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CHARACTERIZATION OF THE METROLOGICAL STRUCTURAL RESOLUTION OF CT SYSTEMS USING A MULTI-WAVE STANDARD

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Abstract – This paper presents a method and procedure for characterizing the metrological structural resolution (MSR) of CT systems. The method is based on the frequency response analysis on sinusoidal surfaces. The procedure involves performing evaluations with multiple voxel sizes. To test the method, a comparative evaluation of two CT measuring systems was performed. The results demonstrate the potential of the proposal for assessing the metrological structural resolution of CT systems.

Keywords: Dimensional metrology, computed tomography, surface extraction, structural resolution, transfer function.

1. INTRODUCTION

X-ray computed tomography (CT) is becoming an important technology in the field of dimensional metrology. As CT systems gain acceptance as coordinate measuring systems (CMS) for industrial applications, it becomes necessary to define metrological characteristics and standard procedures to ensure comparability among CT measuring systems (and other CMS) and to allow demonstrating compliance with manufacturer’s specifications.

The national guideline VDI/VDE 2630 Part 1.3 [1] is currently the most comprehensive published document regarding acceptance and reverification tests for CT systems. In addition to including particular aspects of the CT measuring principle to the ISO 10360 tests [2], it introduces a metrological characteristic of particular interest for CT measuring systems: the structural resolution for dimensional measurements.

This paper presents a method and procedure for characterizing the structural resolution for dimensional measurements of CT systems using a multi-wave standard.

2. METROLOGICAL STRUCTURAL RESOLUTION

The structural resolution for dimensional measurements, also termed *metrological structural resolution* (MSR), defines “the size of the smallest structures that can still be measured dimensionally” [1]. The importance of this characteristic for acceptance and reverification tests can be described by at least two aspects. The first is closely related to the very definition: when the application involves small geometries, the structural resolution plays a major role in the accuracy of measurements.

The second is related with the trade-off between the structural resolution and the noise (both random and structured) generated during the surface extraction chain. Changing hardware and/or software parameters to improve the structural resolution implies in accentuating the low-pass filtering characteristic of the CT system. This often reduces the noise that reaches the extracted surface, thus improving the results of surface deviation tests (such as the probing form error P_F according to [1]). In view of the latter aspect, structural resolution and surface deviation tests should be designed to be mutually complementary.

For imaging systems, the methods that have been most widely used to determine the structural resolution are the modulation transfer function (MTF) and the use of line pair gauges. These methods have standard procedures described in industrial CT standards such as ASTM E1695 [3] and EN 16016-3 [4], respectively. However, these methods are implemented on reconstructed image, thus they do not cover the complete dimensional measurement chain. For this reason, they have been considered as not suitable to evaluate the metrological structural resolution of CT systems [1].

The VDI/VDE 2630 Part 1.3 proposes defining the structural resolution as the diameter of the smallest sphere that can be correctly measured by the CT system. As stated in the guideline, this method is provided only as a first guidance while a specific guideline on the structural resolution of CMS is not available. More recently, it has been pointed out [5] that no satisfactory method has yet been defined for the CT part of the ISO 10360 series. Therefore, a suitable method for assessing the structural resolution of CT measuring systems is still to be defined.

Surface-based proposals for determining the metrological structural resolution of CT systems consider:

- Measuring the radius of the curvature formed at sharp edges [6];
- Measuring the height of an image artefact formed between two touching spheres [7];
- Measuring the increase of the radii of small features and determining an equivalent Gaussian function [8];
- Performing a frequency response analysis on an aperiodic spatial frequency standard [9].

The next session describes the method and procedure for characterizing the metrological structural resolution of CT systems using a multi-wave standard (MWS).

3. PROPOSAL OF A METHOD USING A MWS

The method to determine the metrological structural resolution based on the frequency response analysis on sinusoidal surfaces, briefly described in [10], can be summarized as follows:

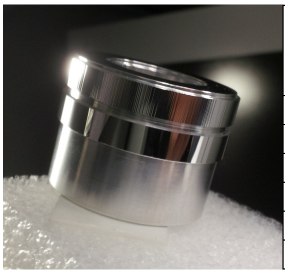
1. Scanning a calibrated CT-MWS and extracting a circumferential line from the multi-wave surface;
2. Calculating the relative transmission values of the multi-wave content by making a frequency response analysis on the extracted circumferential line;
3. Determining the amplitude transmission model by fitting a frequency domain generalized Gaussian function to the relative transmission values;
4. Defining the MSR as the cut-off wavelength value at an amplitude transmission value of 50%.

Theoretical background and implementation formulae on the above steps are provided in the next lines. The procedure using multiple voxel sizes is described after.

3.1 Multi-wave standard for CT systems

Multi-wave standards (MWS) are material measures consisting of well-defined sinusoidal spatial frequencies and were initially developed to evaluate the signal transmission of form measuring machines [11],[12]. MWS are also considered suitable material measures to determine the structural resolution of CMS using optical sensors [13].

The first MWS designed to evaluate the frequency response of CT measuring systems (see Figure 1) was presented in [14]. This MWS is made of aluminium, uses a circular multi-wave arrangement and has two additional reference surfaces for alignment. The characteristics of the multi-wave content of the CT-MWS are presented in Fig. 1.



Spatial frequency [UPR]	Wavelenght [mm]	Spatial frequency [mm^{-1}]	Amplitude (p-ref) [µm]
25	5.03	0.20	2.5
50	2.51	0.40	2.5
100	1.26	0.80	2.5
200	0.63	1.59	2.5
400	0.31	3.18	2.5
Radius: 20 mm			

Fig. 1. CT-MWS and multi-wave content's nominal characteristics.

In MWS with circular arrangements, the peak-to-reference amplitudes (Ap, in µm) and phases of the multi-wave content are usually expressed as a function of the angular spatial frequency (ω, in UPR). However, methods for evaluating the structural resolution normally use linear spatial frequencies (sf, in mm^{-1}) and/or wavelengths (λ, in mm) as basis. The relation among wavelength, linear spatial frequency and angular spatial frequency is given in (1):

$$\lambda = 1/sf = 2\pi R/\omega \qquad (1)$$

where R (in mm) is the radius of the least squares circle associated to the extracted circumferential line.

3.2 Frequency response analysis on circumferential lines

To perform the spatial frequency response analysis, first the extracted circumferential lines must be represented in the spatial frequency domain. This is done by applying a discrete Fourier transform (DFT) to the space domain representation of the extracted lines. The amplitude spectrum $\mathbf{Ap}(\omega)$ is obtained by taking the modulus of the complex spectrum and scaling by the Nyquist frequency. This set of operations is represented in (2):

$$\mathbf{Ap}(\omega) = |\, DFT\,\{\,\mathbf{r}(\theta)\,\}\,|\;/\;N/2 \qquad (2)$$

where $\mathbf{r}(\theta)$ is the space domain representation of the extracted circumferential line in polar coordinates and N is the number of points. The analysis of the phase spectrum will not be dealt on this paper.

For exemplification and further comparisons, graphical representations of the extracted circumferential line and the amplitude spectrum from the CT-MWS calibration are presented in Fig. 2.

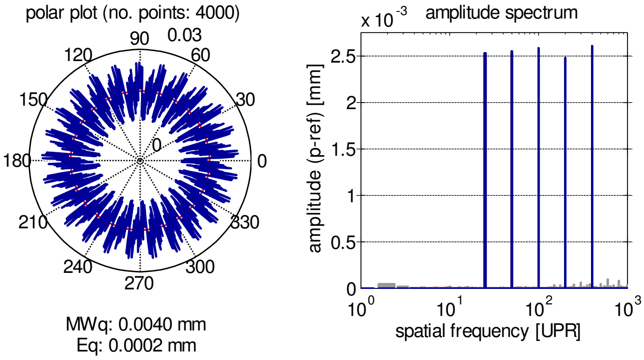


Fig. 2. Reference extracted circumferential line from the calibration of the CT-MWS. MWq is the RMS amplitude of the multi-wave content (signal, represented in blue), Eq is the RMS amplitude of the surface error content (noise, represented in grey).

The frequency response analysis itself is performed to obtain the relative transmission values ($Tr(sf)$) of the multi-wave content. This operation is done by relating the CT transmitted amplitude values ($Ap_{CT}(sf)$) and the calibrated amplitude values ($Ap_{cal}(sf)$) according to (3).

$$Tr(sf) = Ap_{CT}(sf)/Ap_{cal}(sf) \qquad (3)$$

At this point, it is necessary mentioning that, as well as for the MTF, the above measurement model assumes linearity and shift (spatial) invariance of the CT system. In the case of a nonlinear response, energy transfer (intermodulation) occur among spatial frequencies, distorting the aspect of the amplitude spectrum. In the case of a spatially-variant response, the structural resolution will change over the measurement volume. Even knowing that rigorous satisfaction of these requirements is seldom achieved for CT systems [15],[16], the MTF has still been successfully used for verification, comparison and design of CT systems.

3.3 Amplitude transmission model

Because the information provided by the multi-wave content is sparse on the spatial frequency domain, it becomes necessary determining an amplitude transmission model prior to defining the metrological structural resolution.

The Gaussian model has been used earlier to describe the frequency response of CT imaging systems [17]. Also, the results of a CT simulation for extracting structured surfaces showed a very good agreement with the Gaussian model [10]. However, as pointed out in [9] and [16], the response of a real CT measuring system is subject to many influencing factors. Thus, without a priori knowledge on the response of the CT system for a specific measurement condition, a more general model is required.

The presented method uses the frequency domain generalized Gaussian model proposed in [20] to describe the MTF of electro-optical devices. The generalized Gaussian transmission model equation is presented in (4):

$$\widehat{Tr}(sf) = \exp[-k\ (sf/sfc)^n] \tag{4}$$

where $\widehat{Tr}(sf)$ are the transmission model values, n is the transmission model index, *sf*c (in mm^{-1}) is the cut-off spatial frequency of the model and k is the constant that determines the transmission model value on the cut-off spatial frequency.

The value of the index n describes the shape of the transmission model. With this respect, two particular models are worth mentioning. For an index equal to 2, the transmission model is a pure Gaussian, with a corresponding space domain Gaussian model. For an index equal to 1, the transmission model is a pure double[1] exponential decay, with a corresponding space domain Lorentzian model [18].

Fitting the model described in (4) will require a nonlinear regression method. The objective function adopted on the presented method is the minimization of the sum of the squared residuals (also called ordinary least squares).

3.4 Defining the metrological structural resolution

The metrological structural resolution is defined as the cut-off wavelength value (λc, in mm) for a transmission model value of 50%. This criterion is used in the ISO series of surface topography standards (e.g. [19]) for defining the structural resolution. The value of the constant for this criterion is $k = -\ln(0.5)$.

Other criteria exist and are worth mentioning. For instance, in the original work [20] the author used $k = 1$ (transmission of approx. 37% on the cut-off). The national guideline [13] defines a transmission value of –3 dB (approx. 71%) for the cut-off. The national guideline [3] defines a transmission value of 10% for the cut-off.

3.5 Procedure using multiple voxel sizes

Most modern CT measuring systems are capable of changing the source-to-object distance (therefore the magnification) and/ or the detector binning (thus the effective pixel size) in order to obtain optimized measurement results. As a direct consequence, CT measuring systems have not one, but a range of structural resolution values.

For this reason, it is proposed to normalize the structural resolution by the voxel size (Vx, in mm) in order to obtain a dimensionless parameter defined as the *number of voxels per wavelength* ($Nvpw$). This parameter is a factor that unifies the structural resolution over a specific range of voxel sizes and also provides an insight on the resolution similar to sampling the surface content using a virtual voxel matrix. The number of voxels per wavelength can be calculated according to (5).

$$Nvpw = \lambda/Vx\ = 1/(Vx.sf) \tag{5}$$

By using this relation, it should be possible to define a unique, dimensionless transmission model for a specific range of voxel sizes. The underlying assumption in using this relation is that the influence of other factors (e.g. the focal spot size or the rotary table position error) remain invariant with respect to the changes in voxel size.

4. EXPERIMENTAL EVALUATION

4.1 Experimental setup

To test the described method using the MWS, the structural resolution of two CT measuring systems was evaluated. The characteristics of the two CT systems are described in Table 1. The main differences between the CTs are the detector (twice the resolution for CT #1) and the positioning system (no vertical positioning for CT #2).

Table 1. Characteristics of the CT measuring systems.

Voltage	Current	Prefilter (Cu)	Focal spot size	Pixel size	Int. time	ROI	Proj.
U [kV]	I [µA]	V [mm]	Br [µm]	Sp [mm]	B [ms]	W_{ROI} [px]	P
180	250	0.50	45	0.4	2000	700	1100

The data acquisition parameters were kept as close as possible between the CTs. The inclination between the axis of the MWS and the axis of the rotary table was about 15°. Table 2 shows the parameters used for both CT systems.

Table 2. Data acquisition parameters used for both CT systems.

System	Max. voltage	Max. current	Src. det. distance	Pos. system	Detector material	Detector res.	Detector pitch
	U_{max} [kV]	I_{max} [µA]	Dsd [mm]	DoF	-	Np	Dp [mm]
CT #1	225	1000	1500	X, Y, Z, R	Gd_2O_2S	2048	0.2
CT #2	225	1000	1500	X, Y, R	Gd_2O_2S	1024	0.4

The voxel sixe configuration was defined by measuring the MWS in four source-to-object distances (*Dso*, in mm). Due to the resolution difference between detectors, a binning of 2x2 was used for the CT #1. This resulted in the same pixel size, thus the same voxel sizes, for both CT systems. The voxel sixe configuration for evaluating the metrological structural resolution is shown in Table 3. This table also shows the geometrical unsharpness (*Ug*, in mm) caused by the focal spot size. This value must be smaller than the pixel size (*Sp*, in mm) so that the focal spot size has no significant influence on the structural resolution.

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[1] The equation describes only one side of the spectrum.

Table 3. Voxel size configuration used for both CT systems.

Position	Magnif.	Voxel size	Focal spot blur
Dso [mm]	*Vg*	*Vx* [µm]	*Ug* [mm]
295	5.1	78.7	0.18
350	4.3	93.3	0.15
417	3.6	111.2	0.12
495	3.0	132.0	0.09

Three measurement cycles were performed with CT #1, and two measurement cycles with CT #2. For both CTs, a full qualification was performed before each measurement cycle.

4.2 Data Processing

The surface determination and circumferential line extraction were performed using a commercial CT data processing software [21]. The global thresholding method was used for all cases. The frequency response analysis was performed with a dedicated analysis application [22]. The transmission model fitting was carried out by means of a nonlinear generalized reduced gradient (GRG) algorithm [23].

5. RESULTS

5.1 Analysis of the circumferential lines

Examples of circumferential lines extracted with both CT systems are shown in Fig. 3. This graphics show that the CT measurements present a relatively high surface error content, resulting in quite unfavourable signal-to-noise ratios on the surface (SNRs).

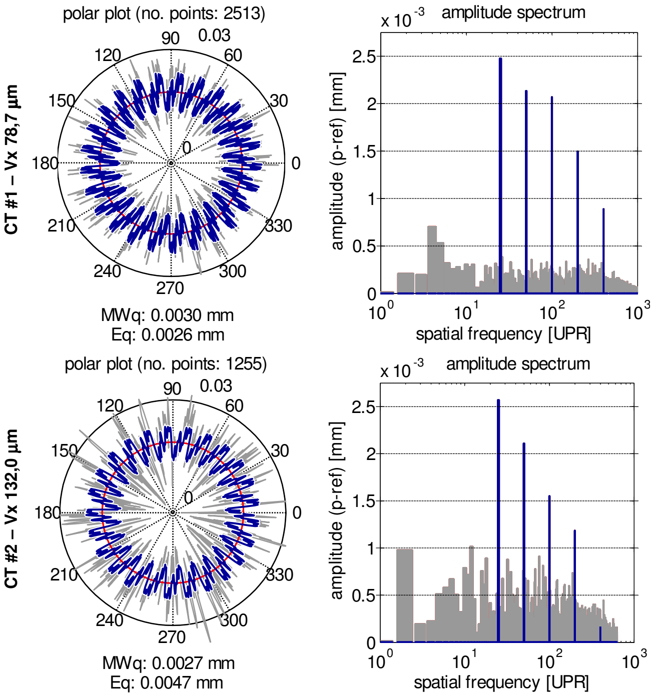

Fig. 3. Extracted lines obtained from the CT-MWS using CT #1 with a voxel size of 78.7 mm (top) and the CT # 2 with a voxel size of 132.0 mm (bottom). MWq is the RMS amplitude of the multi-wave content (signal, represented in blue), Eq is the RMS amplitude of the surface error content (noise, represented in grey).

Furthermore, by observing the amplitude transmitted values, one can note some perturbations, indicating that statistical noise may be interfering and that nonlinearities may be occurring. At the moment, however, it is not possible to take definite conclusions regarding this issue.

On the other hand, the multi-wave content is clearly separable from the surface error content (e.g. no spectral leakage is noticeable). Moreover, the influence of the amplitude perturbations on the analysis was reduced by using multiple measuring cycles.

5.2 Influence of the magnification

The relative transmission values and associated models obtained with multiple voxel sizes using both CT systems are shown in Fig. 4 and Fig. 5, respectively. For this analysis, the index *n* was constrained to a common value for each CT.

This results show the dependence of the structural resolution on the voxel size, also demonstrating that single-value statements of structural resolution without information on the specific measuring conditions are of little practical use.

Because the voxels sizes were obtain by varying only the magnification, these transmission models reflect the influence of this factor alone. The influence of the binning as a component of the voxel size still have to be investigated.

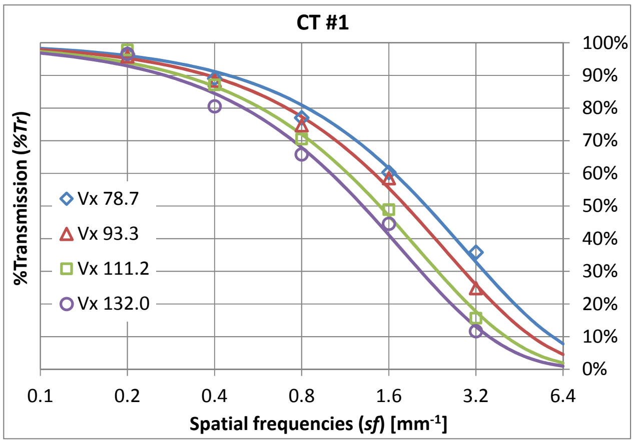

Fig. 4. Transmission models of CT #1 for different voxels sizes. The common index of the models is 1.20.

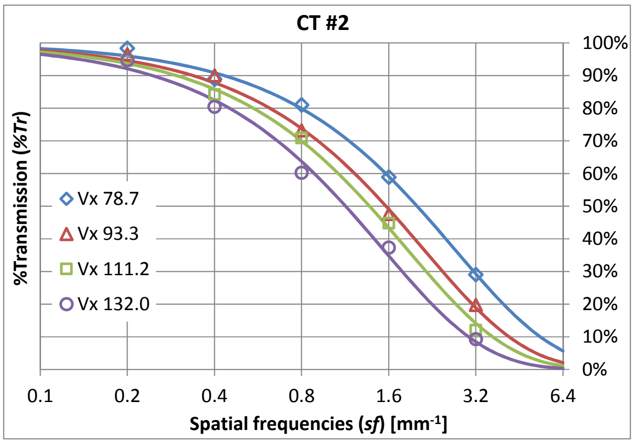

Fig. 5. Transmission models of CT #2 for different voxels sizes. The common index of the models is 1.23.

Regarding the shape of the transmission models, the common index of approximately 1.2 for both CTs reveals a model that is closer to the exponential decay than to the Gaussian model. The index values of the transmission models obtained without the equality constrain varied from 1.0 to 1.3.

5.3 Comparison of the CT measuring systems

For a direct comparison of the CT systems, the cut-off wavelengths obtained using different voxel sizes are presented in Fig. 6. By analysing these results, and under the assumption that the voxel size is the only changing influence factor, it can be said that CT #1 has a consistently better metrological structural resolution than CT #2. Also, it is interesting to note the linear relation between voxel size (magnification) and the structural resolution.

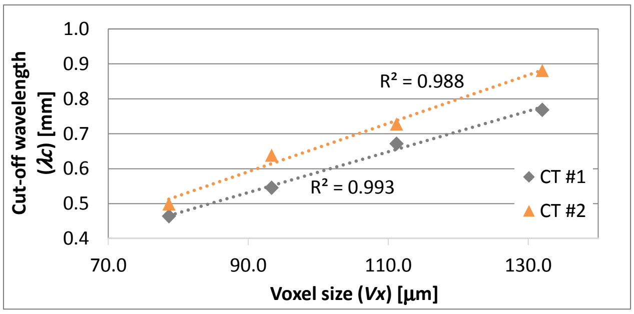

Fig. 6. Cut-off wavelengths obtained with both CTs for different voxel sizes.

The unified transmission model obtained with both CTs are show in Fig. 7. Note that the direction of the horizontal axis was inverted to maintain the analysis similar to the spatial frequency based analysis. Considering the assumption that the voxel size is the only changing influence factor, it can be said that the CT #1 has a better overall frequency response than CT #2.

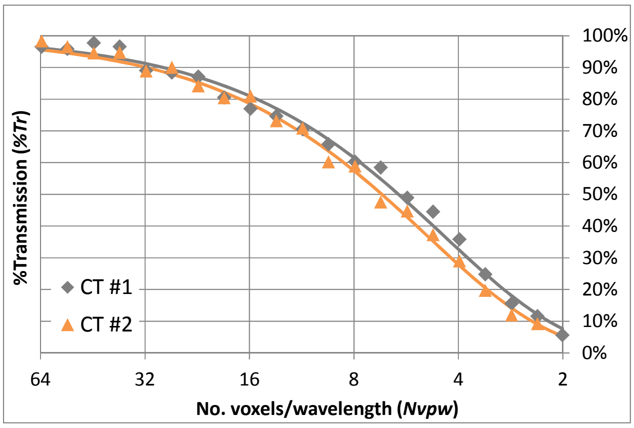

Fig. 7. Unified transmission models obtained with both CTs. The index for both CTs is 1.2. The cut-off number of voxels per wavelength (*Nvpwc*) for the CT #1 and CT #2 are 6.0 and 6.6, respectively.

The interpretation of this transmission models regarding the sampling of the surface content can be made as follows. In order to transmit 80% of the amplitude of a wavelength, CT #1 would require 16 voxels. For transmitting 10% of a wavelength, CT #2 would require 2.5 voxels. It is worth mentioning that these interpretations are also conditioned to the specific range of voxels evaluated and to the measurement conditions used for these experiments.

6. DISCUSSION

The experimental results demonstrated that the CT-MWS can provide useful information regarding the signal transmission capabilities of CT measuring systems. Multi-wave standards are well-known material measures in the field of dimensional metrology [12],[13], yet resembling, from the viewpoint of the output information, the line pair gages used for many years to evaluate CT imaging systems. However, the sinusoidal content of MWS make them better suited than square-wave line pair gauges for using as input signal in a frequency response analysis. More importantly, the spatial frequency information of MWS is *on the surface*, which make them appropriate for evaluating the metrological structural resolution of CT systems.

As mentioned in [13], and in accordance to the theory of systems, resolution limits can be represented in the spatial domain as well as in the spatial frequency domain. Both representations carry the same information, and conversion from one to another is possible via Fourier transform. The frequency response analysis is a convolutional method, and as such, it is subject to assumptions of linearity and stationarity. Even if rigorous attainment of these requirements is rarely achieved for CT systems [15],[16], techniques and/or specific setups with better transmission models will likely correspond to CT systems, techniques and/or specific setups with better structural resolution [16]. For this reason, convolutional methods remain a useful means for verification, comparison and design of CT imaging systems. The same is expected regarding the metrological structural resolution of CT measuring systems.

The use of the frequency domain generalized Gaussian model provided a good means of describing the surface content transmission capabilities of CT measuring systems. The main advantage in using this model is that it allows describing a wide range of effective transmission characteristics by means of only two parameters (*n* and *sfc*) [20]. The importance of using a general transmission model can be drawn from the experimental results: the CT systems (on the evaluated condition) revealed an amplitude transmission approaching more the exponential model than the commonly assumed Gaussian model. The use of a general transmission model also offers the advantage of providing a better basis for comparison in the case of small variations on the shape of the amplitude spectrum (e.g. the overall analysis will be less sensitive to unfavourable signal-to-noise ratios and/or small nonlinearities of the CT system).

Regarding the definition of the metrological structural resolution (cut-off wavelength for a transmission model value of 50%), it was made according to criteria adopted in international standards [19]. Despite it does not have a physical meaning (e.g. does not yield a direct relation to the current definition concept of metrological structural resolution [1]), it produces cut-off values which are the less sensitive to variations on the shape of the transmission model.

The proposed dimensionless parameter named number of voxels per wavelength showed to be a useful means to define the structural resolution of CT systems regardless of the magnification. By using the voxel size normalization, a unique, dimensionless transmission model can be used to fully define the structural resolution over a specific range of voxel sizes. This allows a more consistent comparison among CT systems. However, it does not mean that the *Nvpw*c cut-off value (or any other definition) can be viewed as *the* structural resolution of the CT system: using different data acquisition and processing parameters will change the value of the structural resolution (possibly also the shape of the transmission model), either in minor or major degree.

In order to implement structural resolution tests that allow a straight comparison between CT measuring systems, the measurement conditions (e.g. geometry and material of the standards, measurement procedures including setup parameters and data processing routines) should be properly defined [15].

7. CONCLUDING REMARKS

This paper presented a method and procedure for evaluating the metrological structural resolution of CT measuring systems using a MWS as material measure. Discussions on the applicability and limitations of the method were carried out. In general, the results demonstrate the potential of the method for characterizing and comparing CT systems regarding their metrological structural resolution.

The described method and procedure are under development. Further work on the method include defining an uncertainty model for the method, investigating linearity related issues and improving the design of the CT-MWS. Also, another applications of the method are being carried out e.g. comparing CT systems with more notably different characteristics, investigating a wider range of influencing factors and evaluating the stability of CT systems.

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