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X-ray Computed Tomography of the Oscillating Beam

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Abstract: This work presents X-ray computed tomography of a harmonically oscillating elastic beam. The tomographic imaging is achieved by obtaining projections of the object in its maximum amplitude to capture the eigenmode of the beam using a triggered computed tomography method synchronized with the oscillation of the beam. Related instrumentation, experimental methodology and data post-processing are presented. Results are demonstrated on the reconstructed 3D images of the polymeric oscillating beam in its deformed shape corresponding with the harmonic excitation using the first eigenfrequency. A comparison with conventional non-synchronized tomography of the oscillating beam in its first eigenfrequency is presented to highlight the fundamental advantages of such tomographical imaging.

Keywords: in-situ computed tomography; high-speed X-ray imaging; modal analysis; eigenmode visualization.

1 Introduction

The X-ray computed tomography (CT) has become a common nondestructive inspection method in many scientific fields. Its 4D CT variant is devoted to monitoring the structural and geometrical changes of the objects during time-dependent processes. In this particular case study, computed tomography is employed as a tool for modal analysis and volumetric visualization of the beam oscillation at its first eigenfrequency.

The standard 4D CT method, which uses conventional laboratory CT scanners, allows for reaching temporal resolution typically in a range of seconds in the best case while the limitation is in most cases caused by CT hardware restrictions. The X-ray source would need to be very intense to effectively reduce the exposure time while the detector would need to have a frame rate in the thousands of frames per second. Here, to perform a tomographical scan of an object, hundreds or even thousands of projections need to be recorded within the temporal resolution time interval. An exception to this temporal resolution restriction is the monitoring of periodically moving objects. In this case, the required number of projections can be repetitively captured within a short time window temporally synchronized with the physical process, thus eliminating the need to capture them all within a single temporal resolution interval.

Several articles related to time-lapse CT measurements of objects subjected to time-dependent processes can be found in the literature. For instance, the 4D CT of a beating heart triggered by an electrocardiogram is discussed in [1]. The combination of motion estimation and motion-compensated reconstruction in 4D-CT imaging has been used to improve CT image reconstruction and reduce X-ray dosage in lungs and livers [2]. The time evolution of beer foam and the muffin baking process have been investigated using CT [3]. Synchrotron-based measurements, such as those discussed in [4], are capable of recording projections very quickly. One of the newest methods is tomoscopy [5], which uses a strong synchrotron source and is capable of taking hundreds of projections per second. The first three mentioned 4D CT methods [1, 2, 3] are suitable for slowly moving or evolving objects. Synchrotron-based methods can achieve higher temporal resolution scans, but such measurement is much more hardware-demanding compared to the use of conventional X-ray tubes.

This study presents a triggered CT (tCT) system that delivers exceptional temporal and spatial resolution of a moving object with the use of a conventional sealed X-ray source. A unique CT data recording protocol where each projection is produced by integrating short individual images captured at the same position of a periodically moving object makes this approach a promising alternative to the established methods. A critical requirement for this approach is a precise and multi-dimensional synchronization of all key elements of the tCT system, including the angular position of the CT scanner’s rotary stage and the X-ray detector read-out triggered by the object's actual position. To ensure the precise and reliable acquisition of projections, the system employs real-time hardware synchronization of all components through specialized control software that interfaces with the X-ray detector data acquisition software.

In this work, we present the tCT of a beam oscillating at 4 Hz captured during the amplitude of its periodic motion induced by the exciter. The oscillatory motion is performed by an electromagnetic shaker mounted on the CT rotary stage.

2 Measurement Setup

2.1 Specimen

A slender beam made of epoxy resin PR102 with EM420 hardener with a total mass of 2.79 g was used in the experiments. To achieve optimal material properties and a constant cross-section of the sample curing in a negative mold at a constant temperature of 20 °C and low humidity of approximately 20 % was necessary. Aluminum particles with a diameter of 0.2 - 0.3 mm were added to the resin to improve the beam’s contrast in the X-ray projections. Once fixed in the shaker, this beam becomes a cantilever with a length of 188.5 mm from the end of the composite base to the top and constant cross and constant cross-section of 9.9 mm x 1.4 mm. The dimensions of the beam are depicted in Fig 1.

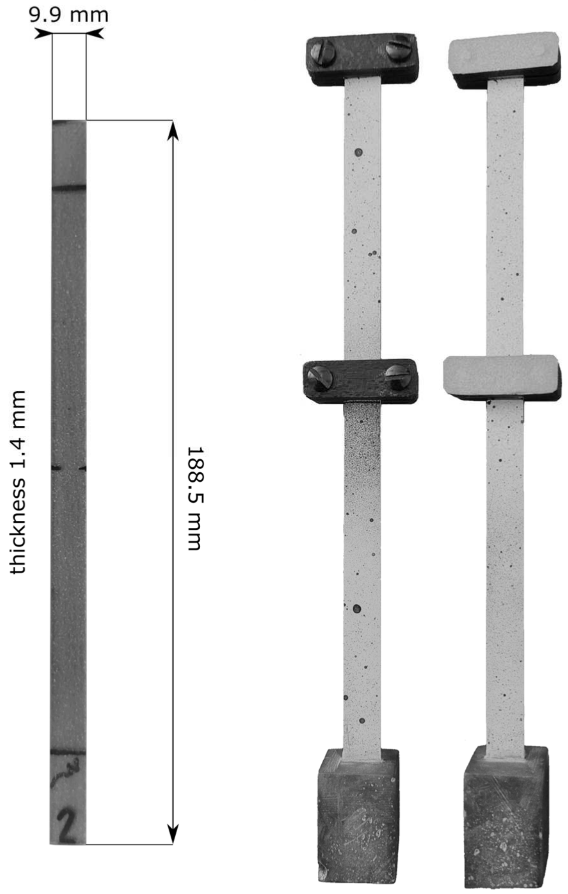


Fig. 1: Sample beam dimensions and front and back view.

This entire beam was bonded into a cubic base made from carbon fiber composite to achieve better repeatability of the measurements through consistency of boundary conditions and the beam length is set to exactly the same value for each measurement.

Due to the display and triggering capabilities and the fact that this is a pilot test, we chose the analogy of a simple analytical model with 2 degrees of freedom. This was obtained by adding two plastic weights to the beam, one in the middle and one at the free end. Both were fixed with plastic screws to avoid potential photon scatter in the reconstructed 3D images. The middle-added weight is a prism with dimensions 17 x 10 x 30 mm, a weight of 5.38 g including the plastic screws, and the center of gravity of the weight was placed 100.5 mm above the end of the cube base. The top added mass was the same shape as the middle mass except the thickness was 8.5 x 10 x 30 mm, the mass including plastic screws was 2.69 g and the center of gravity of the mass was located 183.5 mm above the cube base. The first and second natural frequencies of the cantilever, as measured by laser vibrometry, were 4.15 Hz and 23.75 Hz, respectively.

2.2 tCT Setup

The in-house developed CT system consisting of a Dexela detector and Hamatsu X-ray source was combined with a shaker stage providing harmonic excitation of the specimen. The shaker was mounted on top of the rotary stage and was based on a voice coil actuator (MGV41, Akribis, Singapore) controlled by the Akribis ASD system (Fig. 2). The frequency bandwidth of the shaker can reach up to 50 Hz, maximum stroke is 25 mm, typical position accuracy during harmonic oscillations in position control mode is better than 1.5 μm with position control sensitivity as low as 0.1 µm. The Dexela 1512 NDT CMOS detector with CsI scintillator (Varex Imaging, Germany) was used for the acquisition of the X-ray projections. Its native resolution is 1944 x 1536 pixels with binning–dependent maximum framerate reaching up to 86 Hz. Sealed-type X-ray source Hamamatsu Photonics L10321 with an acceleration voltage range of 40 – 100 kV, maximum target power of 20 W, and focal spot range of 5 μm to 30 μm was used for irradiation of the sample.

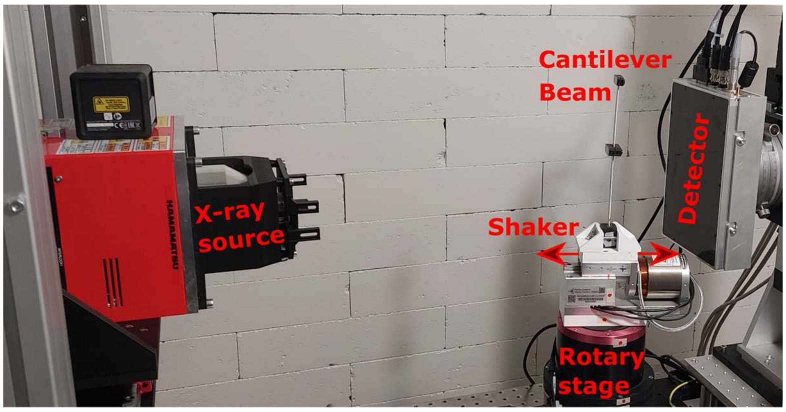


Fig. 2: Measurement setup.

A fundamental requirement for a reliable tCT system is precise synchronization of all key components. These include the shaker, the rotary stage, and the detector acquisition trigger and image exposition. The key strategy is to place the image exposure symmetrically around the maximum amplitude of the oscillating beam to minimize negative motion blur effects. As an additional condition, the rotary stage has to be stationary during image exposure. This task was accomplished through the use of an in-house developed control software package working under the LinuxCNC open-source software platform. The tCT system gains better image statistics by taking multiple projections at identical conditions repeatedly and averaging them. A closer description of the tCT method can be found in [6].

3 Tomography of the Beam

The cantilever beam, as described in Section 2.1, was tomographically scanned while oscillating at a first eigenfrequency of 4.15 Hz. The X-ray source for the tCT measurements was operated at 100 kV of acceleration voltage, 200 µA of target current, and a spot size of 30 µm. Detector binning of 2 x 2 was used during the measurements to increase the maximum frame rate and image statistics. The exposure time was set to 20 ms (15 ms is minimal time with 2 x 2 binning, 5 ms added for better image statistics), with averaging performed over 10 projections. The geometry of the CT setup for tCT measurement was as follows: focus to detector distance of 519.4 mm, focus to object distance of 387 mm, resulting geometrical magnification of 1.34, and voxel size of 55.9 µm.in

The tomography scan consisted of 956 projections acquired with an equiangular step size of 0.38 degrees. Following the tCT measurement, a conventional non-triggered CT measurement of a stationary object was performed using the following parameters: an exposure time of 20 ms 1434 equiangular projections without averaging with an angular step size of 0.25 degrees. An overview of all the parameters is summarized in Tab. 1.

Tab. 1: Scanning parameters tCT/non triggered measurements.

Target power [W]	10.7	Acceleration voltage [kV]	100
Spot size [µm]	30	Projections count	956/1434
Binning	2×2	Frame averaging	10/1
X-ray object dist. [mm]	111.95	Magnification	1.314
X-ray detector dist. [mm]	519.23	Voxel size [µm]	113.79

The tCT-triggered measurement was 2h 34min long compared to approximately 24 minutes of the non-triggered measurement. CT reconstruction was performed using a filtered backprojection algorithm (FBP) implemented in the VGSTUDIO MAX software [7].

Due to the length of the investigated beam and the selected geometrical magnification, it was necessary to scan the specimen by half, it resulted in 3D images of its bottom and top parts, that were then numerically merged. In this procedure, the overlapping part of the merged tomographs is approximately estimated by the user and the merging points are selected in the first CT in the overlapping part during the first step. The positions of these points are then determined in the second volume to be fused by digital image correlation. Due to the internal structure of the beam with small metallic particles resulting in possible misidentification of point pairs, the RANSAC method [8] is employed to determine the mutual transformation. After determining the position of the second tomography in the overall resulting volume, the two volumes are combined by linear weighting in the longitudinal direction of the beam as a simplified version of panorama stitching [9] generalized to 3D.

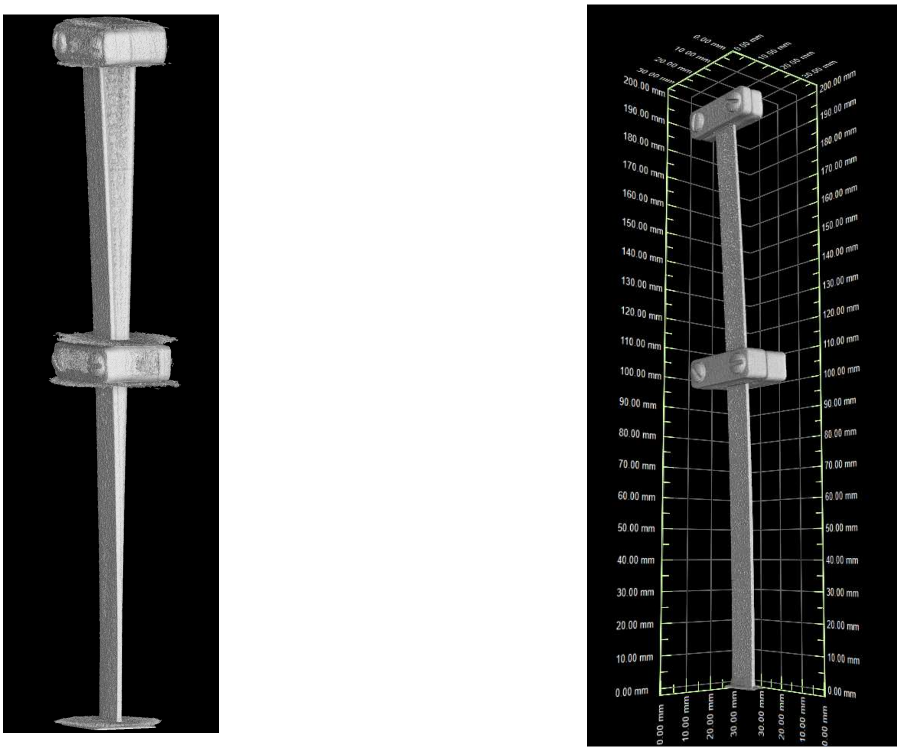
4 Results

Fig. 3 compares reconstructions of the same beam obtained by the standard non-triggered CT method and the presented tCT method. In the standard CT image Fig. 3a, the reconstructed volume represents a superposition of all its deformed states during oscillation randomly distributed between the amplitudes. It can be seen that the object edges are sharper in the amplitude positions as the object statistically spends more time in this position while the internal structure is irrecoverable due to its superposition from the whole oscillatory movement.

The tCT method Fig. 3b, in contrast, offers a clear image of the entire oscillating object at its amplitude positions. This allows for simultaneous visualization of the object's actual oscillation shape and its internal structure.

By enabling simultaneous visualization of the object's shape and internal structure during oscillation, the tCT method presents a significant improvement over the conventional non-triggered CT method. This capability offers valuable insights into the dynamic behavior of oscillating objects, which would be obscured using traditional methods.

Fig. 4 shows the comparison of the vertical section through the beam when CT is measured at a static state, and tCT is measured at the oscillation amplitude of the beam. A distinct material structure is clearly observable in the lower section of the beam. In the upper region, as a result of higher velocity of motion, the structure remains discernible but slightly blurred. Fig. 5 showcases the displacements observed in the amplitude CT scan. These displacements were determined through the computation of differences in the central plane of mass between the amplitude and stationary state CT scans.



a) Standard non-triggered CT

b) tCT of amplitude

Fig. 3: Oscillating beam.

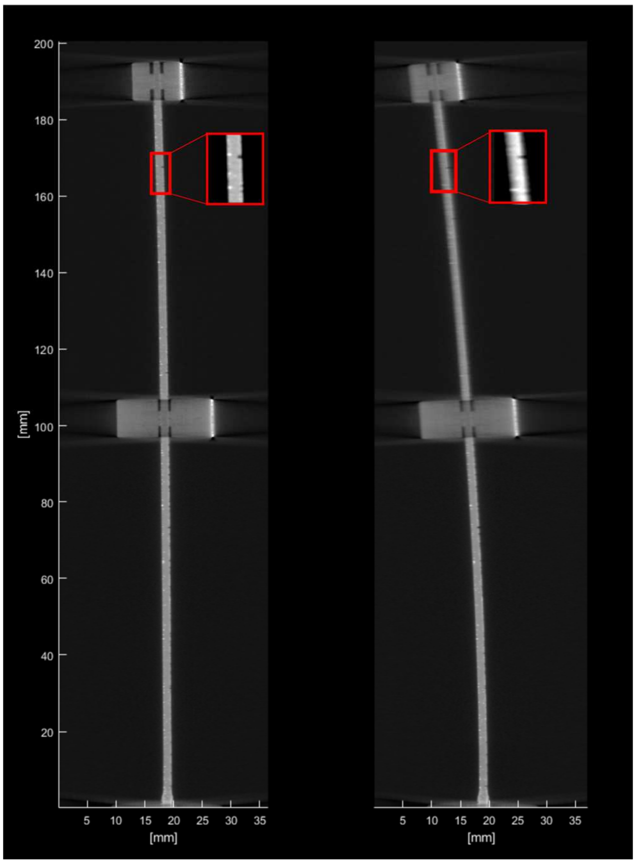


Fig. 4: Slices through CTs from side for static case and amplitude case with material structure detail.

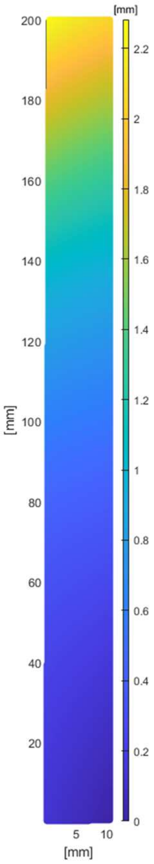


Fig. 5: Displacement values based on difference of the beam's center of mass plane.

5 Conclusion

The principle of the triggered CT (tCT) method was introduced and the method was successfully applied to perform tomography of an oscillating object represented by a slender epoxy resin beam vibrating in its first eigenmode. The measurement of shape in the amplitude was made by a series of 956 projections with an angular step size of 0.38 degrees while each projection was averaged over 10 projections to improve image statistics and thus its quality. The tCT results were compared with a standard CT by analyzing longitudinal sections of the oscillating beam in both its amplitude during vibrations and static state. Both results were comparable while the internal structural details from the conventional stationary tomography scan could be identified in the tCT data of the deformed shape.

The tCT system presented in this study has the potential for various applications, including three-dimensional modal analysis of oscillating objects together with visualization of their internal structure. This approach allows for the identification of defects, such as component separation, that are challenging to distinguish statically. Additionally, it offers the opportunity to validate theoretical dynamic models that are difficult to verify through conventional methods.

In conclusion, the tCT method presents a significant advancement over the conventional non-triggered CT method. It provides a clear and comprehensive image of the oscillating object at its amplitude position. A proof of concept of tCT has been achieved, and with the use of better hardware such as detector Medipix 3 and X-ray tube MetalJet D2+ 160 kV, further work will focus on increasing the temporal resolution and accuracy of the method to obtain relevant modal analysis of more complex objects.

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