The Bimodal Neutron And Photon Imaging Driven By A Single Electron Linear Accelerator

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Abstract

Both X-ray imaging and neutron imaging are essential methods in non-destructive testing. In this work, a bimodal imaging method combining neutron and X-ray imaging is introduced. The experiment is based on a compact electron accelerator that can simultaneously generate two kinds of radiation: X-ray and neutron. This identification method utilizes the attenuation difference of the two rays' incidence on the same material to determine the material's properties based on dual-imaging fusion. It can enhance the identification of the materials from single ray imaging and has the potential for widespread use in on-site, non-destructive testing where metallic materials and non-metallic materials are mixed.

Introduction

Both X-ray imaging and neutron imaging have proven capabilities in non-destructive assays (NDAs)¹. Unlike the cross sections of photons sensitive to the atomic number, neutrons are sensitive to nuclides but not elements. In the imaging process, whether for photons or neutrons, the attenuation is determined by the product of (1) the inspected object's mass thickness (g/cm^2) and (2) its mass attenuation coefficient (cm^2/g). In most cases, the inspected object's mass thickness is unknown and material identification cannot be accomplished merely by the photon or the neutron attenuation information. In this context, some researchers began investigating fusing X-ray imaging and neutron imaging technologies to enhance the capability for identifying materials². Combining the two imaging technologies can be beneficial in the study of renewable energies³, biology⁴, paleontology⁵, porous media⁶, and cultural heritage⁷. This bimodal imaging approach was first implemented by E.H. Lehmann in 2006 by two separate facilities for X-ray and neutron radiography¹. Analogous facilities were later constructed by many institutes such as PSI, NIST, and ILL⁹⁻¹². All the studies are conducted on large neutron sources (reactor or spallation neutron sources) with the aid of a 100 ~ 200 kV X-ray tube. However, material identification based on the fusion of neutron and X-ray imaging technology can hardly be applied in situ for two reasons: (1) due to the high cost, it is less probable to construct a large neutron source for industrial applications; (2) the neutron and X-ray imaging cannot share the same imaging beam geometry, and their different imaging beam geometries introduce a difficulty to form a bivariate histogram for the pixel-wise comparison between the images from two modalities⁹. Usually, the computerized tomography for both neutrons and photons is necessary to align the two images via linear translation, rotation, scaling, or skew.

Using two different imaging systems within a state-of-art bimodal imaging system also requires oversight to avoid interference. For example, the neutron detector perhaps shadows the photons before they penetrate the object being inspected⁹. Although this problem could be partially resolved by increasing the distance between the detector and the sample, the imaging unsharpness caused by penumbra blurring for photons and neutrons must be considered. Thus, using a one-source-detector-system, instead of a two-source-detector-system, should reduce such inaccuracies and simplify data processing. This article proposes a technology that realizes both neutron imaging and photon imaging within one single e-LINAC

(electron linear accelerator) driven system. The experimental results demonstrate that both the photon image and the neutron image can be acquired simultaneously within the same e-LINAC operation, and be free from the different imaging beam geometries. The pixel-wise matching of the two images can be efficiently conducted to form the inspected object's bivariate histogram to identify different materials of various mass thicknesses. In the case that the inspected sample is evolving with time or stochastic processes, the traditional two-source-detector-system may inevitably introduce error in fusing the two images, because each imaging mode may take several hours or even longer and the inspected sample is perhaps not identical for the two imaging modes. In this study, the time delay between the two imaging modes can be as small as 10 ms (when the e-LINAC works at the repetition rate of 100 Hz), which intrinsically ensure that the inspected sample is identical for the two imaging modes. Consequently, being suitable to inspect samples evolving with time or stochastic processes would be an intrinsic advantage with the one-source-detector-system presented in this study.

Results

System overview

In **Fig. 1**, we illustrate the principle to produce neutrons and photons used for the bimodal imaging driven by a single e-LINAC system. The 9 MeV electrons are very energetic, and hence the bremsstrahlung photons generated on the tungsten target are forward emitted. A heavy water convertor is placed ahead of the tungsten target to generate both the imaging neutrons and photons. Heavy water is chosen as the material to convert bremsstrahlung photons to neutrons due to (1) the low (γ, n) threshold of ^2H ($E_{\text{th}} = 2.223$ MeV) and (2) the superb neutron moderation capability of ^2H and ^{16}O . The neutron moderation capability is critical in this study because the fast photoneutrons produced by the $^2\text{H}(\gamma, n)^1\text{H}$ reaction, in general, should be decelerated to slow neutrons to improve the imaging sensitivity. The orbital electrons of the ^{16}O atoms and those of the ^2H atoms can induce the scattering of bremsstrahlung photons. When the emitting angle of scattered photons is chosen as 90° with respect to the direction of bombarding electrons, the energy of incident photons interrogating the inspected object will typically be less than 511 keV (due to the Compton scattering), as shown in **Fig. 2 (a)**. Photons with such an energy spectrum mainly interact with atoms via Compton scattering, which shows an almost constant mass attenuation coefficient for different elements¹³, and hence are helpful to analyze the mass thickness of the inspected object compared with x-ray tube measurements, as shown in **Fig. 2 (b)**.

The neutron emission direction should be the same as the photons to conform the photon imaging geometry. In fact, the energy spectrum of emitted neutrons is not sensitive to the emission direction due to the almost isotropic moderation process of neutrons within the heavy water converter. In **Fig. 3**, we present the neutron energy spectrum measured with the time of flight (TOF) method by a ^3He counter placed 10 meters away from the heavy water converter at the angle of 90° . The simulated neutron energy spectrum is also shown, and the two spectra match fairly well. The results show that when the 9 MeV e-

LINAC works at 100 μA current, a 2500 neutron/ cm^2/s thermal neutron flux at 10 meters away can be anticipated for the neutron imaging. Its counterpart for photons is 10^8 photon/ cm^2/s .

Imaging sequence

Although imaging photons and neutrons produced by the bremsstrahlung photons share the same imaging geometry, their imaging processes' interference should be considered. As e-LINAC works at a pulse mode of 5 μs duration and 100 Hz repetition rate, the photon flight time from the heavy water converter to the detector is merely 5.033 μs , in which the 5 μs is the pulse width of photons and the 0.033 μs is the photon's flight time across 10 meters. Considering the decay time for the light emitted by the scintillation screen is 0.2 μs , in order to let the photons' influence on the detection system die away, an additional time delay of 2 μs after the last photon bombarding the $^{\text{n}}$ MCP detector should be set for the photon imaging and before triggering the acquisition of neutron imaging. Therefore, in principle, the duration of [7.033 μs , 10 ms] after each electron pulse can be assigned to neutrons for neutron imaging. In the experiments, we chose [50 μs , 9.95 ms] as the duration for neutron imaging to avoid the mutual interference between the two imaging processes. Thermal neutrons used for neutron imaging have a characteristic speed of 2200 m/s and require 4.5 ms for the 10-meter flight. Thus, both the photon imaging and neutron imaging can be perfectly accommodated by the [33ns, 7.033 μs] and [50 μs , 9.95 ms] durations, respectively, as shown in **Fig. 4**.

The spatial distributions of imaging neutrons and imaging photons

Data acquisition of the last collision positions of neutrons inside the heavy water converter indicates the heavy water converter acts as a volume neutron source. As the detector system is typically placed 10 meters from the heavy water converter, this volume neutron source will be reduced to a surface source with a disk shape (the diameter is 10 cm, determined by the flight tube in **Fig. 1(b)**), as shown in **Fig. 5 (a)**, with its counterpart for photons shown in **Fig. 5 (b)**. The centers of gravity for neutrons and photons are ($Y = -0.29$ cm, $Z = -0.0061$ cm) and ($Y = -1.31$ cm, $Z = 0.0037$ cm), respectively. The 1.02 cm distance between them is caused by the different scattering physics of neutrons and photons. This difference results in a mismatching error between the neutron image and the photon image, which is about 20 μm and can be neglected when the distance between the inspected object and the detector is only 1/500 of the heavy water converter to the detector. The full width at half maximum (FWHM) along the Y or Z directions for neutrons and photons is calculated as $\text{FWHM}_n = 5.5$ cm, and $\text{FWHM}_p = 5.2$ cm, which can introduce a penumbra blurring of 110 μm and 104 μm for neutrons imaging and photons imaging, respectively

Fusion of the neutron image and the photon image

With the imaging sequence shown in **Fig. 4**, the same inspected object's neutron image and photon image can be acquired successively within a single e-LINAC operation. As shown in **Fig. 6(a)**, two keys clamped by the aluminium holder are inspected. **Fig. 6(b)** and **Fig. 6(c)** show the photon image and neutron image, respectively. The difference between **Fig. 6(b)** and **Fig. 6(c)** is apparent. The key's plastic handle can

hardly be noticed in **Fig. 6(b)**, while it is evident in **Fig. 6(c)**. On the contrary, the aluminium key is clear in **Fig. 6(b)** while almost transparent in **Fig. 6(c)**. The underlying principle is that the cross section of ^1H is large (30.4 barns@25.3 meV) for neutrons but very small for photons (0.406 barn@200 keV, for ^{12}C is 2.452barns@200 keV), while the opposite is true for ^{27}Al (1.68 barns@25.3 meV for neutrons and 5.48 barns@200 keV for photons). **Fig. 7** (a) shows the fused image from **Fig. 6(b)** and **Fig. 6(c)**, in which the color indicates the type of the material, while the shade may reflect the mass thickness of the inspected object. There are 2048×2048 pixels of 200- μm size in the image. For each pixel, its neutron attenuation and photon attenuation will determine the coordinate of a point in **Fig. 7(b)**. All the pixels in **Fig. 6(b)** and **Fig. 6(c)** thus help form **Fig. 7(b)**, in which we can see six clusters. Cluster (1) shows a large neutron attenuation and a small photon attenuation, and **Fig. 7(c)(1)** indicates it is the plastic handle of the key. Cluster (2) shows both strong attenuation for neutrons and photons, and **Fig. 7(c)(2)** indicates this zone has both plastic and aluminium. Clusters (3) to (6) have the same slope in **Fig. 7(c)(2)**, implying that they are the same material because the ratios between the neutron attenuation and photon attenuation are the same. Their different distances to the origin reflect the various mass thicknesses of the aluminium material in the key. The results shown in **Fig. 7** indicate that bimodal imaging can be a very effective method to identify different materials with various mass thicknesses.

Benefitting from the drastic difference between the attenuation coefficients for neutrons and photons, this technology can help find the residual core material in cast turbine blade¹⁴. **Fig. 8** (b) and (d) are the photon image and neutron image for a blade shown in **Fig. 8** (a) with residual gadolinium tracer (gadolinium oxide powder in this study), respectively, while **Fig. 8(c)** and (e) are that for a blade without residual gadolinium tracer, respectively. There is no significant difference that can be noticed between the **Fig. 8** (c) and (e), indicating the inability for photons to investigate the residual gadolinium tracer inside the blade. On the contrary, the difference between **Fig. 8** (b) and (d) is evident, implying that the blade with residual gadolinium tracer can be effectively discriminated by neutrons. By fusing the images of **Fig. 8** (b) to (e), a new image reflecting the position distribution of residual gadolinium tracer inside the blade is formed and shown in **Fig. 9(a)**. To conduct a more quantitative comparison between the blades with or without gadolinium tracer, the distributions of the value, which is the ratio between the mass attenuation coefficient of neutrons and that of photons, of each pixel in the six squares of **Fig. 9(a)** are calculated and shown in **Fig. 9(b)(1)~(6)**, with their counterparts for blade without gadolinium tracer are also shown for comparison. Because of the existence of gadolinium tracer, the separation between the two curves in **Fig. 9(b)(1)(2)(5)** are evident. Due to the lack of gadolinium tracer in **Fig. 9(b)(3)(4)(6)**, the two curves in which conform to each other and does not show significant difference. **Fig. 9(c)(1)(2)** show the bivariate histograms of turbine blades without or with gadolinium tracer. The turbine blade with gadolinium tracer differs from that without gadolinium tracer obviously.

Discussion

The industrial applications of neutron imaging have long suffered from the lack of a suitable neutron source that can deliver an intense neutron beam with a long lifespan¹. Reactor sources, or spallation

neutron sources, are ruled out for their high construction and operating costs. Isotopic neutron sources cannot provide the necessary high-yield neutron beam, and some suffer from the short half-lives¹⁵. Therefore, only the accelerator-driven neutron sources can be considered. Although the proton or deuteron-induced neutron emission reactions, with lithium or beryllium as the neutron production target, show a relatively larger cross section, their real applications are hindered for two reasons. First, the protons or deuterons that bombard the lithium or beryllium target typically have the 3.5 MeV to 13 MeV energies^{16–19}, which limit their penetration depth in the target to around 100 μm ²⁰. This, in turn, limits the neutron yield since the number of involved target nuclei is small. Second, and perhaps more intrinsically, the target's lifetime is severely affected by the deposited hydrogen elements and the heat generated by more than 10 kW²² of power deposited within the target's 100- μm thin surface layer. We observed the proton beam broke several beryllium targets after just several hours of bombarding. While the e-LINAC-driven neutron source might be considered to possess a lower photoneutron cross section, it can provide the same neutron yield as the proton or deuteron accelerator sources because the large mean free path of the MeV photons, which implies more target nuclei are involved in neutron production. Moreover, both electrons and photons will not deposit particles of non-zero-rest-mass inside the tungsten target and the heavy water, respectively; thus, the source's lifetime can be infinite provided the e-LINAC system operates normally.

Besides the relatively low cost and modest footprint²¹, the most attractive property of the e-LINAC-driven system is that it can provide the imaging photon beam and imaging neutron beam simultaneously with a negligible difference between their imaging beam geometries. The successive photon imaging and neutron imaging measurements within one e-LINAC operation facilitate the fusion of the photon image and the neutron image. This unique property makes the e-LINAC driven system be one of the most promising bimodal imaging systems.

The spectra of photons and neutrons would undergo the hardening process when they penetrate inspected objects of various mass thicknesses. Therefore, the ratio between the neutron attenuation and photon attenuation might not be constant even for a particular material. However, a curve in the plane of **Fig. 7(b)** and **Fig. 9(c)** can be anticipated to be assigned to a particular material when its mass thickness is varied. As can be seen in **Fig. 10**, by improving the counting statistics, the spread of the curve for nickel can be reduced, and the ability for separating different materials can be enhanced.

The most straightforward way to improve the counting statistics is to increase the neutron yield of the neutron source. The neutron yield can be further enhanced when the electron energy, or the current of electrons bombarding the tungsten target, can be augmented. For a 10 MeV/ 20 kW²³ or a 50 MeV/ 25 kW e-LINAC system, the neutron yields can be 40 or 100 times higher, respectively, than the 9 MeV/0.9kW of this study, when their optimal neutron converters are used. The available flux at the detector position can thus be significantly improved, and the acquisition times for the neutron image and the photon image can be significantly shortened to decades of seconds or less. The high thermal power on the tungsten target deposited by the electrons may pose technical problems similar to other accelerator-based neutron

sources. The finite element analysis shows that a water-cooling system can effectively remove the heat deposited on the tungsten target to maintain its robust operation²³.

Methods

Electron linear accelerator

The electron linear accelerator used in this study is a 9 MeV e-LINAC manufactured by NUCTECH Co. Ltd., which can deliver 9 MeV electron pulses of 5- μ s width. The repetition rates are adjustable, ranging from 20 Hz to 250 Hz, and the corresponding electron gun current is from 8 μ A to 100 μ A.

Heavy water converter

Heavy water is used as the photon-to-neutron converter. After the 9 MV bremsstrahlung photons are generated from the 9 MeV electrons bombarding the 1.5-mm-thick tungsten target, photoneutrons are produced when an energetic photon breaks the ^2H nucleus into proton and neutron. Monte Carlo simulations were carried out to determine the geometry of the heavy water converter to achieve a high neutron flux of a suitable energy spectrum in the detector position. Total weight of 6.5 kg heavy water is contained within an aluminium vessel of $\Phi 16\text{ cm} \times 28\text{ cm}$ and 3-mm-thickness.

Neutron moderator

The neutron moderator is made up of high-density polyethylene and heavy water. The generated fast neutrons undergo collisions with the light nuclei in moderators such as ^1H , ^2H , ^{12}C , and ^{16}O . From the collisions, the velocity of the neutrons will gradually decrease to the thermal neutron region. The optimized outer size of the polyethylene element is $\Phi 36\text{ cm} \times 44\text{ cm}$, and the mean energy of the emitted neutrons is 44.26 meV.

Shielding and Collimator

A 10-meter-long vacuum tube is designed for neutron transport and collimation. Eleven ring-shaped neutron absorbers made of boron carbide ceramics are placed inside the vacuum tube with an interval of 1 meter between each to collimate the neutrons traveling inside the tube. The tube's outer surface is covered by boron-containing rubber with 60 wt % boron to absorb the neutrons that may escape from inside the tube. The detector is placed in a shielded container, from inside to outside, by 10 cm lead, 0.5 cm boron-containing rubber, and 30 cm boron-containing polyethylene. The S/B (signal neutrons versus background neutrons, where signal neutrons are the neutrons that travel directly from the heavy water converter, and background neutrons stand for those undergo scattering in the circumstances) ratio of this system is larger than 200.

Detector

Both neutrons and photons are measured by the same detector, a neutron-sensitive micro-channel plate (nMCP) produced by Photonis Co. Ltd. Its sensitive area is 95 mm × 95 mm. The neutron or x-ray will be converted to avalanched electrons by the nMCP at first. After the absorption of each neutron or photon, the avalanched electrons then produce fluorescence on the P46 scintillation screen with a decay time of 200 ns. The pictures present in the P46 scintillation screen will be registered by a CMOS camera (Andor iStar series with image intensifier) with the aid of an optical system that provides a 90° reflection and scaling for matching the sensitive area of the CMOS camera. The shutter of the CMOS camera can be set with a variable time delay with respect to the triggering signal that indicates the production of an X-ray pulse to separate the acquisition of the photon image and the neutron image.

Fusion of images

Benefiting from the almost same imaging beam geometries for neutrons and photons, the pixel-wise matching between the neutron image and photon image can be conducted directly, without additional linear translation, rotation, scaling, or skew. For the same pixel of the inspected object's images, the corresponding values of neutron attenuation and photon attenuation can be extracted from the two images compared with the images of "air" of neutrons or photons, respectively. The value for neutron attenuation and that for photon attenuation of the same pixel determine a point in the coordinate system whose x-axis is the photon attenuation, and y-axis is the neutron attenuation. By analyzing all the pixels present in the two images, a bivariate histogram, in which different materials with various mass thicknesses can be identified, is formed.

For both neutrons and photons, the attenuation can be calculated as

$$Att = \log \frac{I_0}{I} = \mu_m t_m \quad (1)$$

Where Att is the attenuation of neutrons or photons, equals to the product of μ_m and t_m , which are the mass attenuation coefficients for neutrons or photons and the mass thickness of the inspected objects, respectively; I_0 and I are the measured counts for neutrons or photons penetrating "air" or the inspected object, respectively. The ratio between for neutrons and photons thus determines a slope to identify different materials given by

$$Slope = \frac{Att_n}{Att_p} = \frac{\mu_{m,n}}{\mu_{m,p}} \quad (2)$$

where subscript n and p stand for neutrons and photons, respectively; the t_m cancels because it is the same for neutron penetration and photon penetration. Therefore, when the hardening effect is not severe (the energy spectra of neutrons or photons are not significantly influenced when the inspected object's mass thickness is varied), in the bivariate histogram, a specific material will have a certain slope. In the case that several different materials are successively penetrated by neutrons and photons, the slope might be modified as

$$Slope = \frac{\sum_{i=1}^N \mu_{m,n,i} \cdot t_{m,i}}{\sum_{i=1}^N \mu_{m,p,i} \cdot t_{m,i}} \quad (3)$$

where N is the number of materials. In general, we cannot separate three or more materials with the information provided by the bivariate histogram. However, considering that the pulse working mode of the e-LINAC-driven system enables energy-resolving neutron imaging, a multivariate histogram can be formed for the further identification of materials. We have successfully conducted an isotope identification experiment, which realizes the energy-resolving neutron measurement, demonstrating the possibility of the multivariate image data acquisition within the framework of the system in this study.

Declarations

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Ethics declarations

Competing interests

Submission of a competing interests statement is required for all content of the journal.

Data Availability

For more information on data availability, click [here](#). Certain data types must be deposited in an appropriate public structured data depository (details are available [here](#)) and the accession number(s) provided in the manuscript. Full access is required at acceptance. Should full access to data be required for peer review, authors must provide it. *Nature Communications* encourage provision of other source data in unstructured public depositories such as Dryad or figshare, or as supplementary information. To maximize data reuse, *Nature Communications* encourage publication of detailed descriptions of datasets in Scientific Data.

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References should be numbered sequentially first throughout the text, then in tables, followed by figures and, finally, boxes. References may only contain citations and should list only one publication with each number. Examples:

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Figures

Figure 1

(a) The principle to produce imaging neutrons and photons simultaneously. Energetic electrons are delivered by a 9 MeV e-LINAC and bombard the tungsten target to produce bremsstrahlung photons firstly. The bremsstrahlung photons then hit the ${}^2\text{H}$ nuclei to produce the photoneutrons via the ${}^2\text{H}(\gamma, n){}^1\text{H}$ reaction and the electrons surrounding the ${}^{16}\text{O}$ nuclei to produce scattered photons, respectively. Both the neutrons and photons will penetrate the inspected object and be collected by a neutron-sensitive microchannel plate (nMCP) detector and converted to electron clouds, leading to a scintillation on the scintillation screen and formation of the photon and neutron images successively. A complementary metal oxide semiconductor (CMOS) camera then registers the two images with the aid of an optic system composed of the mirror and lenses. (b) Photograph of the bimodal imaging system driven by a 9 MeV e-LINAC.

Figure 2

(a) The simulated spectrum of photons along the 90° direction for photon imaging; (b) Mass attenuation coefficients of 90° scattered X-rays (“□”) and 200 kV X-rays (“●”).

Figure 3

The simulated and experimentally measured spectra of neutrons along the 90° direction for neutron imaging.

Figure 4

The measuring time sequence for photon imaging and neutron imaging.

Figure 5

(a) The 2-dimensional distribution of neutrons observed by the detector placed 10 meters away; (b) The 2-dimensional distribution of photons observed by the detector placed 10 meters away.

(a)

(b)

(c)

Figure 6

(a) The photo of the clamped keys; (b) the photon image of the keys; (c) the neutron image of the keys.

Figure 7

(a) The image fused from the neutron image and photon image; (b) the material identification based on the information from neutron attenuation and photon attenuation; (c) The six clusters in (b) are related to different zones of the inspected object, as shown in (1) to (6). The pixel density stands for the number of pixels within a region of $0.0075 \mu_{m,ntm} \times 0.0075 \mu_{m,ptm}$.

(a)

(b)

(c)

(d)

(e)

Figure 8

(a) The photo of an inspected blade; (b) the photon image of the blade without gadolinium tracer; (c) the neutron image of the blade without gadolinium tracer; (d) the photon image of the blade with gadolinium tracer; (e) the neutron image of the blade with gadolinium tracer.

Figure 9

(a) Fused image of the turbine blade; (b) the distributions of $\mu_{m,n}/\mu_{m,p}$ for turbine blades with or without gadolinium tracer, for six different positions of the turbine blade (selected region is 40×40 pixels, and each pixel is $\sim 120 \mu m \times 120 \mu m$); (c) the bivariate histograms for turbine blades (1) with gadolinium tracer and (2) without gadolinium tracer. The pixel density stands for the number of pixels within a region of $0.0075 \mu m_{ntm} \times 0.0075 \mu m_{ptm}$.

Figure 10

The bivariate histograms of the turbine blade (without gadolinium tracer) measured with different acquisition times. The pixel density stands for the number of pixels within a region of $0.0075 \mu\text{m}, \text{ntm} \times 0.0075 \mu\text{m}, \text{ptm}$.

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