CT simulation study to demonstrate material impact using hole plates

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Abstract
In non-destructive testing computed tomography (CT) is increasingly used for dimensional measurement tasks such as the industrial inspection of work pieces. The use of a hole plate to analyse the accuracy of CT-results is subject of ongoing discussion in ISO standardization, as described e.g. in ISO TC213WG10N0967. The procedure is used to evaluate deviations of size and form of reconstructed CT data using different measurement parameters. At the moment, there is a controversial discussion, whether hole plates are suitable for assessing the material impact.

Within this simulation study we evaluate beam hardening effects on the above named task for different materials.

Keywords: Computed tomography, simulation, beam hardening, dimensional metrology, Scorpius XLab

1. Introduction

Industrial x-ray-computed-tomography (CT) has been an overall accepted technology in the field of non-destructive-testing for decades. Since CT becomes more and more attractive for dimensional metrology in the past ten years, there is a need to develop standards and guidelines especially at international level. Currently an international committee, the ISO TC 213 WG 10, is working on specifications concerning dimensional metrology by means of CT. These work will become a new standard on CT in the series ISO 10360 and will get the identification ISO 10360-11 when finalized. One major task within ISO TC 213 WG 10 is to estimate the length measurement error E arising from material influence. Therefore the German PTB together with the NMIJ/AIST developed hole plate reference standards, where the dimensional measures of holes are strongly affected by the surrounding material [Bartscher 2014]. In order to demonstrate material impact on CT-data, a test study was performed.

The CT reconstruction process is based on the assumption that attenuation at a point is independent of the path by which the X-rays have reached this point. This is valid only for a beam consisting of monoenergetic radiation. For polyenergetic X-ray beams used in the field of non-destructive testing (NDT), the x-ray spectrum becomes harder, while the beam propagates through the object. This is due to the stronger attenuation of lower energy photons and the resulting effect is called beam hardening (BH). BH, if not corrected, gives rise to artefacts, i.e. observable errors in the reconstructed volume. We have analysed the effect in a simulation study [Kasperl 2013] on a step cylinder, suggested by a national committee [VDI/VDE 2630]. BH effects can be quantified via comparison of the poly- and monoenergetic reconstructions.

The main intention of this work is to demonstrate that material effects cause additional measurement errors. For these investigations deterministic simulation tools are best suited. In this work poly- and monoenergetic attenuation of different hole plates is simulated using the deterministic simulation software ScorpiusXLab. Additionally a verification of the results with Monte-Carlo simulations was done.
This paper is organised as follows. In the second section the principle of both used simulation tools is described. The third section deals with the experimental setup of the scan geometry and the hole plate respectively. In the fourth section the results of the simulations are discussed. Finally we give a conclusion.

2. Simulation Tools

2.1. Principles Deterministic CT simulation

For fast simulation of the complete radiographic imaging process at energies up to 450 keV, ScorpiusXLab® has been developed at Fraunhofer EZRT [Wenig 2006]. It models most of the imaging properties (source spectrum, object and detector scattering, MTF, DQE, quantum noise, focal spot etc.) analytically. The actual specimens are generated by nested primitives, e.g. cubes or cylinders, and triangulated surfaces from STL-models. To reduce the computation time for STL data, it is performed on the graphics card. Key application of the software is the validation of algorithms that are developed for reconstruction and artefact correction. In addition, ScorpiusXLab® may be employed for the estimation of the uncertainty of measurements [Hiller 2007].

The simulation is based on the ray-tracing approach (Fig. 1). The pixel value for each detector pixel $P$ of a virtual detector is given by:

$$\bar{P} = \sum N(E_i) QE(E_i) \Delta E$$  \hspace{1cm} (1)$$

where $N(E_i) = \bar{N}_0 (E_i) e^{-\sum_k \mu_k(E_i) x_i}$  \hspace{1cm} (2)

Here $QE(E_i)$ is the energy dependent quantum detection efficiency of the simulated detector type [Yaffe 1997], $\Delta E$ is the sampling interval of the X-ray spectra, $N_0 (E_i)$ is the source spectra, $k$ is the number of objects with a specific material, $x_i$ is the distance traversed by a photon inside the specimen and $\mu_k$ is the (energy- and material-dependent) linear attenuation coefficient.

2.2. Principles of Monte Carlo simulation

When realistic simulations of physical effects during the imaging process are needed, Monte-Carlo simulation methods can be used. ROSI [Giersch 2003] is one simulation framework
based on the physics libraries EGS4 [Nelson 1985] and LSCAT [Namito 2000], which describe electromagnetic interactions of photons, electrons and positrons with matter. ROSI uses probability distributions either defined by the user, for example spectrum, focal spot intensity distribution, angular distribution of emitted primary particles or given by a material database regarding physics interaction probabilities. Primary particles – in case of imaging simulations photons – are generated one after another in a virtual X-ray environment with randomly determined energy, point of origin and propagation direction correspondent to the probability distributions defined by the user. Objects and detector volumes can be defined by either using primitive geometries or STL data. All particles, primaries and secondaries generated during physics processes traverse through the X-ray environment, undergo every possible physical process until leaving the world or losing sufficient energy dropping below a certain value. At every point of interaction information can be obtained about the interaction type, participating particles and energy transferred to the material. In the case of imaging simulations, the energy deposition of impinging X-rays in a sensor volume (either scintillator or semi-conductor) is usually read out. The spatial distribution of that energy deposition forms the X-ray image.

With this method very realistic simulations can be performed and in-depth analysis of processes can be made.

It has to be stressed that the computing time for the deterministic simulation was less than 1% of the time needed to perform an MC-simulation. Since the agreement of MC-simulations with real measurements is well-known, the comparison MC- to deterministic simulation proves its validity.

3. Experimental Setup

For the simulation study we used the newly developed hole plate design from NMIJ/AIST and PTB. In order to emphasize the material influence on the evaluation we chose a low magnification of 1.5. The sizes of the two hole plates, a smaller iron one and a larger out of aluminium are given in table 1.

<table>
<thead>
<tr>
<th>Hole plate</th>
<th>Side length [mm]</th>
<th>Thickness [mm]</th>
<th>Diameter of holes [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>6 x 6</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Aluminium</td>
<td>48 x 48</td>
<td>8</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 1: Dimensions of square-shaped hole plates

Figure 2 shows a reconstruction of the larger aluminium hole plate with the number labels of the evaluated holes. Most of the simulations were done with a tilted position of 45 degrees, which is also shown in figure 2. In table 2 the scanning parameters for the simulations are given. To validate the results of the analytical simulation tool we compare them with results of the Monte-Carlo-software ROSI for both hole plates. The reconstruction algorithm is based on filtered backprojection.
focus-detector-distance 100 cm  
focus-object-distance 67 cm  
focal spot size point source model  
number of projections (360°) 200  

<table>
<thead>
<tr>
<th></th>
<th>Al hole plate</th>
<th>Fe hole plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>tube voltage (bremspectra)</td>
<td>190 kV</td>
<td>140 kV</td>
</tr>
<tr>
<td>tube voltage (monoenergetic)</td>
<td>68 keV</td>
<td>54 keV</td>
</tr>
<tr>
<td>tube prefilter</td>
<td>0.3 mm Cu</td>
<td>0.25 mm Al</td>
</tr>
<tr>
<td>detector size</td>
<td>10.24 x 10.24 cm²</td>
<td>1.28 x 1.28 cm²</td>
</tr>
<tr>
<td>number of pixels</td>
<td>256x256</td>
<td>256x256</td>
</tr>
<tr>
<td>voxel size</td>
<td>(267.5)³ μm³</td>
<td>(33.6)³ μm³</td>
</tr>
<tr>
<td>number of photons per projection (according to tube current 1 mA and 100 ms exposure time)</td>
<td>7E+9</td>
<td>9E+9</td>
</tr>
</tbody>
</table>

**MC simulation**

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Table 2: Parameters for Scorpius XLab® and Monte Carlo simulation tool ROSI

**4. Results and discussion**

All data presented in this work were created with the simulation tools described above and evaluated with software Volume Graphics Studio Max Version 2.2.2. The surface of the examined volumes was determined as usual in a two-stage process. In the first step the averaged grey value of the volume was calculated. Based on this global threshold a state-of-the-art adaptive thresholding was performed. This surface creation technique is based on the locally gradient.

To show the material influence in a more qualitative way a first estimation was carried out by a actual-nominal value comparison. The comparison was done using surface data in STL format as a reference object for both hole plates. Figures 3 and 4 show in false colored representation the aluminum and the iron hole plate for poly- respectively monoenergetic simulations with Scorpius XLab®. For better comparability we used the same color gradient (±0.05 mm) for all images. Beam hardening artifacts are clearly visible in the polyenergetic measurements. And, as expected, the BH influence of the material is larger for the iron hole plate.
A quantitative estimation was done by the investigation of geometrical characteristics like local form errors, length measurements errors and planarity errors. Therefore in each of the nine holes (see figure 2) an ideal cylinder was fitted and evaluated by its diameter and probing error. Figure 5 shows a fitted cylinder for the aluminum hole plate, for both XLab and ROSI-MC simulation. Figure 6 shows for the aluminium and iron hole plate the probing error for the nine fitted cylinders.
Both the iron and the aluminum hole plate show larger probing errors in consequence of BH artifacts. Both simulations indicate this effect, the Monte Carlo simulation more clear in the case of the aluminum plate.

For the case of hole plates the unidirectional length measurement errors are identical to the hole distance errors. Figure 7 shows the center to center distance errors for the various directions: horizontal (1-2, 2-3, 4-5, 5-6, 7-8, 8-9), vertical (1-4, 2-5, 3-6, 4-7, 5-8, 6-9) and diagonal (1-5, 5-9, 7-5, 5-3). For both hole plates there is only a small material influence on length measurement errors. Both simulation tools show slightly better results in the monoenergetic case, but it is not possible to detect the material influence reliably.
In order to examine geometrical deformations we calculated the planarity errors of the top and bottom surface of the hole plate. This was done by fitting a plane and compute the distance of the maximum and minimum deviation. Figure 8 shows the results for the poly- and monoenergetic case.

The planarity errors are clearly different for monoenergetic and polyenergetic simulations. For both hole plates the Scorpius XLab® simulation provides the difference.

Finally we changed the angle between the hole plate and the rotary plate from horizontal to diagonal position (0°, 15°, 30°, 45°). Changing the angles means changing the x-ray path length. Figure 9 shows the probing errors for the aluminum hole plate. The polyenergetic simulation was done with Scorpius XLab®. As expected the probing errors of the cylinders decrease with increasing angles. The center cylinder 5 has the largest probing errors.

To find out the influence of the global threshold we chose a too low and a too highly selective grey value. In figure 10 you can see that the influence of a incorrect chosen global threshold can be neglected on the final result of surface creation.

Figure 7: length measurement errors for Al hole plate (left) and Fe hole plate (right). The simulation was done for polyenergetic and monoenergetic sources with a tilted position of 45 degrees.
Figure 8: planarity errors of the top and bottom surface for Al hole plate (left) and Fe hole plate (right). The simulation was done for polyenergetic and monoenergetic.

Figure 9: probing errors for Al hole plate. The simulation was done for a polyenergetic source with a tilted position from 0 to 45 degrees.
Figure 10: The ROSI-MC simulation was done for Al hole plate with a polyenergetic source and shows the deviation for all geometrical characteristics under investigation. From left to right the global threshold changes from too high to too low grey values.

4. Conclusions
This paper presents hole plate simulations and the evaluation of three characteristics to show material influence in computed tomography. This effect is not significantly observed for unidirectional length measurement errors. But for probing errors and planarity errors beam hardening artefacts could clearly be shown. The results of the fast analytical simulation tool Scorpius XLab® are in close agreement with those of the Monte-Carlo simulations.

Future international standards should define exactly the measurement procedure, e.g. fitting tools and threshold definition for surface generation.

A free trial version of Scorpius XLab® can be download at http://www.iis.fraunhofer.de/xlab

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