THREE DIMENSIONAL MODELING OF PROJECTION RADIOGRAPHY

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INTRODUCTION

The availability of a computer simulation for the X-ray projection image formation process, capable of modeling a rich variety of machine, configuration, and detector parameters, has a number of far reaching implications for quantitative nondestructive evaluation (NDE). The applications of such a tool occur both at the design stage and at the quality control inspection stages of the manufacturing process. Some of the notable uses include designing inspectability as a part of a computer aided design (CAD) package and developing an optimal inspection scheme for the component, while at the other end of the manufacturing process, a package of image processing routines, using the results of the forward model, can deconvolve a number of deterministic processes from the resulting radiograph. The promise of the potential applications of a quantitatively accurate forward model of the radiographic system has generated much interest in the basic physics of the process and the subsequent modeling of these processes. (1-5) For the model to be a flexible tool all of the various elements of an experimental equipment must be accurately described with enough variability to be useful over a large number of machines and experimental configurations. This begins with the models for the generation of the initial X-ray beam, the description of the experimental configuration, the X-ray interaction with matter, the detector response to X-rays, and finally a model of the detectability of an indication. The experimental verification of each of these components is an integral step of the development of the final model of X-ray projection radiography.

The preliminary developments in the complete computer simulation of the image formation process for X-ray projection radiography have matured to the point of comparing the predictions to quantitatively measured responses in real systems. We wish to report on the results to date for the various elements on the model together with example applications of the forward model of the X-ray projection process.
The description of the elements of the model is divided into five parts, the first is the generation of the X-ray beam, the second is the sample and the interaction of the beam with the sample, the third describes the experimental configuration, the fourth part describes the detector and its interaction with the X-ray radiation and finally there is a description of the detectability criteria used. One of the key elements that has been incorporated into the model is a large number of parameters that are typical of a radiographic setup.

The model consists of eqns. (1) and (2),

\[ I(x,y,E) = I_0(E) \int_{source} e^{-\mu(x,y,E)p} \frac{1}{r^2(x,y)} dA \]

and

\[ D(E) = D_0(1 - e^{-\sigma(x,y)(E) + \delta}) \]

where \( I \) is the intensity immediately above the detector, \( I_0 \) is the initial intensity produced from the X-ray generator, \( \mu \) is the energy dependent linear absorption coefficient, \( \rho \) is the X-ray path length through the sample, \( r \) is the distance from the source to the detector, and \( x \) and \( y \) are the coordinates at the detector surface. \( D \) is the film density, \( \sigma \) is the interaction cross section of an X-ray with a film grain, \( \eta \) is the coefficient for the X-ray scattering, \( \delta \) is the natural film fog density, and \( D_0 \) is the maximum film density.

The initial x-ray beam has been calculated by several groups(6-8). We follow the method calculated from the electron- electron interaction cross sections(8). These cross sections are calculated from the interaction of the relativistic electron beam with the bound atomic electrons of the target atom. The calculations are based on a one photon production process. The angular dependence of the bremsstrahlung production is integrated over all angles. This simplification implies that the calculated intensities will require a scaling factor to match the experimentally measured values. This procedure will yield the proper energy distribution as is seen in Figure 1. The energy dependence of the spectrum is calculated assuming a thick target attenuation of the electron beam. The parameters that can influence the spectrum include the target material, the energy of the electron beam, the electron current shape, density and magnitude, and the angle of incidence of the electron beam to the target surface. All of these parameters are adjustable in this model giving it the capability to be applied to a large number of X-ray generators. The experimental configuration of the experimental setup has a number of parameters that are controlled by the operator and, as with the initial spectrum, a number that are not. Those controlled by the operator are the source-sample-detector distances. Material properties of the sample and physical and material properties of the flaw are not under explicit control; indeed, it is the flaw that is to be characterized. The simulation, to be able to study the effects, has two flaw morphologies, a truncated cone and an ellipsoid. The ellipsoid, which can be arbitrarily orientated, has independently variable major axises, and can be positioned in the host material at will.

The interaction of the X-rays with the matter of the sample in the energy ranges of typical radiography are via the photoelectric, coherent, and Compton interactions. The simulation takes account of the energy dependence of these interactions(9). The scattering component of the signal is dominated by the Compton interaction. This component is tracked in a coarse fashion. The major factors controlling the photon scattering are the geometry and thickness of the part and the energy distribution of the incident X-ray beam. The energy effects of the scattering that reaches the detector are complicated by the fact that
Compton scattering that occurs at a location near the source side of the sample must penetrate the entire thickness of the sample. Thus, this component of the scattering is attenuated much more than the scattering that takes place nearer the detector side of the sample. As can be imagined, a complicated part geometry makes the tracking of the scattering intensity difficult. In the present model the part geometry is a simple flat plate. The scattering, at present, is tracked in a coarse fashion. The effects of multiple scattering and the energy dependence of the scattering are modeled as a buildup factor, the values being obtained from experimental observations.

![Graph](image)

Fig. 1. A typical spectrum measurement compared to the scaled model result. The data was taken from a Ridge HOMX 160A microfocus x-ray generator with a NaI scintillation detector.

The x-ray detector model is of great importance in that it is the qualities of the detector that most strongly control the image quality. The detector modeled for the present simulation is film. The model, as seen from equation (2), has several features that allow the modeling of many types of film. The speed, inherent fog, and the maximum density of the film are the features used to characterize film types. We note that scattering is considered in a limited way. This component of the total density is very dependent upon the geometry of the part. In the case of a flat plate geometry the result of scattering is to add a constant to the photon intensity reaching the film. This is modeled in the scattering coefficient $\eta$.

An experimental verification of the film model can be done by taking an X-ray photograph of an aluminum plate with a cone machined into the surface. By measuring the film densities of the flaw region and then comparing it to the normal density, we can, using the film model, extract the ratio of the flaw thickness to the sample thickness. The ratio of the flaw thickness to the sample thickness can be measured directly from the plate with a caliper. By stacking an additional aluminum plate on top of the plate with the machined cone, we can change the ratio of the flaw thickness to the thickness of the plate. Similarly by adding additional plates to the stack, we can get a range of ratios which can be measured with a caliper. These results are shown in Figure 2.
SIMULATION RESULTS

A simulation such as the one outlined in eqns. (1) and (2) can be used to do trade-off studies. We will discuss two such examples, both concern the quality of the information obtained from the image versus the economy to acquire the image. It is well known that as the hardness of the beam increases the sensitivity decreases; however, as the beam hardness increases, the time to obtain the required exposure decreases, thus allowing more inspections in the same time. The effect of the average energy of the X-ray beam on the percent thickness sensitivity can be quantitatively calculated, as can be seen in Figure 3. The simulation not only correctly reproduces the qualitative result that harder X-ray beams produce radiographs with less sensitivity, it also gives a quantitative measure of how much sensitivity is lost with increasing beam hardness. This allows a quantitative trade-off of sensitivity versus the time required for the exposure.

![Graph](image)

Fig. 2. The abscissa is the actual measured sample to thickness ratio of the machined artifact, while the ordinate is the ratio extracted from the data using the film model. Perfect agreement would follow the line.

The second example is the determination of a scheme for adequate inspection for cracks in a part. A well known feature of radiographs of cracks is the strong angular dependence of the orientation. Using the ellipsoid flaw morphology, we have calculated the range of angles for which a flaw of a given aspect ratio can reliably be detected for different crack closures. As can be seen in Figure 4, the range of angles is strongly dependent upon two parameters, the aspect ratio and the angular orientation. The ability to simulate such an inspection allows the quantitative determination of the minimum number of exposures.
Fig. 3. Simulation results showing the effects on thickness sensitivity of the x-ray beam hardness and the relative size of the flaw to sample thickness.

Fig. 4. The detectability of ellipsoidal flaws as a function of various aspect ratios and flaw orientations is shown. Note that at ninety degrees the crack-like flaw is optimally oriented.
CONCLUSIONS

We have illustrated a flexible x-ray simulation of projection radiography with the above examples. The usefulness of this simulation is dependent upon the degree of accuracy of the numerical results to those that are observed. We have done the first measurements verifying the elements of the model. In particular the beam spectrum model generates the energy spectrum of our generator. The intensity needs to be scaled to obtain agreement to the observed data; however, this was not an unexpected result. Research is in progress to enhance the beam generation model so the calibration is not necessary. The film model has given results that are in agreement, within the error of the experiments, to the measured quantities. The general features of the shapes of the projected images, although not shown here, show excellent agreement with those observed. We have taken radiographs of a cone machined in an aluminum plate and have observed good similarity between the simulated images and the actual image. Further results on the details of these measurements and results reflecting refinement of the existing models will be reported elsewhere.

The applications of such a quantitative model include the ability to perform tradeoff studies on the effects of different set up configurations, experimental parameters such as beam hardness effects, and sensitivity of different types of detectors. These tradeoff studies, when done at the design stage as a part of a CAD package, allow the inspectability of the part to be insured at the design stage. It further assures an inspection scheme for the actual quality control on the manufacturing floor. The trade off studies can be further extended to comparisons of techniques such as the quality of an ultrasonic versus an x-ray inspection. The existence of a quantitative forward model allows the development of a rule based expert system, where the simulation is the expert. This expert system can be used, among other things, to train radiographers and to aid in the inspection of novel parts. Finally, as the accuracy of the model attains better precision, the model can take on the role of standards in the process of radiographic inspection. The work presented here, in light of these applications, is at the preliminary stages. The development of these applications are presently ongoing.

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REFERENCES

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