Transmission computerized tomography with a high-energy and quasi-monochromatic photon beam

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Abstract

A high-energy and quasi-monochromatic photon transmission Computerized Tomography system has been developed. The system is used for a nondestructive inspection of industrial products with high-atomic number and high density, and for high-quality inspection of homogeneity/heterogeneity of sintered materials or metal diecasts. Overall system description and some experimental results measured with the prototype CT system are presented.

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1. Introduction

High-energy photon transmission radiography and Computerized Tomography (CT) is one of the simple and conventional methods for nondestructive inspection of industrial products. Some systems use high-energy gamma-rays from radioactive isotopes [1,2], and some use high-energy Bremsstrahlung X-rays from an electron accelerator. The latter one is widely used in many industrial and research facilities for inspections of industrial products with high-atomic numbers or high density, such as composite parts for electronic devices, motor vehicle, aircraft, and power plant. Many of them apply a compact electron accelerator whose electron energy is less than about 10 MeV to suppress neutron production, so that the overall system can be compact.

It is pointed out, however, that the energy spectrum of the Bremsstrahlung X-rays is a continuum and the average photon energy is very low, while the highest photon energy extends to the maximum electron energy. So, there are two major problems associated with this system,
because the attenuation coefficient [3] for low-energy photons, such as soft X-rays and hard X-rays is many orders larger than that for high-energy photons or gamma-rays of about 0.5 MeV or higher. The first one is that without a proper preprocessing of the data, the beam hardening effect causes an artifact on the reconstructed images because the photons are polychromatic. The second one is that the overall transmission efficiency of the Bremsstrahlung X-ray is very low. So, significant amount of photons have to be incident on the test object to compensate the transmission loss. The widespread use of the radiography system using an electron accelerator owes to the fact that the photon intensity can be made high compared to the conventional radiography system using X-rays and Gamma-rays from radioactive isotopes.

Both problems can be cleared for the CT system using high-energy and quasi-monochromatic photons [4,5]. Because the beam hardening effect stems from the fact that the photon attenuation coefficient is a strong function of the photon energy, the artifact does not appear on the CT image with monochromatic photons, or with polychromatic photons of same attenuation coefficients. The photon transmission efficiency is at its maximum when the attenuation coefficient is at its minimum. For elements of high-atomic numbers, such as iron and lead which are commonly used for many industrial products, the total attenuation coefficient is at its minimum, and shows moderate dependence on the photon energy about a few MeV or higher, where the pair creation interaction is dominant. So, we will be able to enhance the image quality by a reduction of the beam-hardening effect, enhancement of transmission efficiency and linearity of measured attenuation coefficient. In this study, we will briefly describe a prototype CT system for nondestructive industrial inspection with high-energy and quasi-monochromatic photon beam.

2. High-energy and quasi-monochromatic photon beam

High-energy and quasi-monochromatic photons can be produced by the laser-Compton scattering (LCS) of an intense laser beam with relativistic electrons [6]. One of the excellent properties of the LCS photons is that the beam divergence is very small. It is on the same order of the synchrotron radiation. Fig. 1 shows a schematic drawing of the kinematics of the LCS. One can obtain photons with good directionality and with narrow spectrum width by putting a collimator along the photon beam line, because the energy of the scattered photons via the Compton scattering depends on the scattered angle, $\theta_2$. Here is a formula, which describes the scattered photon energy as a function of the collision angles:

$$E_\gamma = \frac{E_L(1-\beta \cos(\theta_1))}{1-\beta \cos(\theta_2)+E_L(1-\beta \cos(\theta_2-\theta_1))}$$

where $\beta = \sqrt{1 - \gamma^2}$, $\gamma = E_e/0.511$ (1)

where $E_\gamma$, $E_L$ and $E_e$ stand for the energies of a LCS photon, a laser quantum and an electron, respectively, in MeV. $\theta_1$ and $\theta_2$ are the angles of the laser quantum before and after the Compton scattering, measured with respect to the motion of the electron, where $\theta_1$ becomes $\pi$ in the head-on configuration that we applied in this study.

We have been developing the LCS photon radiography and CT systems using the LCS photon facility of National Institute of Advanced Industrial Science and Technology (AIST) in Japan [7,8]. The photon facility generates 1–40 MeV quasi-monochromatic and energy-tunable photon beams of up to $10^6$ photons cm$^{-2}$ s$^{-1}$ using 300–800 MeV electron storage ring...
“TERAS” [9] and various lasers. Fig. 2 shows the energy of the scattered photon as a function of the scattered angle, $\theta_2$, assuming the head-on collision ($\theta_1 = \pi$) of a 1064 nm laser quantum with a 760 MeV electron, calculated from the Klein–Nishina formula. It is understood that energy spread of a few percent can be obtained by confining the angular divergence to a few hundreds of $\mu$rad.

3. Experiment

CT experiments were done at the LCS-3 beam line of AIST-LCS photon facility. We used a commercial Nd:YVO$_4$ laser (SPECTRA-PHY-SICS, Millennia IR, TEM$_{00}$ CW 10W, 1064 nm) and an electron beam of 760 MeV, which produced the LCS photon beam whose Compton edge was 10 MeV. Fig. 3 shows a schematic view of the upstream-end of the LCS-3 beam line of AIST-LCS photon facility. The laser light is mode-matched with the mode-matching optics, and guided into the vacuum chamber by the 1st and 2nd steering mirrors. The photon beam is generated via the Compton scattering at the center of one of the straight sections of TERAS where the laser beam waist is located. We call this point the collision point. The LCS photons go along with the electrons that are swept away at one of the bending magnets of the storage ring downstream of the collision point, and penetrate the view-port made of a fused silica window, which divide the ultra-high-vacuum inside the storage ring and the atmospheric pressure, while the laser beam transmit through it without significant attenuation. Then, the LCS photons transmit the 2nd steering mirror depositing negligible energy on these components.

Fig. 4 shows a drawing of the downstream-end of the beam line together with the prototype CT system. There is a lead collimator along the LCS photon beam line 6.2 m downstream of the collision point, called the 1st collimator, with inner diameter of 2.8 mm and thickness of 100 mm. The role of this collimator is to roughly shape the energy spectrum and the beam profile of the LCS photons, and to suppress the low-energy background photons, which are mainly produced from
the Bremsstrahlung of the relativistic electrons that collided with the residual gas molecules in the vacuum chamber. The photon beam is guided about 12 m in the air out of the view-port to the experimental room.

Because the diameter and the divergence of the photon beam were very small, we built a 1st generation CT system. The test object was put on a PC-controlled CT stage, which had three axes of motion; rotation, horizontal and vertical with respect to the photon beam. They are driven and controlled by AC servomotors systematically controlled by the software running on LabVIEW of NATIONAL INSTRUMENTS on Windows 2000 on a PC. The absolute travel distance for each axis is 360° for rotation, 175 mm for horizontal, and 140 mm for vertical. The position reproducibility is better than 50 μm by clearing the backlash each time using precision photo-sensors. The stage can support test object of as much as 10 kg mass.

The 2nd collimator, which was placed behind the test object not only defined the spectrum width and spatial resolution, but also reduced the background photons that originated from the test object with small angles via the Compton scattering. We used the lead collimator of 2 mm of inner diameter. The resulting beam diameter and the divergence are 1.8 mm and 70 μrad, respectively, at the object position.

A large NaI(Tl) scintillation photon detector whose diameter and height was 8 and 12 in., respectively, measures the energy and the intensity of the photons. It almost fully absorbs the photons with the energies up to 40 MeV. Fig. 5 shows the energy spectrum of the LCS photons measured with the NaI(Tl) photon detector. Assuming an energy resolution of the NaI(Tl) scintillation
detector for 10 MeV photons of 7%, that is the measured one at 1460.75 keV for gamma-rays from $^{40}$K, the spectrum width of the LCS photon is about 19% in FWHM.

Fig. 6 shows the radiograph of the sample object. It is an FM tetrode tube TH571A of THOMSON TUBES ELECTRONIQUES consisting of iron, copper, aluminum, ceramics, and so on, whose inside structures were invisible from outside. This tube is used in the RF system of the storage ring TERAS. The solid lines with sequentially labeled A–H are the CT-scanned slice positions. The slice thickness and the scanned width were 1 and 100 mm, respectively. The measurement took about 1 h for each slice, and was done as follows:

1. Continuously rotating the sample while accumulating the photon counts in each 3.6°-step until the object turns 360°.
2. Moving the stage 1 mm horizontally.
3. Repeat processes 1 and 2, until the stage has moved 100 mm.
4. Complete one set of measurements. Then, move the stage vertically, and repeat processes 1–3.

Figs. 7 show the reconstructed CT images. We can see the cross-sectional views of inside the sample object. The letters on the top of the images correspond to the slice positions. The gray level shows the areas of high density or large linear attenuation coefficient. The reconstruction was done with the filtered-back-projection method offline. The logarithms of the counts per 3.6°/mm normalized to the incident photon intensity were Fourier transformed using the Fast Fourier Transformation (FFT) algorithm, and multiplied with the filtering function in the Fourier regime. We used a rectangular filtering function with the highest cutoff frequency at the Nyquist frequency. The data in the Fourier regime were, then, inversely Fourier transformed followed by the
coordinate exchange according to the standard tomography method.

4. Discussion

The present results obtained with the experiment using the prototype CT system showed that we will be able to build the high-energy and quasi-monochromatic transmission photon CT system effective for the inspection of large industrial products. However, we should reduce the scanning time to improve the immediacy of information of the present CT system. We are currently trying to make the intensity of the LCS photons higher by increasing the effective laser power that interacts with the electrons. Further studies are required with this method, and it will be discussed in future work.

Our next plan is to evaluate the spatial resolution, and the linearity of the measured attenuation coefficient and the actual density of the sample object, so that we know the relation of the LCS photon intensity and the scanning time to give the best performance of the overall system for non-destructive inspection of test objects.

5. Summary

A high-energy and quasi-monochromatic photon radiography and CT system using the LCS photon beam of the AIST-LCS facility has been developed, and the first CT experiments were done with the 10 MeV LCS photons with 19% energy spread. The test object was the RF tetrode tube made of iron, copper, aluminum, ceramics, and so on. We successfully obtained the cross-sectional images of the sample object. Further studies on the CT system using the LCS photon beam are undergoing.

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References