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In-line microfocus X-ray focal spot condition monitoring for computed tomography

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Abstract
The resolution of radiographic systems is often limited by the size of the X-ray focal spot, i.e. the region where X-rays are generated. Due to wear of the target and drifts in the electron optics, the focal spot size and shape are expected to change over time. Therefore, monitoring these parameters is key to gain confidence in measurements and take action, e.g. perform re-focussing or maintenance. We have developed a manipulator to position a gauge in the primary X-ray beam to determine focal spot size and shape. It operates independently from the sample stage of the computed tomography system. Thanks to a kinematic coupling mechanism, a high reproducibility was achieved despite the use of a low-precision linear axis. The system enabled the characterisation of focal spot sizes down to about 1 µm (FWHM). It is used to focus the focal spot prior to measurements, monitor it over the course of long computed tomography scans (several hours), and take corresponding measures to restore the focal spot quality.

Radiography, X-ray computed tomography, focal spot, traceability, condition monitoring

1. Introduction

The size of the X-ray focal spot governs the attainable resolution for high-resolution radiographic setups, such as computed tomography (CT) systems [1]. Due to the size of the focal spot, i.e. the region where X-rays are generated, blur is introduced in the radiographic projections, rendering small structures no longer detectable. Because X-ray tube wear or thermal drifts might change the focal spot size and shape, it is necessary to monitor it for resolution-critical applications. The method employed to map the intensity distribution of focal spots, is to reconstruct it from radiographs of circular apertures (Figure 1). It was validated for focal spot size from below 1 µm to several 100 µm [2,3].

Here, we present a system to automatically characterise the focal spot of an X-ray tube, which is part of a high-resolution CT system. A manipulator accurately places a circular aperture gauge in the X-ray beam that enables the reconstruction of the focal spot. It can be used to optimise the focal spot prior to or monitor it during a measurement, e.g. a CT scan.

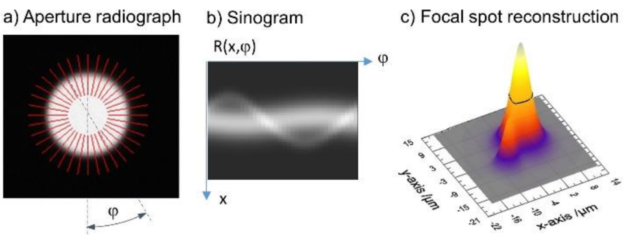

Figure 1. Principle of focal spot reconstruction: a) Profiles extracted from radiographs of a circular aperture are deconvoluted, arranged into a sinogram b), and the two-dimensional intensity distribution reconstructed c) (a synthetic focal spot is shown).

2. Focal spot gauge manipulator

The automatic focal spot gauge manipulator (Figure 2) was implemented on a home-built metrology CT with an XWT-190-TCNF X-ray tube (X-RAY WorX) [4]. The circular aperture was a custom tungsten-carbide ring gauge with a diameter of 100 µm (CARY). A low-accuracy linear actuator (repeatability ±15 µm, FESTO ELGS-BS-KF) moves the gauge in and out of the X-ray beam (Figure 3). The three-sphere support is placed in three v-grooves on top of the X-ray tube forming a kinematic coupling, which is robust against thermal expansion. A mechanism mechanically decouples the three-sphere support from the linear actuator, which ensures that no mechanical interference is transmitted. Three fine-threaded screws allow adjusting the horizontal and vertical position of the gauge. An L-shaped carbon fibre reinforced polymer (CFRP) lever extends in front of the X-ray tube to place the gauge in the X-ray beam. Gauge holders were additively manufactured (AM) from ABS.

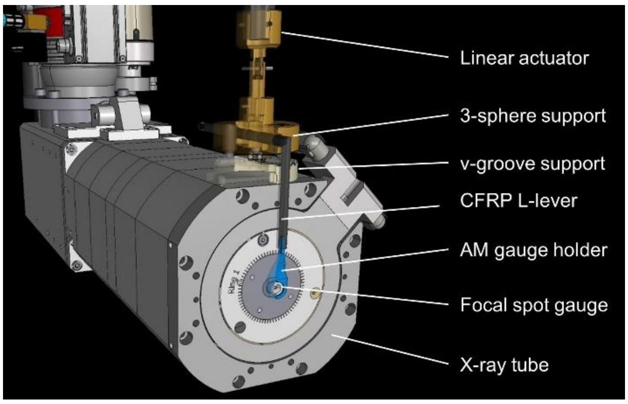

Figure 2. Design of the focal spot gauge manipulator. The gauge is accurately placed in the X-ray beam using a kinematic coupling. Half of the gauge is transparent to render the mechanism visible.

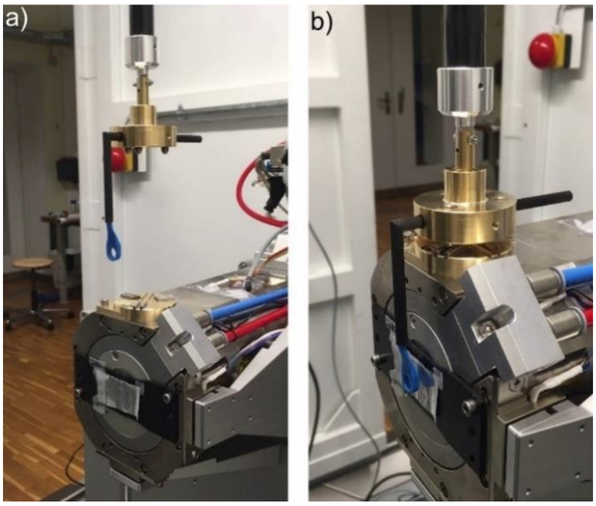

Figure 3. Photograph of focal spot gauge manipulator: (a) Withdrawn and (b) in front of the X-ray tube. The blue adapter holds the focal spot gauge.

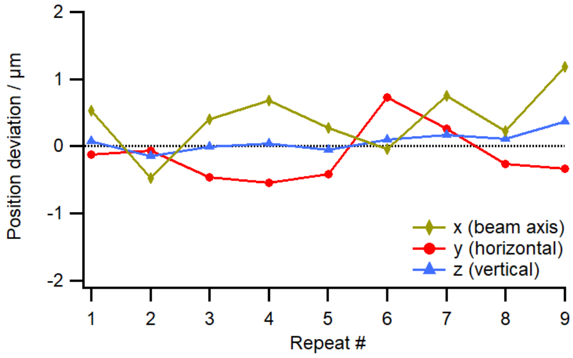

Figure 4. Short-term repeatability of the kinematic coupling at the focal spot gauge position.

Figure 4 shows the short-term repeatability of the kinematic coupling when withdrawing and repositioning the gauge. It was derived from radiographs of the gauge and was below ±1 µm. The x (beam direction) and y (horizontal) positioning were less precise due to the long lever. The X-ray collimator and filter mount limited the minimum distance between the focal spot and the gauge to magnifications below 400× or resolutions of about 0.25 µm. This is sufficient to measure the full width at half maximum (FWHM) for focal spots down to about 1 µm.

3. X-ray focal spot monitoring

Focal spot monitoring is especially important for resolution-critical CT scans, e.g. of precision engineered workpieces, porosity in AM parts or energy storage materials. Since the focal spot gauge manipulator operates independently of the CT sample stage, it can be used to monitor the focal spot prior to and in regular intervals during a CT scan. Thereby, a radiograph of the circular aperture is recorded and the focal spot intensity distribution reconstructed (see Figure 1). A two-dimensional pseudo-Voigt function (superposition of a Gaussian and a Lorentzian distribution) is fitted to obtain the FWHM. Prior to a CT scan, it might be necessary to re-focus the electron-beam, owed to the fact that the focussing currents of the electron optics are stored in a look-up table (LUT) and change over time. Figure 5 shows such a focussing curve, where the focal spot size was improved from 2 µm (coil current from LUT: 893 mA) to about 1.5 µm. Figure 6 shows monitoring of the focal spot size and shape over the length of a typical CT scan. To this end, the gauge was automatically moved into the X-ray beam in predetermined intervals. Here, the stability of the size (FWHM) and shape (Voigt ratio) was higher than the measurement scatter. However, this can change with the operating parameters of the X-ray tube and the wear of the components, e.g. the X-ray tube target.

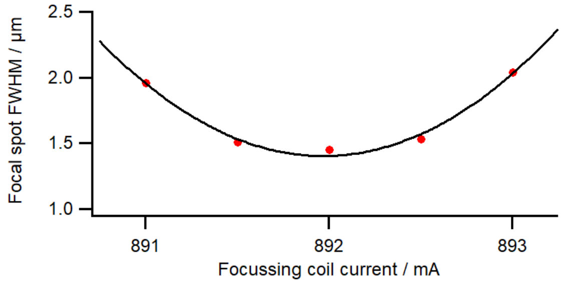

Figure 5. Focussing of the X-ray focal spot by optimising the focussing current of the electron optics (100 kV, 1 W, nanofocus mode).

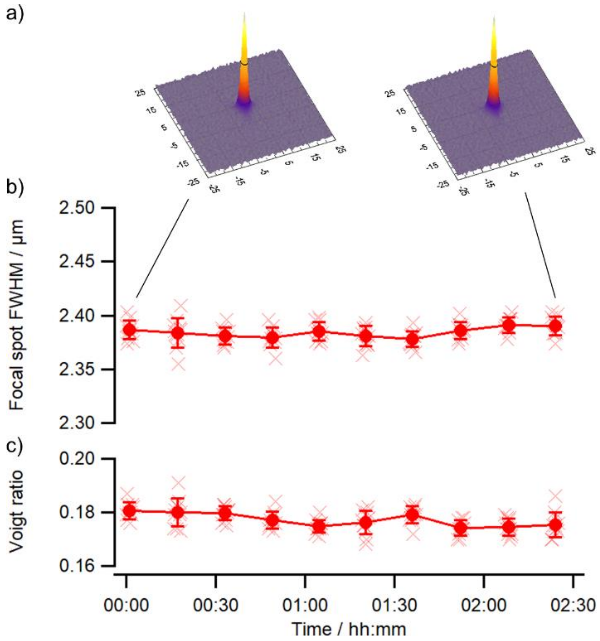

Figure 6. Focal spot monitoring over the course of a CT scan: a) first and last reconstructed focal spot distribution (axis values in µm). b) Focal spot size and c) shape described by the Voigt ratio, i.e. Lorentz-to-Gauss weight (100 kV, 5 W, microfocus mode).

4. Conclusions

We presented an in-line system to automatically characterise the focal spot of an X-ray tube. A manipulator places a circular aperture gauge in the X-ray beam with a repeatability below ±1 µm. From aperture radiographs, microfocal spots down to 1.5 µm FWHM were reconstructed. The data was used to focus the focal spot prior to or monitor it during a CT scan. Such monitoring is important to optimise the focal spot, gain confidence in resolution-critical CT scans, and indicate the need for maintenance. Future work includes investigation of the long-term stability and predictive maintenance studies.

References

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