The Selection of Computed Tomography Scanning Schemes for Lengthy Symmetric Objects

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Abstract. The article describes the basic computed tomography scan schemes for lengthy symmetric objects: continuous (discrete) rotation with a discrete linear movement; continuous (discrete) rotation with discrete linear movement to acquire 2D projection; continuous (discrete) linear movement with discrete rotation to acquire one–dimensional projection and continuous (discrete) rotation to acquire of 2D projection. The general method to calculate the scanning time is discussed in detail. It should be extracted the comparison principle to select a scanning scheme. This is because data are the same for all scanning schemes: the maximum energy of the X–ray radiation; the power of X–ray radiation source; the angle of the X-ray cone beam; the transverse dimension of a single detector; specified resolution and the maximum time, which is need to form one point of the original image and complies the number of registered photons). It demonstrates the possibilities of the above proposed method to compare the scanning schemes. Scanning object was a cylindrical object with the mass thickness is 4 g/cm^2, the effective atomic number is 15 and length is 1300 mm. It analyzes data of scanning time and concludes about the efficiency of scanning schemes. It examines the productivity of all schemes and selects the effective one.

1. Introduction

The manufacturing of modern nuclear fuel (NF), according to a given level of functionality, safety and reliability, is impossible without the complex control of NF's parameters. Since the middle of 80s X–ray computed tomography method (CT scan) is used to control the fuel elements [1–4]. CT scan allows valuate the internal object structure, correctness of assembly, etc. Due to the development of computer facilities and X–ray detection systems recently the 3D CT [5–11] is developed rapidly, which differs from the 2D CT scan realization by higher performance. A change of the fuel elements design leads to the necessity of complex theoretical and experimental studies, analysis of the results which will allow make a conclusion about the possibility of CT scan usage for multi–parameter examination of the fuel elements.

2. Basic CT Scan Schemes and Method for Calculation of Scanning Time

Let us discuss all the most popular scanning schemes of lengthy symmetric objects, a cylindrical fuel element with diameter H and length L is presented as example. The performance is inversely proportional to the total examination time T of the object. For all schemes the time T is defined by t_0 is the residence time of the detector systems in one position (the time to produce a projection), Δt is the time to travel the source–detectors system from one position to another, $\Delta\theta$ is a step of the rotation angle, k is the required number of time intervals for the "black" and "white" calibrations.

Scheme 1: Figure 1 displays the scheme for the classical CT scan method. In this scheme the object rotates discretely or continuously around the axis and a set of one–dimensional projections are acquired. After acquisition of projections for a one layer, the object is moved with scanning step Δx and the process repeats. Scanning step should not exceed the size of the sensitive volume of the detector in the scanning direction d.

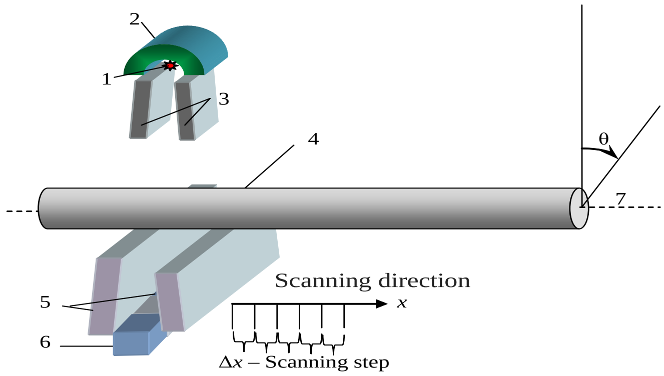

Figure 1. Continuous (discrete) rotation with a discrete linear movement, there 1 is radiation source; 2 is protection of the radiation source; 3 is collimator of source; 4 is scanning object; 5 is collimator of detector; 6 are detectors; 7 is rotation axis of scanning object.

The Equation to calculate the scanning time T for the first scheme has a form (1):

$$T = t_0 \times \frac{180}{\Delta\theta} \times \frac{L}{\Delta x} + \Delta t \frac{L}{\Delta x} + t_0 \times k, \tag{1}$$

Scheme 2: This modification of first scheme is based on the usage of the X–rays panel detector or the matrix of radiometric detectors. The scanning process generates a set of two–dimensional projections (Figure 2). In this scheme the object rotates discretely or continuously around the axis and a set of two–dimensional projections are acquired. After acquisition of projections for some layers, the object is moved with scanning step ΔX and the process repeats. Scanning step should not exceed the size of the sensitive size of the panel detector in the scanning direction D.

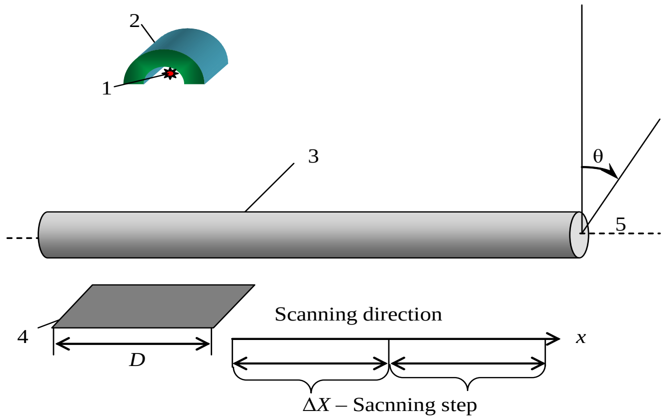

Figure 2. Continuous (discrete) rotation with discrete linear movement to acquire 2D projection, there 1 is radiation source; 2 is protection of radiation source; 3 is scanning object; 4 are matrix of detectors; 5 is rotation axis of scanning object.

The scanning time T is estimated by the Equation (2):

$$T = t_0 \times \frac{180}{\Delta\theta} \times \frac{L}{\Delta X} + \Delta t \frac{L}{\Delta X} + t_0 \times k \,. \tag{2}$$

The difference of second scheme from the first one is the acquisition of 2D projections and a discrete step of linear movement ΔX which is not compared with the size of a single detector d, but it is compared with the size of the detection system in the scanning direction D ($\Delta X \leq D$).

Scheme 3: In first scheme the axis of radiometric detector is perpendicular to the rotation axis. In this scheme, we use the lengthy radiometric detectors, which overlap a shadow of scanning object allow orientate the axis of radiometric detector parallel to the rotation axis (Figure 3). In this scheme the object moves discretely or continuously perpendicularly the axis and a set of one–dimensional projections are acquired. After acquisition of projections for some layers, the object is rotated with step $\Delta\theta$ and the process repeats.

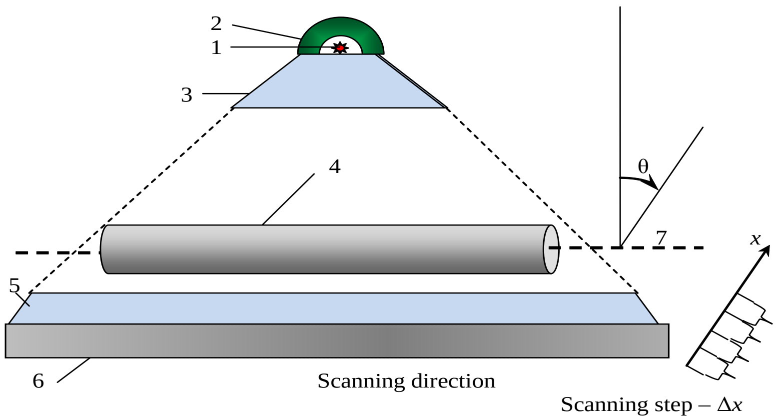

Figure 3. Continuous (discrete) linear movement with discrete rotation to acquire one– dimensional projection, there 1 is radiation source; 2 is protection of radiation source; 3 is collimator of source; 4 is scanning object; 5 is collimator of detector; 6 are detectors; 7 is rotation axis of scanning object.

As result of the discrete linear movement of scanning object relatively to the radiation source–detectors system, the first stage is a formation of shadow image. Then object is rotated on a predetermined angle and operation to form the one–dimensional projection is repeated as necessary.

Equation to evaluate the scanning time T for scheme 3 is (3):

$$T = t_0 \times \frac{180}{\Delta\theta} \times \frac{D_0}{\Delta x} + \Delta t \frac{180}{\Delta\theta} + t_0 \times k \,, \tag{3}$$

Here D_0 is transverse size of the scanning object shadow.

Scheme 4: The following scheme differs from the third scheme in X–ray recorder, as which is a panel detector or matrix of radiometric detectors. The mandatory requirement for the size of the detection system: The shadow of the scanning object is placed completely on the frontal surface of the detection system. Compliance with this requirement excludes the linear movement of the object, and retains only the rotation (Figure 4). In one position, two–dimensional projections of the whole object are acquired. After that, the object is rotated with step $\Delta\theta$ and the process repeats.

The Equation to calculate the scanning time T is:

$$T = t_0 \times \frac{180}{\Delta\theta} + \Delta t \frac{180}{\Delta\theta} + t_0 \times k \,, \tag{4}$$

There are many other scanning schemes, but all of them are derived from the schemes, which are shown in Figures 1–4.

For each of scanning schemes we must calculate the total time *T*, which need to receipt information to reconstruct a 3D structure.

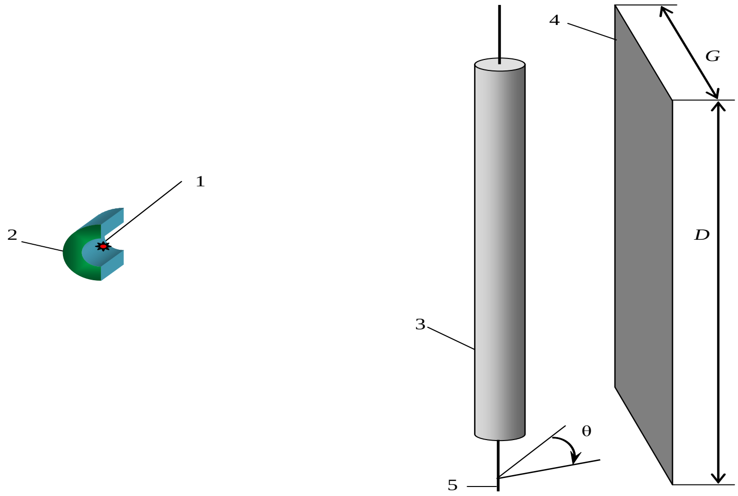

Figure 4. Continuous (discrete) rotation to acquire of 2D projection, there 1 is radiation source; 2 is protection of radiation source; 3 is scanning object; 4 are matrix of detectors; 5 is rotation axis of scanning object.

3. The Comparative Parameters of Scanning Scheme Productivity

The comparison principle to select a scanning scheme can be expressed by the phrase – "ceteris paribus". For "ceteris paribus" in this case is related that the data are same for all scanning schemes. The initial data are: $E_{\max}$ is the maximum energy of the X–ray radiation; P is a power of X–ray radiation source; ω is an angle of the X-ray cone beam; d is the transverse dimension of a single detector; r_{lim} is specified resolution, H is the diameter of the object.

Another parameter must have the same value for all scanning schemes, it is the maximum time t_0, which is need to form one point of the original image and complies the number of registered photons n_0. Time t_0 is chosen to maximize a value of product of the geometric easing and radiation easing. We assume that the anisotropy of X–ray radiation is insignificantly, the Equation to evaluate t_0 has the form (5):

$$t_0 = cP(\xi,\varphi)\max_{\xi,\varphi}\frac{e^{-\mu(E_{eff}(\rho H(\xi,\varphi)))\rho H(\xi,\varphi)}}{F^2(\xi,\varphi)}, \tag{5}$$

Here ξ, φ are the polar and azimuth angles in the coordinate system, which is associated with the radiation source; $\rho H(\xi,\varphi)$ is the average mass thickness of the object in the direction ξ, φ; E_{eff} is effective energy of X–rays; c is recalculated coefficient of power in the number of particles. In the first and third schemes only polar angle is significant.

The above presented method is allowed to compare productivity of different scanning schemes for lengthy symmetric objects.

4. Example of Calculation for ScanningTime

Let demonstrate the possibilities of the above proposed method to compare the scanning schemes. Scanning object was the cylindrical object. The mass thickness is 4 g/cm^2, the effective atomic number is 15 and length is 1300 mm. The transverse size of a single detector is 0.1×0.1 mm^2. Angle θ = 40°, 60°, 80°. Highest energy of radiation was E_{max}=*250 keV*.

We calculated the scanning time for all schemes. The results of calculation are summarized in Table 1.

Table 1. Scanning time *T*.

Angle θ, °	Scanning scheme	Scanning time (unit of time)
40	1	1.000
40	2	0.840
40	3	30.000
40	4	1.459
60	1	1.000
60	2	0.039
60	3	20.570
60	4	0.665
80	1	1.000
80	2	0.019
80	3	13.419
80	4	0.328

5. Conclusions

From the analysis data we can conclude that the scanning scheme “Continuous (discrete) rotation with discrete linear movement for the formation of 2D projection” has greatest efficiency. The scheme “Continuous (discrete) linear movement with discrete rotation for the formation of one–dimensional projection” is least effective. The reason of this fact is the necessity to save the radiation field. That leads to increase in distance from the radiation source to the scanning object. With increasing the scanning angle, the efficiency of the scanning schemes is changed and scheme “Continuous (discrete) linear movement with discrete rotation for the formation of one–dimensional projection” would be the most inefficient. The selection between the scanning scheme “Continuous (discrete) rotation with discrete linear movement for the formation of 2D projection” and scheme“Continuous (discrete) rotation for the formation of 2D projection”must do the user.

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