Utilization of dual-source X-ray tomography for reduction of scanning time of wooden samples

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ABSTRACT: We present a novel dual-source/dual energy (DSCT/DECT) micro-tomography system including results of high-resolution DSCT reconstruction. The DSCT micro-tomography setup was designed as a multi-purpose X-ray imaging device equipped with two pairs of X-ray tubes and detectors in orthogonal arrangement with independent control of beam parameters. Both pairs (tube-detector) are mounted on a computer numerical control positioning system and can be independently set up to different geometries (e.g. with different magnification of each pair). In this work the simultaneous scanning of the object by two tube-detector pairs was used for approximately half reduction of tomography scanning time. The developed imaging procedure was applied for scanning of a wooden sample locally damaged during a semi-destructive test for assessment of wood quality. Prior to the tomography measurements the setup geometry was precisely adjusted in terms of magnification, horizontal and vertical tube-specimen-detector alignment of both pairs. DSCT measurements were carried out in sequence (2 × 90° for each tube) with identical 100 μm image resolution. It was proven that the presented experimental setup combined with appropriate control technique significantly reduces tomography scanning time of materials with complex micro-structure.

KEYWORDS: Computerized Tomography (CT) and Computed Radiography (CR); Overall mechanics design (support structures and materials, vibration analysis etc); Inspection with x-rays

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1 Introduction

X-ray computed tomography (CT) is widely used as a non-destructive method for inspection and visualization of inner structure of complex materials. Requirements for higher spatial resolution and quality of CT results resulted in development of micro-CT scanners that are widely used in both industrial and scientific applications. Recent research in the field of micro-CT imaging led to introduction of novel techniques for advanced non-destructive testing (NDT) [1, 2], material identification [1–3] or scanning with high temporal resolution [4, 5]. Utilization of such methods requires more sophisticated, more complex and modular CT systems.

In this work a novel multi-purpose dual-source/dual-energy micro-CT (DSCT/DECT) device with two pairs of X-ray tubes and detectors with independent geometry adjustment (of each pair) is introduced. The system was developed with emphasis on its modularity, flexibility and usability in wide range of conventional and novel X-ray applications. One of the key benefits of the system is orthogonal arrangement of tube-detector pairs with shared rotational stage together with independent geometry adjustment for each pair. Because of this feature the system can be used for e. g. DSCT scanning (faster tomography with simultaneous irradiation by two X-ray tubes at the same energy), DECT scanning (measurement with two X-ray tubes each at different energy) or simultaneous acquisition of orthogonal X-ray projections (with different detectors, at different magnifications etc.).

DSCT is a well established method in medical imaging that enabled optimized measurements and higher temporal resolution (particularly in coronary imaging [6]). The main limitation of conventional medical DSCT method for material’s science imaging is relatively low spatial resolution (limit 0.5 – 0.7 mm for conventional setups [7], 0.24 – 0.3 mm for the most advanced multi-slice dual-source medical scanners [8]). Source-object-detector distances of the devices are fixed and
thus have limited geometry variability in comparison with single-source industrial CT scanners with adjustable source-object-detector positions.

Utilization of DSCT in micro-CT applications requires another arrangement of the system. Stationary arrangement of two perpendicularly oriented X-ray pairs (tube-detector) with shared fixed-position rotational stage is one possible solution for the task [4]. However, this setup allows high resolution measurements only at fixed geometry and its eventual modification requires time-consuming rearrangements [4]. Final geometry alignment procedure of the system is also complicated [4] and can not be easily repeated (restored). Presented multi-purpose X-ray system can perform dual source measurements in high resolution based on principles similar to [4, 9] however its computer numerical controlled (CNC) geometry is non-stationary and relatively easily adjustable and recoverable (in comparison to stationary systems). Thus, the device is very flexible and combines advantages of DSCT/DECT systems with features and spatial resolution of industrial micro-CT systems.

In this work first results with DSCT scanning and the presented multi-purpose system are described. The method was utilized for approximately half reduction of tomography scanning time of wooden sample. The investigated sample was locally damaged using novel semi-destructive technique for assessment of wood quality [10]. To enhance this measurement technique, CT analysis can be used for study of the post-damage behaviour in the material. As relevant and reliable analysis requires inspection of a large number of samples, the DSCT technique was employed and its speed, complexity, resolution and applicability for inspection of wooden samples are evaluated.

2 Material and methods

2.1 DSCT/DECT micro-tomography device

The novel DSCT/DECT micro-tomography device was developed at the Centre of Excellence Telč and was assembled in its X-ray laboratory in 2013 (patent pending, European Patent Office No. 14002662.6-1559 and Industrial Property Office of Czech Republic No. PV2013-607). The device was developed as complex, flexible and modular multi-purpose X-ray system and therefore is equipped with two X-ray tubes: i) reflection type XWT-240-SE (X-ray Worx, Germany) with voltage range 20 – 240kV, minimum focal spot size 5 µm, maximum target power 280W and ii) transmission type XWT-160-TCHR (X-ray Worx, Germany) with voltage range 10 – 160kV, minimum focal spot size 1 µm and maximum target power 25W. The transmission X-ray tube was selected as a micro-focus high resolution tomography source. The reflection type was selected as a high energy source because of its wide voltage range and maximum target power. Nevertheless, both tubes can operate with identical parameters of spot size 5µm, beam geometry and voltage (in range 10 – 160kV) up to target power 25W. Therefore, tubes can operate together as a high resolution dual source tomography system. Image acquisition is possible either using two large area flat panel detectors XRD1622 (PerkinElmer, U.S.A.) with active area 41 × 41 cm, resolution 2048 × 2048px (pixel size 200 µm) and minimum full-scale integration time 1000ms. The detectors were chosen because of wide energy range sensitivity 20 – 15000kV, large dimensions of active area together with large number of pixels and minimized radiation hardening effect (gadolium oxyysulfide — GOS scintillator). The workplace is also equipped with one Wide-PIX [11] single particle counting radiation imaging detector with resolution 2560 × 2560px that
can be mounted instead one flat panel detector. WidePIX consists of matrix of $10 \times 10$ Timepix hybrid detectors with edgeless silicon sensors and minimum energy threshold 5keV. The scanned samples are placed on a high-precision air bearing rotational stage ABRT-150 (Aerotech, U.S.A.). The main parts of the assembly are arranged in two cross-oriented scanning pairs with shared rotational stage and are mounted on a complex 16-axis CNC positioning system. The positioning of the device is performed by linear motion guides, precious ball screws with zero backlash and stepper motors. Movement accuracy is monitored by absolute position sensors with micrometric precision (RLS, Slovenia). The geometry of each scanning pair can be adjusted independently without influence on the other scanning pair. Maximum source-detector distance is 1255 mm for pair with transmission tube and 1335 mm for pair with reflection tube. Minimum source-object distance is theoretically 4 mm as the rotational stage axis can be positioned to tube window locations. Both X-ray pairs can be adjusted vertically in range approx. 200 mm (tubes) and approx. 400 mm (detectors). Samples with dimensions in micrometers (theoretically with size of focal spot) up to several dozen centimetres can be irradiated with the system (mass limit is 45 kg). The assembled device and its simplified scheme are depicted in figure 1.

2.2 DSCT scanning

The basic idea of dual source scanning is in this case to get two sets of corresponding projections (from two scanning pairs), merge them and perform reconstruction. Thus, prior to the dual-source scanning, a precise adjustment of both tube-detector pairs and rotational stage has to be carried out. Both tube-detector pairs should have identical irradiation geometry to be able to merge data from both detectors for consequent tomographic reconstruction without necessity of the rather complicated corrections. Two identical large area flat panel detectors (XRD1622) were used for data acquisition. At first, a required magnification (given by the ratio ‘focus detector distance/focus object distance’) was selected and the scanner geometry was pre-positioned. Laser measurement tools were used for preliminary alignment of the ‘tube spot — rotation axis — detector centre’ vertically and ‘tube spot — detector centre’ horizontally. Then, the precise geometry adjustment of each tube-detector pair was carried out using a technique similar to the method based on identification of ellipse parameters [12]. Two well registered spots identified in the testing object were tracked during rotation at two different magnifications. The geometry was adjusted to have spot tracks symmetric to both vertical and horizontal central axes of the detector at both magnifications.
Afterwards, geometry adjustments were performed for the second tube-detector pair using the same principle. Congruency of both irradiation geometries was checked comparing a difference of perpendicular projection images from both detectors at several rotational angles of the object. For elimination of reconstruction artefacts caused by geometry mismatch the maximal shift difference of images in all compared projections has to be smaller than 1 px. Geometry adjustment was time consuming and overall procedure took approximately 5h. Nevertheless, the adjusted CT scanner geometry was saved and can be anytime recalled utilizing absolute position sensors and feedback controlled positioning. The expected outcome of the geometry adjustment procedure was not to obtain two identical images (with zero difference in every pixel), but to perfectly match the geometry of scanning pairs and thus to place projections of object to the same pixels of both detectors in several rotational angles. Image differences of a small object (clip) prior to the geometry adjustment is shown in figure 2a. Difference of projections after the final geometry refinement is shown in figure 2b. Detailed view of region of interest prior and after the refinement is depicted in figure 2c and figure 2d together with appropriate line profiles in figure 2e and figure 2f. Approximately 8px shift can be seen in figure 2c with image difference peaks (positive and negative) in the line profile in figure 2e around positions marked 1, 2, 3. After the geometry refinement the image difference was near zero in the same positions (see figure 2f). Beam hardening correction method [13] was used for final calibration of both detector signals, noise reduction and bad pixels correction. For higher efficiency acquisition of beam hardening correction data can be carried out in dual-source mode. Detector signals after beam hardening correction can be considered identical.

Tomography scanning was performed with data acquisition from both tube-detector pairs.
Figure 3. Scheme of dual-source tomography procedure.

Scanning was divided in two data acquisition sequences with respect to orthogonal arrangement of the assembly. Scheme of the tomography procedure and acquisition sequences is shown in figure 3. In the first acquisition sequence, the detector 1 was used to acquire projections in the first quadrant and the detector 2 was used to acquire projections in the second quadrant. Then, the rotational stage was rotated $90^\circ$ and a second acquisition sequence was initialized. In this sequence the detector 1 was used to acquire projections in the third quadrant and the detector 2 was used to acquire projections in the fourth quadrant. All projections of the object were collected in approximately half the time when compared to single-source tomography. Tomography data were read out using the Pixelman software [14] developed at the Institute of Experimental and Applied Physics of the Czech Technical University in Prague and custom Python and C++ software tools enabling real-time parallel acquisition from both flat panel detectors.

2.3 Semi-destructive wood testing method

The novel semi-destructive device for in situ evaluation of wood quality using compressive loading inside a pre-drilled hole was developed at the Centre of Excellence Telč and was patented in 2012 (Industrial Property Office of Czech republic No. 304384). The device is designed for both laboratory and in-situ measurements of wood [10, 15]. The device consists of a planetary gear unit, a frame containing positioning mechanism, grooved screws with different lengths (for loading in different depths) and loading elements manufactured from high-performance tool steel. The wood structure is loaded by spreading the small size jack inserted in a pre-drilled hole with recording of force-displacement diagram. The loading is driven by cordless drill mounted to the device. The wood condition can be evaluated and analysed based on measured dependencies. The device and principle of measurement are depicted in figure 4a.

The described wood testing method combined with tomography measurement can be utilized for assessment of post-loading behaviour of wooden samples (possible relaxation of deformed structure). X-ray tomography results can produce relevant data to analyse overall deformation of the pre-drilled hole (in direction of loading and in direction perpendicular to loading) and local damage caused by pin of the loading device. The analysis of the CT results together with force-displacement diagram recorded in test can be used for identification of loading test quality (proper boundary conditions e. g. contact position of pin, homogeneous shape of imprints etc.) and reaction of the wood after unloading (change of dimensions, evaluation of residual plastic deformation).
However, measurements of a number of samples is required for relevant and reliable analysis. Thus, dual-source scanning technique was tested to evaluate its applicability and accuracy for such measurements.

2.4 Wooden sample

The wooden sample was prepared from spruce as a block with dimensions 106 × 70 × 25 mm. A hole with nominal diameter 12 mm was drilled in the middle of the narrow side of the sample. The loading pin of the semi-destructive device was inserted in the pre-drilled hole and the initial part of the loading was carried out. The measured force-displacement diagram is shown in figure 4c. Numbered positions in the graph represent: 1) initial contact of loading pin with the sample, 2) beginning of linear-elastic region, 3) end of linear elastic region and 4) end of test with small plastic deformation induced. After the loading a relaxation period of 72 hours was held. The deformation response in the sample was localized in the vicinity of the drilled hole and as such did not influence the boundary conditions of the test (overall deformation did not affect original dimensions of the sample). The sample is depicted in figure 4b.

2.5 Pilot DSCT experiment

Implementation of DSCT technique was time-consuming task that required development of several software tools and experimental procedures. A simplified pilot DSCT experiment was carried out during the development stage of the method and the feasibility of the procedure was validated using tomography of a complex-shaped wooden object (hedgehog-in-the-cage puzzle). In this measurement the basic principle of the method, the precision of geometry adjustment and the reconstruction quality from two sources were validated. Software tools for dual-source scanning and parallel readout of the detectors were not utilized as they were finalized after pilot experiment verification. Therefore, tomography scanning was carried out in two consequent series with acquisitions using individual tube-detector pairs. The setup geometry was arranged to obtain magnification 3.33 × with source-object distance 376.5 mm, source-detector distance 1255 mm and spatial resolution 60 μm. The X-ray tube voltage and target current were set to 60 kV and 160 μA resulting in target power 9.6 W. The acquisition time of the detector was set to 1 s with 400 angular projections taken in each series. Image data for the reconstruction were combined from the first detector (only the first and the third quadrant) and from the second detector (the second and the fourth quadrant). Dual-source CT reconstruction was carried out using Volex software (Fraunhofer-Allianz Vision,
Germany). Results of the pilot experiment were satisfactory (see Results) and tested experimental procedures were used for final development of appropriate software tools. A puzzle object in scanner is shown in figure 5a.

### 2.6 Full DSCT experiment

The wooden sample was measured in a full experiment which was carried out with real-time parallel readout of the images from both detectors in one tomography sequence controlled by Python script. The setup geometry was arranged to obtain magnification $2 \times$ with source-object distance 627.5 mm, source-detector distance 1255 mm and spatial resolution 100 $\mu$m. The X-ray tube voltage and target current were set at 70 kV and 130 $\mu$A resulting in target power 9.1 W. The acquisition time of detectors was set to $2 \times 2$ s with 800 angular projections taken (400 for each detector). Image data were processed by beam hardening correction algorithm [13] prior to reconstruction. Dual-source CT reconstruction was carried out using the Volex software. Influence of simultaneous irradiation by two X-ray tubes was not observed in the results. The wooden sample in scanner is shown in figure 5b.

### 3 Results and discussion

Dual-source CT reconstruction of the puzzle object measured in the pilot experiment is shown in figure 6. CT reconstructions of the wooden sample are shown in figure 7. Quality and spatial resolution of reconstruction allowed for clear identification of structural details such as glue used in the puzzle object (see figure 6c) and damage caused by semi-destructive testing device in wooden sample (see figure 7c). Direct comparison between identical slices of DSCT reconstruction and conventional single-source reconstruction with identical settings is shown in figure 8. Comparison of important dimensions evaluated from tomography data is shown in figure 8c,d. Maximum difference of the dimensions was 1 px and only minor differences can be identified within all comparative images. The tomography measurement of the wooden sample was carried out in 2743 s with time of single step 6.85 s and rotation time between two measurement sequences approximately 3 s. The comparison of tomography time between dual-source and single-source measurement with the same acquisition parameters is summarized in table 1. The scanning times for the most common $1 \times 1$ s acquisitions in 400 angular projections are also listed in table 2. Processing time of dual-
source and single-source method can be considered equal as the only difference is a merging of
two data sets in single folder prior to the reconstruction.

Results of proposed dual-source tomography technique show significant scanning time reduc-
tion in comparison with single X-ray source measurement. Pixel-size of projections was better

Figure 6. (a) CT reconstruction of wooden puzzle (400 projections), (b) Inner structure of wood, (c) Slice with visible glue.

Figure 7. (a) CT reconstruction of wooden sample (800 projections), (b) Inner structure of wood, (c) Slice with visible damaged zone.

Figure 8. (a) Slice of DSCT reconstruction, (b) Slice of conventional CT reconstruction, (c) Region of interest — conventional CT reconstruction, (d) Region of interest — DSCT reconstruction, (e) Slice of DSCT reconstruction, (f) Slice of conventional CT reconstruction.
Table 1. Comparison of experimentally measured single-source and dual-source tomography time (acquisition $2 \times 2$ s, 800 projections).

| Type            | Tomography time | Ratio |
|-----------------|-----------------|-------|
| single-source    | 4960 s          | 100   |
| dual-source      | 2743 s          | 55.3  |

Table 2. Comparison of single-source and dual-source tomography time (acquisition $1 \times 1$ s, 400 projections).

| Type            | Tomography time | Ratio |
|-----------------|-----------------|-------|
| single-source    | 1280 s          | 100   |
| dual-source      | 770 s           | 60.1  |

than resolution of the top dual-source medical devices with only minor artefacts observed in reconstruction results. Dimensions of damaged zone in wooden sample were clearly identified and corresponded to dimensions evaluated by conventional single-source tomography with identical settings. The presented dual-source technique can be considered suitable for reliable analysis of post-damage behaviour in wooden samples.

Improvement of the temporal resolution utilizing dual-source approach is also an important feature regardless on the detector used. Used detectors XRD1622 have relatively long read-out time 1.2 s and maximum frame rate 1FPS at maximal resolution (2048 lines recorded in single projection). Read-out time is equivalent to dead-time of the single source CT scan at maximal resolution. Thus, the dead time is reduced to 0.2 s utilizing DSCT approach and can be reduced to zero by the 20% reduction of the active area read from the detector. Temporal resolution can be further increased if detector is operated in binning regime (binning $2 \times 2$ leads to 4FPS). The presented features provides important basis for dual-energy scanning using two X-ray tubes projected as a further step of the assembly application. In further development more sophisticated and automatized algorithm for calibration of cone beam setup [16] will be integrated for higher efficiency and precision of the calibration procedure.

4 Conclusions

A novel dual-source/dual-energy computed tomography device was developed together with dual-source measurement technique proposing faster tomography scanning and higher temporal resolution. Evaluation and tests of the method were performed on wooden objects. The experimentally measured tomography time was 44.7% lower than time of a single-source tomography scan with identical settings. Processing time of both methods can be considered equal. Possible application of the method for faster CT analysis of post-damage behaviour of a large number of wooden samples was tested and the technique was found suitable for the task. It can be concluded that the presented dual source assembly and developed method can be utilized in the field of industrial and material X-ray inspection, can reach high spatial resolution similar to industrial single source scanners and have potential for further development.
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