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COMPUTED TOMOGRAPHY SYSTEM WITH STRICT REAL-TIME SYNCHRONIZATION FOR IN-SITU 3D ANALYSIS OF PERIODICALLY VIBRATING OBJECTS

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Abstract. In the contribution, we present a laboratory system capable of X-ray computed tomography (XCT) scanning of an periodically moving or oscillating object. The system is an in-house developed XCT setup with electromagnetic voice coil actuator mounted on top of the rotary stage of the setup. The strict synchronization of the components, the rotary stage, the electromagnetic actuator movement and the detector readout is accomplished with use of the detector hardware trigger and hard real-time Linux operating system. Cylindrical sample manufactured from epoxy resin with metal particles to enable movement tracking is scanned in a stationary position and during periodical movement induced by the vibration stage. The volumetric data of the scans is compared and the results of this contribution represent an important step towards identification of defects through modal analysis of in-situ harmonically vibrating object.

Keywords: Harmonic motion, real-time synchronization, computed tomography, hardware trigger, subtraction tomography.

1. Introduction

In-situ X-ray computed tomography (XCT) has become commonly used imaging method for the vizualization and analysis of internal structure and defects of materials in the field experimental mechanics. Especially materials with complex shapes and internal structure, such as rocks, biomaterials, 3D-printed lattices, other heterogenous materials, etc. subjected to quasi-static mechanical loading and recently, in-situ computed tomography has been the topic of intensive scientific interest. Using the XCT technique, volumetric investigation of complex phenomena such as crack propagation [1, 2], damage development or failure mechanism identification [3–6] has become possible. Furthermore, X-ray imaging techniques have been adopted for state-of-the-art inspection of non-stationary objects and material samples subjected to dynamic loading [7]. X-ray imaging of non-stationary objects or imaging of short-lived deformation phenomenons require precisely timed synchronization of all the components of the XCT setup, such as rotary stage position, X-ray detector readout, etc.

In this paper, we present an in-house designed XCT system for scanning of periodically moving objects with the intention and future goal of modal analysis of oscillating beams using XCT or to vizualize and analyze defects inside the specimens induced by dynamic loading, such as fatique crack growth inside the oscillating beams. To be able to precisely and reliably acquire X-ray data, the proposed system employs real-time hardware synchronization of all the necessary components with in-house developed control software including custom software for the X-ray detector image acquisition. The concept and functionality of the system is tested and verified by obtaining the XCT of the periodically moving rigid body and comparing it to the reference XCT and evaluating the difference between the reference XCT volume and the volume of the periodically moving rigid body.

2. Materials and methods

At the authors' workplace, an in-house developed X-ray setup is used for XCT imaging. The setup consists of numerous positioning axes including rotary stage and can be equipped with various X-ray sources and detectors. In the modal analysis configuration, on top of the rotary stage is placed the shaker, which is the linear voice-coil actuator, which drives the periodic motion of the sample, see Figure 1. In this study, the X-ray source used is the sealed type L10321 (Hamamatsu Photonics, Japan) with maximum acceleration voltage of 100 kV, 20 W of maximum target power, and lowest achievable focal spot size of 5 µm. The detector used is the Dexela 1512 NDT (Varex Imaging, USA) CMOS detector equipped with CsI scintillator and resolution of 1944×1536 px and framerate up to 86 Hz depending on binning. The shaker is the MGV41 (Akribis Systems, Singapore) with position sensitivity 0.1 µm, position repeatability 1.5 µm, stroke up to 20 mm and frequency range up to 50 Hz.

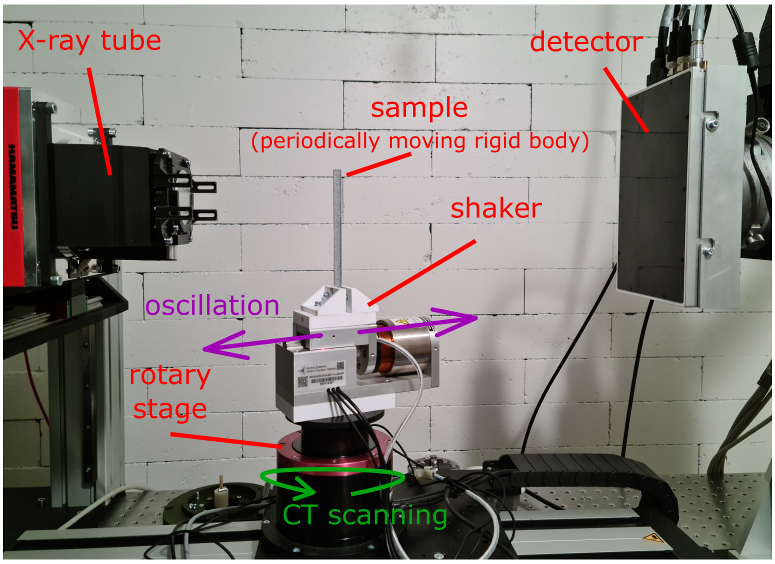


Figure 1. Experimental setup.

2.1. Detector synchronization

Proper X-ray image acquisition of non-stationary or oscillating object requires precise timing and synchronization of the imaging chain and the positioning components, including detector exposure, shaker position or rotary stage position. This is achieved by utilizing the hardware trigger interface of the Dexela 1512 NDT detector and integrating it through the hardware trigger interface into the in-house developed control system of the XCT setup. The detector exposure takes place while the shaker reaches its peak amplitude (the image exposure was started so that the peak amplitude value was reached exxactly in the middle of the image exposure time window). Inherently, throughout the image exposure, the periodically moving rigid body sample is moving, see Figure 2. The image exposure occurs at the zone of the peak amplitude due to the intention to use the proposed system for modal analysis of oscillating beams, for instance to 3D visualize eigenshapes of the beams, etc.

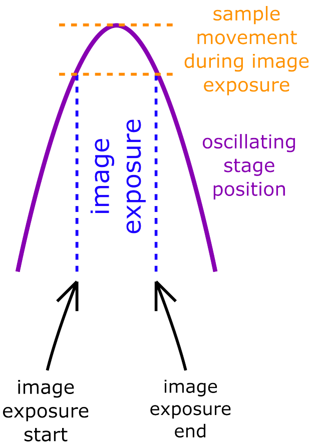


Figure 2. Image exposure at the peak amplitude.

For detailed diagram of the hardware synchronization logic, see Figure 3. As the shaker position (purple line signal in Figure 3) reaches the zone of the peak amplitude and the rotary stage is in position and stationary (i.e. not moving – green signal in Figure 3 is in the lower position), the image exposure is started (rising edge on the blue line signal in Figure 3) with the rising edge of the hardware trigger signal (red line in Figure 3). After the image exposure is finished (falling edge on the blue line signal in Figure 3), the rotary stage starts moving (rising edge on the green line signal in Figure 3) and once the rotary stage reaches desired position to acquire XCT projection, whole process is repeated.

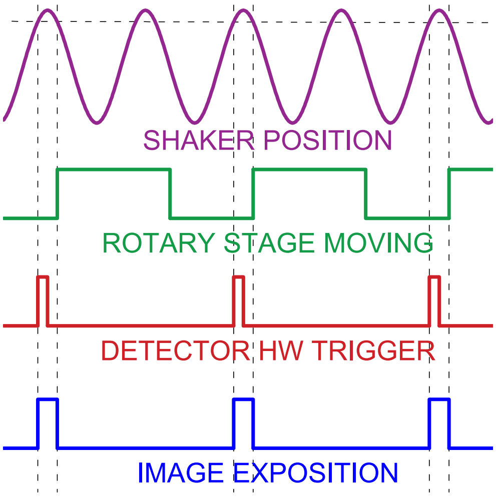


Figure 3. Synchronization of the detector.

The control system, which handles the synchronization of the XCT experimental setup and the aforementioned signal processing, is done using an in-house developed control software package based on open-source software platform LinuxCNC. The control software employs real-time capabilities of the Debian GNU/Linux system to assure precise timing and synchronization with the synchronization frequency of 5 kHz.

2.2. Computed tomography

The sample observed by the XCT is a cylindrical sample ($D \approx 8$ mm; $H \approx 140$ mm) manufactured from an epoxy resin with dispersed aluminium particles to increase contrast in the reconstructed 3D images. First, the reference tomography of the sample was acquired (with the shaker in stationary position). The reference tomography volume can be found in Figure 4 and parameters of the XCT scanning are listed in Table 1.

The same imaging parameters were used for the acquisition with the shaker periodically moving. The shaker was set up to produce sinusoidal movement with the amplitude of 5 mm and the frequency of 4 Hz. With this setup and the shaker movement throughout the image exposure is approx. 245 µm, see Figures 2 and 5. In Table 1, note the difference in the duration of the tomography scanning. The much higher scanning duration with the shaker periodically moving is caused by the image exposure taking place only when the shaker reaches its peak amplitude. With the harmonic motion frequency 4 Hz, the image exposure occurs with 250 ms period, as opposed to the tomography scanning with the shaker stationary, in which case the image exposure takes place in succession without any delay. Furthermore, the oscillation of the shaker has negative influence on the rotary stage position control due to moving mass of the shaker on top of the rotary stage. For that reason, a mandatory time delay needed to be added for the rotary stage position error to settle and meet the control system conditions after the rotary stage position increment. Only after the positioning condition were met, the exposure of the subsequent image could be started.

Tomography parameters	
Target power	20 W
Acceleration voltage	100 kV
Spot size	30 µm
Exposure time	25 ms
FDD	497.2 mm
FOD	162.6 mm
No. of projections	1 912
Frame averaging	10
Detector binning	2 × 2
Detector pixel size	150 µm
Magnification	≈ 3.1
Voxel size	48 µm
Scanning duration (shaker stationary)	≈ 12 min
Scanning duration (shaker oscillating)	≈ 90 min

Table 1. Tomography parameters.

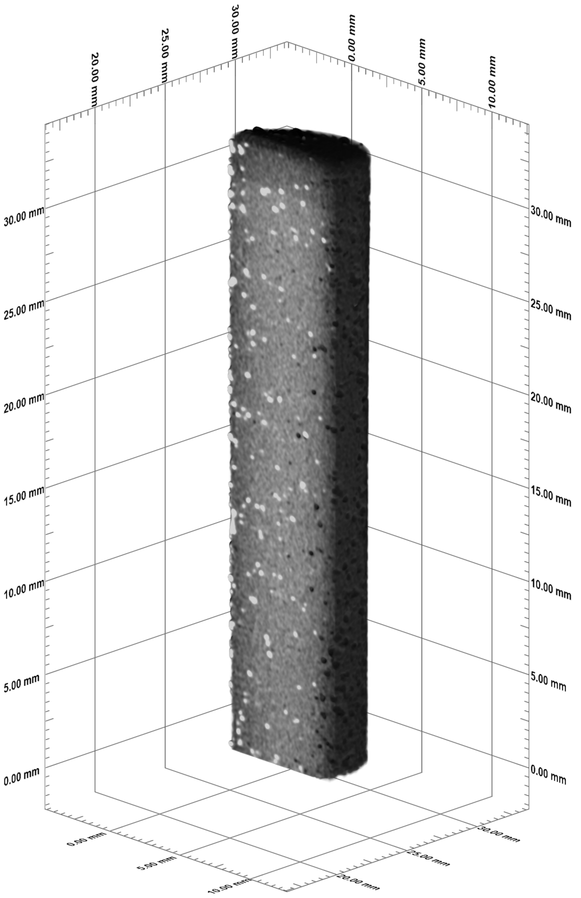


Figure 4. Section through the reference volume showing aluminium particles (white) and voids (black).

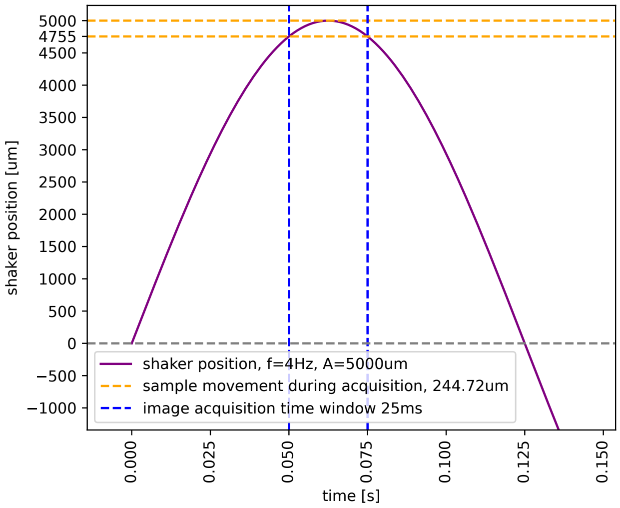
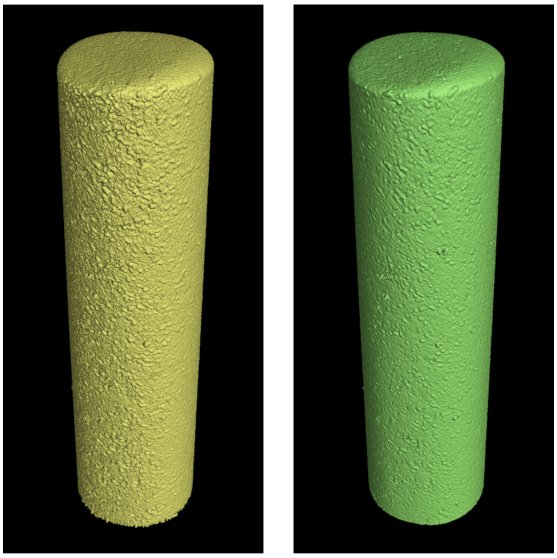


Figure 5. Sample movement during image exposure.

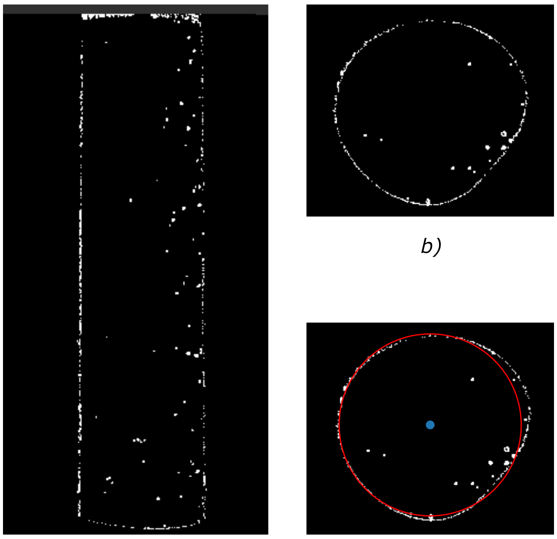
3. Results

The goal of the study is to validate the feasibility and reliability of the tomographical system for the vizualization of periodically moving or oscillating objects. In order to quantify the influence of the periodic motion, the reference tomogaphy volume (with the shaker stationary) was compared to the tomography volume acquired with the shaker performing sinusoidal



a) b)

Figure 6. (a) Reference volume (shaker stationary); (b) periodically moving tomography (shaker moving).



a) b) c)

Figure 7. (a) Vertical slice through the subtracted volume; (b) horizontal slice through the subtracted volume; (c) horizontal slice through the subtracted volume with polar coordinate system.

motion. The overview of the volumes is shown in Figure 6. The volumes were binarized with threshold and then subracted in order to vizualize the difference between the volumes using the subtraction tomography method, see Figure 7.

The difference of the volumes is mostly distributed near the surface of the subtracted volume envelope. The aim of the comparison was to evaluate the thickness of the subtracted volume envelope in radial directions. For that, each horizontal slice of the subtracted envelope was fitted with a circle, the center and the radius of the circle was fitted using the sum of the squared differences, see Figure 7c. The circle represents a polar coordinate system which is used for the evaluation. The thickness of the envelope in all directions in the polar coordinate systems of each horizontal slice is shown in Figure 8. The results show the envelope thickness ranging from 0.5 up to 2.1 voxels, due to the reconstructed volume of the periodically moving object being blurry compared to the reference volume.

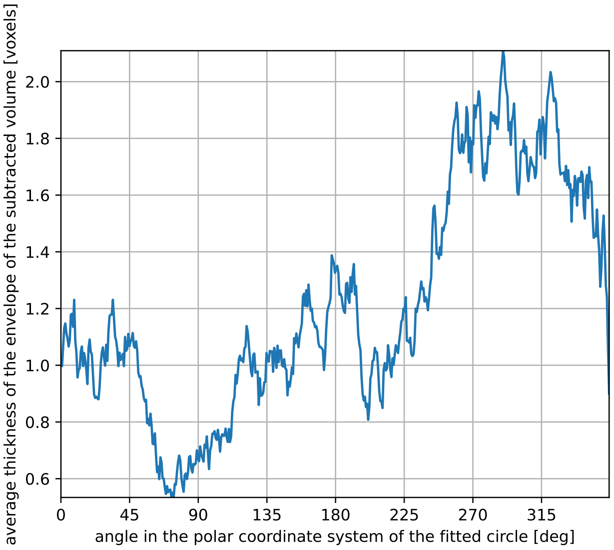


Figure 8. Thickness of the subtracted volume envelope.

4. Conclusions

In this study, we present an in-house developed tomography system capable of scanning periodically moving rigid body. The proof of concept was validated with pilot tomography scanning of epoxy resin rigid body. First, the tomography of the rigid body with shaker stationary was acquired and secondly with the shaker performing sinusoidal motion. The resulting volumes of the tomography scanning were binarized and compared and exhibit small difference in the magnitude of less than 2.1 voxels, even though the motion of the rigid body was approximately 5 voxels during the image exposure. The small difference of the resulting volumes show that the system is capable of tomography scanning of periodically moving objects. In this case, the object was moving periodically with the amplitude of 5 000 µm and the maximum difference of 2.1 voxels (voxel size 48 µm is equivalent to 100 µm in the real world).

Additionaly, the quality of the acquired data can be improved with shorter exposure time of the detector to decrease the motion of the sample during the image exposure, which was not viable due to the limited flux of the X-ray source used in this study. However, in furter studies regarding this topic, the higher flux X-ray source MetalJet D2+ will be used, thus allowing for decreasing the exposure time of the detector up to 15 ms which is the limit of the currently used detector Dexela 1512 NDT (framerate up to 70 Hz with binning 2 × 2). With the exposure time 15 ms (instead of 25 ms presented in this study) and the same harmonic motion of the shaker (frequency 4 Hz, amplitude 5 000 µm the motion of the sample during the image exposure can be decreased from the 245 µm (5 voxels with the voxel size of 48 µm) up to 89 µm (less than 2 voxels with the voxel size of 48 µm).

The ultimate goal of the proposed imaging system is to use it for modal analysis of oscillating beams using XCT and for analyzing eigenshapes and eigenfrequencies of oscillating beams. Furthermore, the future research will be aimed at in-situ computed tomography of oscillating beams and the analysis of internal defects, such as fatique cracks development, etc.

Acknowledgements

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