Image Artefacts in Industrial Computed Tomography

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Abstract: Computed tomography is a method that has been used for many years in medicine and material analysis, and recently it has also been introduced in dimensional measurements. The method has a lot of advantages compared to other 3D measurement methods, with the largest one being the possibility to perform a non-destructive measurement of an object's inner geometry. However, it is a complex method with a large number of parameters that influence measurement results. Some of these parameters are image artefacts that occur in the scanning and reconstruction process. An artefact is any artificial feature which appears on the CT image, but does not correspond to the physical feature of an object. In order to achieve metrological traceability, it is necessary to eliminate and minimize the influence of image artefacts on measurement results. This paper presents and explains image artefacts in industrial computed tomography as the consequences of different influence parameters in the CT system.

Keywords: computed tomography; dimensional measurements; image artefacts

1 INTRODUCTION

Computed tomography (CT) is one of the three--dimensional methods used in dimensional measurement. The method uses the nature of an X-ray to measure both the outer and inner objects' structures and geometries. The method was developed by Godfrey N. Hounsfield and Allan M. Cormack in the 1960s. The method was firstly used in medicine, where it still has great applicability and significance. Later on, the method was applied in material science, and in the last few decades, it has also found its application in dimensional metrology. Given the afore-mentioned, computed tomography can be divided into two groups – medical computed tomography and industrial computed tomography. Medical and industrial computed tomography differ in several components, such as radiation doses, the kinematic system, the method of scanning, and related to that, the performance of CT scanners. Fig. 1 shows a medical and industrial CT scanner.

Figure 1 CT scanner: a) medical CT scanner [1], b) industrial CT scanner

In industrial CT scanners, the object rotates during the scanning process, while the X-ray source and detector either move vertically (in line beam CT scanners) or do not move (in cone beam CT scanners). In medical CT scanners, patients are translated horizontally through the ring where the X-ray source and the detector are placed. In this paper, special emphasis is placed on industrial computed tomography.

Computed tomography is a method with a lot of advantages, for example:

- the possibility to measure and analyse inner objects' geometries in a non-destructive way
- the inspection of individual parts in assemblies
- the possibility of conducting many different analyses with one scan (e.g. the pore and inclusion analysis, analysis of polymer fibre orientation, dimensional measurements)
- suitable for deformable, reflective, transparent materials
- application in reversible engineering, etc.

However, it is a complex system where the process of dimensional measurement can be divided into three subprocesses: the subprocess of CT scanning, the model reconstruction subprocess and the subprocess of performing the analysis on the obtained 3D model, here the analysis of dimensional measurements (Fig. 2).
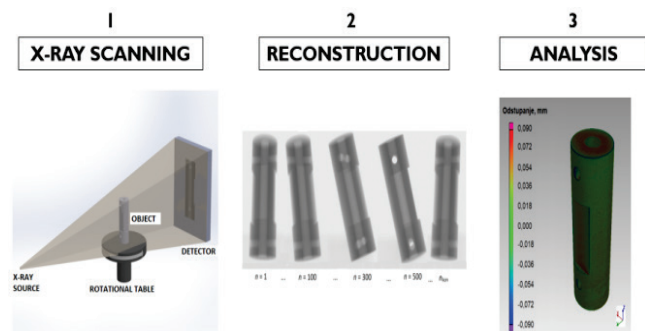

Figure 2 CT measurement process

The first subprocess, CT scanning, is conducted in CT scanners. CT scanning involves collecting the data generated by a passing X-ray through the object during its rotation on a rotational table for at least one cycle of rotation. In the process, the detector captures the remaining radiation which is attenuated while passing through the object and it records them in the form of a large number of 2D records.

Each 2D record corresponds to the image of the object taken from a specific angle. The next step includes the reconstruction of a 3D model from the captured 2D images. The reconstruction process is based on a filtered

backprojection. Since reconstruction includes processing a lot of information, a powerful computer configuration with adequate software support is required. The result of image reconstruction is a voxel model with different greyscale values. Voxel is a three-dimensional pixel. The final sub-process in the CT dimensional measurement involves the process of analysing and measuring features on the reconstructed 3D model.

Dimensional measurement with the use of computed tomography represents a complex system with a large number of influencing parameters. With the aim to achieve metrological traceability, all influencing parameters should be identified and corrected. Until today, many different classifications of influencing parameters in CT dimensional measurements have been proposed. One of the classifications suggests the division of the influencing parameters according to the subprocess in which they occur [2]. Consequently, influencing parameters can be divided into: parameters influencing the scanning process, parameters influencing the reconstruction process and parameters influencing the measurement process. Fig. 3 shows the influencing parameters classified according to the subprocess in which they occur.
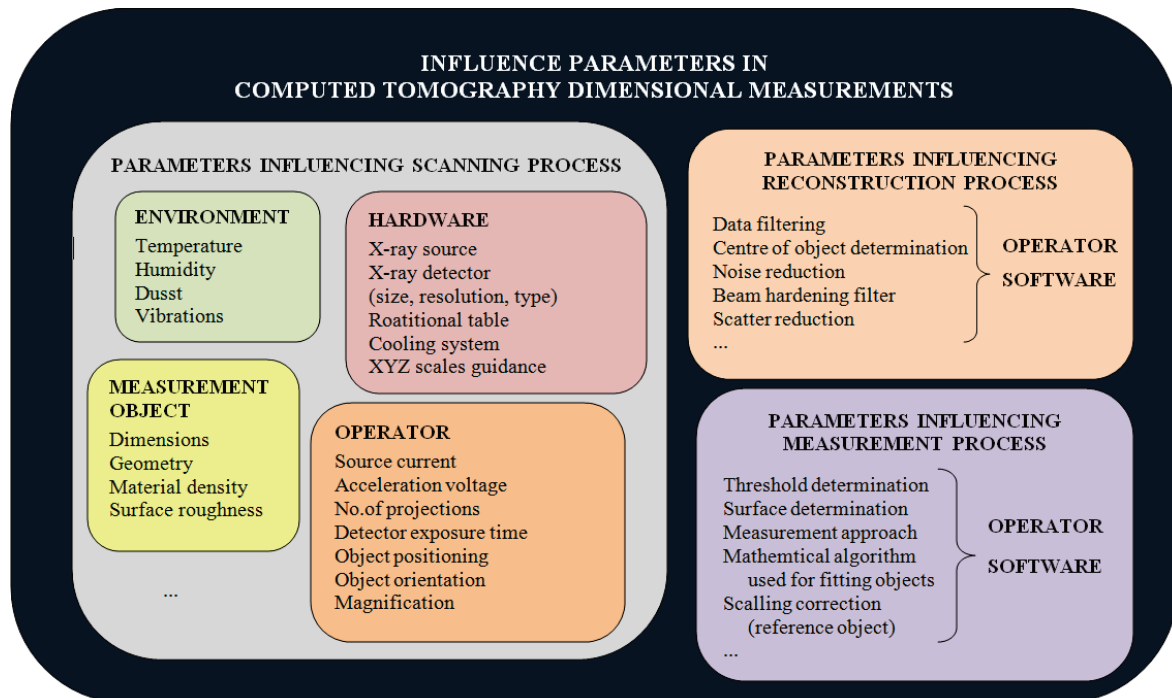

Figure 3 Classification of influencing parameters in computed tomography [2].

This paper present and explains image artefacts as the consequences of different influencing parameters in the CT system. According to the international standard ISO 15708-1, an artefact is any artificial feature which appears on the CT image, but does not correspond to the physical feature of an object [3]. Image artefacts mostly appear as apparent gradient changes inside homogeneous materials or as apparent darker or lighter lines between materials of different densities which do not exist in the object. These artefacts have a considerable influence on the greyscale profile and hinder the determination of an optimal greyscale threshold, which leads to significant deviations in measurement results [4].

2 IMAGE ARTEFACTS

During the CT scanning process, different phenomena occur as a result of: the physical nature of an X-ray, the interaction between the photons and measurement object, or imperfections of the CT scanner and its parts. These imperfections manifest as image artefacts. Given the cause of the occurrences, different authors classify artefacts in several

categories. Sun et al. [5] group artefacts in physics-based artefacts, scanner-based artefacts and computer-based artefacts. Amirkhanov et al. [6] classify artefacts in reconstruction and 3DXCT artefacts, while authors researching the use of the cone beam CT in medicine divide artefacts in physically-based artefacts, patient-based artefacts, scanner-based artefacts and motion artefacts [7, 8].

Artefacts caused by an imperfection of the CT measurement system are:
- beam hardening artefacts
- scattered radiation artefacts
- ring artefacts
- metal artefacts
- motion artefacts and
- partial volume artefacts.

The most common artefacts in cone beam CT scanning are beam hardening artefacts, scattered radiation artefacts and ring artefacts [9]. Below is an overview of the images that are generated in the process of scanning the object with the cone beam CT scanner.

2.1 Beam Hardening Artefact

Beam hardening artefacts are caused by the process of beam hardening. Beam hardening is a physical phenomenon resulting from the polychromatic nature of X-ray radiation. When X-ray beams pass through the object, photons which have less energy (softer beams) are more attenuated than those with higher energies (harder beams) [10].

During the absorption of polychromatic radiation, a nonlinear gradient of attenuation occurs during the propagation path of an X-ray through a material. However, most image processing algorithms assume a linear relationship between the propagated path and the number of photons attenuated, resulting 2D images show beam hardening artefacts, in the form of thin lines (streaks), brighter or darker edges compared to the based material also known as cupping and capping artefacts [4].

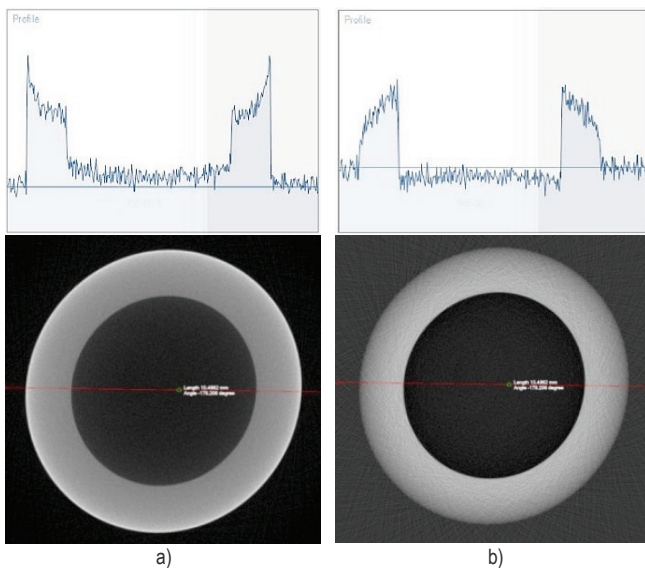Fig. 4 shows the most significant errors of the 2D images resulting from beam hardening.

Figure 4 Beam hardening artefacts: a) cupping, b) capping.

Fig. 4a shows the error of the brighter object edges, the so-called cupping, while Fig. 4b shows the error of the darker object edges, the so-called capping. The grey value profiles shown in the figure, for the red-marked cross-sections, correspond to the cup shape in the left figure, i.e. the cup shape in the right figure.

Fig. 5 shows streak artefacts which occur in the reconstruction process of a cylinder.

The presence of beam hardening artefacts considerably affects the quality of 2D images and hinders proper determination of an object's edges. This directly affects the results of dimensional measurements [11]. Since beam hardening artefacts are considered to be one of the most significant influence parameters in CT measuring, their influence on the 2D image quality has to be eliminated or compensated. How the determination of a border between the material and background, or a border between two different materials, influences the measurement uncertainty is explained in more detail by Lifton and Liu in [12].
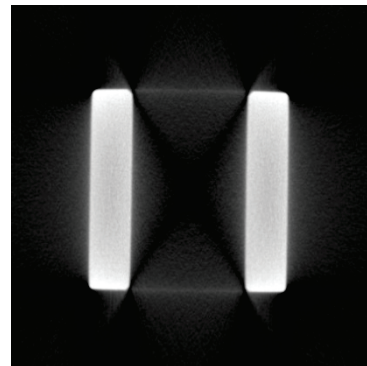

Figure 5 Streaking artefacts as a result of beam hardening

For beam hardening correction, several methods are suggested: scanning with a monochromatic X-ray, using different types of physical filters in order to limit the X-ray spectra, scanning with dual energy and using linearization methods based on polynomial curves. Moreover, authors in [13] use a polychromatic statistical image reconstruction for the reduction of beam hardening artefacts.

2.2 Scattered Radiation Artefacts

Scattered radiation artefacts are caused by scattered (secondary) radiation. One of the possible interactions between the incident photon and electrons in the scanned material is incoherent scattering, also known as Compton scattering. Scattering is defined as the redirection of radiation-beam photons caused by interactions with matter in their path [3]. During incoherent scattering, the incident photon uses a part of its energy to eject an electron from its host atom and a part of its energy is transferred to the ejected (recoiled) electron as its kinetic energy, while the rest of the energy is emitted as a new photon with less energy. The newly-emitted photons form secondary radiation [14]. This radiation is emitted at a specific angle, as a result of the law of the conservation of a momentum. Since photon energies observed here have much larger energies than the electron binding energy, the binding energy can be omitted so that the energy of the incident photon is given as (1):

$$E_i = E_e + E_f, \tag{1}$$

where: E_i - energy of the incident photon, E_e - kinetic energy of the recoil electron, E_f - energy of the scattered photon.

Fig. 6 illustrates the incoherent (Compton) scattering.

Because of incoherent scattering, some of the photons detected on the detector will be those of secondary radiation. Secondary photons cause deviations of the detected signal, compared to the wanted primary radiation signal, which results in shadows or lines on the reconstructed images [14]. Fig. 7 illustrates the impact of incoherent scattering on the detected signal. The scanned object in this case consists of a base material of lower density and a smaller object of higher density inside it, which absorbs and scatters more photons

than the base material, as seen in Fig. 7. Given that the path of scattered photons is arbitrary, the intensity distribution of secondary photons is seen as background noise with lower frequencies. The superposition of the primary and secondary signal results in a combined signal which lowers the image contrast and lowers the signal-to-noise ratio [14].
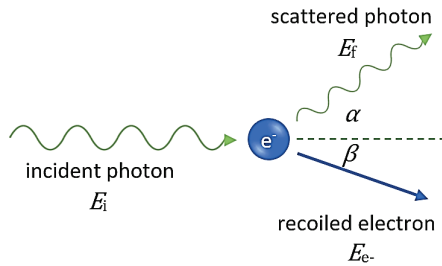

Figure 6 Incoherent scattering

The application of a simplified mathematical algorithm of a 3D model contributes to the formation of artefacts. In order to ease the reconstruction calculation, the detected signal is assumed to be equal with the linearly attenuated primary radiation [15].
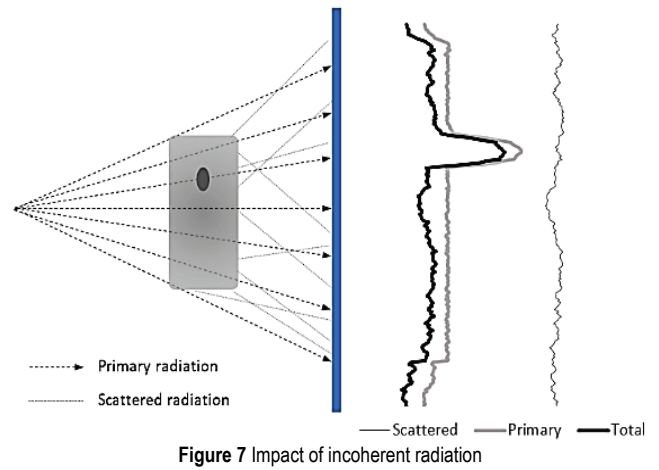

Figure 7 Impact of incoherent radiation

Fig. 8 shows artefacts caused by scattered radiation within the cross-sections of 3D models. The artefacts shown in Fig. 8 are observed as darker lines on the edges of the material and blurred borders on an object's surface.
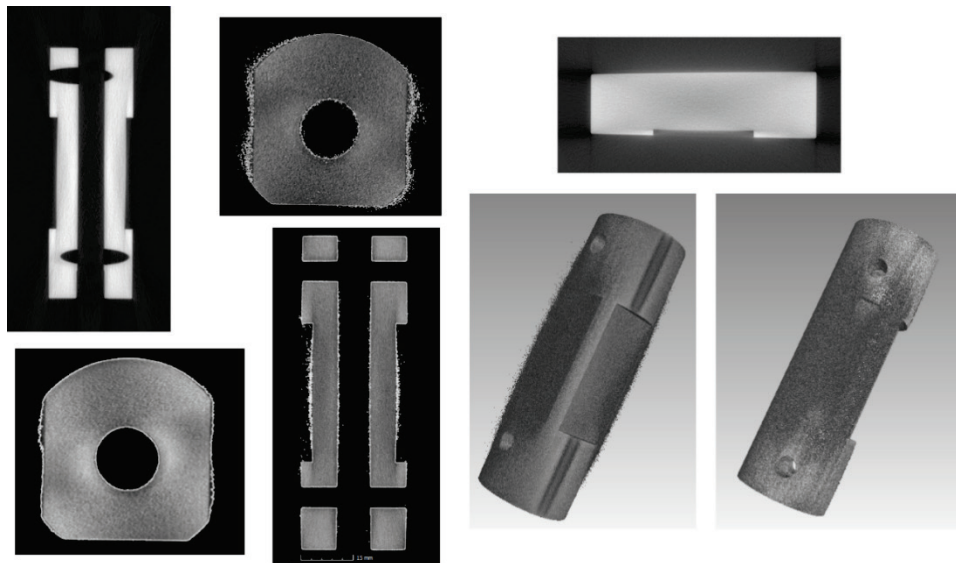

Figure 8 Reconstructed models with an observable impact of secondary radiation
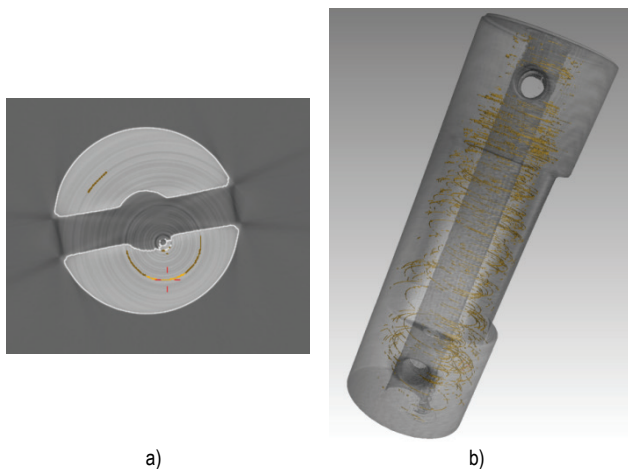

a)   b)
Figure 9 Ring artefact: a) in one slice, b) in a 3D model

2.3 Ring Artefact

Ring artefacts are systematic errors that occur due to a miscalibrated or defective X-ray detector [16]. Ring artefacts are manifested in the form of circles or circle arcs concentric to the rotational axis of the turning table. Artefacts are easily detectable and recognized due to its geometry and it is hard to misinterpret them as the object's geometry. However, the presence of ring artefacts can significantly disturb (impair) the performance of some analyses, e.g. the pore analysis where ring artefacts are wrongly recognized by the software analysis as pores in the material. The example of such a wrongly conducted analysis is shown in Fig. 9. The solution to the problems lies in detector calibration. With calibration, constant sensitivity along the entire detector can be achieved.

2.4 Metal Artefact

Metal artefacts result from the CT scanning of an object composed of or made of several materials with significantly different absorption coefficients, where at least one of the materials is metal. In the industrial application of computed tomography, metal artefacts usually occur when scanning polymer objects with inserted metal parts. Metal artefacts are more common in the medical use of CT if patients do not remove their metal jewellery before scanning, or in the case of implanted metal parts or dentures. The radiation absorbed in the metal parts of the objects is relatively high. As a result, the absorption detected just behind the metal parts is also artificially high [7]. This leads to misinterpretation of the attenuation coefficient in the material of lesser density while producing 2D images. The resulting metal artefacts appear in the form of brighter or darker lines on 2D images which lower the image quality [8]. Larger deviations in measurement results are expected when measuring parts with much higher absorption, e.g. metal parts, as well as when measuring those features that are closer to those (metal) components [17]. An example of metal artefacts in industrial computed tomography is given in [18], where metal artefacts manifested as brilliant stars that bound metal rods.

There are several different approaches in metal artefact corrections, but the most used ones are software correction methods, the so-called post-processing methods. A detailed overview of the available correction methods is given in [19, 20].

Some other image artefacts may occur as result of measurement system imperfections, such as motion artefacts and partial volume artefacts. However, the occurrence of these artefacts is more common in the medical application of computed tomography.

2.5 Motion Artefact

Motion artefacts, as their name says, are a result of motion during the CT scanning. Motion artefacts are more common in medicine computed tomography than in industrial computed tomography, where it is difficult to ensure complete absence of patient movement. Besides the controlled movements of a body part, motion artefacts are caused due to breathing or heartbeat. Unlike in medicine, in the industrial CT, motion artefacts are the result of poorly fixed objects during the scanning process, where the object may move relative to the rotational axis or table while rotating. The problem of object movement due to less stable fixation is described by the authors in [21].

2.6 Partial Volume Artefacts

Partial volume artefacts occur when the measurement object is not fully projected on the detector. The reasons for this can be incorrectly chosen geometrical magnification or scanning the object with a size that exceeds the detector size of the available CT scanner. Since reconstruction algorithms assume that the measurement object is fully visible on the detector at all viewing angles, should that not be the case, the reconstructed images can contain truncated-view artefacts, i.e. partial volume artefacts [8]. In order to avoid partial volume artefacts, when placing the object on the table and adjusting the scanning parameters, the operator has to ensure that the whole object is visible on the detector in every rotation angle. The appearance of partial volume artefacts is not frequent in the use of industrial computed tomography [6]. Partial volume artefacts should not be confused with the region of interest (ROI) that results from the targeted scanning of a particular part of the object and/or the processing of that particular part of the object.

3 CONCLUSION

This paper presents image artefacts in industrial computed tomography. Image artefacts occur as result of measurement system imperfections and present errors that influence dimensional measurement results. In this paper, six different image artefacts are further explained: beam hardening artefacts, scatter artefacts, ring artefacts, metal artefacts, motion artefacts and partial volume artefacts. The artefacts cause the blurred edges of an object, hindering the proper determination of the borders between the object and background or the borders between different types of materials. Furthermore, image artefacts manifest as an appearance of noise in 2D images, which complicates the 3D reconstruction of a voxel model. Moreover, in the reconstruction process, the appearance of non-existing features in a model can occur. This is particularly the case with ring artefacts which can be wrongly detected as the parts of a scanned object, e.g. as inclusions. In order to minimize the influence of image artefacts on measurement results, extra care must be taken when adjusting the scanning and 3D reconstruction parameters. At the moment, the operator is the one that needs to recognize image artefacts and differentiate between the image artefacts that are a result of the measurement process or system shortcomings and the real state of the measured object. In order to minimize the influence of image artefacts, further research in this field is recommended. Research should focus on identifying and avoiding the presence of image artefacts. One of the possibilities which needs to be further investigated is the application of artificial intelligence in the measurement process, with the goal of recognizing all artificial features that appear on an image without corresponding to the physical feature of an object.

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