A CAD INTERFACED SIMULATION TOOL FOR X-RAY NDE STUDIES

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INTRODUCTION

Quantitative nondestructive evaluation, which aims at recovering information regarding certain parameters of the materials from the nondestructive evaluation (NDE) measurements, has attracted attention of the researchers in an increasing manner over the last decade. The work presented here represents the ongoing effort in quantitative nondestructive evaluation in the form of a computer simulation of the image formation process (1,2) and represents the x-ray component of broad effort to model all of the major inspection methods (3). To date one of the major limitation of this process modeling effort is the inability to handle complex part geometries. The developed code targets simulating x-ray inspection of parts designed through computer aided design (CAD) packages. For such a simulation tool to have practical applications, the physics of initial x-ray beam generation, x-ray and target interactions, x-ray and detector interactions should be modelled with sufficient accuracy and flexibility that the effects of the adjustable parameters found on the x-ray inspection systems can be simulated. While the physics in the undertaken work is modelled after well established principles, the information regarding the geometrical representation of the target object is provided by a CAD package through the developed interface. The existence of such a simulation tool has implications in a wide range of applications. A CAD package facility to handle realistic part shapes and CAD's present usage by design engineers leads to a natural coupling of inspectability and design. This idea of unified life cycle engineering (4,5,6) or concurrent engineering where the inspectability of part is one of several issues addressed in the optimal design becomes a reality with the availability of quantitative process models. Thus probability of detection and subsequent inspectability can be evaluated in the design stage. Another area where the simulation tool can be easily utilized is the development of the standards. Various institutions preparing radiography standards for industry can use the code as a tool in development of these standards. The simulation code can also be used for developing reference radiographs of the perfect parts for comparing to the actual radiographs. Another place where the simulation can be applied is training of radiography operators. The affect of the various parameters on the radiographs and the signatures of various types of flaws can be displayed easily for the trainees through the simulations and further represents an ideal method for certification of inspectors at all levels.

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MODELING

The physics of the overall x-ray inspection process can be divided into three major independent models represented by the initial x-ray beam model, x-ray and target object interaction and x-ray and detector interaction models. Finally, a model is required for calculating the probability of detection or the figure of merit for inspectability of design of the part.

Initial X-Ray Beam Modeling

The important parameter in the initial x-ray beam modeling is accurate determination x-ray energy spectrum. Since the interaction of x-rays with the target is energy dependent, the initial x-ray beam computations have a vital importance. In this work, initial x-ray beam calculations are based upon the electron-electron interaction cross sections (7). 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. The comparison of the calculated and the experimentally obtained energy spectrum of initial x-ray beam are given in (2). While the model takes the inherent filtration into account, the calibration is most likely for the specific machine since in a sealed tube machine many parameters necessary for the calculations, for example, the angle of the target with the incident electron beam, can not be adequately measured.

X-Ray Beam and Target Object Interaction Modeling

The model used for calculating the x-ray target object interactions are based upon the Boltzmann transport equation.

$$\vec{\Omega}.\nabla I(\vec{r},E,\vec{\Omega})+\mu_t(E)\, I(\vec{r},E,\vec{\Omega}) = \int_0^\infty dE' \int_{4\pi} d\Omega'\, \mu(E'\rightarrow E,\vec{\Omega}'\rightarrow\vec{\Omega}) I(\vec{r},E',\vec{\Omega}')+S(\vec{r},E,\vec{\Omega}) \quad (1)$$

While the left side of the equation (1) represents removal of the photons, the right side of the transport equation is a expression of photons born into the given energy and direction at specified position. The photons born are usually made up of the scattered photons and the photons originating from fluorescence radiation. If the characteristic radiation induced by the x-rays inside the material and the Compton scattering are assumed to be negligible, the transport equation becomes a homogenous differential equation. This no scattering assumption is valid when the photoelectric interaction is dominant. This condition is satisfied for the most part when the accelerating voltage of the generator is less than the K shell electron binding energy. With the boundary conditions assuming that there is no incoming x-rays except for the boundary facing the x-ray source, the solution to the homogenous differential equation is given as

$$I(\vec{r},E) = I_o(E)\int\int_{Source} \frac{e^{-\mu_t(E)\rho(\vec{r},u,w)}}{d^2(\vec{r},u,w)}\cos\theta\, du\, dw \quad (2)$$

Due to the distances between the x-ray source and the detectors, $\cos\theta \cong 1.0$ for most of the cases. Although the final model for x-ray target object interaction is an analytical expression, this expression must be computed by numerical means because of irregular domains and the flaws inserted into the target objects. Introduction of flaws into the overall simulation scheme is done through readjustment of the $\rho(\vec{r},u,w)$. The current version assumes all flaws to be either a truncated cone or an ellipsoid. While the truncated cone can be moved with its axis normal to the detector plane, the other flaw type ellipsoid can be oriented arbitrarily. Both flaws may be treated as either a void or an inclusion with their sizes arbitrarily adjusted.

Interface with CAD Package

As it will be seen from a study of equation 2, the only information not provided by the simulation code is $\rho(\vec{r},u,w)$. This information is provided by the CAD package at the design stage of the part. The current version of the simulation tool is interfaced with SDRC-Ideas for obtaining the path lengths (8). Once the part shape database defining the designed part is prepared by the designer, the path lengths are extracted from this database by an auxiliary program written in Ideas language. The output file resulting from this process are used by the simulation program for computing the transmitted x-ray beam density. Since the flaw morphology and the locations are determined by the simulation code, the extraction of information from CAD package is repeated only if the location and the orientation of the target object is changed.

X-Ray Beam and Detector Interaction Modeling

The most common detector type used in the x-ray NDE inspection is film. We have extended the model presently used for simulating x-ray beam and film interaction to include a more realistic treatment of the x-ray interaction with the silver halide grains. The development of film modeling can be considered in two parts. One is the calculation of the silver halide grains density activated by incident x-rays, the other is the conversion of these activated grain densities into optical film densities. The number of silver halide grain densities contributing to the final optical density (9) is given by

$$N_d = N\,[1 - e^{-\sum_i f(E_i)I(E_i)}] \qquad (3)$$

where N is total number of silver halide grains in the film and f(E) in the above equation is number of grains activated by an incident photon with energy E. Since the silver halide grains are activated by the photoelectrons emitted, their energies should be known for computations of f(E). This, in turn, requires ratios of photoelectrons emitted by K and L shells. The volume fraction of silver halide grains, grains thickness and grain surface area distribution are important parameters in the computation of the number of activated grains. The conversion of the activated grain density into the film density is done by the Nutting formula (10) which is

$$D = \log_{10} e \frac{ns}{A} \tag{4}$$

where A, n and s are aperture area, number of developed grains for given area and grains surface area respectively. Although the information regarding the film parameters such as grain volume fraction, grain thickness and grain surface area distributions are available in the literature, we currently use the ones given in (9).

An important feature of any model is the treatment of the noise processes. There are two important noise processes to be modeled in the x-ray and film interaction. One source of the fluctuations is the random Poisson distributed noise in the number of photons in the beam. The other source comes mainly from the distribution of the grains in the film emulsion. We have extended the modeling of the process noise to include the component originating from the film (11).

PROBABILITY OF DETECTION

As mentioned in the introduction, one purpose of the simulation tool is to carry out probability of detection (POD) studies. Currently, the POD studies is based upon the signal to noise (SNR) computed through match filter methods. The match filter is known to be one of the methods approximating human visual characteristics closely (12,13). The comparison of SNR obtained are compared to experimental values (14).

SIMULATION RESULTS

We used an automobile air conditioner component for demonstrating the idea and capabilities of the simulation package. The component shown in figure 1 has dimensions about 11.0 cm by 5.0 cm and its geometry is a relatively complex one. Through this problem, we illustrated how the changes in the x-ray beam hardness affect the image and how we can simulate a flaw imbedded into the designed part.

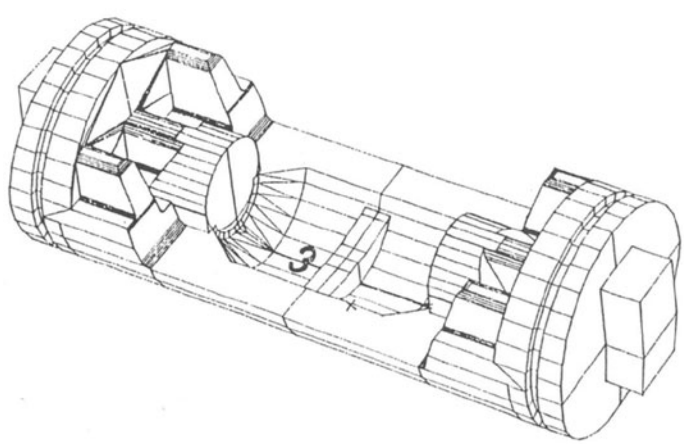

Fig. 1. The CAD design of automobile airconditioner part.

In the first set of demonstrations, the detailed face of the auto component is oriented toward the x-ray source. The distance between x-ray source and the film plane is taken to be 100.0 cm. The target object stands at halfway from the source in 2X magnification. The energy of the initial x-ray beam is increased three times while the current and the position of the target object is kept fixed. As it will be seen from the first image in the figure 2, where the softest x-ray are used, the penetration is very poor. Some penetration is recorded only in the central region where the part is thinnest. As the energy of x-rays are increased, the penetration gets better. In the second image, x-rays can penetrate through most of the part except through end parts where maximum thickness occurs. In the third image, we do get some penetration at the ends but this can be done only when the saturation is reached in the central part of the target. In figure 3, the real radiographs of the auto component are displayed. The trend in the figure 3 confirm the trend we get from the simulations.

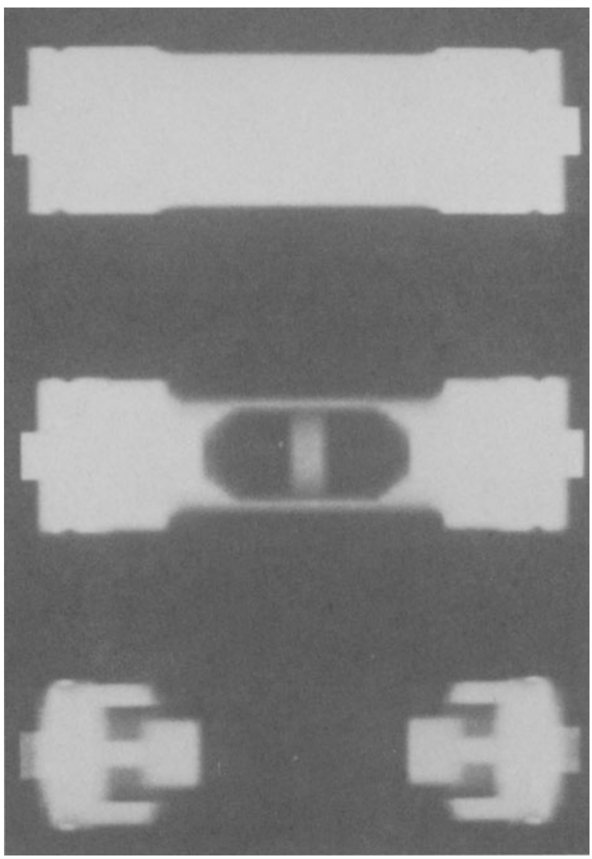

Fig. 2. The simulation of the airconditioner part with various exposure settings.

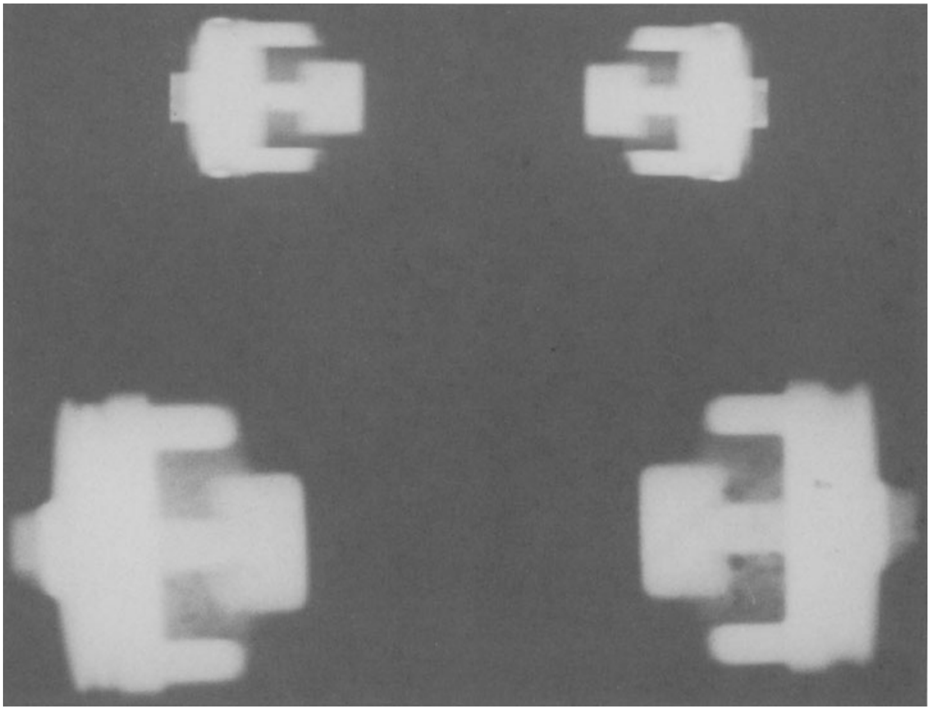

Fig. 3. The qualitative comparison of the simulated radiograph (top) and the real radiograph.

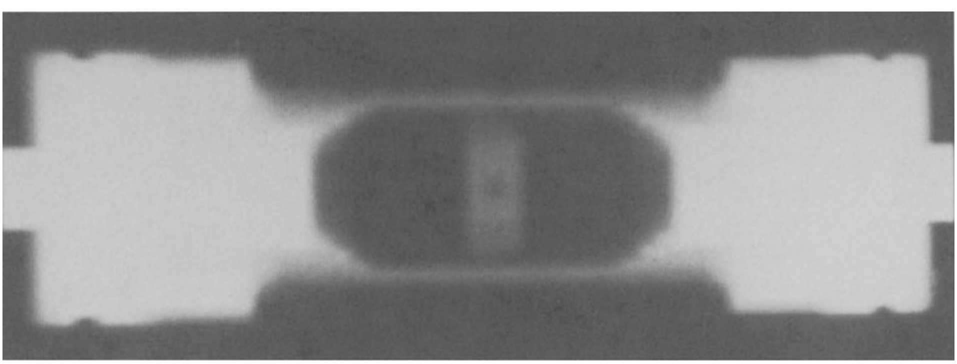

Fig. 4. The simulation of the automobile airconditioner with a flaw built in at the center point.

In the figure 4, we simulated the same auto part with a flaw at the center built in. Although only one case is simulated, we have capabilities simulating flaws in various positions and sizes.

CONCLUSIONS

We have developed a quantitative x-ray inspection simulation tool for computer simulations. The interface of a CAD package to the overall tool adds a high degree of flexibility to the simulation tool. In our examples, we demonstrated that target objects with very complex geometries can be simulated. The weaknesses of the current version of the simulation tool lies with the CAD package interface and the limited extent of the validation of the models. The current interface uses the tools available through the CAD package SDRC-Ideas. These tools extract information from the data bases very slowly and they require a lot of storage space on the computer. We are currently involved with developing a new interface which will overcome both of these drawbacks. Although some experimental verification was done for the x-ray beam computations, we do not have similar verifications for the film and x-ray target object interactions. The work for verification of these models and developing a new x-ray target interaction model based on the inhomogeneous transport equation with scattering is underway. Once the verification and development of the more efficient interface is completed, the simulation tool can be implemented for various purposes. One of the first applications can be in design stage of manufacturing line. The inspectability can be built into the design by carrying out simulations as soon as the design was completed in the CAD package. One other implementation can be in optimizing the inspection parameters. By varying the adjustable parameters, best parameters can be determined for getting the best contrast. The simulation tool would provided images from various angles required for the tomographic reconstruction. In addition to the above implementations, developing flaw free reference radiographs for specific parts, training radiography operators and developing standards are among various possible implementations.

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