CT image quality influence on different material Edge Response Functions for accurate metrological applications

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Abstract: The main objective of the proposed work was to analyse the influence of magnification and focal spot size scan settings on X-ray computed tomography (CT) measurements results under commercial threshold-based algorithms. The relationship between spatial resolution and contrast sensitivity in CT scans of different materials and the accuracy of the resulting CT measurement results is discussed. For that purpose, Aluminium, Copper, Inconel 718 and Titanium disk phantoms were scanned. Preliminary measurements showed that deviations can increase up to 0.48% when the scanning magnification was increased while, for a given magnification, the decrease of a focus size from 1mm to 0.4mm slightly improves the differences up to 0.15%, being negligible at low magnifications. Unsharpness ($U_T$) and contrast-to-noise ratio (CNR) were calculated for each scanning conditions according to standard ASTM E1695 – 20. A new image quality indicator that includes the combined effect of the $U_T$ and CNR was proposed in order to relate measurement error with the image quality. The indicator proves that the influence of CNR is much higher than influence of $U_T$ on the CT measurements.

Keywords: X-ray computed tomography, Image quality, CT measurement, Unsharpness, Contrast-to-noise ratio.

1. Introduction
Technological development is providing faster and highly advanced measurement techniques. Amongst them, computed tomography (CT) is becoming more and more accepted in industrial applications [1]. One of the best advantages of this technology is the possibility of measuring a defect once it has been detected, which is known as metro-tomography. The introduction of CT into the metrological field is justified by the numerous possibilities it brings as a non-destructive inspection method, allowing multi-material testing as well as dimensional quality control. However, quantitative results obtained by CT are strongly influenced by a high number of error sources and thus the accuracy of CT-based measurements remains yet largely uncertain [2]. The measurement setup, the CT equipment, the workpiece shape and the material play a major role in the measurement accuracy [3].

Nowadays, several studies propose new measurement procedures and reference objects to improve this scenario [1,2,4]. Unfortunately, not only the lack of repeatability of CT measurement results but the relationship between CT image quality and measurement accuracy is overlooked and scarce. In most cases, results are difficult to compare as they are strongly methodology-dependent [5]. In addition, one fundamental problem when comparing measurement results is the different measurement principles and
strategies. For example, depending on the physical interaction between the measuring tool and the specimen, the captured surfaces can considerably differ, resulting in a different workpiece surface roughness, for instance. For this reason, the extent to which the surface roughness influences the captured surfaces varies depending on the nature of the technology used for acquiring measuring points. Similar reasoning can be applied to the used of different strategies although the same technology is used. Therefore, is inevitable that when using different measurement principles and strategies for surface determination, differences in measurement results may occur [1].

Carmignato et al. indicate that CT technology requires of practical knowledge of factors influencing the metrological performance, since so far there is no consensus on an accepted method for an international standard [2]. To cover these weaknesses, many studies were carried out during the last decade [3,4,6], which conclude that the influence on CT image quality has an important impact on CT measurements. The main factors that affect the image quality are unsharpness, image noise, scatter and artifacts, which have a direct influence on the surface determination, where dimensional measurements are performed [6]. Since magnification and focal spot size are scanning settings that limit both spatial resolution and contrast sensitivity, the independent consideration of them is necessary for a faithful reliability of CT measurement results [4].

This research work studies the influence of the main factors affecting the image quality on the measurement results. To do so, four disk phantoms were used as reference-objects according to ASTM E 1695-20 [7]. Phantoms were replicated in Aluminium, Copper, Inconel 718, and Titanium. Moreover, each disk phantom measurement process was associated with its corresponding task-specific uncertainty estimation by substitution approach [1]. With the aim of quantifying the image quality, three indicators were used: unsharpness ($U_T$), contrast-to-noise ratio (CNR) and original one coming from the combination of both. This new indicator was directly related to the measurement errors, which can be used to predict the CT measurements accuracy for a given CT image quality. Further, the deviations produced by increasing the magnification and reducing focal spot size (as a rule of thumb assumed by the operators to visualize the smallest features of the specimen) were discussed. The main goal is to improve the quantitative knowledge on the cause-effect relationship when modifying the above-mentioned scan settings, providing better scientific understanding of the measurement by means of CT. Finally, results obtained from the disk phantom tests were applied in an industrial component (external diameter of a motorbike throttle Aluminium pulley) in order to validate the usefulness of the new indicator.

1.1. Main CT images quality factors
Imaging quality is commonly described in terms of contrast, spatial resolution, and artifacts [8]. The latest version of ASTM E1695-20 [7] specifies that the main factors affecting CT image quality are unsharpness, contrast response and image noise.

Unsharpness limits the ability to image fine structural details in an object, that is, the spatial resolution of a CT system. Image noise and contrast response limit the ability to detect the absence or presence of details in an object, that is, the contrast sensitivity of a CT system. Zscherpel et al. [9] concluded that the scattering affect both structural resolution and contrast sensitivity.

Furthermore, there are different artifacts that impair the image fidelity of the scanned object, being the beam hardening one of the most detrimental. In order to minimize measurement errors coming from the beam hardening, dimensional measurements are to be performed by associating standard geometries in planes normal to the X-ray paths, combined with the use of filters and high radiation energy set-ups. Van de Casteele et al. [10] noticed that spatial resolution was improved by means of beam hardening reduction.

Figure 1 shows the main factors that influence the image quality. It can be seen that unsharpness, random noise, contrast response and scattering are directly related to the Edge Response Function (ERF) where surface determination is established.
Figure 1. Main factors that influence image quality and their impact on the ERF.

ERF determines the transition between the component and environment where a threshold value is established. The appropriate threshold selection is essential to avoid overestimation or underestimation of the size of a component, being the threshold the most critical parameter for performing accurate metrological tasks.

1.1.1. Unsharpness. The total unsharpness (\( U_T \)) in the CT image is directly related with ERF by the spatial resolution and can be estimated through different methods. Most widely used methods can be classified as objective and subjective. Although Guo Zhimin, Ni Peijun et al. [11] found a strong relationship between results obtained by both methods, the subjective method requires phantoms which are difficult to manufacture and calibrate. Thus, the objective method known as Modulation Transfer Function (MTF) is commonly used to determine both spatial resolution and \( U_T \). MTF can be defined as the magnitude of Fourier transform of the edge response function. MTF provides the spatial frequency at a specific amplitude percentage of attenuation and the value of 1 divided by the 10% MTF decay is usually taken for determination of the \( U_T \). The calculation procedure is described in the figure 2 according to ASTM E1695-20 [7]. This function does not include noise effects.

\[
U_T = \frac{1}{MTF_{10\%}} \frac{lp}{mm}
\]

Figure 2. MTF calculation procedure.

1.1.2. Scatter. During a CT scan, as the X-rays are attenuated when going through the workpiece, a deflection of the incident photons occurs. It is called Compton Scatter. Since X-ray detector cannot discriminate energy, it receives and processes all radiation, including the scattered radiation. Figure 3 shows the effect of the scattered radiation on the intensity profiles when a part is being scanned. Outside the object boundaries, the X-ray radiation hits directly the detector and within the object the radiation is attenuated by Lambert-Beer's law (figure 3(a)). However, when radiation passes through an object, X-rays are deflected and appears the scattering effect as can be observed in figure 3(b). In addition, a
workpiece edge parallel to X-rays path increases scatter effect, which is added to the total radiation dose (figure 3(c)). Scatter effects result in an edge enhancement [9].

Figure 3. Resulted intensity profiles considering 3 different scenarios. (a) Without scatter effects, (b) Scatter effects only and (c) Scatter effects included.

Special attention should also be paid to the position of the specimen during CT, as there may be a gradual change in X-ray absorption across a parallel edge or boundary [2]. In order to avoid this effect, the workpieces scan position should be tilted 10° - 40° in relation to the vertical position. Generally, scattered radiation effects are related to the appearance of a uniform and global fog that limits the contrast sensitivity and reduces the spatial resolution. As a consequence, the ERF becomes larger and poorly defined [12]. This effect varies with the radiation energy, material and wall thickness [9]. In brief, it can be said that scattering is more intense on the surface of the inspected sample, being maximum when the incident photon has the same direction as the face of the workpiece. Besides, as it decreases with the square of the distance \((1/L^2)\), the scattered radiation is more troublesome when the sample is closer to the detector [9].

1.1.3. Image noise and contrast response. The digital radiological image consists in the interaction of the photons with the part to be inspected. This interaction is reflected in the detector, which converts the energy of the photons that reached the panel into light that is later converted into an electrical signal that forms the final image. Thus, the quality of X-ray images is characterized by the information that detector acquires, commonly referred to as image signal [13]. This signal is affected by noise which smudges the image. As a definition, noise is an undesirable effect which consists of the random appearance of signals that are not part of the original image [2]. In literature [14], signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) are described as the most used image quality indicators of digital noise. Lifton et al. [15] show how the CNR has a direct influence on surface determination as this indicator assesses the difference between the object and background grey values where the threshold is selected. The CNR is defined by equation (1) [16]:

\[
CNR = \frac{\bar{g}_{\text{object}} - \bar{g}_{\text{background}}}{\sigma_{\text{background}}}
\]

where \(\bar{g}_{\text{object}}\) and \(\bar{g}_{\text{background}}\) represent the mean grey value of two Region of Interest (ROI), inside and outside the specimen and \(\sigma_{\text{background}}\) stands for the standard deviation over the same ROI outside the specimen. Furthermore, as contrast response \((\bar{g}_{\text{object}} - \bar{g}_{\text{background}})\) and image noise \((\sigma_{\text{background}})\) limits the contrast sensitivity of a CT system, CNR quality indicator was considered in this work to evaluate the contrast sensitivity of CT images.

2. Materials and methods
General Electric X-Cube Compact machine with 5 axes was used for the scanning purpose. VGStudio MAX 3.4 software was used for analysing results. The maximum voltage and current of the CT system
are 195kV and 8mA respectively and focus size little/big are 0.4/1mm. As recommended in [1,7], voltage and mAs of the X-ray source were considered the most influential parameters in performing accurate CT reconstruction. Thus, the source voltage was selected to avoid the extinction of the X-ray beam in the most unfavourable position. The voltage was adjusted to 150kV and then the tube current value was chosen to be high enough as it leads to a reduced exposure time, allowing the least scanning time without decreasing the image contrast/brightness. This resulted in 4mA and 100ms of exposure time. The combination of 1mm copper and 0.5mm tin filters achieved a homogenization effect of photons energy that reached to the workpiece and reduce the beam hardening effect. In order to independently evaluate the influence of magnification and focal spot size on CT image quality, the scanning parameters were maintained constant in all tests.

2.1. Disk phantom

The disk phantoms were manufactured by Wire Electro Discharge Machining (WEDM) and every diameter was measured 15 times with a millesimal screw micrometre of 0.001mm resolution and 1.1 µm uncertainty (k=2). With the aim of taking into account the measurement procedure specifics and to make the CT values traceable, the corresponded standard deviations of screw micrometre measurements are provided in table 1. The standard deviation values are influenced by the form error and roughness of the disk phantoms, amongst other factors. Even so, this standard deviation is an order of magnitude lower than the difference between the mean diameters obtained by screw micrometre and the ones obtained by CT (see table 2). Furthermore, this value, defined in table 1 as Std Dev, is much smaller than the smallest voxel size used in the study. The mean diameters which were taken as reference values are summarized in table 1. All disk phantom thicknesses were 3 mm.

| Material    | Aluminium | Copper    | Inconel 718 | Titanium |
|-------------|-----------|-----------|-------------|----------|
| Mean diameter (mm) | 23.036    | 23.024    | 22.947      | 22.519   |
| Std Dev (mm)  | 0.005     | 0.012     | 0.007       | 0.005    |

Table 1. Mean diameters and standard deviation (Std Dev) of disk phantoms by screw micrometre.

To assure the traceability, the expanded uncertainty of the CT measurement process (U_mP) of the disk phantom was determined. The presented task-specific uncertainty estimation was based on repeated measurements carried out on an Aluminium disk phantom.

3. Results

This work presents an experimental investigation on the image quality factors influencing the metrological capabilities of the Computerized Tomography. The objective was to analyse the influence of magnification and focal spot size on spatial resolution and contrast sensitivity of different materials. For that purpose, the maximum and minimum magnification (2.231 and 1.283) and focal spot size (1 and 0.4mm) allowed by the CT machine were selected. The voxel size achieved with the selected magnifications was equal to 89 µm and 150 µm respectively, therefore higher magnification is related to a smaller voxel size. The spatial resolution was evaluated by unsharpness (U_T) and the contrast sensitivity by CNR according to ASTM E1695 - 20 guidelines [7].

To consider the repeatability of results, 3 CT scans were replicated with identical set-up and parameters. Afterwards, U_T and CNR were calculated in 2 slice planes positioned at 15 % from the top and bottom of the reconstructed volumes. The final U_T and CNR values were considered averaging the results. The tests were performed in Aluminium, Copper, Inconel 718 and Titanium disk phantoms and the resulted values are shown in table 2.

Moreover, the external diameter of each disk phantom was measured fitting a circumference in its middle section by least squares adjustment after applying both global (GSD) ISO50 and local adaptive
(LASD) surface determinations. The CT external diameter results were compared to reference values obtained by using screw micrometre in table 1. Differences are presented in table 2 (GSD-Ref difference and LASD-Ref difference).

Results from table 2 shows that \( U_T \) and CNR values seems not to have relationship with GSD-Ref and LASD-Ref differences. However, authors found that the following relation between \( U_T \) and CNR (equation (2)) and designated as Measurement Quality Indicator (MQI) can be used as a new image quality indicator:

\[
MQI = \frac{U_T}{\text{CNR}^2} \cdot 10000
\]  

Table 2. Unsharpness (\( U_T \)), contrast-to-noise ratio (CNR), differences between global surface determination and reference value (GSD-Ref), differences between local adaptive surface determination (LASD-Ref) and MQI indicator values at different magnification (Mag.) and focal spot sizes in different materials.

| Focal Spot (mm) | Mag. | \( U_T \)(mm) | CNR | GSD-Ref difference (mm) | LASD-Ref difference(mm) | MQI |
|----------------|------|---------------|-----|-------------------------|-------------------------|-----|
| Aluminium disk phantom | 1    | 2.231        | 0.431 | 82 | 0.159 | 0.159 | 0.6492 |
| Copper disk phantom | 0.4  | 1.283       | 0.464 | 134 | 0.047 | 0.048 | 0.2601 |
| Inconel 718 disk phantom | 1    | 2.231        | 0.297 | 77 | 0.137 | 0.137 | 0.5010 |
| Titanium disk phantom | 0.4  | 1.283       | 0.390 | 131 | 0.043 | 0.044 | 0.2275 |
|  | 2.231 | 0.403 | 56 | 0.225 | 0.225 | 0.129 | 1.3080 |
|  | 2.231 | 0.382 | 57 | 0.153 | 0.153 | 0.066 | 1.1743 |
|  | 2.231 | 0.321 | 51 | 0.189 | 0.189 | 0.126 | 1.2581 |
|  | 1.283 | 0.359 | 57 | 0.150 | 0.150 | 0.055 | 1.1249 |
|  | 2.231 | 0.0402 | 52 | 0.232 | 0.232 | 0.148 | 1.4872 |
|  | 1.283 | 0.373 | 55 | 0.134 | 0.134 | 0.048 | 1.2346 |
|  | 2.231 | 0.307 | 47 | 0.206 | 0.206 | 0.140 | 1.4198 |
|  | 1.283 | 0.351 | 53 | 0.136 | 0.136 | 0.049 | 1.2501 |
|  | 2.231 | 0.340 | 85 | 0.189 | 0.189 | 0.162 | 0.6022 |
|  | 1.283 | 0.374 | 95 | 0.083 | 0.083 | 0.053 | 0.4183 |
|  | 2.231 | 0.305 | 73 | 0.170 | 0.170 | 0.147 | 0.5724 |
|  | 1.283 | 0.365 | 94 | 0.077 | 0.077 | 0.052 | 0.4178 |

Table 2 shows that MQI can be related to the magnitude of the differences in all the cases and materials studied. Qualitatively, if the indicator (MQI) value raises, the difference from the reference increases regardless of which surface determination method is used. Besides, table 2 results show that deviations can increase up to 0.48% when the scanning magnification was increased while, for a given magnification, the decrease of a focus size from 1mm to 0.4mm slightly improves the differences up to 0.15%, being negligible at low magnifications. This is because the CT image quality decreases as the magnification increases. Relationship between MQI and GDS-Ref and LASD-Ref differences only follow a trend when couples of values of a specific material are compared (for a specific material, MQI changes with the focal spot size and with the magnification). Thus, the relationship exists for each specific material to be scanned.

Regarding the uncertainty of the disk phantom CT measurement process, table 3 summarized the resulted expanded uncertainty (\( U_{MP} \)) values. To estimate them, the substitution method uncertainty budget was applied. Uncertainty budget was estimated for Aluminium disk phantom diameter measured by global surface determination and local adaptive surface determination, at the selected magnification and focal spot sizes (see table 3).

The experimental procedure included all significant influencing factors in the \( U_{MP} \) results as suggested in VDI/VDE 2630 Part 2.1[1]. These factors are the standard uncertainty of measurement due
to the uncertainty of calibration of the reference disk phantoms ($u_{cal}$), the measurement process ($u_p$),
the variations in materials ($u_w$), and the systematic errors between the mean values of CT measurements
and the reference values ($b$). The results are determined from 3 identical set-up scans by 3 different
operators. One operator performs 5 measurements on one of these scans. Another operator performs
another 5 measurements on the second of the scans and the same operation is performed by the third
operator on the last scan. Therefore, in order to include the repeatability of the CT process and the
operator influence, the standard deviation of a total of 15 repeated measurements was included in the
calculation of $u_p$. The Aluminium disk phantom is only presented since the validation workpiece is
made of Aluminium. All other materials follow the same approach and trend but the uncertainty values
may be different.

Table 3. Substitution method uncertainty budget for Aluminium disk phantom diameter measured by
both global and local adaptive surface determinations (all values are in mm).

| Uncertainty contribution | Global surface determination | Local adaptive surface determination |
|--------------------------|------------------------------|-------------------------------------|
|                          | 1mm Spot size                | 0.4mm Spot size                     | Magnification                  | Magnification |
|                          | 2.231                        | 1.283                               | 2.231                        | 1.283          |
| $u_{cal}$                | 0.002                        | 0.002                               | 0.002                        | 0.002          |
| $u_p$                    | 0.002                        | 0.002                               | 0.002                        | 0.002          |
| $u_w$                    | 0.006                        | 0.006                               | 0.006                        | 0.006          |
| $b$                      | 0.159                        | 0.047                               | 0.137                        | 0.043          |
| $U_{MP}$ ($K = 2$)       | 0.318                        | 0.095                               | 0.275                        | 0.088          |

Results in table 3 show that the poorest CT image qualities offer the highest $U_{MP}$ values.
Finally, for the validation of the proposed trials, an external diameter of a motorbike throttle
Aluminium pulley was measured by VGStudio MAX 3.4 software fitting a circumference by least
squares adjustment, as seen in figure 4. Following the reference procedure, this component was firstly
measured by screw micrometre.

Figure 4. Motorbike throttle pulley CT measurement.

In this case, results of the indicator MQI fulfils the criteria established in the disk phantom tests, as
shown in figure 5. The Secondary axis of the figure 5 shows the absolute diameter measurement values
obtained by both surface determination (GSD and LASD) and the reference diameter value obtained by
screw micrometre under repeatability conditions and with a standard deviation of 0.002 mm.
Figure 5. Relation between pulley CT diameter measurements deviations (differences with respect to the reference values) achieved for each scanning parameter and MQI indicator value. On the secondary axis, the absolute values obtained by GDS, LASD and micrometre screw.

4. Conclusions
From the research carried out the following conclusions can be drawn:

- Regarding the influence of the image quality parameters on the measurement, from the research carried out it can be said that the CNR influence is much higher than the $U_T$. CNR rises and falls were consistent with changes in magnification and focal spot sizes, unlike the $U_T$. The main reason is that CNR is not affected by the scatter as the $U_T$ is. Therefore, after testing the influence of magnification and focal spot size on spatial resolution and contrast sensitivity, it has been concluded that the non-systematic variations of the $U_T$ are due to the scatter effect, which is enhanced when the inspected object gets closer to the detector.

- The proposed indicator (MQI) predicts the difference between global (GSD) and local iterative (LASD) surface determinations and reference values in all materials studied (Aluminium, Copper, Inconel 718 and Titanium). However, the indicator (MQI) is much more sensitive for low density materials such as Aluminium and Titanium and is specific to each material.

- It can be summarized that at high magnifications (2.231) the measurement error is maximum for a given focus size. Increasing the focus size slightly increases this error. This applies to both surface determinations used (GSD and LASD), which are widely used commercial threshold-based algorithms for adjusting the threshold value. However, at low magnifications (1.283), the focal spot size impact is almost negligible.

- A traceable CT measurements substitution method uncertainty budget is provided. The task-specific uncertainty was estimated for Aluminium disk phantom CT measurements using GSD and LASD.

- This study contains an overview of the influence of image quality parameters on the CT external diameter measurement. However, the evolution of these results in larger measurement contexts, different CT set-up and more complex geometries is unknown and is deserving of more research.

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