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An Improved Method for Simulating Radiographs

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An Improved Method for Simulating Radiographs

Abstract

In our original work, we simulated radiographs of mechanical parts using an exact density map, neglecting the effects of differing radiation sources and film exposure time. Here I examine the parameters involved in generating actual radiographs and discuss what can and cannot be modeled. Using the spectral distribution of the radiation source and the mass absorption curve for the material comprising the part to be modeled, we determine the actual amount of radiation that would pass through the part and reach the film. This method increases our confidence in the results of the simulation and enables us to model parts made of multiple materials.

Introduction

In 1985 I reported on our ability to use a computer to generate pictures that approximate radiographs of mechanical parts.¹ We used a technique called ray tracing to calculate relative densities, which we then converted to gray scales for use on a graphics device. This year we modified the simulation to account for the physical properties of the materials that comprise the part to be radiographed and the characteristics of the radiation source. Called simulated radiographs, these pictures have a number of potential uses: they can

allow mechanical systems to be designed for future nondestructive evaluation, aid in radiation source positioning, and aid in the evaluation of actual radiographs.

Before attempting any kind of simulation, the process to be simulated must be well understood. Therefore, in this paper I first discuss the process of radiography and the three parameters that determine the resulting radiograph. I then explain our method of simulating radiographs.

Radiography

Radiography is a photographic process that uses electromagnetic radiation with wavelengths from about 10^{-3} to 1 nm (Ref. 2), commonly called x rays, to create a density map that enables one to examine an object without disassembling or destroying it. X rays are used because they are capable of penetrating most materials, including metals, at least partially. The radiographic process consists of three elements: the radiation source, the part to be radiographed, and radiation-sensitive film.

Ideally, the density map that is generated is linearly related to the density of the part being radiographed. In our original work we did not try to model radiography rigorously; rather, we assumed linear relations that resulted in an exact density map. Although this map was a useful tool, it was not an accurate simulation because the radi-

ation source was nonlinear and, of course, the attenuation of radiation through an object and the exposure time of the film are always nonlinear. Each of these nonlinearities introduces parameters to the system that must be accounted for in any rigorous simulation of the radiographic process. In the paragraphs to follow, I describe these parameters and their implications on the simulation.

Radiographic Parameters

Spectral Distribution

The first parameter that must be accounted for in the radiographic process is the spectral distribution of the radiation reaching the part to be radiographed. This radiation is generated by bombarding a metal target with high-energy electrons,

as illustrated in Fig. 1. When these electrons hit the target, x rays are generated at many different wavelengths. The x rays that are emitted from the target form a continuous spectra, since x rays are generated at every wavelength within a given range.

Because x rays are a form of electromagnetic radiation, we know that some properties of x rays are best described in terms of waves, while others are best described in terms of particles. Although every x ray can be identified by its wavelength, using wavelength to discuss x rays can become awkward. For our purposes, it is convenient to talk about x rays as particles, called "photons." The wavelength of an x ray can be converted into the energy of a photon (E_{γ}) by

$$E_{\gamma} = hc/\lambda_{\gamma} \quad (1)$$

where λ_{γ} is the wavelength in centimeters, h is Planck's constant, c is the speed of light, and e is the electron charge in electrostatic units.³

Now we can describe x rays as a range of energy levels. Although the range of energy levels emitted by the target is continuous, the majority of x rays is distributed around one energy level, called the "characteristic." The characteristic level is determined by the energy difference in the electron orbits of the target material and the energy of the bombarding electrons. Figure 2 shows the x-ray distribution for an x-ray tube operating at 30 keV. Although the greatest number of x rays is generated over a very small range of energy levels, a significant number of x rays is generated throughout the rest of the continuum. Since the number of x rays not at the characteristic is con-

siderable, the contribution of these x rays must be incorporated into the model along with the characteristic radiation.

Material Cross Section

Another parameter in the radiographic process that must be accounted for is the material cross section. Every element in the periodic table of elements has a unique material cross section that is a function of the atomic density and the energy required to displace electrons from their orbits. Thus, there will be a different cross section for each material in the part to be radiographed. Moreover, the cross section of a material is not a constant; rather, it is a curve that indicates the amount of radiation that will be attenuated (blocked) at each energy level. In other words, each energy level in the incident radiation will be attenuated differently. A low-energy x ray might be completely attenuated by a material, but a higher energy x ray might pass unobstructed through the same material. And, of course, intermediate energy-level x rays would fall somewhere between the two extremes.

Film

The third and final parameter in this process is the radiation-sensitive film, which is placed behind the object being radiographed. When x rays penetrate the object, they hit the film emulsion, displacing electrons. Just as the emulsion of conventional photographic film responds differently to different wavelengths of light, the emulsion of x-ray sensitive film responds differently to the individual energy levels of x rays. For example, a certain amount of x rays at one energy level will

Fig. 1. Diagram of an x-ray tube. X rays are generated when electrons from a heated filament are accelerated by a potential difference (voltage) and strike a metal target. The x rays are channeled by a window that is transparent to the x rays. The window is set into an evacuated metal container.

Fig. 2. Distribution of x rays from an x-ray tube operating at 30 keV with a tungsten target.

create one shade on the film, while the same amount of x rays at another energy level will create a different shade or even fail to create a shade at all. The film is then developed to produce the finished radiograph. Like other types of film, x-ray film comes in a variety of speeds (the speed being the amount of time required to generate an image). To make the effective film speed faster, enhancing screens are often placed in front of the x-ray film. Moreover, the state of the processing chemicals and the developing time affect the final image, which is also true in photography.

Simulating true radiographs requires that we model the effects of film and enhancing screens on the exposure and development processes. Unfortunately, these processes are very difficult to

model for three reasons: (1) film emulsion, and thus film sensitivity, varies slightly from film batch to film batch; (2) the sensitivity of the film over all energy levels is not constant; and (3) the state of the processing chemicals is not constant.

Other Modeling Considerations

Each of the parameters mentioned above is dependent upon an implied variable: time. The amount of radiation emitted at each energy level depends on how long the radiation source is turned on, as does the number of x rays that will penetrate a given thickness of a material. In turn, time determines the number of x rays that will

reach the film. But because we cannot accurately model the exposure of the film, modeling time will not produce any useful information. Therefore, we assume that time is a constant.

If any model of the radiographic process is to be accurate, it must incorporate the three parameters just discussed. It must also model the interaction of x rays with the materials and film. The

remainder of this paper describes our method of simulating radiographs. We incorporate the energy distribution of the radiation source and the material cross sections into our model; however, we do not incorporate the effects of films, enhancing screens, and time. In other words, we perform a relative simulation rather than an absolute simulation.

Simulation

Simulating the visual aspects of radiography is a three-step process: (1) we create a digital representation of the part to be radiographed, (2) we perform the actual simulation on the digital model, and (3) we convert the computer output to film or to some other graphics media. We use a solid modeler called Technical Information Processing System-1 with LLNL enhancements (TIPS-1/LLNL) to generate models using constructive solid geometry (CSG).⁴⁻⁶ CSG enables us to build parts by performing union, subtraction, and intersection operations on a set of primitive volumes (three-dimensional building blocks) that the solid modeler can understand—such as spheres, cones, cylinders, and boxes. Figure 3 shows the results of these operations using two boxes.

One way to simulate the radiograph is by ray tracing. Ray tracing is a method used in the design and analysis of optical systems, and more recently in computer graphics, to generate hidden-surface images. In fact, this method of generating simulated radiographs is very similar to that used to perform hidden-surface calculations. Thus, this simulation can be added to the ray tracing routine that is commonly used by solid modelers to generate shaded pictures—that is, images that appear to be solid as opposed to wireframe.

To simulate a radiograph using ray tracing, we must first establish the positions of the radiation source, the part to be radiographed, and the film plane (see Fig. 4). We then create a two-dimensional array of very small squares to represent the film plane. Each square will later be associated with a pixel (picture element) on a monitor or film recorder. A ray is cast from the radiation source to the center of each of the squares, corresponding to x rays leaving the radiation source in the direction of the film. Because we know both the origin and the termination points of the ray, we can formulate a parametric equation of a line that describes the ray. Then, using this equation, we can calculate the intersections of the ray with

the primitive volumes used to make the part. The solid modeler is queried to determine whether each intersection is inside, outside, or on the boundary of the modeled part.

After throwing away those intersections outside of the part, we can sort the remaining intersections to form a sequence, as shown in Fig. 5(a). Each pair of intersections in the sequence (a1-a2, b1-b2, and c1-c2) defines a segment of constant material type along the ray. Also, each of the intersections is associated with a primitive volume. This allows us to associate each segment with the material used to define the primitive volume and to determine whether a given segment is inside or outside of the model. Additionally, by associating each segment with a material type, we can use multiple materials to define the part. To better understand the need for this association, consider the sequence of intersections shown in Fig. 5(b). If the intersections were not associated with primitive volumes, we would correctly assume that a1-b1 defined a segment inside the model, as does b2-a2; however, we would incorrectly assume that segment b1-b2 was outside of the model. But because we know that intersections b1 and b2 both belong to the same primitive volume (b), we can deduce that the segment b1-b2 represents material inside the part.

Now that we know which segments contain material and which segments do not, we can calculate the intensity of radiation reaching the first segment. Because we are not explicitly modeling the time of exposure, we assume an exposure of 1 s. Thus the amount or intensity of radiation reaching the first segment is the number of photons per second at each contributing energy level for the selected radiation source. Intensity curves for any target material and energy level can be calculated or directly measured.

The next step requires the use of the material cross-section curve. (Material cross sections have been compiled for most elements and are available in a separate report.⁷) X-ray cross-section

Fig. 3. Solids can be constructed by the use of union, subtraction, and intersection operations. As shown, four results can be obtained with two blocks in the given orientation: (a) The large block can be unioned with the small block, (b) the small block can be subtracted from the large block, (c) the large block can be subtracted from the small block, and (d) the large block can be intersected with the small block.

data are usually given in terms of the mass absorption coefficient μ_m (linear absorption coefficient μ divided by the atomic density ρ) because this coefficient results in an atomic property independent of chemical or physical state (Figure 6 shows the mass absorption curve for silver.) For our simulation, it is easiest to use the linear absorption curve. Therefore, we multiply the mass absorption curve by ρ to give us the linear absorption curve. With this information, we can calculate the emergent intensity of radiation I_t for x rays of

a single energy level through a material of a given thickness. This is given by

$$I_t = I_0 \exp(-\mu t) \quad (2)$$

where I_0 is the incident intensity, μ is the linear absorption coefficient for a selected energy level, and t is the material thickness. In other words, if we know the photons per second arriving at the material, Eq. (2) will give us the photons per second leaving the material.

Fig. 4. Radiographs are simulated by casting rays from the radiation source position to the simulated film plane. Densities are calculated and recorded for rays that pass through the part being radiographed.

Fig. 5. A ray may have several intersections with the part before reaching the film. (a) Each intersection (marked X) must be paired with another intersection; that is, if the ray enters the part, it must also leave the part. A pair of intersections defines a segment inside the part. (b) Each intersection must be associated with a segment name—in this case, a1-a2 or b1-b2. Without this association it would be impossible to determine whether segment b1-b2 is inside or outside of the part.

Fig. 6. Typical mass absorption curve (in this case, for silver).

Unfortunately, Eq. (2) accounts for only one energy level of x rays, and we want to account for all of the x rays. Therefore, we must calculate I_i for every energy level. This can be accomplished by multiplying two curves: the incident energy curve and the curve $\exp(-\mu t)$. (It is important to remember that μ is derived from the material cross-section curve, which is a function of energy level.)

$$I_i(e) = I_0(e) \exp[-\mu(e)t] \quad (3)$$

The result is the new curve, $I_i(e)$ (e signifying that this curve is a function of energy level), which describes the intensity of x rays at each energy level passing through a material of thickness t . We can now use $I_i(e)$ as the incident intensity to a second material. Thus the process is repeated for each segment containing material until we get the intensity incident on the film.

Performing the above operations on all segments containing material yields a curve that describes the intensity of all energy levels that are incident on the film. Since we have chosen not to model the exposure of the film (as discussed earlier), we can describe as a single quantity the total intensity of radiation reaching the film at a point. The total intensity I_T is the sum of the intensities at all energy levels; therefore, we perform the integration

$$I_T = \int I_i(e) de \quad (4)$$

over all energy levels. It is too expensive to perform this integration analytically because the integration would have to be evaluated 250 000 to 1 000 000 times per image. Moreover, finding an analytic representation for the repeated multiplication of the intensity curve and the exponentiation of the linear absorption curve would soon

prove impossible. Therefore, to make the simulation feasible, we have approximated the intensity and cross-section curves with a finite number of sampled points. If we sample the intensity and cross-section curves at the same energy levels, then the multiplication in Eq. (3) becomes

$$I_i(e_i) = I_0(e_i) \exp[-\mu(e_i)t], \quad i = 1, 2, \dots, n. \quad (5)$$

This implies that the intensity of radiation reaching the film will be given by a finite number of points sampled at the same energy levels as the intensity and cross-section curves. Thus, we can approximate the intensity of all x rays combined with

$$I_t = \sum_{i=1}^n I_i(e_i) de, \quad (6)$$

where de is the distance between sample points. The value I_t can now be used to calculate the intensity recorded at a point on the film.

Before starting the simulation, we calculate the maximum possible density on the film for selected parameters (i.e., the radiation source, part geometry, and distance between source and part). This is done by finding the minimum and maximum bounds of the part in each of the three defining coordinates. This information is implicit in the TIPS-1/LLNL geometric data base, but it can also be calculated. Of these three minimum/maximum pairs, we find the one that spans the

greatest distance. Next we find the material cross section with the highest density that is a component of this part. Using the greatest minimum/maximum distance and the most dense material cross section, we calculate the intensity of radiation that would reach the film through this material and thickness. This value is equated with zero and the intensity of the radiation source is equated to one, allowing us to get the most use out of our limited number of gray scales. After calculating a value of I_t , we perform the calculation

$$I_t = \frac{I_t - I_{\min}}{I_0 - I_{\min}}. \quad (7)$$

This gives us a value between 0 and 1 for the intensity I_t reaching the film, where 0 represents the minimum energy passing through the object and 1 represents the energy in the incident radiation. This value is remapped into the gray scale being used. In our case, there are 256 different shades of gray (0 to 255), so we multiply I_t by 255 to get the proper shade of gray for this energy level.

Once this process has been repeated for each of the squares on the film plane, the gray-scale value for each square is written to a file. The file can be used to create an image on a graphics monitor or film recorder. To accomplish this, we assign each gray-scale value to a pixel on the monitor or film recorder. The gray-scale value will determine the intensity of the pixel associated with it. From this point on, the image can be viewed directly or converted to film (see Fig. 7).

Potential Uses

Using our current software, we can simulate radiographs that have a number of potential uses.

First, and foremost, they can be used during the design phase of complex mechanical systems—systems that are usually designed, prototyped, and even produced without concern for future nondestructive examination. When a radiograph of some component of the assembled system is required, a useful image often cannot be obtained, because the component of interest has been surrounded by other components that act as a mask. This results in the disassembling of the system. Considering the time and effort required to disassemble the system and the possibility that components will be ruined in the process, this is a very undesirable situation. However, by generating a simulated radiograph of the assembly, a de-

signer could determine that a particular component will not be visible in a radiograph before the component is even manufactured. With this knowledge, the design could be altered to allow for future nondestructive examination.

Second, simulated radiographs can be used to evaluate actual radiographs. This is possible because the model of the part in the solid modeler is guaranteed to have no flaws. Thus, a simulated radiograph generated from the perfect model is the radiograph of a perfect part. We can compare an actual radiograph with the perfect radiograph, which helps us to detect flaws.

Third, simulated radiographs can be useful in the area of source positioning. A technician can reduce the number of actual radiographs that would have to be generated by using simulated

Fig. 7. The results of a simulation can be converted to film: (a) a part modeled by a solid modeler and (b) a simulated radiograph of the part shown in (a).

radiographs to get a rough estimate of the proper source placement.

Finally, simulated radiographs can be used to subtract unwanted features from an actual radiograph. Unwanted features in a radiograph are often so numerous that the feature of interest is difficult to see. This problem could be reduced by using simulated radiographs and an image-processing system. First a model of the part would be created, with the feature of interest omitted. Next a simulated radiograph of the part would be

generated. Then, using the image-processing system, the simulated radiograph would be subtracted from the actual radiograph. Although the simulated radiograph would not simulate the radiograph exactly, unwanted features would be suppressed so that the feature of interest could be clearer.

With considerable improvements to our current software, simulated radiographs might also be used to estimate exposure times and film and enhancing screen requirements.

Conclusions

A simulated radiograph can be an important aid to radiography. However, there are two things that it cannot do, and will probably never do. First, it cannot exactly emulate the film densities in an actual radiograph. There are only 256 possible densities on the simulated radiograph, while there are many times that number of densities on x-ray film. Moreover, the exposure of the x-ray film and the print film for the simulation will constantly vary; no two lots of film will be exactly the same. Consequently, and secondly, x-ray exposure cannot be predicted precisely.

A third limitation emerges. A radiograph enables us to check the uniformity of materials,

which is one of its most attractive uses. X rays of welds and of material samples are used for this purpose. However, in the case of simulated radiographs, because we assume our material is uniform, there is no way to simulate or predict non-uniformity.

While it is not clear that the expense of running the simulation is less than the expense of generating an actual radiograph, the ability to simulate radiographs can be a very useful tool—especially during the design process with its tremendous potential for cost savings.

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