Evaluation of transmission based image quality optimisation for X-ray computed tomography

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Abstract
This paper presents a study on the optimisation of scan parameters for industrial X-ray computed tomography (XCT). The selection and optimisation of scan parameters for a specific application is typically done by the system operator, which leads to subjective and often suboptimal scan results. Standards for XCT propose a parameter optimisation based on the minimal X-ray transmission occurring during the scan. The EN 16016 standard proposes a minimal transmission of about 10 to 20%, whereas the ISO 15708 standard proposes 14% minimal transmission. Advantageously, transmission based parameter selection does not need any preliminary knowledge about the specimen’s geometry and material compared to simulation based approaches.

In this work XCT scans for selected specimens, with a varying minimal transmission, are done on an industrial micro XCT device, to test and verify the applicability of transmission based parameter selection. The quality of each dataset is quantified by calculating the measures signal to noise and contrast to noise ratio for different regions and features. Afterwards the correlation between those quality measures and the minimal transmission is shown and discussed.

Keywords: X-ray computed tomography, transmission, optimised scan, parameter optimisation

1 Introduction
Scan parameters of XCT devices are typically selected and optimised by the user. This leads often to a suboptimal scan quality and thus subjective evaluation results. Since the parameter optimisation for a specific scan task is very time-consuming, XCT simulation tools can optimise the acquisition automatically [3-6]. However, if preliminary information of the specimen’s geometry and material is not available a transmission based optimisation is desirable, since the minimal transmission during the scan may be determined with some effort prior to the actual XCT scan. On the one hand the EN 16016-2 standard proposes a minimal transmission of about 10 to 20% for best SNR and measurement results [1]. On the other hand ISO 15708-2 suggests 14% minimal transmission for optimal contrast
sensitivities. In addition, the standards state that users should carry out optimisation tests \cite{2}. The main objective of our work is to verify the applicability of a transmission based parameter selection proposed in the mentioned standards.

2 Description of the investigation

Chapter 2.1 describes the theory behind the transmission based scan parameter optimisation, which will be tested on a series of scans of selected specimens as described in 2.2. The scan parameters used on the micro XCT system for these specimens are listed in 2.3. Detailed descriptions of the evaluation procedure regarding the correlation between the reconstructed image quality and the minimal X-ray transmission in the projection images are shown in section 2.4.

2.1 Theory for optimal exposure conditions with ideal detectors

The theory behind the transmission values \cite{7} mentioned in the standards \cite{1,2} is based on Lambert-Beers Law given in Equation 1. \( I_0 \) is the radiation intensity before and \( I_p \) the primary intensity after an absorption defined by a linear attenuation coefficient \( \mu \) and a penetration length \( d \). Equation 2 is the first derivative of \( I_p \) with respect to \( d \), which is further used to calculate the contrast caused by an infinitely small change of the penetration length \( \Delta d \) (Equation 3).

\[
I_p = I_0 \cdot e^{-\mu(E)d} \tag{1}
\]

\[
\frac{\partial I_p}{\partial d} = \frac{\Delta I_p}{\Delta d} = -I_p \cdot \mu(E) = -I_0 \cdot e^{-\mu(E)d} \cdot \mu(E) \tag{2}
\]

\[
C = \Delta I_p = I_0 \cdot e^{-\mu(E)d} \cdot \mu(E) \cdot \Delta d \tag{3}
\]

By combining Equation 3 with the photon noise detected by an ideal detector (Equation 4) a contrast to noise ratio (Equation 5) may be calculated for a small penetration length change \( \Delta d \).

\[
\sigma = \sqrt{I_p} \tag{4}
\]

\[
CNR = \frac{C}{\sigma} = \frac{I_0 \cdot e^{-\mu(E)d} \cdot \mu(E) \cdot \Delta d}{\sqrt{I_0 \cdot e^{-\mu(E)d}}} = \sqrt{I_0 \cdot e^{-\mu(E)d} \cdot \mu(E) \cdot \Delta d} \tag{5}
\]

The contrast to noise ratio (CNR) reaches its maximum, when the first derivative of the CNR with respect to \( \mu \) is zero. This results in a theoretical maximum at about 14% transmission.

\[
\frac{\partial CNR}{\partial \mu} = \Delta d \cdot \sqrt{I_0 \cdot e^{-\mu(E)d}} \cdot \left(1 - \frac{\mu(E) \cdot d}{2}\right) = 0 \Rightarrow \mu(E) = \frac{2}{d} \tag{6}
\]

\[
\frac{I_p}{I_0} = e^{-\mu(E)d} = e^{-2} \approx 0.14 \tag{7}
\]
2.2 Description of the used XCT device and the selected specimens

All scans are done on a RayScan 250E cone beam XCT device. The system consists of a Viscom 225 kV micro-focus tube with a tungsten reflection target and a Perkin Elmer flat panel detector XRD 1620 AN14 (2048x2048 pixel, pixel size 200 µm).

The chosen specimens fit into the typical part spectrum of this micro XCT device. To cover the range of possible X-ray absorptions, first an injection moulded component (part A), made of rubber with a wall thickness of about 2 mm and low X-ray absorption has been selected (Figure 1a). Furthermore an aluminium step cylinder (part B) consisting of 5 steps, each 10 mm in height, has been chosen. The outer diameter is increasing from 15 mm to 55 mm in steps of 10 mm (Figure 1b). The central drill hole has a diameter of 8 mm [6]. Additionally the investigation has been done for an injection moulded multi-material component (part C) consisting of plastic, rubber seals and metallic pins as shown in Figure 1c.

![Photographs of the selected specimens part A (a) made of rubber, part B made of EN AW-7075 (b) and a multi-material part C (c).](image)

2.3 Scan parameter selection for the series of micro XCT scans

Table 1 lists scan parameters to achieve different minimal X-ray transmissions during the XCT scans of test part A, B and C. Generally the transmission may be increased by increasing the acceleration voltage of the X-ray tube. Using filter plates in front of the tube’s X-ray window further increases the transmission while reducing beam hardening artefacts due to the hardened polychromatic X-ray spectrum. Additionally, filter plates reduce the number of photons and lead to lower signal to noise ratio (SNR) values. This SNR reduction may be compensated by increasing the exposure time.

Within this work the acceleration voltages 40/80/120/160/200 kV and copper prefilter plates with the thicknesses 0/0.5/1.0 mm are used to achieve a wide range of transmission values, while limiting the exposure time to about 2.5 hours. Values for the minimal X-ray transmission do not correspond to one unique X-ray spectrum. Similar transmission values can be gained by different combinations of acceleration voltages and prefilter plates which may lead to different image qualities.

To ensure similar conditions regarding image blur originating from the focal spot of the X-ray tube, the electric power is kept constant. This is possible since common micro focus tubes are defocusing the electron beam proportionally to the electric power to prevent the target from thermal destruction. The voltage values are selected to achieve different transmissions, whereby the X-ray tube currents are chosen to assure a constant power of 40 Watts. This leads to similar blurring for all scans which should be negligible.
Figure 2: First projection image of part A (a), part B (b) and of part C (c). The blue air region is used to calculate $\text{SNR}_{\text{proj}}$. The red regions are used to calculate minimal greyvalues and transmissions per step.

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Table 1: Scan parameters varying the minimal X-ray transmission and assure a constant mean SNR value over all projection images in a region containing air. Further parameters: 1440 projections, detector gain 0.5 pF, FDK reconstruction with Shepp-Logan filtering, reconstructed data mapped from float32 to uint16, distance source-detector=1530 mm.
In this work we focus on the optimisation of the image quality without considering exposure times. Hence the detector integration time and the number of averaged images have been selected to gain a constant SNR in a small projection image region with intensity $I_0$. Figure 2 shows the first projection for every part where the mentioned regions are marked blue (50x50 pixels). The mean SNR of all projection images in the following is referred to $\text{SNR}_{\text{proj}}$. Constant $\text{SNR}_{\text{proj}}$ values for different voltage and prefilter combinations allow drawing conclusions on the influence of the minimal X-ray transmission on the XCT image quality. Table 1 depicts a constant $\text{SNR}_{\text{proj}}$ of about 230 for a wide range of transmissions. Only the scans with the highest exposure times showed a slight drop of $\text{SNR}_{\text{proj}}$ due to thermal effects in the X-ray tube.

The placements of part A and C on the rotary table are selected with regard to the placement technique optimisation proposed by A. Amirkhanov et al. [8]. Contrary for part B the placement has been selected to create regions with well-known maximal penetration lengths to analyse the quality measures for different ranges of penetration lengths. In detail the transmission values are calculated by dividing the minimal grey value of a projection image after 3x3 median filtering by the mean greyvalue in a region of air (blue region in Figure 2). Figure 2b shows additional regions marked in red that are used to calculate minimal greyvalues and transmissions per step for part B. The minimal transmissions listed in Table 1 are the lowest transmissions during the XCT scan of the specimen, occurring at the rotation position with the highest absorption.

### 2.4 Evaluation procedure

The main goal of this evaluation is to show the correlation between XCT image quality and the minimal X-ray transmission in the projection images. Furthermore the applicability of a transmission based parameter selection and the suggested minimal transmission values of 10 to 20% proposed in standards [1,2] for best scan results is verified. Therefore several XCT scans are done for the parts described in section 2.2. The used scan parameters and reached minimal transmission values are listed in Table 1. The XCT image quality of each dataset is quantified by calculating SNR and CNR values of several regions and combinations of regions. Equation 7 and 8 show the definition of the quality measures SNR and CNR [1,2], whereas $\mu$ is the mean greyvalue and $\sigma$ is the standard deviation of $\mu$ in a defined region.

\[
\text{SNR} = \frac{\mu}{\sigma} \quad (7)
\]
\[
\text{CNR}_{\text{background,foreground}} = \frac{|\mu_{\text{foreground}} - \mu_{\text{background}}|}{\sigma_{\text{background}}} \quad (8)
\]

The SNR generally describes the ability to detect structures within a noisy and inhomogeneous image region. The latter are usually caused by artefacts, e.g. beam hardening. Compared to CNR values the contrast of a specific structure in or near this region is not considered. There are two ways to use the measure CNR, depending on the assignment of foreground and background in Equation 8. For example, if there are regions of material and air, one can use the standard deviation of the air greyvalues to calculate a CNR which describes the ability to detect material beside air. On the other hand one can use the standard deviation of the material greyvalues which describes the ability to detect air within material. In this work we focus on the case of using the standard deviation of the higher absorbing material for Equation 8, which gives insight into the behaviour of the higher absorbing material greyvalue distribution that is affected by photon noise and artefact mechanisms like beam...
hardening and scattering. Greyvalue modifications by artefacts in air or surrounding materials are considered in the contrast term of the CNR.

The renderings in Figure 3 show the evaluation regions for the XCT images of all parts used to calculate the SNR and CNR plots of chapter 3. In detail Figure 3a shows two regions for part A, created using the XCT image of the 40 kV scan. The material region (green) is created by applying an ISO50 threshold to this XCT image. Further this region is eroded by a rectangular 7x7 erosion operator. In the centre of the specimen a cylindrical air region (blue) is placed, 121 voxels in diameter and 1401 voxels in height. Part B’s SNR and CNR is analysed in each of the 5 diameter steps separately by the use of cylindrical and ring like regions (green) each 101 voxels in height (Figure 3b). The cylindrical surfaces of the evaluation regions are set to assure a distance of about 10 voxels to the specimen’s surface. Part C is analysed in rectangular regions coloured yellow in zones of air, plastics, a rubber seal and a metallic pin (Figure 3c and 3d).

Alignment errors of the specimens in the XCT datasets are smaller than one voxel. Such errors may origin from thermal movements of the specimen and the specimen holder during the scan series or from changing focal spot positions.

Figure 3: Renderings of the evaluation regions that are used to calculate SNR and CNR values in the XCT image (a) for part A in green and blue, (b) for part B in green, (c) and (d) for part C in yellow with XCT data in grey.

3 Results

3.1 Part A: rubber gaiter

Figure 4 shows XCT slices of part A. The magnified cut-outs depict that rubber may be visualised with similar contrast for minimal transmissions ranging from 14.2 to 33.7%. The plots of the SNR for rubber and the CNR between rubber and air over the minimal transmission (Figure 5) confirm the visual impression, but show a slight degradation of the image quality towards higher transmission. Especially the plots of SNR for air regions point out, that structures with very low absorption for example the polystyrene foam mounting (Figure 4 b,c,d) may be visualised slightly better with lower transmission values. Hence, minimal transmissions from 10 to 20% result in good XCT images for this application, but it is not possible to determine a local maximum of the SNR or CNR in this transmission range. Practically it is not possible to get minimal transmissions under 14% on the used XCT system, because voltages below 40 kV would lead to very high exposure times.
Figure 4: Cut-outs of (a) a reconstructed zx-slice of part A made of rubber acquired with (b) 40 kV without prefilter and 14.2% minimal transmission, (c) 120 kV without prefilter and 29.1% minimal transmission and (d) 200 kV without prefilter and 33.7% minimal transmission.

Figure 5: Plot of SNR and CNR in the XCT images over the minimal transmission of the projection images for testpart A.

3.2 Part B: aluminium step cylinder

Figure 6 shows slice images of part B, where the minimal transmission ranges from 1.6% to 9.6%. For this kind of application high exposure times are necessary to reach at least a minimal transmission of 10% and preserve an SNR$_{proj}$ of about 230. The images point out that beam hardening artefacts are reduced by increasing the effective energy of the used X-ray spectrum, which is proportionally increasing the transmission for this experimental setup.

The shape of the SNR and CNR graphs (Figure 7) is similar and leads to the same scan parameter selections, although the optimised selection is not globally distinct for the whole dataset, it depends on the local penetration lengths occurring during the XCT scan. The data points for each individual step in Figure 7 are discontinuous due to the use of discrete prefilter plate thicknesses, therefore an interpolation between the data points is critical. SNR and CNR values plotted against the minimal transmission for each step indicate maximum image quality at transmission values between 36 and 50% for penetration lengths up to about 7 mm (step 1). For penetration lengths up to 17 mm (step 2) the optimum is expected between 28 and 31% minimal transmission and for penetrations lengths up to 27 mm at about 20% minimal transmission (step 3). For higher penetrations lengths (step 4 and 5) the determination of a local maximum was not possible due to the maximal accepted exposure time of about 2.5 hours.
The image quality for this application is mainly limited by inhomogeneous greyvalue distributions caused by cupping artefacts. Since the strength of these artefacts depend on the penetration length, an optimal parameter combination and minimal X-ray transmission is only suitable per step and range of penetration lengths. The determined optimal transmission values for this aluminium part may vary between different XCT system configurations.

Figure 6: Reconstructed zx-slice of part B made of aluminium acquired with (a) 80 kV without prefilter and 1.6% minimal transmission, (b) 200 kV without prefilter and 5.0% minimal transmission and (c) 200 kV with 1 mm Cu prefilter and 9.6% minimal transmission.

Figure 7: Plots of SNR and CNR in the XCT images over the minimal transmission per step of the projection images for part B. The transmission gap from point 4 to 5 per step is caused by the use of a 0.5 mm copper prefilter plate.

3.3 Part C: multi-material component

Figure 8 shows a slice through the XCT dataset of a connector made of plastic equipped with rubber seals and metallic contacts. The zoom-out of the green solid region shows plastic with pores and a rubber seal. An increased transmission results in a loss of contrast between these features, which is caused by the energy dependency of the X-ray attenuation coefficients. The difference between the total attenuation coefficients of plastic and rubber is getting smaller for higher photon energies, which makes a separation of these materials difficult. Apart from that the zoom-out of the blue dashed region indicates that an increasing transmission causes fewer artefacts between the metallic contacts. These artefacts are mainly caused by non-linearities between X-ray attenuation and penetration length of high absorbing materials and are induced by the use of polychromatic X-rays.

The SNR plot of Figure 9a depicts that low absorbing materials show losses of SNR with an increasing transmission, whereas high absorbing materials benefit from an increasing transmission. The loss in contrast between rubber and plastic is only represented in the CNR plot of Figure 9b. When the CNR
value falls beyond 3 structures become hard to distinguish [1]. Therefore the critical upper limit for the minimal transmission to inspect the low absorbing parts of the specimen is about 10%.

Figure 8: Reconstructed zx-slice of part C a multi-material component acquired with (a) 80 kV without prefilter and 3.0% minimal transmission, (b) 200 kV without prefilter and 10.0% minimal transmission and (c) 200 kV with 1 mm Cu prefilter and 20.0% minimal transmission.

Figure 9: Plot of SNR and CNR in the XCT images over the minimal transmission of the projection images for part C. The transmission gap from point 4 to 5 per step is caused by the use of a 0.5 mm copper prefilter plate.

4 Conclusions
The optimisation based on the minimal X-ray transmission in the projection images as proposed in standards [1,2] obviously may work only in regions with highest absorptions. Image regions with higher transmissions may be acquired with suboptimal image quality. This is documented by the evaluation results of the aluminium step cylinder, where the optimal combinations of acceleration voltages and prefilter plates show a dependency on the local occurring penetration lengths. Furthermore, it has to be considered that transmission values can be gained by different combinations of acceleration voltages and prefilter plates which may cause different image qualities.

For the specimen with low absorption a minimal transmission from 10 to 20% resulted in good but not the best XCT images. SNR and CNR were nearly constant over a wide range of minimal transmission values caused by different scan parameter combinations.

The scan optimisation for the multi-material component is a trade-off, either high CNR values in regions with low absorbing materials are possible or artefacts around the high absorbing materials are
minimized. The EN 16016 states, beside the optimisation based on the minimal transmission, that it may be necessary to adjust the accelerating voltage to maximise the difference between linear attenuation coefficients in order to distinguish between different materials [1].

To sum up, it was not possible to approve a clear local maximum of the SNR or CNR between 10 and 20% minimal transmission for the selected scan tasks. This may be caused by mechanisms used for XCT that are not considered in the theoretical model for the optimal minimal transmission of radiographs (Equation 6). Additionally, other important effects may be caused by the used reconstruction algorithm, the specimen materials and their distribution in the scanned volume as well as their different energy dependent attenuation coefficients.

Finally, setting the minimal transmission between 10 and 20% guarantees that the specimen is penetrable by the X-rays in all projection images, which is a crucial requirement for successful XCT.

Acknowledgments

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[1] ÖNORM EN 16016:2011-08 Non destructive testing - Radiation methods - Computed tomography; part 2 chapter 5.1 and 8.2; part 3 chapter 4.1.1, 4.1.3, 5.1.3 and 5.1.4