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A feasibility study on gamma-ray tomography by Monte Carlo simulation for development of portable tomographic system

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ABSTRACT

The electron beam X-ray tomographic scanner has been used in industrial and medical field since it was developed two decades ago. However, X-ray electron beam tomography has remained as indoor equipment because of its bulky hardware of X-ray generation devices. By replacing X-ray devices of electron beam CT with a gamma-ray source, a tomographic system can be a portable device. This paper introduces analysis and simulation results on industrial gamma-ray tomographic system with scanning geometry similar to electron beam CT. The gamma-ray tomographic system is introduced through the geometrical layout and analysis on non-uniformly distributed problem. The proposed system adopts clamp-on type device to actualize portable industrial system. MCNPx is used to generate virtual experimental data. Pulse height spectra from F8 tally of MCNPx are obtained for single channel counting data of photo-peak and gross counting. Photo-peak and gross counting data are reconstructed for the cross-sectional image of simulation phantoms by ART, Total Variation algorithm and ML-EM. Image reconstruction results from Monte Carlo simulation show that the proposed tomographic system can provide the image solution for industrial objects. Those results provide the preliminary data for the tomographic scanner, which will be developed in future work.

1. Introduction

Electron beam tomography was introduced in the medical field more than two decades ago, where it was mainly used for cardiovascular diagnostics (Boyd and Lipton, 1983). Later, it was also used to trace multiphase flows (Fischer et al., 2008). In their system, detector array of arc shape overlapped with the arc shaped target anode ring in opposite side. In their studies, the detection systems were fixed and a scanning electron beam was rapidly swept across an X-ray target using deflection coils. Thus very fast scanning was possible in these studies, but their geometry resulted in a heavy and bulky system because of a complex control system and vacuum tube. Because of its heavy hardware, electron beam tomography has remained as indoor equipment. Large portion of the systems are related to the radiation generating device in electron beam tomography. If a radiation generating device is replaced by a gamma-ray source, a tomographic system will have a small size source device. In addition, a tomographic system with a gamma-ray source can be designed clamp-on type system because it does not need a vacuum guide for an electron beam. There is a lot of need for a portable tomographic system in industrial application, but so far no definitive solution has been created. The inspection of industrial on-line pipes, wood telephone poles and cultural assets are some application areas (IAEA, 2008; Johansen and Jackson, 2004; Chaouki et al., 1997).

This paper carries out a feasibility study on a clamp-on portable tomographic system with a gamma-ray source. The system has a similar scanning geometry to electron beam CT excepting radiation generation part. The hardware description of the system is introduced in chapter 2. Analysis on non-uniformly distributed projection case is presented in chapter 3. Using the MCNPx (Los Alamos, 2003), virtual experimental data for two phantoms are calculated. Image reconstructions have been performed for those data by the algorithms, which are known to be suitable for the non-uniformly distributed projection problems. The image reconstruction method, Monte Carlo simulation setup, image reconstruction results are introduced in chapters 4–5.

2. Design of clamp-on tomographic scanner

2.1. Hardware description

Fig. 1 shows the CAD drawing of clamp-on portable gamma-ray tomographic scanner. In this scanning geometry, the

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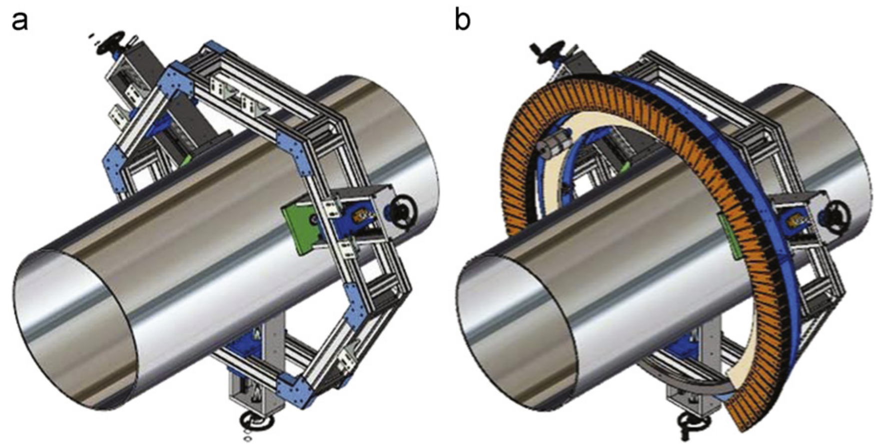

Fig. 1. Cad drawing of the clamp-on portable gamma-ray tomographic scanner: (a) clamping device and (b) tomographic scanner with clamping device.

tomographic scanner has a fixed detection system with a moving radiation emitting source. A sealed radioisotope of ^{137}Cs is used instead of radiation generator. The source has active region of about 6 mm × 7.5 mm in dimension of cylindrical shape. The gamma-ray source is installed in collimator of 6 cm diameter and attached to a source moving track. The detection system and source moving track are shaped like a "C" and can envelope a pipe-like object. To envelope and scan an object, the opening size of scanner must be bigger than the object size. Bigger sized object requires larger missing angle while smaller size object requires smaller missing angle. There is optimal combination of open angle and maximum object size in designing the system. Their relationship is characterized and discussed in chapter 3 in details. For industrial application, accessory devices such as clamping units are needed. The clamping device is attached to the object first, and the tomographic scanner is attached to the clamping device as in Fig. 1. For this reason, we call this scanner clamp-on tomographic scanner. The fixed detection and source rotating system has fewer number of effective detector than standard 3rd generation geometry (fan beam geometry). However it has advantages over standard fan beam system in portability. Designing rotation of source and detection system increases mechanical complexity such as more space, weight and complex electronic system. The fixed detector and source rotating system can reduce mechanical complexity and requires a much smaller space than a conventional CT. The weight of proposed scanner without clamping device will be around 25 kg in design specification. Weight is one of the important factors in designing a portable system. For the scanner to encircle an object, the detector arc and source moving track should be in the same open position. When it performs scanning, the source moves along the source moving track in order to generate projections. The route of the source's movement is shaped like a "C" as the detector arc.

2.2. Radiation measurement system

In comparison to X-ray CT, gamma-ray tomographic scanners use isotopic sources. Sealed radioisotope sources such as ^{137}Cs or ^{60}Co are much more flexible to handle. Therefore, they are often in favor for plant inspection areas. However, one drawback is a comparatively low photon flux compared to X-ray sources. Seibert (2004) presented calculation that a typical medical CT scanner operating at 120 kVp produces 6.7×10^6 X-ray photons/mm^2-s per 1 mA of tube current at 50 cm distance from the focal point. The equivalent activity of radioisotope is 2.072×10^{13} Bq (560 Ci) per mA when the isotope has a photon yield per Bq. In a typical medical X-ray CT, tube can produce current up to 500 mA and its equivalent activity for a gamma ray source is around $\sim4.14\times10^{15}$ Bq (112,000 Ci). It shows that X-ray tube can produce the extremely high photon flux compared with a radioactive source. Because of high flux, X-ray tomography systems can adopt current mode high resolution detection system.

In industrial gamma-ray CT, due to low photon flux, pulse mode detection systems have been widely used. Bieberle et al. (2007) introduced the gamma-ray CT using 320 sets of 2 × 8 × 16 mm uncollimated detectors and ^{137}Cs of 5 Ci and it was used for the study of a stirred chemical reactor (Hampel et al., 2007). Boyer and Fanget (2002) introduced a 2.54 × 2.54 collimated BGO detector based gamma-ray CT and ^{137}Cs of 500 mCi and it was used for inspecting a lab scale trickled bed reactor (Boyer et al., 2005). In this paper, PIN diode coupled CsI detector (12 mm × 12 mm × 20 mm) is designed for detection system because of their portability and compact size. The CsI detector can be operated by low voltage DC bias. It is developed for gamma-ray tomographic scanning. It is operated in pulse mode counting with 5 μ shaping time. The CsI detector is used for Monte Carlo simulation model in chapter 5. In MCNPx program, the Full Width at Half Maximum of detector energy resolution is determined by built-in function as Eq. (1). In Eq. (1), E is the energy in MeV, and a, b and c are user defined constants. From the measurement, the energy resolutions of CsI detector are 11.58% and 6.08% for 0.662 and 1.33 MeV, respectively. And by those values, user defined values are calculated as $a=0$, $b=0.08922$ and $c=-0.1537$.

$$FWHM = a + b(E + cE^2)^{1/2} \quad (1)$$

3. Consideration for non-uniformly distributed projection cases

For the scanner in this work, where full scan is impossible to be performed, this paper discusses the stable image reconstruction range by analyzing the range of measurement angle for the point inside the image circle. For simpler explanation, detector spatial resolution, source angular step and cross talk are not considered here.

To simplify the definition of scanning geometries, the general terms as 1st–4th generation scanning are described. Generally, measurement geometry for CT scanners can be categorized into 1st–4th generation (Cho, 1993; Goldman, 2007; Johansen and Jackson, 2004). The 1st generation CT is parallel beam type, which turns the translation and rotation of single source and detector pair. The 2nd generation geometry has multi-detectors, but they cannot cover an object entirely and have to translate to fully cover