Radiography Simulation with aRTist – Combining Analytical and Monte Carlo Methods

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Abstract

Modelling becomes more and more important in modern NDE. It is increasingly used to optimize techniques for complex applications and to support the preparation of written procedures. Hence, computer simulation nowadays has to be able to handle all significant properties of an NDE system with sufficient accuracy. In case of radiographic applications this includes models of the radiation source, of the interaction of radiation with materials, of the detection process, and the geometrical description of the part or the construction. Depending on the given inspection problem and the influencing factors that should be addressed by the simulation an appropriate physical model has to be chosen to describe the underlying interaction mechanisms. The simulator aRTist combines analytical and Monte Carlo methods to efficiently model the radiation transport. Simulation is a powerful tool to separate different influencing factors. Here we focus on Monte-Carlo simulation of scatter contributions within aRTist.

Keywords: CT, multi-angle radiography, modelling, laminography, radiographic testing (RT)

1. Introduction

Efficient and reliable non-destructive evaluation techniques are necessary to ensure the safe operation of complex parts and construction in an industrial environment. Radiation techniques are widely applied e.g. in industry. This includes projection techniques like classical radiography or tomography as well as scatter techniques. Over the years modelling has become more and more important in modern NDE. Computer simulation of radiation techniques can be used for different purposes in NDT, such as qualification of NDT systems, optimization of radiographic parameters, feasibility analysis, model-based data interpretation, and training of NDT/NDE personnel. Hence, computer modelling has to be able to handle all significant properties of an NDE system with sufficient accuracy. In the case of radiological applications, the model includes the radiation source, the interaction of radiation with material, the detection process, and the geometry of the part or the construction. As is known from practice, the latter can be very complex and requires a description allowing the handling of arbitrary geometries. The link between NDE models and CAD provides the ability to quantitatively evaluate complex inspections. Depending on the formulated inspection problem or the influencing factors that should be accessed by modelling, an appropriate physical model has to be chosen to describe the underlying interaction mechanisms.

Here we present the radiographic simulator aRTist [1,2] which is an easy to use and practical simulation tool generating realistic radiographic images from virtual scenes. Test samples are geometrically represented by triangulated closed surfaces defining domains of homogeneous material. The used physical models from generation to detection of radiation allow for quantitative simulation results. An analytical calculation of the attenuation of radiation has been implemented by using an optimized ray tracer determining the lengths of the penetrated material segments. This yields close to real-time frame rates and allows for live preview.

The integrated Monte Carlo code McRay [3,4] completes the scattering model. As Monte Carlo calculations for complex geometries commonly demand extensive computational efforts, McRay has been specifically developed for radiographic testing simulation and for linkage to
Thus it is usually a matter of seconds or minutes to simulate the scatter contribution in radiography using McRay on a personal desktop computer.

This paper presents two basic types of applications: (i) projection techniques like radiography and (ii) back-scatter techniques if only one-sided access to the object is possible. First, aRTist and McRay are discussed in more detail. Then, the two examples are described and the results shown followed by concluding remarks.

2. Basics of Simulation in aRTist and McRay

Modelling of radiation techniques basically consists of four components:
1. radiation source
2. interaction of radiation with material
3. detection of radiation
4. geometry of object under investigation.

X-rays are usually produced by the deceleration of high-energy electrons impinging on a metallic target. X-rays for most practical applications are generated in X-ray tubes, which consist of a cathode and an anode made from a heavy metal with a high melting point. Electrons are emitted from the cathode and accelerated towards the anode in a high-voltage electrical field. When the electrons hit the target of the X-ray tube the energy is transformed in several ways yielding the production of: (i) Bremsstrahlung with a continuous spectrum, (ii) characteristic radiation, and for most of the energy to (iii) heat. The implemented model for X-ray sources [5,6] consists of a coupled semi-analytical description of Bremsstrahlung production and characteristic radiation emission based on fundamental interaction cross sections, describing electron and photon transport via numerical integration of discretized distributions. No free parameters are included in the model. It is capable of handling X-ray sources with thick targets and arbitrary beam geometry as well as transmission targets. Various target materials can be chosen.

For the interaction of radiation with material we restrict our model to photon interactions and do not account for electrons, which are also implemented in McRay. Accordingly the following interaction mechanisms are considered: the photoelectric effect, coherent and incoherent scattering, and for photon energies larger than 1 MeV pair production. To account for electron binding effects form factors and scattering functions are used for coherent and incoherent scattering. Additionally secondary effects such as X-ray fluorescence are considered.

The stationary Boltzmann equation (1) is used to model the photon transport

$$\Omega \cdot \nabla I(r, E, \Omega) + \mu(E) I(r, E, \Omega) = \int_0^\infty \int_{4\pi} dE' d\Omega' \sigma(E' \rightarrow E, \Omega' \rightarrow \Omega) I(r, E', \Omega') + S(r, E, \Omega)$$

(1)

It describes the variation of the photon flux $I(r,E,\Omega)$ at position $r$ with direction $\Omega$ and energy $E$. The left hand side of Eq. (1) accounts for the reduction of the flux by the interaction of photons with matter given by the linear attenuation coefficient $\mu(E)$

$$\mu(E) = \tau + \sigma_{\text{coherent}} + \sigma_{\text{incoherent}} + \pi$$

(2)
with the absorption coefficient \( \tau \), the scattering coefficients \( \sigma_{\text{coherent}} \) and \( \sigma_{\text{incoherent}} \), and the pair production coefficient \( \pi \). The right hand side describes the increase of the photon flux \( I(r,E,\Omega) \) by scattering contributions from other energies \( E' \) and other directions \( \Omega' \) given by the scattering cross section \( \sigma(E \rightarrow E',\Omega \rightarrow \Omega') \) as well as by internal photon sources \( S(r,E,\Omega) \) such as X-ray fluorescence or electron-positron annihilation.

If scattering contributions are neglected, i.e. the right hand side of eq. (1) vanishes; the remaining ordinary differential equation can be directly integrated leading to the well-known attenuation law

\[
I_p(r,\Omega,E) = I_0(r,\Omega,E) e^{-\int_0^r \mu(r') dr'}
\]

(3)

deriving the primary photon flux \( I_p(r,E,\Omega) \) from the initial flux \( I_0(r,E,\Omega) \), which carries the major information for radiographic techniques. Anyway, the contribution of scattered radiation has to be considered to compute the total intensity radiation \( I \) forming the projection image

\[
I = I_p + I_s
\]

(4)

with \( I_s \) being the scattered photon flux.

To simulate \( I_p \) an analytical calculation of the attenuated radiation has been implemented in aRTist by using an optimized ray tracer determining the lengths of the penetrated material segments. This yields close to real-time frame rates and allows for live preview.

For the scattered intensity, which also includes internal sources, two models are implemented in aRTist:

1. Build-up factor model assuming that the contribution of scattered radiation does not carry any information about the object under investigation, i.e. implemented as a constant offset depending on the average penetrated material thickness
2. Monte Carlo model McRay describing the interactions of photons with material in detail and allowing the separation of the primary and scattered contribution to the total intensity

As Monte Carlo calculations for complex geometries commonly demand extensive computational efforts, McRay has been specifically developed for radiographic testing simulation and for linkage to aRTist. Thus it is usually a matter of seconds or minutes to simulate the scatter contribution in radiography using McRay on a personal desktop computer. For a more detailed description of the scatter contribution, e.g. for back-scatter techniques, the McRay calculation can be executed on a remote system (e.g. HPC cluster) if available.

Calculated or measured transmission functions are used in order to describe the conversion of photons registered by the detector and its response. The energy dependence of the response of a specific detector is included. aRTist provides a library for different detectors such as X-ray films, imaging plates, and digital detector arrays. The inner unsharpness is simulated by Gaussian filtering. Noise is added to the image pixel by pixel depending on its grey value.

aRTist models a real inspection scenario by defining a virtual setup. Source and detector are described by raster points on a finite extended plane. Besides source and detector the geometrical computer model of the experimental setup has to support the representation of the spec-
imen geometry. One or more geometrical part representations can be freely arranged in the virtual scene. Parts are described by a boundary representation of closed surfaces, which separate areas of homogeneous material. A facetted (triangulated) boundary description is used within aRTist. Curved boundaries are approximated by an appropriate number of plane facets. For data exchange of this facetted part description the STL format can be used, which is a de-facto standard in the CAD domain. Several interactively arrangeable part representations can easily be managed in the virtual 3D scene. Overlap of geometries in the scene and combination by Boolean operators allow variable defect descriptions independent of the surrounding host material of the defect.

3. Examples

3.1 Radiography Simulation with aRTist and McRay

By selecting the scatter model McRay the scatter contribution is considered in radiographic simulation without the need to specify additional parameters. The steps of simulation including Monte Carlo scatter calculation are:
- Source model
- Analytical primary image
- Separate primary and scatter images simulated with McRay
- Scaling of scatter image based on primary image values from McRay and analytical calculation
- Smoothing of scatter image
- Summation of analytic primary and scaled McRay scatter image
- Detector model

Optionally a scatter image can be calculated once and used for several simulations. This saves computation time in cases where the parameter changes barely affect the scatter contribution. If required a dedicated aRTist module gives extensive control over McRay calculations.

![Figure 1: Simulating radiography with aRTist: virtual setup (left); primary image (center); scatter image (right).](image)

Fig. 1 shows a typical radiographic simulation result with aRTist. On the left the virtual setup is given presenting the arrangement of the X-ray source, the test object (aluminium casting)
and the detector. The center image gives the analytical primary image calculated with the aRTist ray tracer considering the attenuation of the X-rays only. On the right the scatter image is presented as calculated by the algorithm described above. By adding the primary and the scatter image the radiographic image is obtained which is not shown in the figure. For this example it is shown that the scatter from the part contains geometrical information about the object that should not be neglected. The geometrical structure of the object can be identified in the scatter image as well as in the primary image. Therefore for objects with large wall thickness variations like castings a detailed treatment of the scattered radiation is advisable.

aRTist also comes with a module for virtual computer tomography. With McRay integrated, it is possible to account for scatter contributions not only from the test object, but also from non-rotating elements of the CT setup. To minimize the additional computational effort the CTScan module allows reusing one scatter image for a certain number of sequential projections.

3.2 Back-Scatter Imaging with aRTist and McRay

As the Monte Carlo model considers all relevant interactions of photons and electrons, McRay can also be used to simulate back scatter techniques. In this case aRTist is utilized as graphical user interface for McRay. In addition to the interactive composition of the experimental setup, the examination of the resulting images and spectra can also be done with aRTist. Because McRay has been specifically developed for radiographic testing simulation and is not optimized for scatter techniques, it is recommended to execute calculations on a HPC cluster or another hardware allowing parallel computing.

The example presented here discusses the simulation of an imaging X-ray scatter technique using a back scatter camera patented in [7]. Fig 2 shows the measurement setup for back scatter imaging with a bolt in front of a glass of water irradiated from the side. The image distortion is caused by the camera design. To illustrate the contribution to the back scatter image, Fig. 3 visualizes selected photon traces hitting the detector from Monte Carlo simulation with McRay. Here the detector was shielded only from one side (Fig. 3 left) to demonstrate the contribution of scattering in air. Multiple scatter is clearly visible especially in the detailed view (Fig. 3 right). The final back scatter image is presented in Fig. 4.

Figure 2: aRTist virtual setup for back scatter imaging.
4. Conclusions

Radiography simulation with aRTist combining analytical and Mont Carlo methods has been presented. It was shown that the integrated Monte Carlo code McRay together with a specially developed smoothing procedure allows the calculation of the scatter contribution to radiographic images. Because of the optimized implementation of McRay this extension to simpler scatter models like build-up factor models is applicable on personal desktop computers.

In addition the capability of McRay to simulate scatter imaging techniques has been shown. Here aRTist serves as graphical user interface for McRay. Because McRay is optimized for radiographic applications it is recommended to run the simulations for scatter imaging techniques on a HPC cluster or other hardware allowing parallel computing.
References


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