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A Review of Common Beam Hardening Correction Methods for Industrial X-ray Computed Tomography

(Ulasan Mengenai Kaedah Pembetulan Pengerasan Alang bagi Tomografi X-ray Berkomputer Industri)

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ABSTRACT

X-ray computed tomography (XCT) became an important instrument for quality assurance in industry products as a non-destructive testing tool for inspection, evaluation, analysis and dimensional metrology. Thus, a high-quality image is required. Due to the polychromatic nature of X-ray energy in XCT, this leads to errors in attenuation coefficient which is generally known as beam hardening artifact. This leads to a distortion or blurring-like cupping and streak in the reconstruction images, where a significant decrease in imaging quality is observed. In this paper, recent research publications regarding common practical correction methods that were adopted to improve an imaging quality have been discussed. It was observed from the discussion and evaluation, that a problem behind beam hardening reduction for the multi-materials object, especially in the absence of prior information about X-ray spectrum and material characterizations would be a significant research contribution, if the correction could be achieved without the need to perform forward projections and multiple reconstructions.

Keywords: Beam hardening; cupping artifact; images artifact

ABSTRAK

Tomografi x-ray berkomputer (XCT) menjadi instrumen yang penting dalam penjaminan kualiti produk industri sebagai alat ujian tak musnah bagi menjalankan pemeriksaan, penilaian, analisis dan metrologi berdimensi. Oleh itu, imej yang berkualiti tinggi diperlukan. Disebabkan oleh sifat tenaga x-ray XCT yang polikromatik, hal ini boleh menyebabkan dalam pengecilan pekali yang dikenali sebagai artifak pengerasan alang. Hal ini seterusnya menyebabkan lengkungan seperti erot atau kabur dan jejalur pada pembinaan semula imej yang menyebabkan penurunan kualiti yang signifikan pada imej yang dilihat. Kertas ini membincangkan mengenai penerbitan yang mengkaji kaedah pembetulan praktikal yang digunakan untuk meningkatkan kualiti pengimejan. Daripada perbincangan dan penilaian yang dilakukan, masalah di sebalik pengurangan pengerasan alang bagi objek multi-bahan terutamanya pada ketiadaan maklumat awal tentang spektrum X-ray dan sifat bahan boleh menjadi sumbangan kajian yang sangat penting, iaitu sekiranya pembetulan tersebut boleh dicapai tanpa perlu melakukan unjuran awal dan pembinaan semula berganda.

Kata kunci: Artifak imej; artifak lengkung; pengerasan alang

Introduction

X-ray computed tomography (XCT) imaging was developed by Hounsfield (1972). It is a technique of digital imaging based on X-rays where X-rays are emitted by a source, they fall incident on an object, some are absorbed some are scattered. X-rays that are not absorbed fall incident on an X-ray detector, which outputs a digital image of X-ray intensity. These images are made for multiple angular positions of an object. The images are converted to attenuation images and then passed to a reconstruction algorithm, which outputs a CT volume where each voxel represents the linear attenuation coefficient of the scanned object (Chu 1983; De Chiffre et al. 2014). Since the invention, XCT has been widely applied in medical diagnostic images and at present, has become an instrumentation tool for quality assurance in industrial applications especially in non-destructive testing for product inspection, evaluation and analysis. However, to optimize the quality of an image, the image artifact resulting from the physical processes of image reconstruction that are involved in the acquisition of CT data, which lead to systematic inequality in the CT number that reflects an error in attenuation coefficients of the object. The images artifact can be classified into, hardened artifacts, scattering artifacts, geometric artifacts, metal artifacts and ring artifacts (Cantatore & Müller 2011).

Beam hardening is one of the significant artifacts in CT images that come from a polychromatic nature of X-ray energy, which leads to an error in attenuation coefficient where the basic assumption to represent the attenuation in CT is a monochromatic beam, where attenuation does not change with energy spectrum. However, polychromatic beams lead to a deviation in the relationship between the attenuation and material thickness from linearity, which due to low-energy photons within the beam can be absorbed, thus, allowing the beam to become progressively harder (Van de Casteele et al. 2002). As a result of this, the quality of the reconstruction image is significantly reduced. To improve imaging quality, a variety of methods, such as the use of imaging filters or calibrations pre- or post-acquisition data processing can be used. The practical methods used for that are physical filtration, dual-energy and linearization (Hanna & Ketcham 2017).

The physical beam filtration is used in almost all industrial CT scans in metallic parts, where the filter of specified material is placed on an X-ray source face where the low energy X-ray can be absorbed (Rajendran et al. 2014). The main disadvantages of this method are the beam intensity is reduced, which leads to decreasing in signal to noise ratio, and a beam hardening problem does not completely eliminated (Jennings 1988).

Linearization method is a software-based method, which takes the correction into consideration before (pre-processing) or after (post-processing) images reconstruction, where polychromatic projections data, which is a curved function, can be transformed into a linear function, i.e. monochromatic projection data, then apply polynomial regression to get a corrected projection data. The pre-processing method was launched by Brooks and Di Chiro (1976). In 1979, Herman developed a model with details of mathematical nature of a beam hardening problem in medical XCT. Here the beam hardening has been corrected by performing a polynomial fitting to transform the polychromatic data into equivalent monochromatic data, under an assumption that the body of human bane consists of water alone (one object). Many types of research and models based on this method have been carried out. For example, Van de Casteele et al. (2002) developed an algorithmic model (bimodal) that gives a physical description of nonlinearity between the attenuation and thickness in the experimental curve under the assumption that, the characteristic X-ray radiation is dominant. This model can only be adopted in XCT of lower energy, but in high-energy CT, the greater part of x-ray beam bremsstrahlung and X-ray characteristic can be ignored. Wei-Min (2009) applied a polynomial fitting method in combination with physical filtration, where the filter was used to absorb energy lower than 30 KeV, after which the spectrum attuned within the energy range of 0.3-3 MeV. According to the mass attenuation data table, in this range, the value of coefficients is approximately the same. Therefore, the monochromatic projections data were directly approximated and then beam hardening was corrected. Rasoulpour et al. (2015) proposed a correction approach based on the attenuation coefficient of the local spectrum distribution where the corrected attenuation coefficient of mean energy can be calculated according to the expectation-maximization algorithm of the arbitrary thickness of known materials in the object. In this approach, a primary source spectrum is required to calculate the local spectrum in various depth. Kimoto et al. (2017) proposed a method that directly divided the polychromatic spectrum into two regions of energy, after which monochromatic data was estimated by calculating an effective attenuation coefficient for each region and then beam hardening was separately corrected for each region. All these preprocessing models were successfully described and corrected a single material object.

The post-processing method was developed by Nalcioglu and Lou (1979) based on the polynomial fitting concept, which is being used for objects containing multi-materials. The correction can be carried out in two steps, that is a reconstruction of an image based on polychromatic projection to estimate the length of the materials one by one for all and then reconstructing again where the estimation of monochromatic projection data calculated depend on the earlier reconstructions. The problem on this and polynomial fitting methods is that full knowledge of X-ray spectrum and material object characterization like density, elemental content and geometry are required. Gao et al. (2006) also developed a model based on this method, to treat an object consisting of two materials, high Z-material outside and low-Z inside. The correction was in three stages: Correcting polychromatic projections for the outer material, reconstruction of the cross-sectional images from modified projections and for the inner material correction, a new X-ray spectrum was assumed to be delivered for an inner material with a free beam hardening effect because the X-ray beam passed through High-Z material. The drawback of this method is that it needs a specific type of object. Yang et al. (2012) developed a model to solve multi-material objects' correction, which was based on modeling polychromatic X-ray projections based on a cross-section of each material inside the object, then the attenuation factor was calculated based on a density of the material and total cross section. According to this, both monochromatic and polychromatic projections were calculated. The ratio between them was used as a correction factor for the original intensities. Yang's method was tested on a variety of materials with limited validity, as the correction was not found to be optimal. Brabant et al. (2012) proposed a method for a multi-material object which does not require any prior information about the object characterization and beam spectrum. It is based on iterative reconstruction algorithm which it is mainly based on an algebraic and statistical reconstruction algorithm that takes the effect of beam hardening during reconstruction. It is not widely used in practice especially in industrial applications because of its high computational complexity. Krumm et al. (2008) also proposed a method for the case of multi-material objects. The method does not require any previous information about the X-ray spectrum and the material object's characterization. It was based on a re-projection approach where an image is segmented for all materials inside the object and propagated the path lengths for each material and then using these path lengths with measured intensity to compute monochromatic and polychromatic projection data for each. The amount of correction was calculated by subtracting both projections' data. Lifton (2017) proposed a method for multi-material which does not require segmentation, where the polychromatic X-ray attenuation for each material can be measured using cylindrical step-wedges consisting of the substance of known mass attenuation coefficients and steps thickness, the main idea is using the same material as test pieces of step-wedges. From the gotten projections, the effective attenuation coefficient values can be obtained by plotting and fitting the mean attenuation coefficient each step-wedges verse thickness. These values can be used to calculate relative monochromatic attenuation values for each material. Then by applying polynomial fitting, the hardening correction is achieved. The main disadvantage is a reference step-wedges of different materials are required for one object.

Observing from the methods mentioned previously, therefore, the degree to correct is dependent on the objects characterization i.e. one material, multi-materials and the XCT system type i.e. lower energy and high energy. Thus, the beam hardening in industrial XCT has been satisfactorily corrected for one material in multi-materials object, especially in the absence of prior knowledge regarding objects characterization and X-ray spectrum has been excellently corrected having Krumm's method (reconstructed data method) that requires segmentation, forward projection and multiple reconstructions which is time consuming and can be easily fail. Thus, there is a contribution to be made by overcoming these shortcomings.

In this work, a revision, summary and analysis of common practical beam hardening artifact correction methods in recent publications will be presented. This paper has the following outline: In the next section, we described the production of x-ray, energy spectrum nature and type of x-ray source used in industrial CT. Subsequently, the x-ray attenuation will be outlined. Next, we discussed the experimental polychromatic and monochromatic projections algorithm and beam hardening effect evaluation. After that, the beam hardening correction method including filtration, linearization and the Monte Carlo simulation method will be reviewed and finally the conclusion.

X-RAY SOURCE

X-rays are produced based on an electron gun, where a target material (high-Z) can be bombarded by accelerated electrons produced from a source (heated filament.) A continuum of X-ray energies can be generated due to various interactions of the incoming free electrons with a target material. The emitted X-rays are of two kinds: The dominant kind is Bremsstrahlung radiation, where an incident electron decelerates, due to its interactions with target nuclei. The resulting continuous X-ray energy, which has a broad spectrum of energies up to the maximum of the incident electrons, depends on the amount of electron kinetic energy which is transferred from this interaction called polychromatic X-ray energy. The X-ray amount depends on the amount of electron kinetic energy transferred from this interaction. The second is characteristic X-ray which can be generated because of its disruption of orbital electrons due to some excitation process from their normal configuration, where the atom will be in an excited state and naturally the electrons rearrange themselves to return the atom to it lower energy level or ground state, the energy liberated from this transition from excited to ground state takes the form of characteristic x-ray whose energy is given by energy difference between the initial and final state (Knoll 2010).

There are two kinds of polychromatic or bremsstrahlung X-ray sources are often used in industrial CT, which are X-ray tube and linear accelerator (LINAC). X-rays emitted from these sources have high penetration capability, primarily because some of the objects for examination are made of dense materials. Their energy spectrum defines the penetrative ability of the X-rays, as well as their expected relative attenuation as they pass through materials of different densities (Carlsson & Carlsson 1996). The X-ray spectrum output can be controlled through the selection of voltage and current, where the voltage sets the electric potential applied across the chamber which response from an amount of electrons energy and can be accelerated and controlled from minimum to maximum. The current is to measure an amount of radiation per unit time (intensity), the higher intensity is referred to as the better single-to-noise ratio (SNR) in the detection system (Hussein 2011). These kinds of sources have a higher photon flux, which allows shorter scanning times. However, the significant disadvantage is that a lower X-ray energy associated with polychromatic flux, which can be attenuated more readily than higher energy X-rays, producing an artifact of the so-called beam hardening (Hanna & Ketcham 2017).

X-RAY ATTENUATION

The general attenuation of X-rays in a material is governed by Lambert-Beer's Law, where the X-ray attenuation of sample material that is supposed to be homogeneous, is due to the sum of the photoelectric, Compton and pair production effects and can be expressed (Carlsson and Carlsson 1996) as:

$$I = I_0 \exp - \mu L \tag{1}$$

where I is the recorded X-ray intensity; I_0 is the initial X-ray intensity; μ is the linear attenuation coefficient of the material; and L is the path length of the X-ray through the medium. The linear attenuation coefficient is a function of X-ray energy and an atomic number of the absorbing material. When the object contained multi-materials, the linear attenuation of each material and its relative path length L must be accounted for, with considering X-ray attenuation of a polychromatic beam through a heterogeneous object requires solving (2) over the full X-ray spectrum (Hampel 2015),

$$I = \int I_0 \exp - \int - \mu(E)dLdE \quad (2)$$

To solve (2), the full shape of the incident X-ray spectrum is needed, but it is rarely directly measured and depends on several factors, including the target material and accelerating voltage, current and any beam filters used. However, an accurate model of a polychromatic X-ray beam will be difficult to produce and therefore assumes a monochromatic energy beam which most reconstruction algorithms engage integrated (2) without considering the full shape of incident X-ray spectrum. This mathematical simplification can generate beam hardening artifacts within reconstruction data (Cleland & Stichelbaut 2013; Hanna & Ketcham 2017).

BEAM HARDENING ARTIFACT

In XCT, the polychromatic X-ray beam with photon energy E can be attenuated with an object is placed at a fixed position between the X-ray source and the detector. Practically, let N_0 be the photons count by the detector when no object is inserted; and N be the photons count when an object with thickness L is inserted. The linear attenuations coefficient at any point inside the volume of an object, depends on the position of the point (x, y) and the X-ray Energy E. In monochromatic X-ray source, the energy E is a fixed, be E_0. Therefore, the attenuation or monochromatic projection M_L can be written as:

$$M_L = -\ln \frac{N}{N_0} = \int \mu(x, y, E_0) dL \quad (3)$$

In practice, the X-ray beam is polychromatic for a source-detector pair position. However, counting of polychromatic X-rays with an initial count N_0 can be experimentally written as:

$$N_0 = \int S(E)\lambda(E)dE \quad (4)$$

where S(E) is the energy spectrum of X-rays of the incident beam; λ(E) the detector efficiency. When the incident beam passes the object, the counting will be N is given by:

$$N = \int S(E)\lambda(E) \exp - \int \mu(x, y, E)dLdE \quad (5)$$

Experimentally, the polychromatic projections data can be calculated (Casteele et al. 2004) as:

$$P_L = -\ln \frac{N}{N_0} = -\ln \frac{\int S(E)\lambda(E)\exp - \int \mu(x, y, E)\, dL\, dE}{\int S(E)\lambda(E)\, dE} \quad (6)$$

Experimentally, it is clear that P_L can be obtained, for any source-detector pair. P_L is made an error in values of linear attenuation coefficient or gray value of cross-sectional images which directly leads to false in linearity between attenuation and penetration length, that is because the reconstruction procedure requires M_L (Gao et al. 2006). Figure 1 shows the schematics of the X ray attenuation depending on thickness in both cases P_L and M_L.

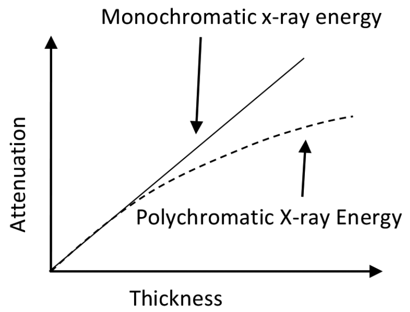

FIGURE 1. The schematics of the X ray attenuation depending on thickness

The feature of a tomographic image appearing to have a shining edge and darker centers. That is because, the internal area of an object are traversed by X rays with energy higher than the edge area, which makes the edges more attenuating than internal areas. However, the CT value of the central image is lower than the edge area, with the shape of the Cup appears in the middle dark edge, also called the cup artifacts, Figure 2 schematic explains the shape of cupping artifacts, that originally coming as an error in the attenuation coefficient, a percentage error can be calculated by Ketcham and Hanna (2014) and Arunmuthu et al. (2013),

$$Cupping = \left[\frac{(a + b/2) - m}{m} \right] \times 100 \quad (7)$$

where a and b are the maximum value of the gray levels of material density, as shown in Figure 2 and (m) is the minimum grey level for material density at the cupping region.

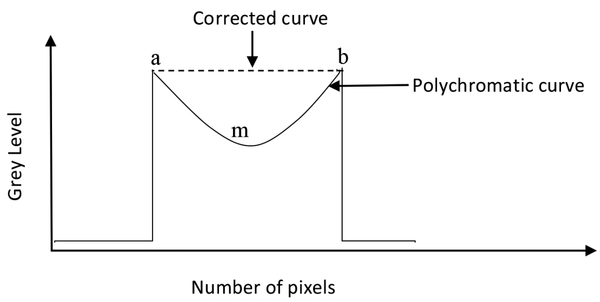

FIGURE 2. The schematics illustrating profile of grey level for image reconstruction in case of polychromatic image and image corrected form hardening artifact (Arunmuthu et al. 2013)

Therefore, reconstruction of an image needs a precise attenuation map, of the object under investigation.

Therefore, an attenuation error coming from beam hardening must be corrected because an image quality can be significantly improved and a grey value of the same material appears identical after reconstruction.

BEAM HARDENING CORRECTION METHODS

Beam hardening correction or reduction must be carried out to interprete XCT images. For a given correct attenuation of polychromatic X-ray beams with the object to estimate the total attenuation of monochromatic X-ray beams where the estimation as accurate as possible for good reconstruction of the monochromatic linear attenuation coefficients in the material object (Ramakrishna et al. 2006). Beam hardening correction has been successively studied through many kinds of correction methods. The correction methods that have been used can be divided into two categories, i.e., hardware and software. In the hardware method, the correction can be applied through the physical filtration. The software method is mainly based on the mechanism of the formation of hardened artifacts, using specific correction algorithms for an X-ray projection image to do a correction before or after reconstruction images. A software method is mainly linearization correction (pre-processing and post-processing) and Monte Carlo correction method as explained next (Gao et al. 2006; Zhou et al. 2009).

FILTRATION CORRECTION METHOD

The aim of filtrations was pre-hardening by putting a filter to reduce the low-energy portion in the energy spectrum to allow high-energy rays to pass an object. It is quite a convenient method and effective to use metal sheets, as filters to pre-hardening the X-ray beams. The filter materials commonly used in industrial XCT are aluminum (Al), copper (Cu) and iron (Fe). The reduction of the beam hardening effect depends on the filter material, thickness and signal to noise ratio of the detector system (Wang 2015; Yan et al. 2000). The change of the spectrum due to filtration is shown in Figure 3.

An essential factor for this method is to select optimum filter material and thickness. Many experiments were required for this previously (Lifton et al. 2013; Thomsen et al. 2015). Recently, Chen et al. (2017) proposed a method to optimize X-ray filters especially for middle energy X-CT, based on Monte Carlo simulation where varying filter materials and thicknesses were simulated and the mean energy ratio (MER) for the post to pre-filter spectrum were calculated (7). The optimum filters were that corresponding to the higher MER for low energy XCT and smaller for higher energy XCT.

$$MER = \frac{\left[\int EI(E)dE \Big/ \int I(E)dE\right]_{post}}{\left[\int EI(E)dE \Big/ \int I(E)dE\right]_{pre}} \tag{8}$$

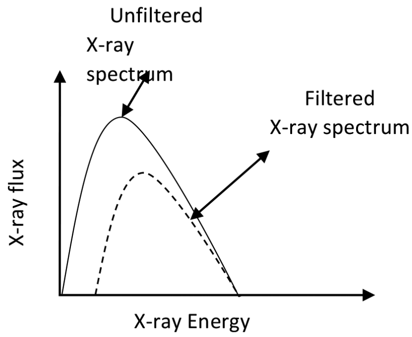

FIGURE 3. The change of spectrum due to filtration diagram

This method is simple and easy, as no additional processing of projection data is required. The main drawback, however, is that the filtration causes the x-ray spectrum to lose a large part of the photon, thus reducing the signal-to-noise ratio. Additionally, the beam hardening problem cannot be completely corrected. Hence, the method is often used together with other calibration methods.

LINEARIZATION CORRECTION METHOD

Herman (1979) developed a mathematical model detailing the nature of a beam hardening problem in medical CT by assuming that the human body consists of water only (one object). In order to correct the beam hardening artifacts by a given equivalent monochromatic data form, the attenuation data of polychromatic beam, which can only be obtained in a real experiment (8), then performs a polynomial regression to normalize it with the monochromatic beam. This method is known as pre-processing linearization or polynomial fitting method. In the case of an object consisting of multi-materials, post-processing can be implemented where firstly, direct reconstructions of the cross-section images from the experimental data can be carried out. Propagation path length at different selected energies for X-ray spectrum for each material inside the object can be obtained, and then equivalent monochromatic projections data can be achieved (4) and polynomial fitting of eight degrees or more in industrial application (Hammersberg & Mangard 1998). This fitting function achieved can be applied to the experimental data to obtain the equivalent monochromatic projection data of the object under study. This method is often used in combination with the projection data and the first reconstruction image to obtain more prior information about the object under investigation (Casteele et al. 2004). Segal et al. (1987) addressed the post-processing method for an object containing different types of materials (ceramic materials) with known compositions, the equivalent monochromatic projections data which were obtained by calculating the effective linear attenuation coefficient over the energy spectrum (9), to estimate an equivalent monochromatic photon energy then polynomial fitting has been applied for normalization.

$$\mu_{eff}(\bar{E}) = \frac{\int \mu(E) S(E) dE}{\int S(E) dE} \tag{9}$$

where μ_{eff} is effective linear attenuation coefficient; *S(E)* is energy spectrum; and $\bar{E}$ is the effective energy of the polychromatic system which can be numerically computed when prior information of x-ray spectrum and material composition are known or experimented (Hammersberg & Mangard 1998). The advantage of this correction method is that the correction is simple and the result has a higher signal-to-noise ratio. It is not limited by scanning conditions, it can apply in most types of CT systems and it has a good effect on the spatial resolution. Linearization method is more comprehensive and a widely used industrial CT, however, the main drawback is that the correction of multi-materials is complex especially if we do not have prior knowledge about x-ray spectrum and material characterization.

MONTE CARLO SIMULATION CORRECTION METHOD

Monte Carlo simulation (MC) is the most important numerical method, using random numbers to perform statistical computations to obtain statistical values such as mean values and probability as a mathematical solution to the problem. The MC simulation is always used as an evidence factor in experimental setup to obtain trusted results by comparing with experimental measurements to be sure about the degree of accuracy of the measurements. Many simulation codes are used in the field of x-ray computed tomography, for example, Geant4, EGS4 and MCNP (Arunmuthu et al. 2013; Kitazawa et al. 2005).

Beam hardening correction using MC simulation can be carried out in three stages: First, simulate the photon transmission process with exact material geometry to obtain the energy spectrum curve of the material. Secondly, the attenuation curve obtained by the simulation is a nonlinear curve collected from the actual polychromatic projections data and then used to estimate an effective energy which corresponds to photons energy having a higher probability. The final step is a reconstruction of the image by using this effective energy to generate monochromatic projection data (Thomsen et al. 2015). This method if chosen to be applied requires knowledge about the detector efficiency and the energy spectrum MC simulation which has been extensively used for investigation of beam hardening artifact in many studies such as Arunmuthu et al. (2013), Lifton et al. (2013), Ramakrishna et al. (2006), Sahebnasagh et al. (2012), Tan et al. (2014), Thomsen et al. (2015) and Yan et al. (2000). It has high precision and is very flexible regarding changes in the beam geometry, sample composition, objects geometry and densities. The drawback nonetheless is that MC simulation is time-consuming in its applicability in practice. However, with the improvement of the computing performance, beam hardening correction will be more and more accurate (Wang 2015).

CONCLUSION AND FURTHER STUDIES

Due to the polychromatic nature of X-ray energy in XCT that lead to an error in attenuation coefficients, resulting in a nonlinear relationship between the attenuation and material thickness with so-called beam hardening artifact, which leads to distortion or blur-like cupping and streak in the reconstruction of the images, where an image appears with a shining edge and darker centers. This causes a cupping and streak in the grey level which significantly decreases its quality. To improve it, however, numerous practical methods for correction such as physical filtration and linearization methods are used. In physical filtration, the lower energy can be absorbed by the filter and the hardening directly corrected with no additional proceedings required. This decreases the signal to noise ratio, however and the beam hardening effect cannot be completely corrected. The linearization with pre-processing and post-processing methods was widely used in the field of industrial tomography, it has a high signal-to-noise ratio, but the correction of the multi-materials is complex. The Monte Carlo simulation is an empirical method which has always used as an evidence factor to verify the experimental measurements. It has high precision and is flexible regarding changes in the incident beam, object geometry, and characterization.

In our review, most of the practical correction methods that have been studied are based on the linearization method. Most of them were used for one material object with satisfactory correction results. However, with an object containing multi-materials, considering the absence of prior knowledge about X-ray spectrum and material characterization, the challenge remains the need for further research to find a new approach without the need to perform forward projections and multiple reconstructions i.e. Krumm's method to correct beam hardening.

Our future research is to make a model that can correct an error of the attenuations due to beam hardening for a multi-material object through, or a combination of some models that may give an improved result.

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