

# ON EVALUATION OF RESOLUTION PERFORMANCE OF HIGH ENERGY X-RAY CT

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## Abstract:

Dimensional X-ray CT has attracted production industry due to its nature [1] enabling not only external dimensional measurement but also internal dimensional measurement which has been difficult for pre-existing dimensional measurement instruments. However, because the reconstruction process of three dimensional volume image may be affected by various kinds of error sources of the hardware and also the software, performance evaluation of dimensional X-ray CT has become one of the major issues [2], especially for X-ray CT system with higher energy such as several MeV. Resolution performance of high energy X-ray CT was evaluated by using a series of phantoms which equip regular line-and-space structures with various pitch sizes from 10,000 down to 100 micrometer. These phantoms were prototyped in the identical pitch sizes with three different materials, namely Tungsten, Molybdenum, and Steel alloy. These phantoms were practically measured by a high energy X-ray. Preliminary evaluation results are presented as well as the design intention.

**Keywords:** X-ray CT, resolution, phantom, performance evaluation

## 1. INTRODUCTION

X ray CT especially designed for dimensional measurement is spreading due to its capability to quantify geometrical characteristic including size or form of industrial product not only for the external features but also the internal ones [3]. As mechanism of X ray CT to measure geometrical features requires collection of sinogram obtained by penetrated X ray magnitude due to distribution of materials to be measured, there are bunch of performance indices which are recognized to be important as qualitatively depicted in **Table-1**. Some of them are depending on performance of electro-thermo-mechanical behavior of components adopted similar to conventional coordinate measurement machines. Other is dominantly influenced by physical property of X ray beam, and so on. Within various components varying performance of X ray CT, resolution is one of the fundamental index since it may be influenced by quality of X ray source, scanning system, detector, imaging process, and also physical property of X ray itself.

Resolution of X ray CT has been tested typically by spread function observed on a material standard structured by point, line or edge. A typical procedure is known as sensory test performed by human eyes. The other may be

done by evaluation of MTF (modulation transfer function). Nevertheless existing phantoms and evaluation procedures are in most cases designed for lower power X-ray CT and not always suitable for X-ray CT with higher power such as several MeV. Emphasis of current study is placed on design proposal of a material standard and an evaluation procedure well suitable for evaluating high energy X-ray CT.

## 2. JAPANESE NATIONAL PROJECT FOR HIGH ENERGY X-RAY CT

It can be said that majority of industrial X-ray CT actually utilized in industry has rather lower power typically less than or equal to 225 kV which may penetrate, roughly saying, 100 mm of Aluminum or 10 mm of steel. Although the penetration ability is not always sufficient one for production industry it is difficult to enhance the penetration ability in drastic way. This situation is caused by well known trade off relation between the penetration ability and the resolution capability. Increasing penetration ability by adopting higher acceleration voltage for the X-ray source, the actual focal point where X-ray emits becomes blurred. For example, X-ray CT today with 225 kV may have several micrometers in size for the actual focal point. However, X-

Table-1 Performance index and dependency of X-ray CT

Congributor-1	Congributor-2	Penetration	Resolution	S/N ratio	Time	Image quality
X-ray source	Tube voltage	●		●		
	Tube current	●		●		
	Focal spot size		●			
	Focal spot drift		●			●
Scanning system	Magnification	●	●			
	Geometric errors					●
Detector	Integral time	●		●	●	
	Sensitivity	●		●		
	Collimation		●	●		
	Pixel size		●			
Imaging process	Geometric errors		●			●
	Filtering		●	●		●
	Voxel size		●		●	●
	Field of view				●	●
Object under test	Corrections		●	●	●	●
	Size			●		●
	Density			●		●
Metrological software	Shape			●		●
	Reconstruction				●	●
	Surfacing				●	●
X-ray Physical	Scattering			●		●
	Refraction		●			●
	Beam hardening					●

ray CT with several MeV may have several hundred micrometers in size. This situation is schematically illustrated in Fig. 1. In this figure, penetration ability of X-ray CT is simplified and represented in the vertical axis as X-ray energy. And resolution capability is indicated along the horizontal axis. Because of the trade-off relation between X-ray energy and resolution, either of them is taken as the prior performance index then the other will have to be suffered.

Recognizing the above technological limitation, we have started Japanese national project for developing high energy X-ray CT with higher resolution [3] since 2013. Development of the CT will be finished at the end of the fiscal year 2015, and the resolution performance will be tested by material standard and procedure proposed by this study.

### 3. DESIGN OF MATERIAL STANDARD

Range of resolution to be tested is considered to determine design of material standard for testing resolution of X-ray CT with higher power. X-ray CT with several MeV may have several hundred millimeters in size in conventional case. Therefore maximum size to be tested for resolution is determined as 5 mm. Minimum size is determined as 0.05 mm based on possible resolution expected to be realized by high energy X-ray CT with higher resolution.

#### 3.1 Structure or material standard for testing resolution

Within several possible structures for the material standard, line-and-space structure is chosen. This is mainly because of difficult material property of heavy metal such as Tungsten. Looks of developed material standard is shown in Fig. 2 and the design scheme is shown in Fig. 3. Representative dimensions are summarized in Table 2. The material standard is composed of two base plates each having ten different line-and-space peaces. The line-and-space peace can be fixed on the base plate either with radial direction or with tangential direction. Preliminary test in this article is performed by line-and-space peace to be in the radial direction.

Material selection of the material standard is also considered. Three different materials each having different X-ray attenuation are adopted, namely Tungsten, Molybdenum, and alloy steel.

As shown in Fig. 2, each material standard has allocated 10 different size of line-and-space structure along a circular formation with equally distanced each other. Each line-and-space structure has 20 lines made of planar material for smaller dimension. Lines made of planar material for larger dimension is decreasing to limit absorption length of X-ray within 20 mm in maximum. In case sufficient absorption length is not realized, a pair of rectangular blocks is attached just besides the line-and-space structure as to adjust respective absorption length. The material standard is located on rotary table of X-ray CT as the center axis of the material standard becomes nominally parallel with the rotation axis of X-ray CT.

Functionality of the prototyped material standards is conceptually shown in Fig. 4. Reconstructed image of the X-ray CT will show line-and-space structure when

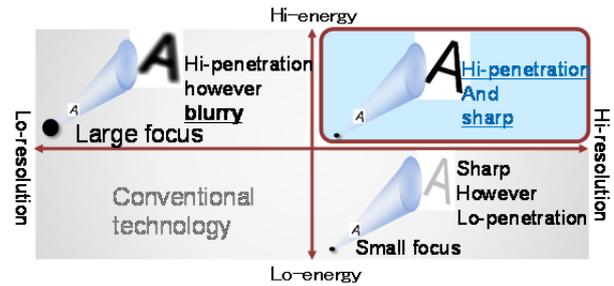


Fig. 1 Characteristics of X-ray CT

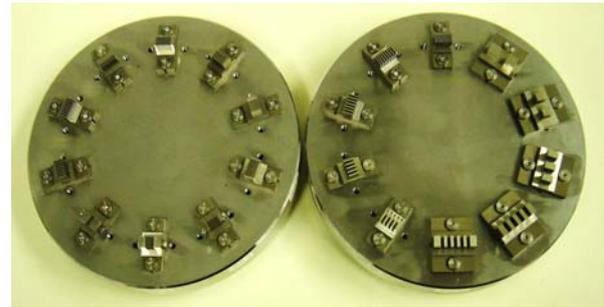


Fig. 2 View of prototyped material standard

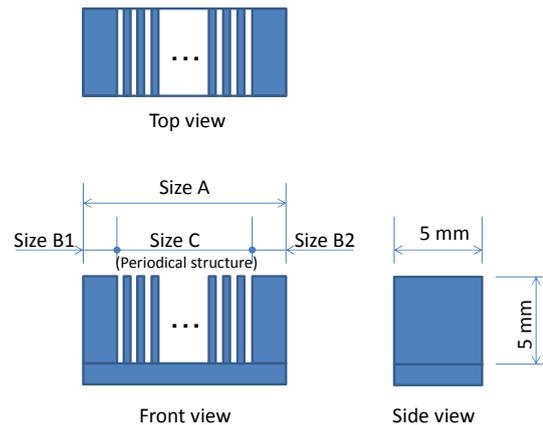


Fig. 3 Design scheme of material standard

Table 2 Representative dimensions of material standard

Identifi- cation No.	Line thickness [mm]	Number of line	Number of space	Size C (Periodical structure) [mm]	Size B1, Size B2 [mm]	Size A [mm]
1	0.05	20	21	2.05	3.975	10
2	0.1	20	21	4.1	2.95	10
3	0.15	20	21	6.15	1.925	10
4	0.2	20	21	8.2	0.9	10
5	0.25	10	11	5.25	2.375	10
6	0.3	10	11	6.3	1.85	10
7	0.35	10	11	7.35	1.325	10
8	0.4	10	11	8.4	0.8	10
9	0.45	10	11	9.45	0	10
10	0.5	10	11	10.5	0	10
11	0.6	8	9	10.2	0	10
12	0.7	6	7	9.1	0.45	10
13	0.8	5	6	8.8	0.6	10
14	0.9	5	6	9.9	0	10
15	1	5	6	11	0	10
16	1.5	4	5	13.5	3.25	20
17	2	3	4	14	3	20
18	3	3	4	21	0	20
19	4	2	3	20	0	20
20	5	2	3	25	0	20

resolution of the X-ray CT is sufficient for resolving volume image into line-and-space. Otherwise contrast of the line-and-space structure may be lost.

#### 4. PRELIMINARY EXPERIMENT

A preliminary test measurement of the prototyped material standard is performed by using a conventional high energy X-ray CT with beam energy of 9 MeV. Figure X depicts a schematic drawing of X-ray CT system used for the test.

##### 4.1 Scanning by high energy X-ray CT

An example of measurement result of the material standard made of Tungsten measured by 9 MeV X-ray CT is presented as Fig. 5. The top figure is the result obtained on the material standard with material thickness of from 0.6 mm up to 5 mm. The bottom one is that done on it from 0.05 mm up to 0.5 mm. It seems to be clear that line-and-space structures in the top figure are reconstructed well. On the other hand the line-and-space structures in the bottom figure are not.

A benefit of resolution testing by referring line-and-space structure is possibility of qualitative but direct eye inspection. However, it is worthwhile to have a possibility to know a quantitative index of resolution performance of X-ray CT.

##### 4.2 Visualization of measurement results

The line-and-space structures on the material standard are allocated along a circle with the pitch diameter of 100 mm. CT value distribution along the circle is extracted from volume data. Figure 6 shows an example of the extracted CT value distribution along the pitch circle of 100 mm. The experimental measurement was performed on the material standard made of Tungsten. Experimental measurement was performed by setting the material standard with fine periodical structures and the other with coarse ones each independently. A pair of CT values extracted from each measurement result is then combined for the succeeding data representation. Therefore CT value plotted in the figure is combined one obtained from two independent measurement results.

The abscissa indicates voxel number along the pitch circle, and the ordinate does relative CT values normalized by that of air to be zero and that of Tungsten to be one. Line thickness within line-and-space periodical structure are chosen as a representative size indication of the material standard and the number is plotted at the top of the figure for easy recognizing what is plotted at which location in the figure,

One sees constant response from the size of 5 mm down to 1.5 mm. One also notices attenuation of response from the size of 1.5 mm down to 0.5 mm. There is almost no response beyond the size of 0.5 mm down to 0.05 mm. The blue and the red arrows indicate the attenuation tendency of the response.

##### 4.3 Evaluation of resolution

Tendency of attenuation of response observed in Fig. 6 is going to be quantified in this section. Although a couple of quantification procedures have been proposed, a simple one

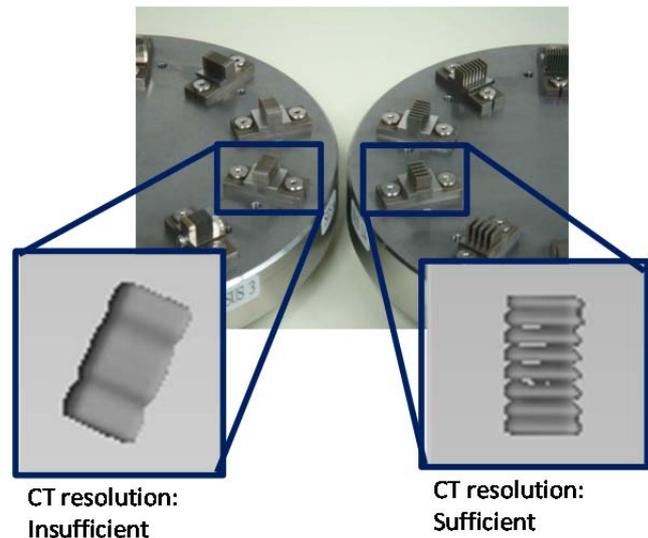
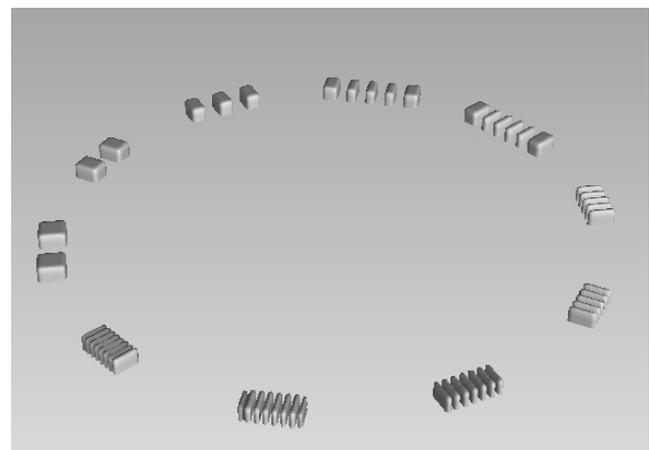
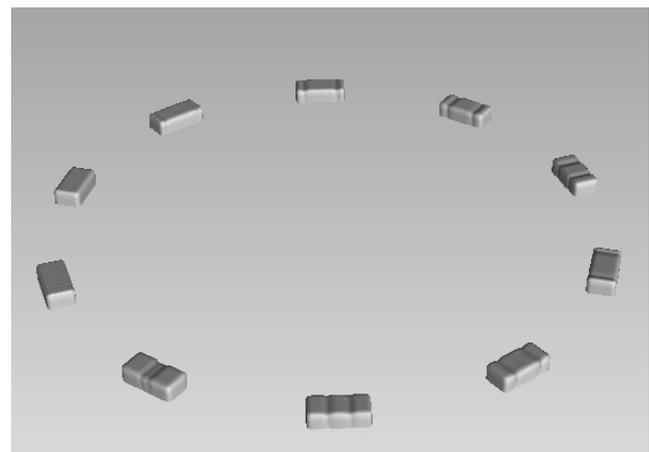


Fig. 4 Functionality of prototyped material standard



Range from 5 mm to 0.6 mm



Range from 0.5 mm to 0.05 mm

Fig. 5 Example of measurement result of material standard by high energy X-ray CT

which assumes response function of total X-ray CT system to be that dominated by a first order delay. In this case one may be able to choose one of following modelling procedures, namely time constant of unity step response, or

cut off spatial frequency of low pass filter response. The former procedure is to be adopted as a preliminary stage.

#### 4.4 Time constant of unity step response

Transient response of unity step response  $Z(t)$  for elapsed time  $t$  is expressed by equation (1) with the time constant  $T$ .

$$Z(t) = 1 - e^{-t/T} \quad (1)$$

With an assumption to the system having characteristic of first order delay, the time constant can either be calculated by a time when a condition of  $Z(t) = 0.63$  is satisfied, or a instance when a tangential line passing  $t = 0$  crosses the steady state value. Either possibility of data processing can be adopted in principle. However, since attenuation of the response is already graphically presented in above Fig. 6, the latter procedure is to be adopted in this study.

Figure 7 depicts relative CT-values experimentally observed when the material standard made of Tungsten with respect to each line size as the representative size. The blue plot is obtained from CT-values of air, and the red plot is done from that of Tungsten. The green plot is derived from CT-value difference between that of air and Tungsten. It is noted that the green plot is started from the value of around 1 when coarse spatial frequency is focused. The relative CT-value starts showing attenuated trend around the size of 1.5 mm and reaches to value around zero. By allocating horizontal line of 63.2% plotted by violet solid line in this figure, the size where the green plot crossed the 63.2% line is calculated as the corresponding time constant of the unity step response. According to definition described here for the resolution, preliminary tested high energy X-ray CT seems to show resolution performance of 0.75 mm.

The high energy X-ray CT was tested according to MTF with criterion of the MTF to be 0.5 as the resolution performance index. The result was reported to be 0.84 mm. It is noted that independently evaluated resolution performance indices conform each other with slight difference of 12 %, which is believed to be satisfactory result as the preliminary one.

### 5. CONCLUSION

Resolution performance of high energy X-ray CT was experimentally evaluated by using a series of material standards which equip regular line-and-space structures with various pitch sizes from 5,000 down to 50 micrometer. These material standards were prototyped in the identical pitch sizes with three different materials, namely Tungsten, Molybdenum, and Steel alloy. These material standards were practically scanned by a high energy X-ray CT, and analyzed by modelling of time constant of unity response. Preliminary evaluation results demonstrate satisfactory experimental result.

#### ACKNOWLEDGEMENTS

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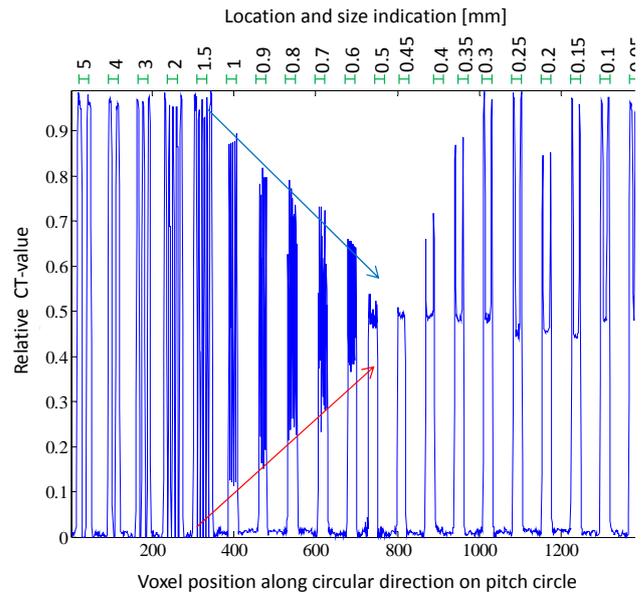


Fig. 6 Example of extracted CT-value distribution Along pitch circle of 100 mm in diameter

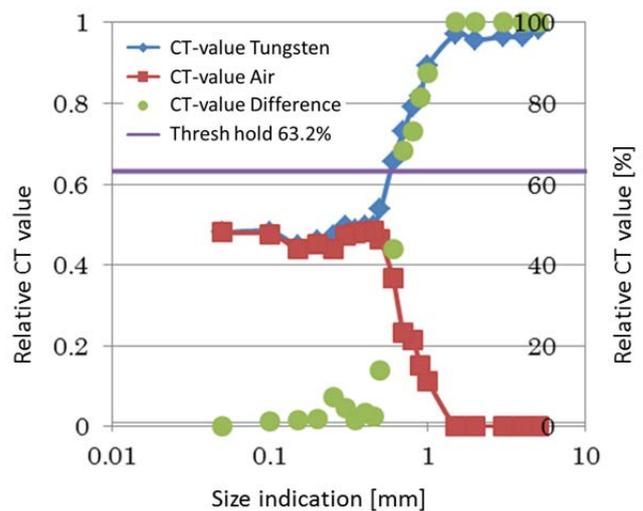


Fig. 7 Example of relative-CT value to derive resolution

Economy, Trade and Industry in Japan) project, Development of High energy, high resolution X-ray CT. Authors greatly appreciate the support.

#### REFERENCES

- [1] J. P. Kruth, et al., "Computed tomography for dimensional metrology", CIRP Annals, pp. 22-44, 2011.
- [2] L. Xue, H. Suzuki, Y. Ohtake, H. Fujimoto, M. Abe, O. Sato and T. Takatsuji, "Numerical Analysis of the FDK Effect on Industrial X-ray CT for Dimensional Metrology", 13th CIRP Conference on Computer Aided Tolerancing, Hangzhou, China, on May 11th-14th, 2014.
- [3] T. Takatsuji, M. Abe, and H. Fujimoto, "Dimensional X-ray CT in Japan, development, application and standardization", Proc. iCT2014, pp. 169-180, 2013.