Precision Engineering xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Multi-material gap measurements using dual-energy computed tomography☆

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ARTICLE INFO

Keywords:
Metrology
Computed tomography
Dual-energy
Multi-material measurements

ABSTRACT

X-ray computed tomography is a highly versatile investigation method with applications in a wide range of areas. One of the areas where the technique has seen an increased usage, and an increased interest from industry, is in dimensional metrology. X-ray computed tomography enables the measurement of features and dimensions that are difficult to inspect using other methods. However, there are issues with the method when it comes to measurements of objects that consist of several materials. In particular, it is difficult to obtain accurate computed tomography results for all materials when the attenuation of materials differs significantly. The aim of this work was to measure small air gaps between different materials using dual-energy X-ray computed tomography. The dual-energy method employed in this work uses two energy spectra and fuses the data in the projections space using non-linear fusion. The results from this study show that the dual-energy method used in this work was able to capture more measurements than regular absorption computed tomography in the case of specimens with highly different attenuation, enabling, in particular, the measurement of smaller gaps. The contrast-to-noise ratio was also increased significantly with the use of dual-energy.

1. Introduction

X-ray computed tomography (CT) has seen an increased usage within the industry in recent years as the awareness of the method's potential has grown [1,2]. The ability of CT systems to investigate internal features in complex details goes hand in hand with the development of new fabrication methods, such as additive manufacturing (AM), giving the interest in CT an additional boost [3,4]. The main interest for many industries lies in dimensional measurements, and thus the accuracy and reliability of the method. However, international standards for CT metrology are not yet available, and the establishment of CT measurement traceability is not a trivial task [5]. CT data are susceptible to various errors and artefacts, further contributing to the uncertainty of measurement results [6–8]. One of the largest influences on measurement results is how the surfaces in a CT volume are determined [9]. There are several surface determination techniques that may be employed, and the results they give can vary significantly [10,11]. Issues may be further enhanced when attempts to measure several materials in the same CT volume are made. This is due to the fact that if materials differ in attenuation, it can be difficult to find scanning settings that can capture all of the materials with sufficient image quality. The same issues can also occur if there are large aspect ratio differences in the part being examined. A possible way to reduce the negative effects when measuring multi-material parts can be the usage of several energy spectra instead of a single spectrum [12]. Such techniques are known as multi- or dual-energy computed tomography (DECT).

The use of DECT is common practice within medical CT where it is used to increase the contrast of images and create monochromatic images from polychromatic spectra [13–15]. In industrial CT, however, the use is still scarce. There are three main types of DECT employed today: rapid voltage switching, sequential acquisition, and dual source. All the methods have their drawbacks and advantages. Rapid voltage switching requires a source that can change energy settings in between each projection, such sources can be expensive and the stability of the source might be poor [12]. Sequential acquisition relies on acquiring a complete scan of a sample, then changing the energy spectrum and acquire a new scan without moving the sample [12]. This method relies on a mechanically stable system that keeps the sample in place but can be employed in any CT system without any additional hardware. Dual

☆ This paper was recommended by Associate Editor Andreas Archenti.

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https://doi.org/10.1016/j.precisioneng.2018.07.012
Received 27 March 2018; Received in revised form 3 July 2018; Accepted 31 July 2018

source relies on having two complete CT systems imaging the sample at the same time, with different spectra at a 90° angle between each other, this can cause scattering issues and the systems are highly expensive [12].

In the field of industrial CT, there have been a few studies of various DECT techniques [16]. Groups have tried methods that fuse the data post-reconstruction [17]. The use of this method indicated that some improvements can be made to the data but the fact that the data is reconstructed before being fused means that both volumes will contain reconstruction artefacts due to over/under exposure. Other groups have tried to perform linear fusions in the projection space [18], selecting a flat amount of intensity from one set of projection and adding it to a flat amount from the other set of projection. This way of fusion seems to be beneficial for certain material combinations and geometries but lacks sensitivity to capture the most appropriate information from each dataset. Attempts have also been made to account for the sensitivity of the different datasets. In the method presented in Ref. [19], the authors use a threshold to select intensities from either a high, or low, energy projection. The issue with this method is that there are no gradual transitions between the datasets but rather a dataset inside of the other. This causes issues since the intensities, and thus densities in the reconstruction, will not correspond to the same material, even though they originate from the same material.

In this work, the measurement accuracy, and detectability, in multi-material parts has been investigated. The measurement reliability was investigated with respect to surface determination techniques and the effects of using DECT. The samples used for measurement references contain air gaps between two different materials and were developed in a previous work [20]. The DECT method used in this work is a non-linear fusion technique that has previously been presented in Ref. [21].

2. Materials and methods

This section starts with a description of the measurement samples that were used in the study; design, fabrication, and used materials. The section continues with a description of the DECT method that was employed and finally there is a presentation of the techniques used to determine the surfaces in the CT volumes and the procedure for the measurements.

2.1. Reference standard

The reference standards used in this work were developed within a collaboration between the University of Padova (Italy) and the Physikalisch-Technische Bundesanstalt (PTB, Germany), and were previously presented in Ref. [20]. In this work, two samples consisting of two different materials were selected. The two parts of the standard are machined to create a stepped surface, and a tempered plane, on one side of the part. The machining of the parts in this work was performed using electrical discharge machining. The machined parts are joined together, with the machined side facing each other, creating stepped air gaps and an air wedge between the parts. An illustration of the reference standard design can be seen in Fig. 1.

The reference standard contains seven steps with the designed gap sizes of 10, 25, 50, 100, 250, 500, and 1000 µm. The air wedge, formed between the tempered planes, ranges from 500 µm to theoretically 0 µm. All the dimensions were verified with a tactile coordinate measuring system (CMS), micro-CMS Zeiss F25 (Carl Zeiss, Germany), before the parts were joined. The micro-CMS measurements represent the reference values that are used throughout this work. Two types of material combinations were studied, Al/Cesic® and Al/Ti, the details of the materials can be found in Table 1.

2.2. Dual-energy method

The DECT method used in this work is a variation of the method presented and used in Refs. [21,22]. The method is based on the sequential acquisition of two complete projection sets for each object to be scanned. The two scans should be optimised for either the highest or lowest attenuating material in the scan, with some considerations to extreme aspect ratios. The projections are fused together using a template that is built using a normalised high energy projection for each projection pair using:

$$I_N(x, y) = \frac{I_H(x, y)}{\max(I_H)}, \tag{1}$$

where I_N is the normalised high energy projection, and I_H the original high energy projection. The variables x and y refer to the pixels in the projections, where x = column and y = row. The template is then built using the normalised projection and a sigmoid function that transitions from selecting data from the high energy projection to selecting data from the low energy projection. In this work, the Al/Ti sample was fused using:

$$I_T(x, y) = 0.5 - 0.4\mathbf{erf}(7.5(I_N(x, y) - 0.5)), \tag{2}$$

where I_T is the template. The Al/Cesic® sample was fused using:

$$I_T(x, y) = 0.5 - 0.4\mathbf{erf}(7.5(I_N(x, y) - 0.25)). \tag{3}$$

The final fused projection was built using:

$$I_F(x, y) = I_T(x, y)I_H(x, y) + (1 - I_T(x, y))I_L(x, y), \tag{4}$$

where I_F is the final fused projection, and I_L the low energy projection.

The idea behind the fusion method is to select information from the high energy projections for highly attenuating/thick material and from the low energy projections for low attenuation/thin materials. The fusion uses the error function because it allows for a smooth transition from one state to the other, with parameters that clearly define the shape of the function. In this work, the controlling parameters were selected so that most of the high attenuating material information was selected from the high energy scans by evaluation of the fusion template. An example of this template can be seen in section 3.3. More information about how the controlling parameters influence the fusion process of multi-material samples and how they should be selected can be found in Ref. [23].

In this work, the Al/Ti sample was scanned six times. For each scan, the energy was alternated between the high and low energy setting. The Al/Cesic® sample was scanned four times using the same procedure. The settings used for the acquisition can be seen in Table 2. Each sample only needs two scans for a full fusion and the extra scans were used for obtaining additional measuring volumes to consider also the repeatability of measurements. All datasets were acquired using a Nikon MCT225 system (Nikon Metrology, UK), with a voxel size of 22 µm.

In order to compare the DECT approach with the traditional single energy scanning, datasets acquired with one energy level were reconstructed as well. In particular, the scans of both samples acquired using the high energy setting (as shown in Table 2) were selected for the comparison as they provide sufficient penetration for the high-attenuating material.

2.3. Measurement procedure

The method used for the evaluation of measurement results is similar to the one presented in Ref. [20]; therefore, only a short description will be given in this section.

A multi-step procedure was developed to analyse the data sets: in a first step, the surface is determined on the lower part and the data set is aligned. Then, the volume is duplicated and the surface is determined on the top part with subsequent realignment of the copied volume. In the next step, measurement features are constructed, the copied volume is realigned again, and the measurement results are extracted. The gaps are measured as a distance between two opposite points constructed according to a dedicated, so-called patch-based, procedure.