DESIGN OF A MULTI-WAVE STANDARD TO EVALUATE THE FREQUENCY RESPONSE OF CT MEASURING SYSTEMS

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Abstract: This paper presents a multi-wave standard (MWS) designed for evaluating the frequency response in extracting surfaces with CT measuring systems. The characteristics of the MWS were defined using prior knowledge on MWS applied to CT and simulations of the CT extraction operation. With basis on the designed geometry, an aluminium MWS specimen was manufactured. A set of preliminary CT measurements demonstrate the suitability of the designed MWS to characterize the frequency response for surface extraction with CT systems.

Keywords: Dimensional metrology, industrial computed tomography, surface extraction, frequency response analysis.

1. INTRODUCTION

The application of computed tomography (CT) as a dimensional measuring technology represented the last major advance in the field of production metrology. Recent advances in hardware and software resulted in CT systems with the potential to produce measurement results as accurate as those produced with established 3D measuring technologies, e.g. optical scanners and tactile CMM. It has been demonstrated [1] that CT systems, besides measuring size, are able to detect form deviations with sub-voxel magnitudes. Nevertheless, the metrological behaviour of CT systems in this application range was not yet comprehensively investigated. The main reason of this state of affairs is the lack of methods and/or material measures that allow evaluating the frequency response related to the surface extraction operation with CT systems.

This paper presents a multi-wave standard (MWS) designed to evaluate the frequency response of CT measuring systems.

2. EARLY APPLICATIONS OF MWS TO CT

Multi-wave standards (MWS) were developed as a material measure to calibrate and evaluate the frequency response of form measuring machines with tactile probing [2]. The first attempts to evaluate the frequency response of CT systems using MWS are documented in [3,4]. Those first experiments confirmed the capability of CT systems in detecting surface content with sub-voxel amplitudes, and also brought into attention the limitations of these systems in resolving high frequency surface content. This demonstrated the potential of using the MWS to evaluate the frequency response in extracting surfaces with CT measuring systems.

On the other hand, those results revealed some issues involving the characteristics of the available MWS when applied to evaluate CT systems, such as:

- Combination of penetration length and material density (aluminium) prone to the occurrence of beam hardening (grey level decay) effects (Fig. 1, left);
- Nickel coating (used to increase hardness) resulting in non-homogeneous X-ray attenuation (Fig. 1, left);
- Excessive interval between the spatial frequencies[1], compromising the evaluation of the amplitude transmission curve (Fig. 1, right).

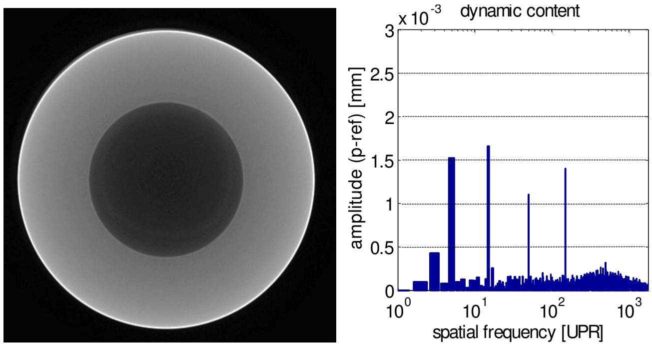


Fig. 1. CT measurements performed in a MWS designed for tactile measurements (external diameter of 80 mm, spatial frequencies of 5, 15, 50, 150, and 500 UPR, nominal amplitudes of 2 µm)

3. DESIGN OF A MWS FOR CT SYSTEMS

The demonstrated potential of application and the above mentioned design related issues motivated the development of a new MWS concerned with specific characteristics of CT systems. The definition of the multi-wave pattern parameters (spatial frequencies, amplitudes and phases) was assisted by a computational simulation developed for this purpose, which is described in the following section.

3.1 CT simulation description

The simulation of the CT data generation (projection formation) process was implemented using a MATLAB based 2D polygons intersection algorithm [5]. The simulation consists in generating a stack of polygons that represents the X-ray geometry and a polygon that represents the boundaries of the workpiece. For each pixel, the area of the intersection between the corresponding X-ray polygon

[1] The ratio between the mean diameter of a circular profile multiplied by pi ($\pi.\varnothing$, in mm) and a given spatial frequency (ω, in UPR) defines a wavelength (λ, in mm).

and the workpiece polygon is calculated. The areas corresponding to each pixel define one projection (Fig. 2). For the following projection, the workpiece polygon is rotated by one angular step, and a new set of areas is taken.

The implemented X-ray geometry was the parallel beam geometry, with each X-ray polygon being a pixel-wide rectangle. To simulate the magnification of the fan beam geometry (and, therefore, the response according to the of voxel size), the workpiece polygon is scaled according to the relation between the source-detector distance and the source-object distance. For being a purely geometrical simulation, no effects from interactions between X-rays and material (e.g. scattering, beam hardening, etc.) nor from hardware non-idealities are taken into account. Therefore, it is expected of the results to represent the best possible frequency response attainable for a given CT system configuration.

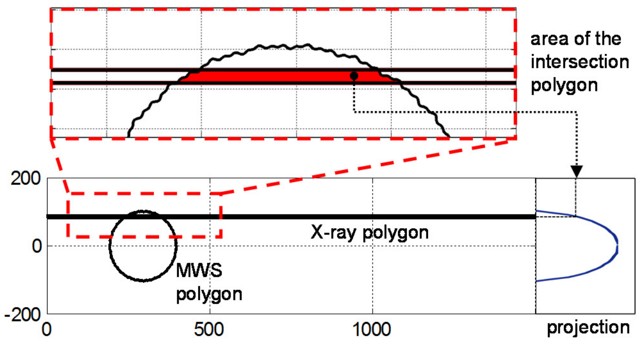


Fig. 2. Formation of projections using polygons intersection

The reconstruction of the CT image was implemented using the MATLAB inverse Radon transform function [6]. The segmentation (line extraction) was performed using the isosurface algorithm of a CT data processing software [7]. The evaluation of the extracted circumferential lines was performed with a dedicated analysis application [8].

3.2 Investigations using the CT simulation

To help defining the parameters for the MWS, the relations between the amplitude transmission and the voxel size were investigated using the above described simulator.

For this purpose, two multi-wave polygons with peak-to-reference wave amplitudes (*Ap*, in mm) of 2.5 and 5 µm were created. Other parameters were kept equal, namely the mean diameter (40 mm), the set of spatial frequencies (100, 133, 200, 266, 400, 532 and 800 UPR) and their phases (equal to zero), and the number vertices (8000). The resulting peak-to-valley roundness deviations (RONt) of the polygons were, respectively, 27.3 and 54.4 µm. The set of spatial frequencies was chosen as two geometric progressions with common ratio equal to 2.

To estimate the frequency response of CT systems within the sub-voxel range, the polygons were extracted using voxel sizes (*Vx*, in µm) of 39.3 and 78.7 µm, selected within a range of typical values (20~200 µm). The voxel size values were chosen as a geometric progression with the same common ratio of the spatial frequencies.

Dynamic content (frequency spectrum) plots of the two polygons extracted with two different voxel sizes are shown in Fig. 3. Numerical results are summarized in Table 1.

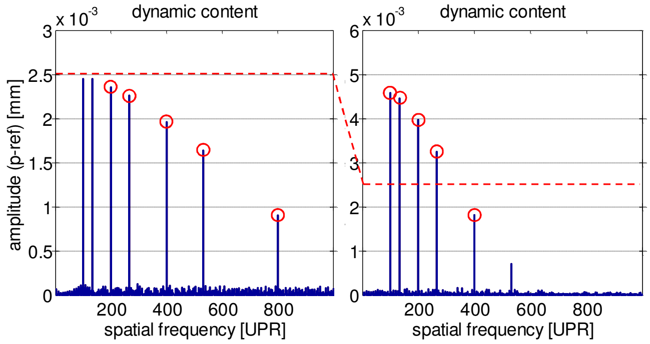


Fig. 3. Multi-wave profiles with amplitudes of 2.5 µm (left) and 5 µm (right) extracted by simulation using voxel sizes of 39.3 µm and 78.7 µm respectively

By analyzing the results of the simulations, important conclusions regarding the response of CT systems within the sub-voxel range could be drawn, as follows.

- The wavelength to voxel size ratio (or number of voxels per wavelength, nVx/λ) is a determinant factor to the amplitude transmission of the wavelengths;
- The transmission is proportional to the value of the amplitude, regardless of the voxel size;
- Small variations in transmission values indicate that other deviations generated during the extraction process interfere with the multi-wave pattern.

Table 1. Number of voxels per wavelength (nVx/λ) and relative transmission (*%Tr*) obtained with the simulated extractions

Vx [µm]	*Ap* [µm]	*ω [UPR]* / *Λ [mm]*	100 / 1.26	133 / 0.94	200 / 0.63	266 / 0.47	400 / 0.31	532 / 0.24	800 / 0.16
39.3	2.5	*nVx/Λ*	32	24	16	12	8	6	4
		%Tr	98%	98%	92%	90%	79%	66%	36%
78.7	2.5	*nVx/Λ*	16	12	8	6	4	3	2
		%Tr	91%	90%	81%	65%	36%	14%	2%
	5.0	*nVx/Λ*	16	12	8	6	4	3	2
		%Tr	92%	89%	79%	65%	36%	14%	1%

3.3 MWS specifications

The specifications for the new MWS were defined with basis on prior knowledge and on the results of the described simulation. Details are given in the following lines. The described specifications are summarized in Fig. 5.

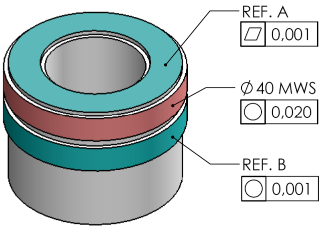
The selected material was a structural aluminum league (ASTM 2024-T3). This choice was based on the high standard mechanical properties of the league such as good machinability and rigidity to allow high accuracy manufacturing and reasonable hardness (HB > 120) to avoid plastic deformation of the surface during the calibration.

The base geometry of the MWS was chosen to be a hollow cylinder (40 mm external diameter, 22 mm internal diameter and 30 mm height). The maximum penetration length provided by this geometry combined with the reasonable low density of the aluminum should keep radiation-material interaction effects (particularly beam hardening effects) at manageable levels.

The specified set of spatial frequencies (25, 50, 100, 200 and 400 UPR) is a geometrical progression with common ratio equal to 2. The set was chosen to start at the 25 UPR in order to let the low-frequency region free to evaluate the occurrence of other effects (e.g. odd harmonics added by the focal spot drift during the data acquisition [9]).

According to the higher spatial frequency in the set (400 UPR), the amplitudes of the multi-wave pattern (2.5 μm) were defined. This value was chosen to be the maximum possible, but still allowing manufacturing without attenuation caused by the limits in frequency response of the machine tool; and calibration with tactile measurement systems without incurring in mechanical filtering effects.

Finally, the phases of the spatial frequencies were not directly specified. Instead, it was required that the combination of spatial frequencies, amplitudes and phases resulted in multi-wave profile with a maximum RONt value of 20 μm, increasing the range of cases were the MWS can be used in to evaluate CT systems in the sub-voxel range.



Ø 40 MWS

Frequency [UPR]	Wavelength [mm]	Amp. (p-ref) [μm]
25	(5.03)	2.5
50	(2.51)	2.5
100	(1.26)	2.5
200	(0.63)	2.5
400	(0.31)	2.5

Fig. 5. Summary of specifications for the MWS

For later comparisons with real CT measurements, simulated extractions of the specified multi-wave pattern using two different voxel sizes (78.7 and 157.3 μm) were performed. The results are shown in Fig. 6. It can be noted herein that the selected set of spatial frequencies provides an improved representation of the amplitude transmission curve for surface measurements with CT systems.

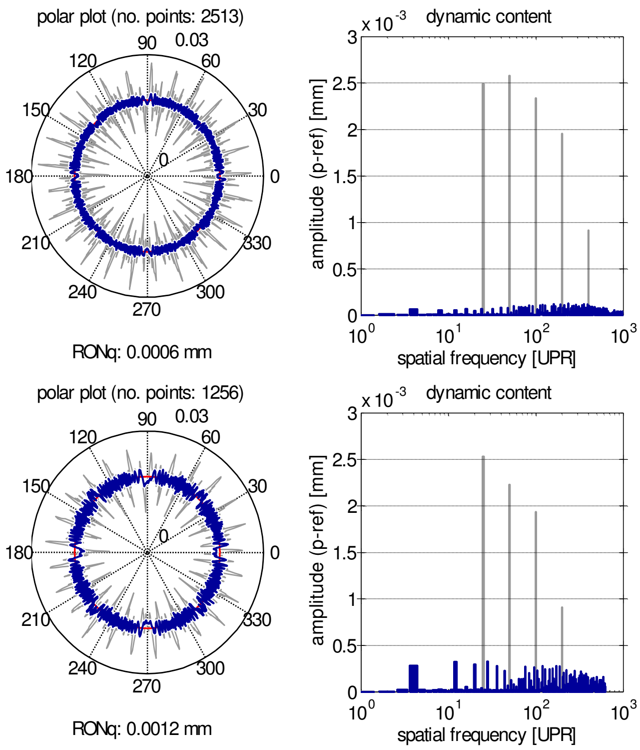


Fig. 6. Specified multi-wave profiles extracted by simulation using voxel sizes of 78.7 μm (top) and 157.3 μm (bottom)

4. IMPLEMENTATION

4.1 Manufacturing and calibration

The reference surfaces and the multi-wave pattern of the MWS were manufactured on an ultra-precision diamond turning machine. A piezoelectric fast tool servo was used to generate the multi-wave pattern (Fig. 7).

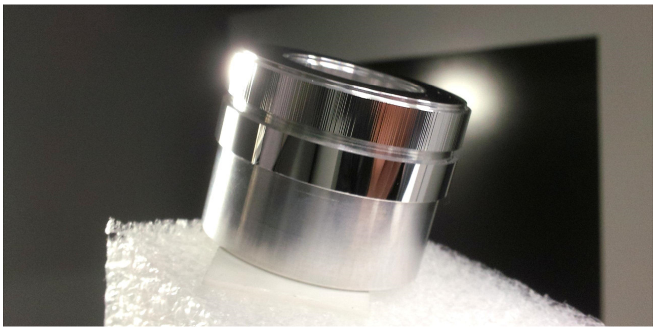


Fig. 7. Manufactured MWS

The calibration was performed in a CMM equipped with a rotary table. A contact force of 0.01 N and stylus having a 1.5 mm diameter silicon nitride sphere were used for extracting the multi-wave profiles. The data processing was performed with a dedicated application [8].

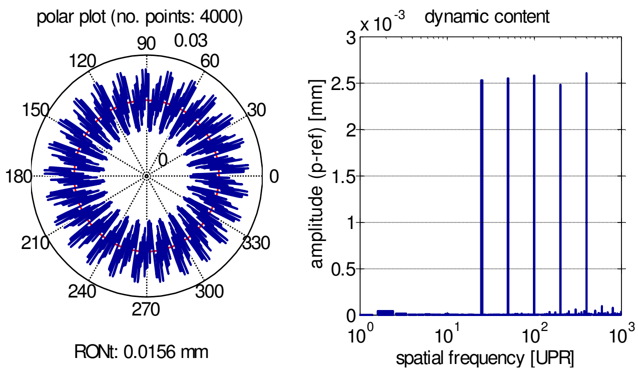


Fig. 8. Processed multi-wave profile extracted with a CMM

The calibrated multi-wave profile is shown in (Fig. 8). This result shows that design requirements were fulfilled. Important achievements regarding the manufacturing were a multi-wave pattern with a well-defined frequency spectrum and amplitudes very close to the nominal value; and a very symmetric space domain distribution (skewness equal to 0.005) with a RONt value of 15.6 μm.

4.2 Preliminary CT measurements

To demonstrate the actual response of a CT system[2] to the MWS, two measurements were performed. The setup parameters used are shown in Table 2.

Table 2. CT setup parameters

Voxel size	Position	Proj.	Prefilter (Cu)	Voltage	Current	Focal spot	Int. time	Gain	Binning
Vx [μm]	*X [mm]*	*P*	*V [mm]*	*U [kV]*	*I [μA]*	*Br [μm]*	*B [ms]*	*E [x]*	*Bn*
78.7	295	1532	1.00	120	500	60	4000	16	2x2
157.1	589	1532	1.00	120	1000	120	2000	16	2x2

[2] X-ray tube of 225 kV; detector with 2048x2048 pixels and pitch of 0.2 mm; source to detector distance of 1500 mm.

For these measurements, the axis of the MWS was inclined about 15° with relation the axis of the rotary table. The multi-wave surface of the MWS was positioned at the mid-height of the detector to avoid cone beam geometry effects. The segmentation was performed using the advanced algorithm of a CT data processing software [7].

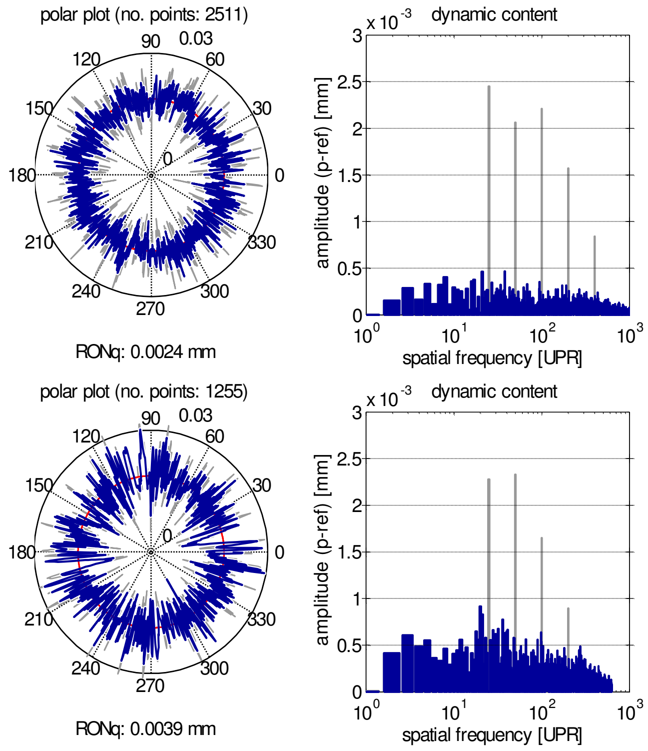


Fig. 9. Multi-wave profile extracted with a CT system using voxel sizes of 78.7 µm (top) and 157.1 µm (bottom)

The multi-wave profiles obtained by CT measurements are shown in Fig. 9. Regarding the transmission of the multi-wave content, a good agreement between CT measurements and simulations (Fig. 6) can be observed. On the other hand, it can be noted that CT measurements present a higher level of random surface deviations. As noted in the simulations, interactions with additional surface deviations affect the observed transmission values.

In order to observe CT image formation aspects, a slice from the volumetric image is shown in Fig. 10. By analysing the image, no evident beam hardening effects can be noted. Additionally, a detail from the multi-wave section shows no trace of the multi-wave pattern, indicating that all the amplitude information lies within the grey values.

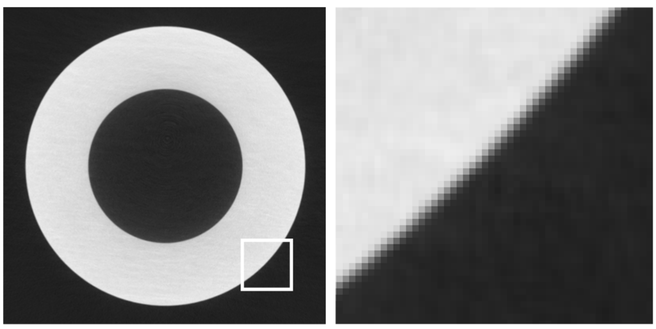


Fig. 10. Slice from the multi-wave section (left) and detail (right) of the 3D image obtained with a voxel size of 78.7 µm

5. CONCLUDING REMARKS

This paper presented a new multi-wave standard designed to evaluate the frequency response of CT systems.

Regarding the method, the simulation proved to be a useful design tool, allowing obtaining knowledge on the response of the CT systems in advance. The good agreement observed between the CT measurements and the simulations demonstrate its potential to analyze other aspects related to the CT data acquisition (as already shown in [9]).

Regarding the new design, important improvements with respect to the former MWS within the scope of evaluating CT systems were obtained. The smaller interval between spatial frequencies and the possibility of overlapping the transmission curve by changing the voxel size provide a more adequate means to experimentally investigate the frequency response of CT systems. Also, the smaller penetration lengths obtained with the new base geometry allows better controlling the occurrence of beam hardening.

With respect to the implementation, it is worth mentioning that the manufacturing process was able to cope with all specifications; and that a low distortion calibration (e.g. negligible mechanical filtering effects) was attained. Therefore, it can be said that the purpose of this development was successfully achieved.

The next steps involve exploring the new capabilities provided by the MWS in qualifying the CT extraction operation. Potential applications include evaluating the influence of CT setup parameters, the effectiveness of CT data processing algorithms and the stability of CT measuring systems.

ACKNOWLEDGEMENTS

This work was supported by CAPES, CNPq and DFG within the scope of the Brazilian-German Collaborative Research Initiative on Manufacturing Technology (BRAGECRIM), and ANP and PETROBRAS within the scope of the LAMIA project.

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