Fast X-ray micro-CT for real-time 4D observation

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Abstract. Fast X-ray computed tomography (CT) system with sub-second order measurement for single CT acquisition has been developed. The system, consisting of a high-speed sample rotation stage and a high-speed X-ray camera, is constructed at synchrotron radiation beamline in order to utilize fully intense X-rays. A time-resolving CT movie (i.e. 4D CT) can be available by operating the fast CT system continuously. Real-time observation of water absorbing process of super-absorbent polymer (SAP) has been successfully performed with the 4D CT operation.

1. Introduction
X-ray CT technique is essential application utilizing X-ray’s transparent characteristics. The technique can reveal inner structures of objects and has been widely applied for not only medical diagnosis but material science and so on. According to recent development of X-ray sources and X-ray optics, micro-CT techniques with high-spatial resolution have been developed and the systems that can resolve below 100 nm order are not special. Otherwise, new approach for x-ray CT, improvement of temporal resolution for observing dynamics of blind inner structures is very promising. This approach has been recently developed for medical diagnosis CT system and excellent multi-slice CT system with sub-second resolution is commercially available [1]. For micro-CT based on synchrotron radiation source, some works of fast CT techniques have been reported [2, 3]. Although they successfully captured high-speed jet or in-situ heart beating, their techniques are available only for repetitive phenomena. In order to realize real-time fast CT, a high-speed X-ray camera for micro-imaging has been developed. The camera system has ability to acquire images with hundreds to a thousand frames per second (fps) and real-time fast micro-CT system can be configured by using high-speed sample rotation system. The fast micro-CT system with the spatial resolution of 30 μm and the fastest acquisition time for single CT of 0.16 s has been successfully developed. In this paper, system components and performance of the fast micro-CT are reported. And as an excellent application of the system for real-time 4D observation, water absorbing process of a piece of SAP set in glass capillary is introduced.

2. System components and experimental set-up
The key components of the fast micro-CT system are a sample rotation stage and an imaging detector. The rotating stage is driven by DC motor with the fastest rotating rate of 3.125 rotations per second (rps). The stage is based on sample rotator generally used for powder diffractometer and the wobbling of rotation centre is tuned within 4 μm. The fast X-ray camera system we developed is visible-light conversion type and consists of P-43 scintillator (10 μm thickness), relay lens optics, and high-speed
CMOS sensor. The relay lens optics has two C-mount camera lens with $F = 0.95$ and a 2x extension lens. The optical path is bent with a plane mirror to avoid direct incidence of X-ray to image sensor. The high-speed CMOS sensor (Hamamatsu, C8201) having $256 \times 256$ arrays of 20 $\mu$m-sized square pixel can take images with 250 fps (1000 fps is also possible with 128 $\times$ 128 arrays readout), and continuous image acquisition for over 40 s is possible on 512MB RAM memory. Therefore, effective pixel size of the fast X-ray camera system is 10 $\mu$m and the view field is 2.56 mm.

The fast micro-CT system is constructed at Hyogo-ID beamline (BL24XU) of synchrotron radiation facility SPring-8. The beamline has a figure-8 type hard X-ray undulator, strong emission with relatively low heat load is available, as the light source and a silicon double-crystal monochromator (DCM). Monochromatized X-ray beam with the energy of 10 keV, the intensity of $5 \times 10^{12}$ photons/s, and the size of about 1.5 mm squares is obtained at experimental hutch about 70 m apart from the undulator source. The overview of the beamline and components of the fast micro-CT system are shown in Fig.1. The X-ray imaging optics we adopted is the simplest projection mode for utilizing the strong intensity, and fully statistic image can be obtained for single exposure (4 ms) with this system. The distance between sample and image detector is set as close as possible in order to reduce edge-enhancement by refraction, and a rotating beam diffuser consisting of sandpapers is installed to reduce unevenness of view field caused by speckle noise from coherent undulator illumination. The control system is very simple to avoid dead-time during measurements. There is no synchronized signal between sample rotation and image acquisition. Just the projection images are started to be acquired with 250 fps after the rotation rate of the sample stage is fully stabilized. Time series dataset of projection images over 40 s (i.e. over 10000 images!) is obtained by the continuous measurement at once. The number of projection images for single CT reconstruction depends on the sample rotation rate. 40 projection images covering 180 degree can be obtained in 0.16 s where the rotation is driven with the highest rate of 3.125 rps. Time series CT data, we call this as 4D CT, can also be obtained by extracting single CT at every 90 degrees from the dataset. Then, 4D CT observation with the fastest interval of 0.08 s is possible as a real-time movie.

In the case of fast CT, number of projection images seems too small to reconstruct fine structure though the effective pixel size of the detector is as small as 10 $\mu$m. The spatial resolution of fast CT is evaluated by reconstructed wall images of thin glass capillary with the wall thickness of 10 $\mu$m. Blur of the reconstructed walls, corresponding to the spatial resolution, is investigated for various projection numbers. The spatial resolution around 30 $\mu$m is obtained in any view field with the projection numbers down to 90 (0.36 s for 1CT). For the fastest projection number of 40, only the centre view field within 0.8 mm satisfies 30 $\mu$m resolution. The evaluated spatial resolution is always inferior to effective pixel size of 10 $\mu$m. The degradation is caused from not CT system but image detector because an edge-response of projection image is evaluated to 30 $\mu$m.

3. Real-time 4D observation of water absorbing process of SAP

The SAP, consisting of sodium polyacrylate [(−CH$_2$−CH(COO−Na$^+$))$_n$], can absorb water of the hundreds times weight for itself. The material is widely applied for various products. We attempt to
observe the water absorbing process of the SAP as 4D CT application. A piece of SAP taken from a
disposal diaper for baby is put into glass capillary tube with the diameter of 1 mm. A water injection
needle is set above the upper edge of the glass capillary. A water drop is injected to SAP just after
starting a measurement with the sample rotation rate of 1.2 rps (0.36 s for single CT acquisition). A
4D CT movie consisting of 226 3D CT reconstructions with the interval of 0.18 s is obtained. Figure 2
shows extracted typical images from the movie data. Water absorbing process and expansion of SAP
can be clearly observed. Moreover, time dependent change of absorption coefficient of SAP can be
observed by analysing histograms of the reconstructed sectional images. Figure 3 shows the time
dependent changes of peak value of the obtained absorption coefficient (corresponds to density). The
density rapidly increases just after water injection and slowly decreases close to that of water. This
type of information is important for understanding mechanism of the process, and is essential
application utilizing advantage of X-ray CT.

![Figure 2. Extracted images from 4D CT movie of water absorbing SAP. The lower images are volume rendering images and the upper images are the corresponding sectional image of CT reconstruction. The images show typical phase of dynamics. (a) is taken before water injection (dry state), and (b) – (f) are time series images taken from just after water injection.](image)

![Figure 3. Time dependant changes of absorption coefficient of SAP. The absorption coefficients are obtained by analyzing histograms of sectional images. The value rapidly increases just after water injection and slowly decreases close to that of water.](image)

4D CT technique is quite promising because it gives direct understanding for dynamical phenomena.
Various applications will be expected by improving the temporal resolution and the spatial resolution.
Although these experiments require the stronger illumination to sample, we can perform further
improvement by using raw undulator radiation (without monochromator).

4. References
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