

Gamma-Ray Inspection of Rotating Object - GIRO

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Introduction

Radioactive tracer technology is widely used in industry for non-destructive, continuous and real-time monitoring of working systems^{1,2)}. One example is the thin-layer activation (TLA) method of wear diagnosis in mechanical engineering, in which near-surface of an object, usually a machine part which slides along the surface, is radio-activated and the degree of wear is estimated in real-time through the decrease of the radioactivity of the object³⁾. The object is radio-activated usually through nuclear reactions in the material by accelerated light ions⁴⁾.

In the TLA, a lubricant circulation system removes the activated debris from the machine to the outside, and a decrease in the radioactivity of the object or, alternatively, an increase thereof in the extracted lubricant is measured. However, in some cases, it is not easy to install a circulation system for this purpose. In such a closed mechanical system, the radioactivity of the object and the lubricant are indistinguishable by measurements of the total radiation intensity alone. It would thus be helpful to obtain the spatial RI-distribution in the object by RI imaging technologies such as positron emission tomography (PET) and single photon emission computerized tomography (SPECT). Some groups have developed RI imaging technologies for industrial applications⁵⁾.

We are developing a method called gamma-ray inspection of rotating object (GIRO) to reconstruct an image of the two-dimensional distribution of positron-emitting RI on a rotating object⁶⁾. In principle, GIRO is the same as medical PET but due to a minimal detector configuration the system is much simpler and less expensive. The following sections present the principle of GIRO, some examples of test-measurement results and discuss possibilities of its application in the diagnosis of wear in continuously rotating machine parts.

Principle

Figure 1 depicts the principle of GIRO: In Fig. 1(a), two collimated gamma-ray detectors are in a parallel reciprocating linear motion on the both sides of a continuously rotating turntable. With a common original point at the center of the rotation, a coordinate (x, y) is fixed to the turntable and a coordinate (X, Y) is fixed in space where the X -axis is

parallel to the linear motion of the detectors. A point source of positron-emitting nuclide is fixed on the turntable at $(x, y) = (r \cos \theta, r \sin \theta)$. Since the two 511-keV gamma-ray photons from positron annihilation are emitted in the almost opposite directions, the detectors can capture the two photons in coincidence only when the source is on a line called line of reference (LOR) which connects the collimators. When the x -axis is at the angle ϕ relative to the X axis, the condition of coincidence detection is expressed as $s = r \cos(\theta + \phi)$, where s is the displacement of LOR from the rotation center. By the continuous rotation of the turntable and the repeated motion of the detectors, the turntable is scanned by LOR at different positions and angles. Finally the coincidence-detection events in the $s - \phi$ plane fall on a sinusoidal curve whose amplitude and phase are determined by the position of the source on the turntable.

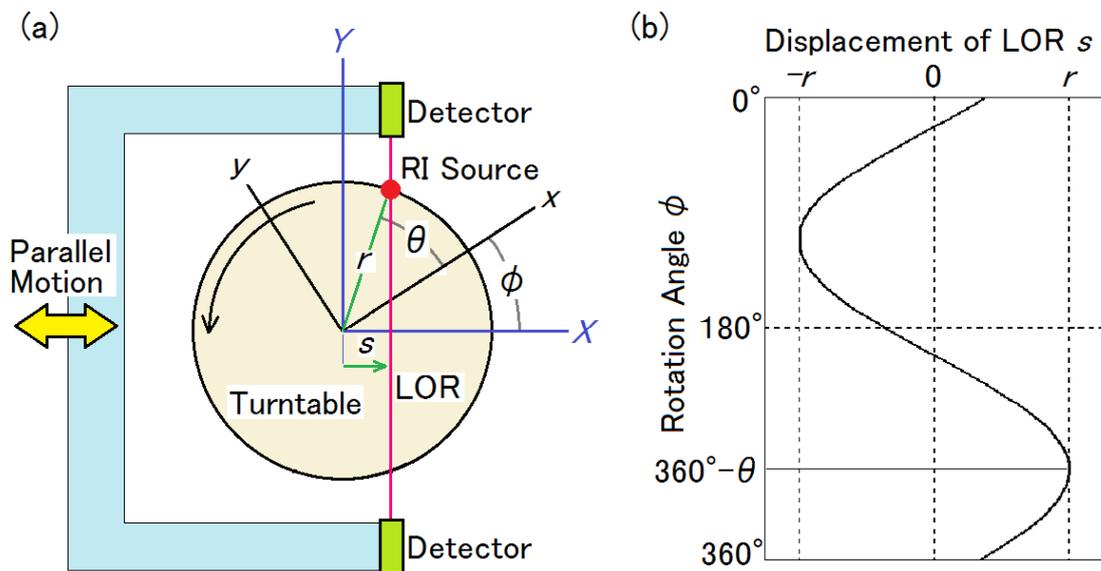


Figure 1: Layout of GIRO with a point source (a) and corresponding sinogram (b).

The two-dimensional plot of coincidence rate on the $s - \phi$ plane is called a sinogram which is widely used in medical tomography. A spatial distribution of RI source determines a sinogram that is the density-weighted superposition of sinusoidal curves corresponding to the positions. Inversely, when a sinogram is given, the source distribution can be reconstructed with a proper algorithm.

Figure 2 conceptually compares the measurements in GIRO and PET in two-dimension: in GIRO shown in (a), one LOR defined by two collimated detectors scans the rotating source whereas in PET in (b), a fixed source is surrounded by many detectors and an LOR is defined as a line connecting the detectors which capture two gamma-ray photons simultaneously. The two measurements provide an equivalent sinogram.

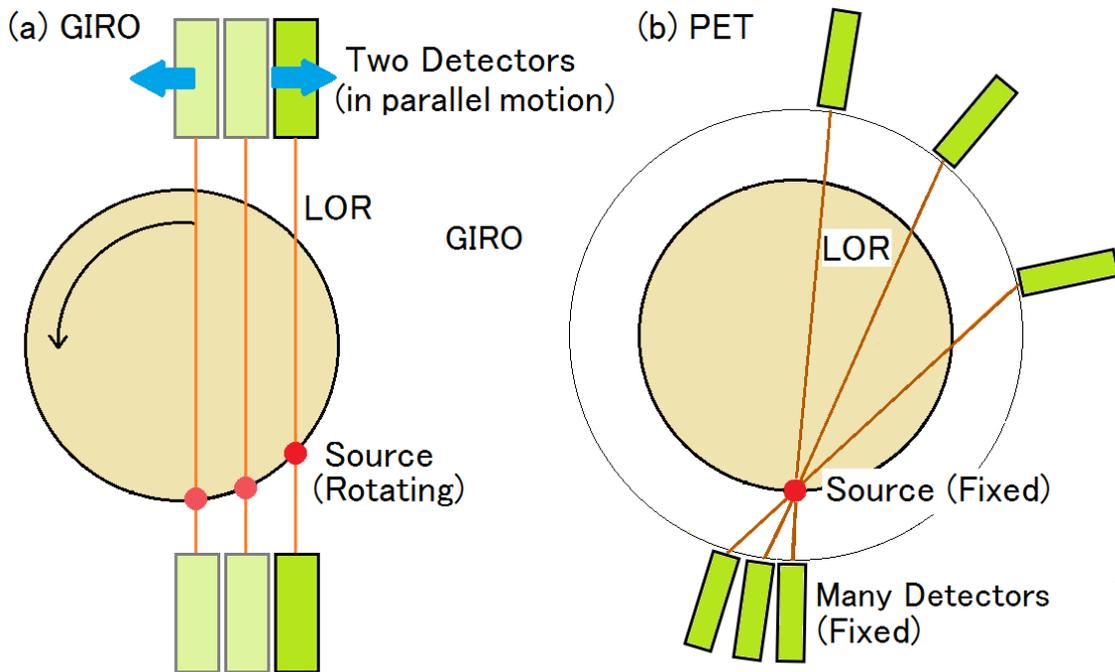


Figure 2: Principle of GIRO (a) and medical PET (b).

Instrumentation

For proof of the principle and evaluation of the resolution, we have built a test-measurement system shown in Fig. 3. A 140 mm-diameter turntable holds positron-emitting sources and continuously rotates. On the both sides of the turntable, two sets of NaI(Tl) scintillator detectors are fixed on a linear-motion stage that makes a continuous reciprocating motion. The scintillator is about 102 mm high, 51 mm wide, and 102 mm long, and a 3-cm thick Pb plate with a 4 mm-wide vertical aperture is placed before the detector as a collimator.

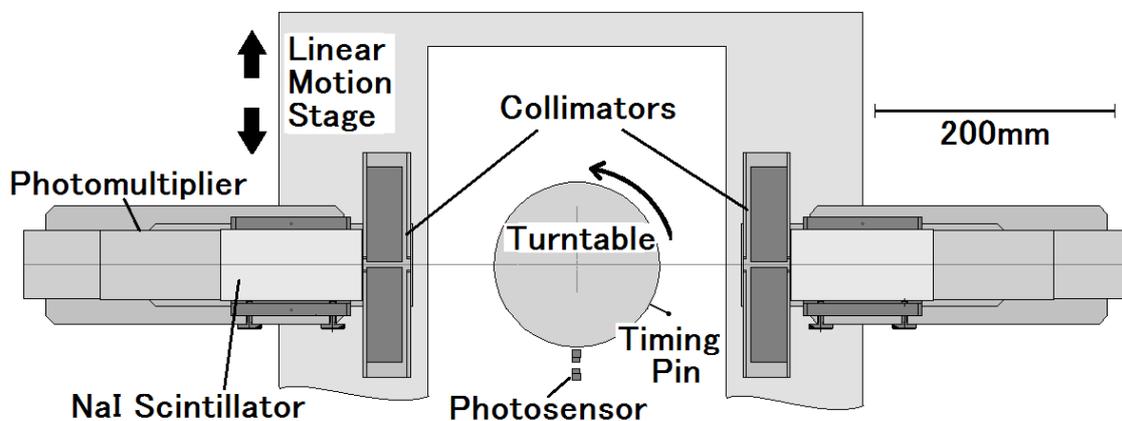


Figure 3: Top view of the test measurement system.

For the measurement of the orientation of the turntable, a timing pin fixed to the turntable passes a photodetector and starts a counting of 500-Hz clock pulse at each turn. The number of the counts at a gamma-ray detection corresponds to the turntable angle. For each coincident gamma-ray detection event, a CAMAC-based system records the energy signals of the gamma rays, the position of the detectors and the angle of the turntable in list mode. Analyses of the list-mode data yield a sinogram.

Image reconstruction algorithm

Since GIRO is basically equivalent to PET, well established algorithms and various computer programs are available for reconstruction of the RI distribution from the sinogram. We use an iterative method, the maximum likelihood – expectation maximization (ML–EM) algorithm⁷⁻⁸. ML-EM is advantageous in that the image values are all non-negative, the signal to noise ratio is higher, there are less artifacts around strong RI sources in the image, and the sum of the image values is preserved during the iteration. These advantages are important in the TLA for easy detection of weak sources of debris near strong sources of original activation.

Measurements and Results

Two examples of measurements with sources of ^{22}Na ($T_{1/2}=2.6$ years) are presented. In these measurements, the turntable rotated at 150 rpm and the gamma-ray detectors moved stepwise by 2 mm every 10 seconds in a range of ± 74 mm. The resolution of the measurement of the turntable angle was 1.8 deg. The sinogram is divided by 75 in the linear-motion direction and 200 in the angle direction. These measurements took about 24 hours.

An ML-EM program downloaded from a publisher's website⁹ to a desktop computer and slightly modified is used to reconstruct the image of the RI distribution. The reconstructed image is a square of 150mm \times 150mm divided by 2mm \times 2mm pixels.

The first example is shown in Fig. 4: (a) shows a photograph of the turntable with three point-like sources with intensities of 347 kBq, 33 kBq and 3 kBq, (b) shows the obtained sinogram where the three sinusoidal curves correspond to the three point sources, and (c) shows the RI distribution reconstructed from the sinogram. The position and intensity of the three sources are well reproduced. Figure 4(d) shows the projection of the two-dimensional distribution in (c) to the y -axis. The full-width half maximum (FWHM) of the 347-kBq peak is about 2.5 mm. The signal-to-noise ratio is high enough to identify the peak of the 3-kBq source well above the background.

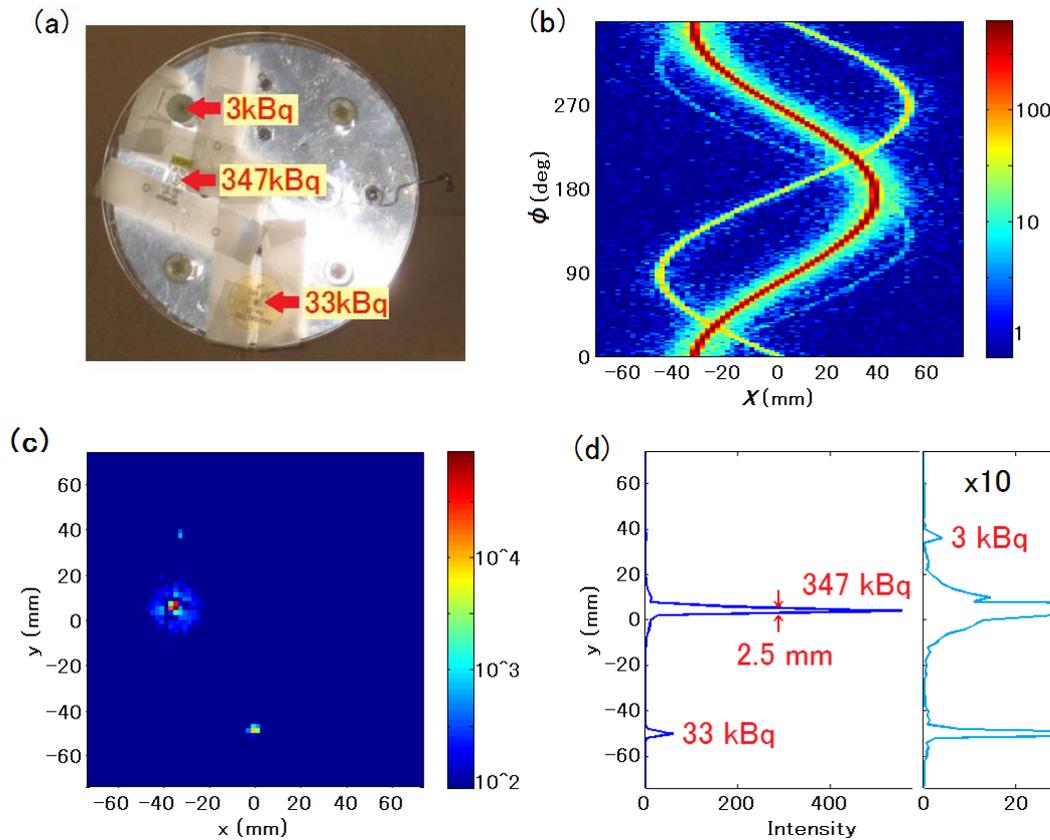


Figure 4: Measurement setup and results for three point-like sources. (a) is a photograph of the turntable with the positions and intensities of the sources, (b) is the sinogram obtained by the measurement, (c) is the RI distribution reconstructed from the sinogram by the ML-EM algorithm, and (d) is the projection of the distribution to the y -axis whose enlarged graph by tenfold is shown on the right-hand side.

More than 99.9 % of the positron emission from ^{22}Na is accompanied by a 1275-keV gamma-ray from the daughter nucleus ^{22}Ne . Its photopeak is well separated from the 511-keV photopeak and does not affect the measurements, but the Compton-scattered photons overlap the 511-keV photopeak and produce in the reconstructed image the background near the peak in the reproduced image.

Figure 5 shows the second example with a source of two-dimensional distribution. Hydrochloric solution of ^{22}Na was trickled down into pieces of filter paper cut to letters with the height of 26-mm. Figure 5(a) is the source distribution obtained by an imaging plate, (b) is the sinogram and (c) is the reconstructed image. The shape of the source distribution is well reproduced.

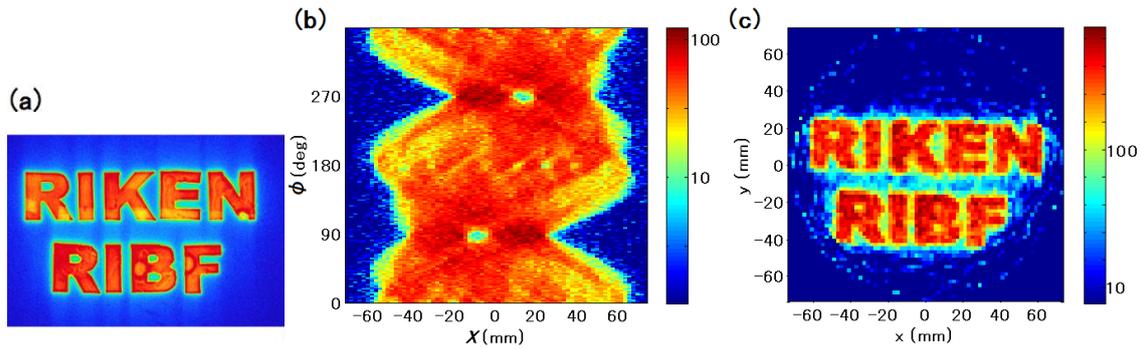


Figure 5: Letter-shaped source: (a) is taken by an imaging plate, (b) is sinogram, and (c) is RI distribution reconstructed from the sinogram.

According to the measurements described above, GIRO reproduces two-dimensional RI distribution with a position resolution of about 2.5 mm FWHM and a high signal to noise ratio with low background.

Summaries and Prospects

By comparing GIRO with the conventional PET, we discuss the possibilities of its applications to the TLA. While the object of a conventional PET is immobile, surrounded by many detectors, the object of GIRO rotates between a pair of detectors in a parallel motion. With the minimal number of the detectors and scanning measurement, GIRO requires longer measurement time. GIRO therefore is not suitable for living bodies and tracing of fast dynamics in the object, but can be applied for slow processes on continuously rotating objects.

The TLA method of wear diagnosis is one possible application where the object machine part rotates as its basic function in a closed system. Light-ion irradiations can convert some important elements for industrial use to positron-emitting nuclides with the lifetime suitable for wear diagnosis; for example, (p,n) reactions can produce ^{56}Co ($T_{1/2}=77$ days) from Fe, ^{65}Zn ($T_{1/2}=244$ days) from Cu, ^{52}Mn ($T_{1/2}=5.59$ days) from Cr, and ^{48}V ($T_{1/2}=16$ days) from Ti. In addition, we are developing at the RIKEN RI Beam Factory a secondary-beam technology to implant ^{22}Na ($T_{1/2}=2.6$ years) from fragment separators¹⁰⁾ in any kind of materials.

Another advantage of GIRO is that the system can easily be disassembled and transported, and that it also has an open structure so the object is less limited in size and shape compared with PET where the object must fit in a bore. It also allows concurrent measurements of other quantities on the object like temperature or vibration.

We are now studying GIRO with some nuclides other than ^{22}Na , and its possibilities to obtain three-dimensional information of the RI distribution. We hope to apply it for more realistic cases such as measuring wear, corrosion and slow chemical reactions in closed systems.

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