NUMERICAL SIMULATION OF RADIOGRAPHIC INSPECTIONS: FAST AND REALISTIC RESULTS EVEN FOR THICK COMPONENTS

A. Schumm[1], Ø. Bremnes, B. Chassignole
Electricité de France (EDF), R&D Division, France

Abstract: Radiographic simulation of thick components represents a particular challenge, since the Monte-Carlo methods generally applied to obtain accurate scattering predictions are inherently slow, and as such not suited to applications for inspection procedure qualification, where a large number of parameter variations has to be studied in a reasonable time. We present a generic radiographic modeling code, which overcomes this impediment by combining a Monte-Carlo approach with a simple straight-line attenuation model and an analytical film-foil model. The code MODERATO has been thoroughly validated and is now used to perform parametric studies for performance demonstration purposes.

Introduction: When modeling radiographic inspections for thin components, scattered radiation can often be entirely ignored. In the intermediate thickness range, a commonly used approach accounts for scattered radiation with tabulated build-up factors, often obtained previously with Monte-Carlo codes. For these situations, straight line attenuation models are sufficient to obtain reasonably accurate results. Another approach which has recently attracted interest in the scientific community attempts to predict first- and sometimes higher order scattering with analytical models (Ref).

However, for the higher wall thicknesses and component geometries typically encountered in nuclear components, the simple build-up factor correction fails to predict the inhomogeneous distribution of the scattered radiation on the final image. In these cases, one usually resorts to solving the associated n-particle transport problem with a Monte-Carlo algorithm. If applied strictly, the Monte-Carlo method simulated a radiography by modeling the complete transport from the source to the film of the number of photons corresponding to the exposition time. For each photon, its path is tracked from emission at the source through the inspected object and to the detector, taking due account of the different interactions of these photons with the object and detector materials. For the film-foil systems commonly used in industrial gamma radiography, the detector represents an additional difficulty, since the photon-electron interactions within the detector have also to be taken into account.

Modeling the Photon transport : The Monte Carlo method treats photon transport in terms of straight path travel between interaction events. For the energy ranges of iridium and cobalt sources, the interaction types to be considered are photoelectric absorption, Compton scattering and Rayleigh scattering. The probability of each interaction event is a material property and is described in terms of cross-sections as the ratio between the individual event's and the total cross section.

Photoelectric absorption is the dominant interaction type for low energies, where the incident photon is absorbed in an inelastic collision and transfers almost all its energy to an ejected electron. Since a detector shield prevents freed electrons to reach the detector, they are neglected in the simulation, and photoelectric absorption is modelled by making the initial photon disappear.

Rayleigh scattering is the result of an elastic collision of the incident photon with a bound electron, causing a modification of the photon's direction. Neither the state of the electron nor the incident photon's energy change. Rayleigh collisions occur at low energy levels, where the incident photon's energy is insufficient to cause an electron transition in the material. In the energy range between 0.1 and 10 MeV, Compton scattering is the dominant interaction, where a photon interacts with a free or weakly bound electron. Upon a Compton collision, the photon transfers a portion of its energy to the ejected electron, and becomes scattered in an angle within 0 to 180°. Pair-production as a fourth type of interaction can typically be neglected for the energy ranges dealt with in iridium or cobalt sources. It would have to be added if higher energy sources had to be considered.

The Monte Carlo algorithm determines repetitively the location and type of the next interaction, until the photon is either lost (by leaving the geometry in a direction with no chance to be scattered again or to intersect the film), absorbed or intersecting the film. A number of optimisation schemes are available to re-use partial photon paths which otherwise would not contribute to the resulting radiographic image.

Geometry representation: A particular characteristic of the code MODERATO [1] is its ability to take into account the object's geometry, including its geometrical environment. To that end, two means to define a geometry scene have been made available: In MODERATO, the inspected object's geometry is either defined by an imported file obtained with a CAD modeler, or by a parametric geometry model. While a CAD modeler provides more flexibility in defining complex geometries, parametric models are more convenient for simple geometries where the same shape can serve at different dimensions. As such, MODERATO provides a parametric CAD library with components constructed from patches with constant curvature, such as cylinders, cones and tores. Furthermore, curved patches reduce significantly the processing time to evaluate the photon's intersections with the geometry, as opposed to a facetted representation based on triangles.

CAD formats available include Inventor/VRML, STL, DXF and others.

Detector and film response function: A common film cartridge consists of a layered film-foil stack, with two stacked films, each of which is placed between a front and a back screen. A thicker foil acting as a filter is placed in the cartridge before the film/foil stack. The film itself is modeled as a gelatine layer, the active elements being the silver halide grains distributed uniformly within the gelatine layer.

As the latent radiographic image formation involves electrons emitted during photon collisions, which "darken" the grains encountered along its trajectory through the film layer, modelling the film cartridge requires a more complex Monte-Carlo model, treating both photons and electrons. Moderato uses a second, dedicated model to handle the more complex interactions within the film. It must be noted that the simulation of the film cartridge takes a considerable amount of the total processing time for a single photon, although the film's geometry is relatively simple compared to the inspected object. The processing time in the cartridge is mainly due to the electron's small free path between interactions, so that a large number of iterations must be calculated. Furthermore, one photon will usually generate several electrons, resulting in a cascade of elements to propagate.

It was therefore considered vital to reduce the processing time of the film cartridge. An efficient means to accelerate the photon handling within the film is obtained by replacing the time-consuming cartridge simulation with a film response function (see figure 1). If the point spread function is neglected, the cartridge response can be described in terms of the incident photon's energy and its impact angle. This two-dimensional weighting function is obtained by a series of simulations with monochromatic photon beams and made available in terms of two polynomials. The film response function is of course only valid for a given film configuration, and must be recalculated if a different film or different foils are employed. Since the calibration takes place only once, however, the gain is considerable. The film response function also takes all incident photons in account, which is a significant gain as most of the photons go through the real film cartridge without interacting.

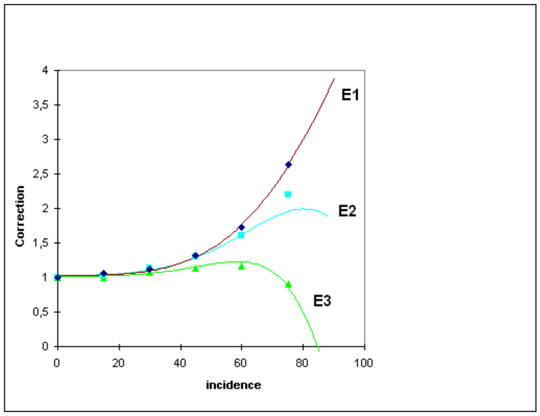

Figure 1: Photon impact as a function of incidence for three different energies

Combining direct and scattered radiation: A complete radiography simulation using the Monte-Carlo method would be prohibitively long for most configurations, even with the simplified cartridge model described in the previous paragraph. However, a consideration of the direct and scattered radiation's different contributions to the resulting image suggests the benefits of their distinctive treatment.

The direct radiation is responsible for the image projection of the object upon the film. The scattered radiation contributes to this image in a destructive manner, adding noise and reducing the image contrast. Since the direct radiation reproduces the high-frequency components of the projected image with high detail, a very large number of photons is required before the Monte-Carlo simulation converges towards the result. The scattered radiation, on the other hand, varies only smoothly with geometry variations, averaging out small local variations. Based on this observation, it is possible to extrapolate the scattered radiation result, obtained from a smaller number of photons, to the effective contribution, by applying a suitable low-pass filter. The extrapolation method implemented in MODERATO is relatively simple and is based on the assumption that the final image contains almost no noise, which is true for the long exposure times usually applied. Given this assumption, the simulated scattered image, which is relatively noisy, is low-pass filtered by a polynomial fit of sufficiently high order, able to reproduce the relatively smooth variations of the scattered radiation over the film.

The Monte-Carlo simulation also provides the direct radiation's contribution as a separate result, which only serves to determine the scaling factor of the scattered radiation. Applying this scaling factor, the noise-free result is extrapolated to the required optical density and combined with the direct scattering result obtained with a straight-line attenuation model. The straight-line attenuation model determines the path lengths between the point source and each film pixel. It then calculates for each discrete energy of the source spectrum the corresponding attenuation. Physically, the image obtained by the straight-line attenuation model corresponds to a Monte-Carlo simulation of the direct radiation with an extremely high number of photons. It reproduces the fine detail of defects present within the geometry, as opposed to the Monte-Carlo image, which is too noisy to render the same level of detail.

Validation of MODERATO: simulations were compared with success to analytical absorption models, to other simulation codes results (MACALU by CEA / DAMRI, France, and SINDBAD by CEA / LETI, France), and to real experimental results. The differences observed were each time below 10%. The MODERATO - SINDBAD comparison was especially interesting for the validation of direct and scattered photon physics as the two codes were developed independently and tested on several thickness profiles and materials. The comparisons with experiment also showed a very good match for the wide explored thickness range as shown by the example in figure 2.

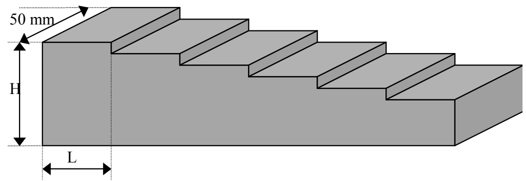

Figure 2: Step-like block used for simulation - experiment comparison. The steps are 50 mm wide, 53 mm long and respectively 44.4, 39.6, 35.9, 32.8, 29.9 and 27.4 mm high.

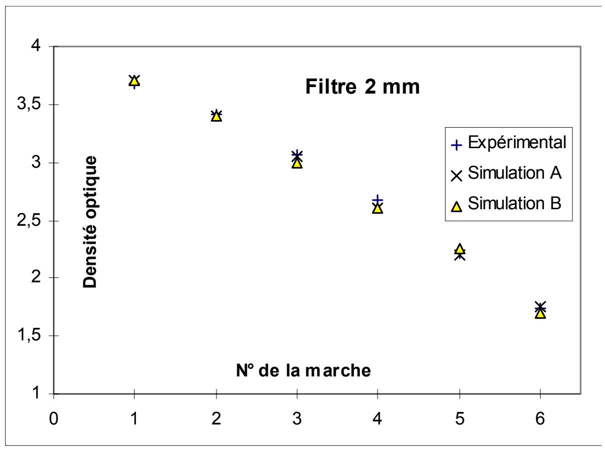

Figure 3: Simulation - experiment comparison for the step-like block. Iridium source, double M100 film cartridge with 0.2 mm lead intensifying screens, 2 mm lead filter. Film - source distance: 700 mm.

Detectability of simulated indications: Once the simulated radiogram is obtained, one must be able to determine whether the defect indication can be seen by controllers qualified according to COFREND Level II in radiography. The "simulation interpretation" can be obtained only by calculation and must be coherent with real radiogram interpretations.

To determine a robust detection criterion, a series of experiments was carried out on specifically designed mock-ups with various cylindrical and plane defects. The radiograms were interpreted by several qualified interpreters and a list of "visible", "barely visible" and "not visible" defect indications was established (see figure 4). The same configurations were then simulated and the visibility of the simulated defects were calculated using different criteria taking into account the indication's shape, size and contrast. The criterion that showed highest coherence between simulation and experiment is the mean defect contrast in a 1.6 mm^2 area that does not exceed 2 mm in length. The yield detection level 0.013 was chosen to be sure to classify as "not visible" any defect that was not visible in the experiment (plane or cylindrical). This criterion is yet only valid if the background of the defect indication is relatively smooth. A more general criterion, or at least a validity check, is planned as near-future development.

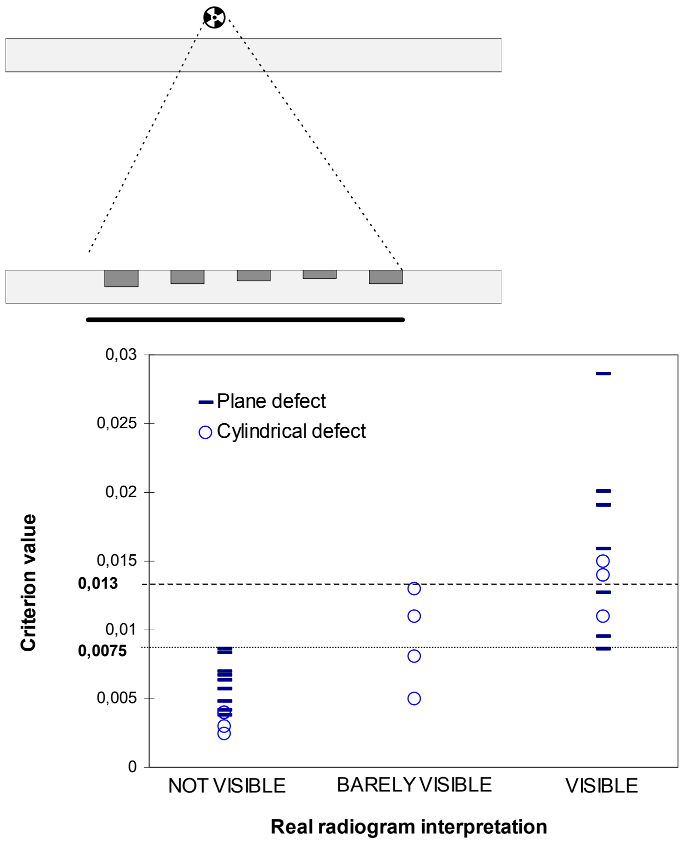

Figure 4: Determination of detectability criterion based on real radiogram interpretations obtained on mock-ups (right). For the most coherent criterion, the defect indication is considered "visible" if the visibility is higher than 0.013, "barely visible" between 0.0075 and 0.013, and "not visible" under 0.0075.

Application to radiographic test qualification: MODERATO was first developed as a tool to be used in the process of qualification of RT procedure in order to conduct parametric studies contributing to performance demonstration. A standard complete simulation lasts about two days. If only the defect is modified, 20 min are sufficient to recalculate its new radiogram. Parametric studies are thus very easy to perform even with many parameters. High value is given to the information made available by simulation:

- Quantitative estimation of visibility in addition to the single binary "visible" or "not visible" information obtained by experiments,
- Quantitative estimation of the visibility evolution when a test parameter is changed (component, source, screens, filter, defect position, shape and orientation, etc),
- Easy physical interpretation of the result evolution,
- Easy identification of the most influent parameters.

In the process of qualification, parametric studies are expected to be very valuable, since they represent a significant gain in time, money and flexibility compared to the use of numerous and costly mock-ups.

Application to an industrial component: Besides parametric studies and qualification, a simulation tool such as MODERATO may prove useful by providing a better understanding of the sometimes complex phenomena involved in NDE, and thus be very helpful for the interpretation of data in expertise situations.

A good example is provided by the study of the influence on the detectability of the angular misalignment between the incident radiation and a planar discontinuity. Such a situation can be encountered, for example when a defect is not perpendicular to the surface of the inspected component, or when it is misaligned with the source position. Experimental and modelling studies were conducted for a planar defect in a block inspected with an iridium source. The test configuration is described in Figure 5. It is representative of the testing of pipes in pressurized water reactors. Two planar blocks in ferritic steel are positioned with their outer surfaces separated by 323 mm. The thickness of each block is 30 mm. Block #1 contains a crack type defect and the cartridge is in contact with its outer surface. Block #2 has no defect and the iridium source (size 2x3 mm) is in contact with its outer surface. The cartridge is made up of one anterior lead filter of 1 mm thickness, two Kodak M100 films, three lead intensifying screens of 0.2 mm thickness and one posterior lead filter of 3 mm thickness. The film density in the defect zone, for a double film interpretation, is 3.5 ± 0.2.

The defect length is equal to the block's width (95 mm). Characterization of the defect is made by optical and ultrasonic measurement :

- height varying between 5 and 6 mm ;
- mean width at the bottom equal to 65 µm ;
- width at the tip equal to 25 µm.

We present the result for a 10° shift around the perfect source and defect plane alignment. It is well-known that the radiographic detectability of a planar defect is more difficult when the beam angle increases [2] [3]. The radiograms have been independently examined by five interpreters qualified according to COFREND Level II in radiography. Despite the source tilt, all the interpreters have detected the defect and have indicated a length of 95 mm.

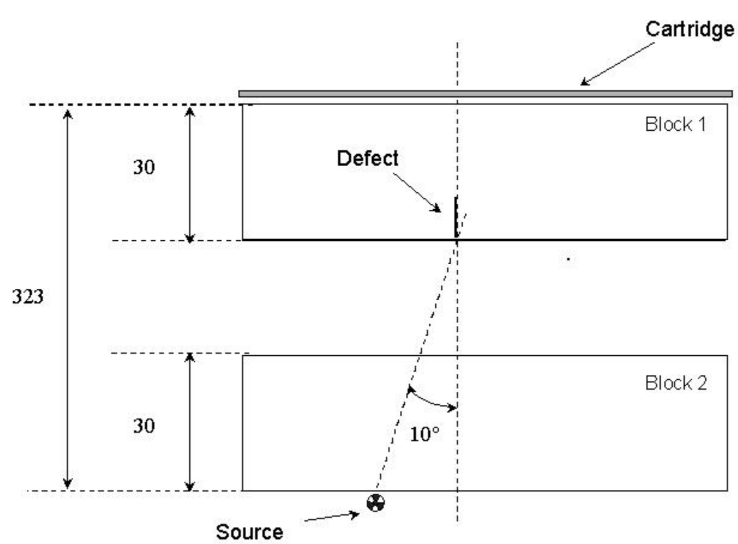

Figure 5 : Tested configuration with a 10° shift around the perfect source and defect plane alignment

On the other hand, this configuration has been simulated with MODERATO. We have chosen a film size equal to 20x20 mm and a pixel size equal to 20 µm. The radius of the cone-shaped beam in the film plane must be at least equal to 300 mm. A lower value will lead to an underestimated build-up factor value : there is a high number of scattered photons arriving on the cartridge due to the double wall configuration and the source in contact to the first wall.
The calculations were made with five billions of photons. The values of the detectability criterion given by MODERATO (see corresponding paragraph) is superior to 0.013. Then the simulation's diagnostic would indicate that the defect is visible, which is coherent with the experimental diagnostic.
Future studies may address more realistic situations by taking into account the influence of combined parameters, e.g., in the previously described case, how the detectability will be affected by the presence of a weld bead on the inner surface of the block.

Conclusions: The radiographic modeling code MODERATO combines a Monte Carlo method to calculate scattered radiation with a straight-line attenuation model for the direct radiation's contribution. The code is able to handle a complex geometry created with a solid modeller. With a dedicated film-foil model, it is able to predict radiographic images obtained with gamma sources and industrial film cartridges. The integration of a defect visibility criterion greatly simplifies its use in performance demonstration applications. The code is available as a software package running on Windows PCs.
MODERATO has been successfully used in different applications partly representative of industrial situations,and thus appears as a high-potential tool, which can be applied to qualification approaches through parametric studies, as well as a comprehension support in expertise situations. Simulations give, in addition to the radiographic image itself, a wide and quantitative understanding of the effect of radiography parameters such as the source position, defect orientation and position, component thickness, etc. With each parameter, one can see the effect on the build-up factor, defect indication shape and contrast, etc. MODERATO is thus a very helpful tool for

- learning,
- assistance to radiogram interpretation,
- parametric studies for radiographic test performance demonstration,
- optimisation of experimental procedures.

A number of evolutions are envisaged in the near future or already underway, such as the implementation of high energy sources, for which pair-production as an additional interaction event type must be implemented, and multiple source models to calculate ambient radiation's contribution.

References:

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