Investigation of the CT-induced random surface deviations using a multi-wave standard

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Abstract
This paper presents an experimental investigation on the CT-induced random surface deviations using a multi-wave standard. To quantify the amount of random surface deviation in the performed measurements, the root-mean-square deviation of the extracted features was used. Discussions on the obtained results and on the evaluation procedure are included.

Keywords: Industrial computed tomography, geometrical evaluations, random surface deviations.

1 Introduction and background
One significant issue in using of x-ray CT systems to perform geometrical evaluations is the introduction of random surface deviations to real features during the extraction operation [1]. Provided that random surface deviations are not feasible of correction as other CT-induced errors (e.g. magnification and offset deviations), minimizing its occurrence is fundamental in obtaining reliable and satisfactorily accurate measurement results.

Many of the causes of random surface deviations are related with CT setup parameters, and therefore can be minimized by selecting adequate sets of setup parameters. Causes of random surface deviations (and related intermediary effects) which can be minimized through an adequate selection of setup parameters include (but are not restricted to):

- Quantum noise, scattering and detector noise generated during the image acquisition, producing random disturbances in the projections and in the voxel matrix [2];
- Relatively large voxel size, leading to aliasing in the projections and producing Moiré patterns in the voxel matrix [3];
- Relatively small number of projections, producing aliasing artifacts (streaks) in the voxel matrix [3];
- Relatively large sampling intervals when performing global or local threshold operations, leading to additional aliasing [1].

However, selecting the setup parameters that will lead to a minimum amount of random surface deviation is not a trivial task. This task requires a reasonable understanding on general and task-specific cause-effect relations leading to random surface deviations.

This paper presents an experimental investigation on the CT-induced random surface deviation (and some related issues) using a multi-wave standard (MWS) [4]. To better understand causes leading to random surface deviations, the MWS was measured with different sets of CT setup parameters. The amount of the random surface deviation generated during the extraction operation was quantified by a
root-mean-square parameterization of the extracted integral features [5]. Discussions on the obtained results and on the evaluation procedure are included.

2 Materials and methods

2.1 Experimental setup

The experiment consisted in extracting circumferential lines from two external cylindrical elements of a calibrated, highly geometrically accurate aluminum-made MWS (Figure 1). The first element consists of a standard cylindrical feature, with a nominal diameter of 76 mm, a peak-to-valley roundness deviation (RONt) value smaller than 0.1 µm and a maximum height of profile (Rz) value smaller than 0.05 µm. The second element consists of a structured sinusoidal (multi-wave) feature, with a nominal diameter of 80 mm and containing dominant harmonics with UPR numbers (and respective amplitudes, in µm) of: 5 (1.70), 15 (1.75), 50 (1.75), 150 (1.80), and 500 (2.05). These characteristics of the MWS permit to evaluate the random surface deviations in absence of geometrical deviations typical from real production workpieces.

![Standard element](Image1)  
RONt < 0.1 µm  
Rz < 0.05 µm  

![Multi-wave element](Image2)  
5 UPR (1.70 µm)  
15 UPR (1.75 µm)  
50 UPR (1.75 µm)  
150 UPR (1.80 µm)  
500 UPR (2.05 µm)

Figure 1: Multi-wave standard used in the experiments.

To evaluate the influence of setup parameters on the random surface deviations, the circumferential lines were extracted using six different sets of CT setup parameters (Table 1). Setup #1 is a more conservative approach, without compromise with the scanning time. Setup #2 is basically the same but with a binning of 2x2 on the projections. This results in a larger voxel size, but the number of projections and therefore scanning time can be reduced. For Setup #3 the detector gain is increased requiring a lower integration time. For Setup #4 the thickness of the pre-filter is reduced, increasing the energetic intensity and allowing integration time to be reduced. On the other hand, it may increase beam-hardening effects. Setup #5 has a thicker pre-filter and increased gain, compensating the reduction on intensity. For Setup #6 the tube voltage and the thickness of the pre-filter were reduced.

<table>
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<tr>
<th>Setup</th>
<th>Voltage [kV]</th>
<th>Current [µA]</th>
<th>Int. time [ms]</th>
<th>Gain</th>
<th>Pre-filter [pF]</th>
<th>Proj.</th>
<th>Binning</th>
<th>Voxel size [µm]</th>
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<td>420</td>
<td>2000</td>
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<td>1440</td>
<td>1 x 1</td>
<td>93.3</td>
</tr>
</tbody>
</table>

Table 1: CT setup parameters for used for the MWS measurements.
The CT measuring system used on this experiment has a MPE\(_E = 9 + L/50\) μm, a maximum photon energy of 225 keV and a detector resolution of 1024 x 1024 pixels. For illustration purposes, the multi-wave element was also measured with a scanning coordinate measuring machine (CMM), using a 1.5 mm tip diameter stylus and a contact force of 0.2 N. All the extracted circumferential lines were exported as ASCII files by the measurement software and processed with a dedicated application [6].

2.2 Evaluation procedure

To quantify the amount of random surface deviation contained in the extracted circumferential lines, the root-mean-square roundness deviation (RONq) parameter [7] was chosen. The main reason in choosing this parameter is because it is based on extracted integral features, therefore encompassing the whole extraction operation and all the intermediary effects that occur within it. Moreover, this parameter is preferable over zone parameters (e.g. the RONt parameter) because it takes into account the whole feature in the evaluation rather than extreme points only, becoming less sensitive (although not immune) to small local deviations (such as outliers). To evaluate repeatability, five measurement cycles were performed in random order with each set of setup parameters.

The comparison of the RONq values obtained for each setup was performed using Averages & Ranges (X-bar/R) Control Charts [8]. The control charts are statistical tests which allow evaluating the significance of the differences (both in position and dispersion) observed among multiple subgroups (in this case, among values obtained with different CT setups). If one or more points fall out of the control limits, the null hypothesis can be refuted, and a difference in results obtained with the different CT setups can be said to exist. In addition, a graphical analysis of the extracted circumferential lines represented in both the space and the frequency domains was performed. The graphical analysis provides rich information on effects related with the random surface deviations such as aliasing artifacts and higher frequency content attenuation, as already demonstrated in [1].

3 Results

3.1 From the standard element

The X-bar/R control charts presented in Figure 2 shows the comparison of the RONq values obtained from the standard element with different CT setups. The Range Chart shows all the subgroup ranges below the upper control limit, thus no significant difference among variances could be demonstrated. This allows the use of the mean range to calculate the control limits of the Average Chart.

By observing the Averages Chart, it can be noted that most average RONq values lies outside the control limits, evidencing a significant difference in the amount of random surface deviation generated with different CT setups. It can be easily noted that Setup #2, which have a bigger voxel size, produces the higher amounts of random surface deviation. Following are Setups #3 and #5, both of which used a higher gain, amplifying the noise generated during acquisition. Finally, the lower amounts of random surface deviations were obtained with Setups #1, #4 and #6. Considering the distance between the control limits, no difference can be said to exist among RONq values obtained with these three setups.
Figure 2: X-bar/R control charts for the RONq values of the profiles obtained from the standard element.

Figure 3: Polar plot and dynamic content plot of the profiles extracted from standard element.
The graphical analysis of the circumferential lines extracted from the standard element with Setups #1 and #2 is shown in Figure 3. Provided that geometry and surface finish of the standard element are very accurate, the observed random surface deviations can be mainly regarded to the extraction operation performed with the CT measuring system. It is also possible to qualitatively observe differences between results obtained with the over mentioned CT setups, with Setup #1 presenting considerably lower random surface deviation. Moreover, the dynamic plot of the circumferential line extracted with Setup #2 shows an abrupt cut at the Nyquist frequency, evidencing the occurrence of aliasing. Consequently, local surface deviations start to occur, as can be seen in the polar plot of the same setup. This effect is directly related to the increase of the voxel size, which also limited the number of points available to define the extracted circumferential line.

### 3.2 From the multi-wave element

The X-bar/R control charts of the RONq values obtained from the multi-wave element is presented in Figure 4. The Range Chart shows all the subgroup ranges below the upper control limit, thus no significant difference among variances could be demonstrated. The Average Chart again shows detectable differences among results obtained with different setups. It is also possible to note that the RONq values obtained from the multi-wave element are directly correlated to the ones obtained from the standard element. The higher average values obtained from the multi-wave element occurs due to the inclusion of the dominant harmonics in the calculation of the RONq values. One can also observe higher values on the Range Chart (meaning worst repeatability) obtained from measuring the multi-wave element. This produces wider control limits on the Average Chart, and leads a loss in sensitivity to identify differences among setups.

![Multi-wave feature](image)

Figure 4: X-bar/R control charts for the RONq values of the profiles obtained from the multi-wave element.

The graphical analysis of the circumferential lines extracted from the multi-wave element with CT Setups #1 and #2 and with the CMM is shown in Figure 5. By observing the CT results, it can be noted that the random surface deviations on the circumferential lines extracted from the multi-wave element show good correlation with the deviations already observed in the lines extracted from standard...
element. In spite of the random surface deviation, most of the dominant harmonics of the multi-wave element can be clearly distinguished in the frequency domain analysis. Furthermore, it can be noted that harmonics are heterogeneously modified within and between setups.

![Multi-wave - CMM](image1)

![Multi-wave - CT Setup #1](image2)

![Multi-wave - CT Setup #2](image3)

Figure 5: Polar plot and dynamic content plot of the profiles extracted from the multi-wave element.

However, it can be noted that the 500 UPR harmonic (corresponding to a wavelength of approximately 0.5 mm) has been almost completely vanished from the CT extracted circumferential lines. Limited frequency response is an issue common to every measuring system. The attenuation of the 500 UPR harmonic was observed for all the evaluated CT setups, and may represent a limit in the frequency
response of the evaluated CT measuring system regarding the measurement of the two specific cylindrical elements.

4 Discussions
This paper presented an experimental investigation on the random surface deviations generated during a CT extraction operation. From the results obtained with the use of the MWS, some conclusions can be drawn. Given the highly accurate surface finishing and geometry of the standard element, it is possible to assert that the observed random surface deviations can be mainly attributed to inaccuracies and limitations of the CT measuring system. This remark, together with the observed attenuation of the 500 UPR harmonic, set limits to capability of the evaluated CT measuring systems to resolve high frequency content such as waviness and roughness deviations.

Regarding the evaluation procedure, the results shown that use of RMS deviation parameters calculated from extracted integral features is quite appropriate in quantifying the CT-induced random surface deviations. In this sense, the RMS deviation parameter can be considered as a quality index for the CT extracted data to be used on geometrical evaluations. By covering the whole extraction operation, it encompasses most intermediary effects that leads to random surface deviations, and summarizes several image quality indexes (e.g. contrast, SNR, etc.) into one single indicator.

Moreover, for being plainly sensitive to changes in setup parameters, the RMS parameter calculated from extracted integral features can be used along with statistical tests (such as control charts) to support CT users in minimizing the occurrence of random surface deviations. As the comparison of control charts obtained from the two cylindrical elements shown, the form deviations of the workpiece may reduce the sensitivity of the analysis. Therefore, a subtraction of the real features from the extracted integral features may be required to perform this analysis on real production parts.

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References