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Development of an ultra-high-speed scanning neutron tomography system for high-quality and four-dimensional visualizations

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ABSTRACT

A new neutron tomography imaging system was developed in order to realize high-quality three-dimensional (3D) and four-dimensional (4D) visualizations by fusing the high-frame-rate neutron radiography and computed tomography (CT) techniques. The fundamental idea is that the object is revolved with high rotating speed and the neutron radiography images are recorded with a high-speed video camera and an image intensifier, and then the consecutive images are processed by a 3D CT technique. The 4D dynamic images of the sand flow in the sandglasses could be visualized clearly. This new technique has also an advantage in that it can reduce radio-activation of the object materials remarkably.

1. Introduction

A neutron tomography technique is one of the radiographic 2D/3D visualization and measurement techniques making use of the difference in attenuation characteristics of neutron in the material. The neutron tomography system is composed of a neutron radiography system and a computed tomography (CT) system. Japan Atomic Energy Agency (JAEA) has developed the neutron tomography system to the visualization and measurement of the 3D void fraction distribution of boiling flow in heated rod bundles, which were simulated to an advanced nuclear reactor core [1–3]. Takenaka and Asano [4] applied the neutron tomography technique to measure the void fraction distribution of air/water two-phase flow. All existing experimental results were time-averaged values because of long scanning time (ranging from 30 min to 4 h) for the CT. Moreover, radio-activation of a test object became a problem at the practical use of the neutron tomography technique.

The purpose of this development is to realize high-quality 3D CT and 4D CT, that is, time change of the 3D object, and to reduce radio-activation of the test object significantly. In this paper, basic idea of an ultra-high-speed scanning (UHSS) neutron tomography technique (patent-JP2008-4247) and some experimental results are reported. The object was fixed on the high-speed turntable.

2. Imaging system and data processing methods

Traditional imaging device for neutron tomography is a CCD camera. Generally, the CCD camera transports data from the CCD device to the recording computer system by normal serial interface of a personal computer. Therefore, recording speed is normally low, e.g. 30 frames/s. Fundamental idea of the UHSS neutron tomography technique is that the consecutive neutron radiography images are recorded with a high-speed imaging system and the test object is rotated with a high rotating speed (*RPS*) ranging from 0.1 to 10 revolving per second (rps) at the same time, and after that the consecutive images are processed by the 3D CT technique as shown in Fig. 1. Using a high-speed recording system, consecutive images can be recorded with high time resolution Δt, e.g. $\Delta t = 0.5$ ms when the recording speed (*FPS*) is 2000 frames/s. Frame number per revolution (*FPR*) (frames/revolution) can be calculated by Eq. (1):

$$FPR = \frac{FPS}{RPS}. \quad (1)$$

The *FPR* is approximately the projection number per revolution ($n/360^\circ$).

Revolution angle per frame (*DPF*) ($^\circ$/frame) is given by the following equation:

$$DPF = \frac{360RPS}{FPS} = \frac{360}{FPR}. \quad (2)$$

Maximum pixel-mapping size of projection images and reconstructed volume size of our system were 1024×1024 pixel^2 and $1024 \times 1024 \times 1024$ voxel^3, respectively. Resolution of the bright-

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ness was 1024 grayscale (10 bit). The fundamental data processing method was the same as the neutron tomography technique reported in Ref. [1].

The tomographic projection reconstruction algorithm was selected from the following three methods:

(a) FBP (filtered back projection method),
(b) ML-EM (maximum likelihood-expectation maximization method), and
(c) MAP-EM (maximum a posteriori-expectation maximization method).

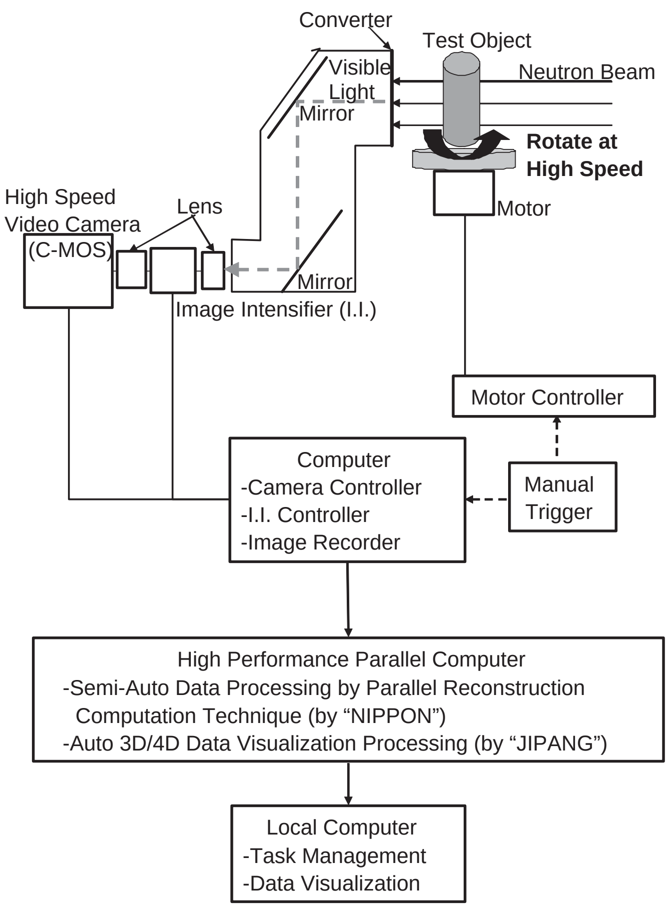

Fig. 1. Basic concept of UHSS neutron tomography imaging technique.

In order to realize the high-quality 3D CT and 4D CT using the UHSS neutron tomography, we need a high-performance computer and exclusive data processing and visualization software. Therefore, we have developed a semi-automatic data processing program named NIPPON and the 2D/3D/4D visualization program named JIPANG, which work on the high-performance parallel computer. Nominal CPU number for the parallel data processing was set to 64.

3. Experiment and discussion

The UHSS neutron tomography system was installed in the neutron radiography facility TNRF-2 of the research reactor JRR-3 of JAEA. The thermal neutron flux and the collimator radio of the TNRF-2 were ($\phi_{th} = 1.5 \times 10^8\,n/cm^2/s$) and ($L/D = 185H$, $154V$), respectively [5].

3.1. High-quality 3D CT

Fig. 2 shows the 3D CT images of the sample. Test sample was a manual valve made by brass for a 1 in. pipe. Recording and revolving set-up were as follows: $FPS = 2000$ frames/s, $RPS = 1$ rps. The FPR and DPF were 2000 frames/revolution and 0.18°/frame, respectively. The ML-EM method was used for the reconstruction. The irradiation time necessary for the reconstruction with the projection angle ranging from 0° to 180° was 0.5 s. Fig. 2(b) and (c) shows the side and outside views of the reconstructed data, that is, 3D distribution of the CT value. Vertical cross-sectional view of the same experimental result is shown in Fig. 2(d). It was confirmed from Fig. 2(d) that the details of the inside of the valve could be visualized. Volume size of the sample is $460 \times 460 \times 415$ voxel^3.

The following are the advantages of this new technique:

(a) High-quality 3D CT result can be obtained because of the high projection number.
(b) Very low radio-activation of the test object because of the very short irradiation time of neutron beam.

On the other hand, some disadvantages exist as follows:

(a) A large amount of computer power for the data processing is required because of the huge projection number and volume size.
(b) The DPF is better to be controlled under 1°/frame because the motion blur of the revolving object reduces the quality of the result.

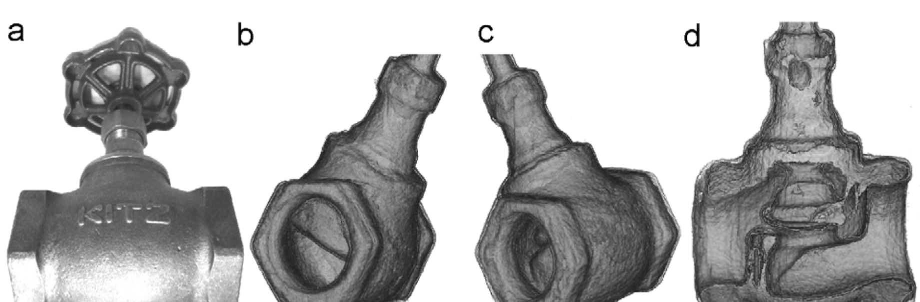

Fig. 2. Sample 3D-CT images (valve; 2000 projection numbers; 2000 frames/s; 1 revolution/s). (a) Photo (Valve), (b) Result (side view), (c) Result (outside view) and (d) Result (vertical cross section).