the image quality using the system which had the infinitesimal bias voltage correction circuit. In this measurement, the target object was aφ 100mm aluminum piece. The object was scanned at a constant interval and the time change of the S/N ratio of the images was measured. As the index which shows the S/N ratio of the image, the ratio σ/M was used, where M is the average pixel value and σ is the standard deviation of about 500 pixels in the central part of the object image. Variation from the initial value of image S/N ratio is shown in Fig.4. In 8 hours, after the elapse, too, the change of S/N is less than 1% and the image quality is stable.

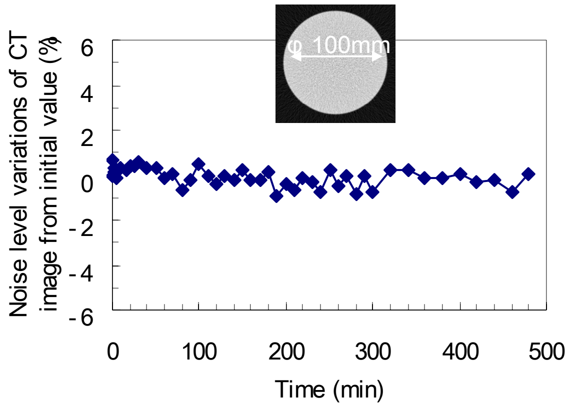
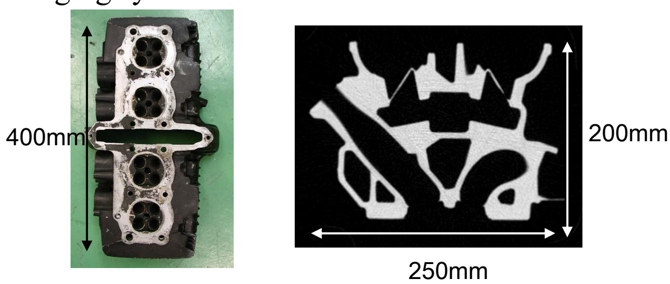


Fig.4 Variations of S/N ratio of CT image relative to the initial value.

4. Some Digital Engineering Applications

4.1 Motorcycle parts

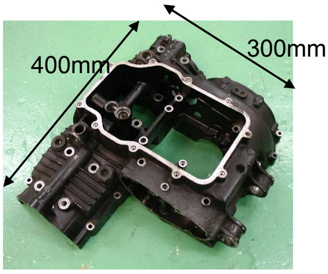
Some parts from a 400cc motorcycle were imaged with our x-ray CT system. Fig.5 is a photo and a cross-sectional image of the aluminum cylinder head. Imaging was done at 6 seconds/slice, which is the same high speed as for a third generation system (rotate-only scanning mode). This gave 800 sections when doing imaging at a 0.5mm pitch relative to the longer direction but when generating solid data for this object, imaging of the whole section was possible within about 120min with our system. This was about 1/13 the imaging time for a second generation imaging system.



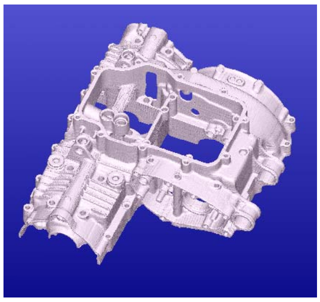
(a) Photo. (b) Cross-sectional image.

Fig.5 Application of the system to a motorcycle cylinder head.

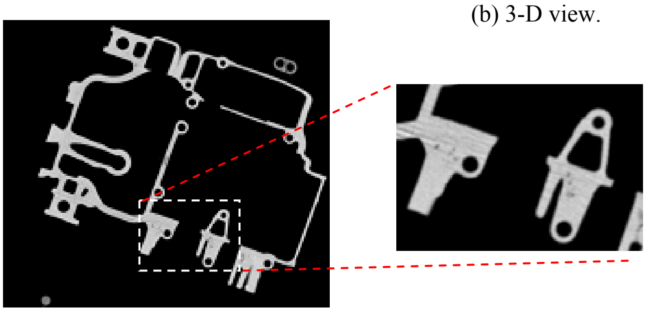
Fig.6 is a photo, 3-D view (stereoimage), a cross-sectional image of the aluminum engine cover of the motorcycle. Imaging was done at about 12 seconds/slice. The 3-D view was made of aliquation to the direction of the height of 130 sections, and the whole imaging time was about 35min. We confirmed from the cross-sectional image that there was more than one casting nest sized from 1mm to 3mm inside. Also, the measurement of the casting nest size below the pixel size and the high-precision measurement with a figure become possible in using measurement software[4].



(a) Photo.



(b) 3-D view.

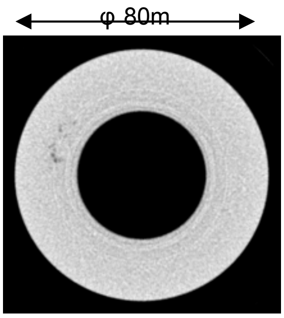


(c) Cross-sectional image and enlargement of defect section of (b).

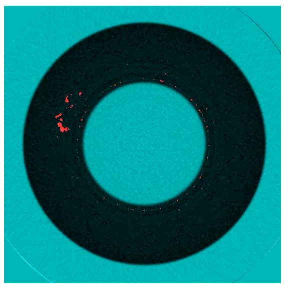
Fig.6 Application of the system to a motorcycle engine cover.

4.2 Casting Defect Detection

Fig.7 shows results for an example of casting defect detection done using measurement software[4]. The sample was an aluminum ring about 80mm in diameter. Casting defect detection is shown by the red mark in (b).Defects under 1mm were found when the sample was cut open and observed.



(a) Cross-sectional image.



(b) Results of casting defect detection by software.

Fig.7 Example of casting defect detection by software.

5. Conclusions

We have developed a 450kV x-ray CT system which uses silicon semiconductor detectors. Silicon semiconductor detectors provide good S/N ratio for measurements with large output current due to incident photons. The input bias voltage by the unbalance of the preamplifier changed the detector leakage current roughly and caused quality degradation of CT images. But we overcame this by developing a circuit to adjust the input bias voltage and realize long term stability of leakage current and maintain quality of CT images.

The system can provide imaging in 6 seconds and generate solid data at the high speed. The image quality is good enough to inspect for internal defects in industrial objects.

References

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[2] H. Miyai, K. Satou, H. Kitaguchi, and S. Izumi: A High Energy X-ray Computed Tomography Using Silicon Semiconductor Detectors, 1996 Nuclear Science Symposium Conference Record, vol.2, pp.816-821(1997)
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