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3D imaging of geometrical structure and defect location of inner cavity in aviation devices by positron injection

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***Abstract* — Aviation devices such as aero powertrain, hydraulic system are usually with inner cavity structure which is relatively complex. One of the most important challenges are how to determine the spatial geometrical structure and defect in the inner cavity. A 3D imaging method of interior and defect in inner cavity by positron injection is presented on the basis of positron annihilation theory in this paper. Low energy radionuclide is injected into inner cavity in which radionuclide produce positron. PET records the amount of γ photons produced by positron annihilation. Then the maximum likelihood estimation model is introduced and by solving which a 2D slice image sequence is obtained by Ordered Subset Expectation Maximization algorithm (OSEM). At last, a 3D image is reconstructed by the 2D slice image sequence and the 3D image is used to analyze the spatial geometrical structure and defect of inner cavity and thus a new method for the analysis of spatial geometrical structure and defect of inner cavity in aviation devices is generated.**

I. Introduction

At present, the image of inner cavity with complex structure is obtained by industrial CT 3D imaging which has some limitations in actual application. [1-2]The high energy linear accelerator acceleration produces X-ray or γ-ray with up to several megabytes energy which then penetrate the under testing object. 2D plane projection is generated according to energy attenuation degree. This method has a big radiation hazard; [3]The under testing object should be fixed on a sliding-rotary table on which the object could move up and down and vortically following the table when tested by industrial CT. The structure of the system determines that a single 2D plane projection image can be generated each moment and thus the industrial CT imaging is a plane asynchronous imaging method which is not a real-time dynamic detection method. [4]Parts with complex structural inner cavity are often used in power system of hydraulic pressure, engine, gearbox and the parts must be separated from the power system when tested by industrial CT. Thus the industrial CT is a static testing for geometric structure of the inner cavity. Aiming at the above problems, a 3D imaging method of interior and defect in inner cavity by positron injection is presented which has the following three properties. [5]The radionuclide half-life of 18F is only 110 minutes, the positron production rate is as high as 97% and the largest energy just 0.635MeV. The amount of radiation hazard is far less than industrial CT; the parts is just placed inside the detector ring of PET when tested by positron injection, and the detectors record the amount of γ photons produced by positron annihilation in inner cavity. [6]2D slice image sequence is a profile image sequence of inner cavity by adopting the OSEM algorithm and thus the 3D imaging by positron injection is a space synchronous imaging method. Parts do not need to be separated from the power system when tested by positron injection as long as choosing the proper radionuclide and carrier solution. A real-time dynamic detection for structure of inner cavity and state change could be directly operated through the liquid radioactive nuclide.

PET 3D imaging need to find a proper mathematical model to form the relation between radionuclide concentration distribution and the amount of tested γ photons. [7] The maximum likelihood estimation model is presented due to the amount of tested γ photons which follows Possion distribution. It is hard to solve the likelihood equation directly and iteratively which is a complex nonlinear system of equations. While a Maximum Likelihood Expectation Method (MLEM) could achieve the goal of maximum the likelihood function indirectly which could avoid solving the likelihood equation directly; [8]The OSEM algorithm is present on the basis of MLEM algorithm to obtain a higher accuracy of the reconstructed slice image. The projection data is divided into n subsets in each iteration of MLEM algorithm. Each subset will revise all pixel value of reconstructed image and the reconstructed image will be updated correspondingly. The targets such as interior and defects need to be enhanced in slice image before 3D image reconstruction and hence an image segmentation problem appears. While threshold segmentation is a widely used and effective image segmentation method. 3D image could be reconstructed by the enhanced slice images which obtained from OSEM algorithm.

Some scholars has applied PET 3D imaging to industrial and medical research. [9] High-energy photons up to 16MeV provided by the superconducting electron linear accelerator in Helmholtz-Zentrum Dresden-Rossendorf transport to a 25 mm diameter PTFE (Teflon) cylinder with embedded slabs made from Copper, Iron, and Aluminium having the same volume (12 mm2 × 25 mm) but different geometrical shapes. In-situ production of positrons inside the sample from bremsstrahlung production generates and then annihilates. 3D annihilation lifetime maps have been created in an offline-analysis employing well-known techniques from PET; [10] Myocardial blood flow from dynamic PET using independent component analysis.

II. THEORY OF PET 3D IMAGING

The parts is placed inside the detector ring of PET after radionuclide solution is injected into inner cavity of parts with complex structure and the Bi_2O_3-GeO_2 (BGO) detectors record the amount of γ photons produced by positron annihilation in inner cavity. Assumed that slice image contains n pixels and the estimated value of pixel j is xj (j = 1, 2,..., n) which is directly proportional to the concentration of the radioactive nuclide. bi is the amount of detected γ photons along the i line of the response(LOR) and the annihilation data which is the amount of γ photons detected by the detector pair mutual into 180° in direction is recorded by the response values. The relation between image pixel and the amount of γ photons is showed in Fig. 1.

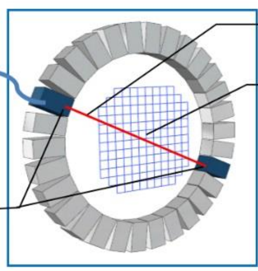

Fig. 1. Relation between image pixel and amount of γ photons

The offline 3D imaging of interior and defect in inner cavity adopts OSEM-OTSU algorithm after BGO detectors obtain the image data. A maximum likelihood estimation model complying by Possion distribution is established due to the amount of detected γ photons is a certain variant complying by Possion distribution and OSEM algorithm could accurately obtain the optimal solution of the model. Thus 2D slice image of interior and defect in inner cavity generates. The targets such as interior and defects in 2D slice image sequence need to be enhanced due to the existence of blocking or defect which leads to an image segmentation problem. While threshold segmentation is a widely used and effective image segmentation method. OTSU algorithm is widely adopted because of its better segmentation effect, wide range of application and effectiveness. 3D image could be reconstructed by the enhanced slice images which obtained from OSEM-OTSU algorithm.

III. POSITRON INJECTION METHOD

The radioactive nuclides which belong to low energy nuclide is chosen according to the specific requirements of the experiment and the its inherent half-life (such as ^{18}F has a half-life of 110 min and the maximum energy of 0.635MeV, 64Cu has a half-life of 12.8 h and the maximum energy of 0.573MeV). Positron could annihilates in inner cavity by the way that the radioactive nuclides are soluble in other medium solution due to the inherent property that the radioactive nuclides are soluble in carrier solution in the form of ions and γ photons produce later with the energy of 511KeV. Positron annihilation has two forms in the above process: free state annihilation and captured state annihilation which can represent the interior and the defect in inner cavity. The former represents that positrons annihilate in interior and inner wall with a complete structure. The latter represents that positrons annihilate in defects and blockings in inner cavity. The offline mathematical model could be established that represents the relation between image pixel and amount of γ photons according to the detected image data. 3D images of interior and defect in inner cavity generate by solving the model and thus the spatial geometrical shape of inner cavity in parts can be analyzed directly.

The single energy γ-ray with intensity I_0 inject into the flat absorber vertically with the thickness of L cm and whose intensity decay following the exponential decay according to the theory of photon energy attenuation.

$$I = I_0 e^{-\mu L} . \tag{1}$$

μ is the decay parameter, I/I0 is the transmittance of γ-ray which increases along with the increase of γ-ray energy and decreases along with the increase of the thickness of the absorber. [11]The attenuation coefficients of γ-ray with different energy penetrating different absorber are obtained by monte carlo simulation (cm^{-1}) as showed in Tab. 1.

TABLE I
THE ATTENUATION COEFFICIENTS OF Γ-RAY WITH DIFFERENT ENERGY PENETRATING DIFFERENT ABSORBER

Mev	Al	Iron	Cu	Lead	Tin	PLA
0.5	0.227	0.573	0.642	1.213	0.629	0.1197
1	0.166	0.468	0.515	0.77	0.405	0.0905
1.5	0.135	0.383	0.423	0.581	0.328	0.0768

The depths γ-ray with energy of 0.511MeV penetrate the aluminum alloy and PLA material are 30mm~200mm and 57mm~384mm respectively when γ-ray energy decay to 50%~1%. The energy resolution of BGO detector is 15% used in the experiments conducted in this paper. So the depths γ-ray penetrate the aluminum alloy and PLA material are 83.574mm and 158.490mm respectively which meet the requirements of the experiments due to the biggest thicknesses of aluminum material U-tube and trapezoidal PLA chunk are 3mm and

40mm. The γ photons produced by positron annihilation in inner cavity of the two parts can be completely detected by BGO detectors. Never had a scholar engaged in the research of 3D imaging of interior and defect in inner cavity by positron injection due to the limitation of the factors such as photons penetrating ability, energy resolution of detectors, detector ring size .etc.

IV. THE EXPERIMENT PROCESS

(1) The preparation of parts with complex inner cavity structure

In the aluminum material experiment, an aluminum tube is chosen with the wall thickness of 2mm, the internal diameter of 10mm and the length of 400mm as showed in Fig. 2. In order to verify the imaging accuracy of 3D imaging to the parts with random bending shape, the aluminum tube is bent into U shape in the form of cold rolling and made upwarps on both ends of the tube so as to holding a certain volume of liquid. There exists a butterfly shaped compression deformation in the bending area of U-tube during cold rolling. In order to make the model more in line with the actual internal structure of parts, 8 pieces of steel balls with diameters ranging from 4mm to 8 mm represent diverter valve cores of parts which could roll in the U-tube to increase the complexity of the inner cavity structure of the experimental model as showed in Fig. 3.

Fig. 2. Al tube

Fig.3. Steel balls

(2) The experiment and 3D imaging of interior and defect in inner cavity

The MINItrace cyclotron produces radionuclide ^{18}F the experiment needed. 8 pieces of steel balls with different size are put into U-tube and 1254μCi of ^{18}F and 35ml of pure water are injected into U-tube respectively. The sealing membrane and duct tape seal the two ends of U-tube which then is placed on the PET scanning bed for static scanning (the BGO detectors count the amount of γ photons by positron annihilation) that lasts 10min. The PET equipment is Trans - PET ® BioCaliburn ® 700 which has 12 BGO detectors and whose sensitivity is 2.00%, spatial resolution is 1.00mm, time resolution is 1.5ns and energy resolution is 15%.

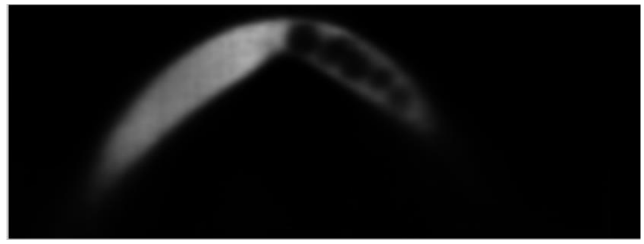

Fig. 4. 2D slice image of U-tube by OSEM algorithm

Fig. 5. Threshold is 100

Fig. 6. Threshold is 130

V. THE RESULT ANALYSIS

Fig. 4 is one of 2D slice images of U-tube by positron annihilation and OSEM algorithm. Fig. 5-6 are the 3D reconstructed images with thresholds of 100and 130 respectively. The imaging process of the experiment forms the basis that the blocks in inner cavity of aviation devices can be detected by positron injection. The spatial location and distribution of steel balls can be accurately determined by 3D imaging as showed in Fig. 6. A feasible testing scheme is provided for aviation devices with the similar inner cavity structure such as hydraulic system.

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