MATERIAL THICKNESS MEASUREMENTS USING COMPTON BACKSCATTER

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INTRODUCTION

As the age of airplanes in the commercial fleet has increased, inspection and maintenance costs have steadily increased. The fact that aircraft have a fairly complicated structure and operate under a wide range of environmental conditions means that detection of the onset of structural deterioration is often difficult. In particular, corrosion of aluminum structures may begin on interior layers and be visually evident only at fairly advanced stages. Present maintenance requirements dictate that airplane skin (typical thickness 1mm) must be repaired if more than 10% thickness of the material has corroded[1]. A number of nondestructive inspection techniques are being applied to assist in early detection of corrosion in aircraft structures[2]. However, it is often difficult to determine whether these small thickness variations are due to corrosive material loss or to inherent variations introduced in the manufacturing process. X-ray scattering is sensitive to variations in material type and density, and hence offers the possibility of distinguishing between corroded material and intrinsic thickness variations.

X-ray interactions with matter can be described in terms of three physical phenomena: photoelectric effect, Compton scattering, and coherent (or Rayleigh) scattering. The relative strengths of these interactions in aluminum are plotted in Fig. 1 as a function of x-ray energy. Conventional radiography techniques are based on the attenuation of an x-ray beam due primarily to the photoelectric effect. This method can provide high contrast, especially at low energies, but access to both sides of an object is necessary. We have recently demonstrated high sensitivity for detection of corrosion using an energy dispersive detector in a transmission configuration[3]. At higher x-ray energies Compton scattering dominates the interactions in matter. This opens the possibility of measuring backscattered radiation to do a single-sided inspection for corrosion.

Compton scattering is characterized by a unique relation between the energy and angle of the scattered photon relative to the incident photon. A photon of energy E scattered off a free electron through an angle θ will have energy

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 12
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1993

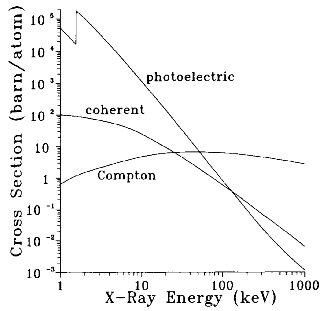

Fig. 1. X-ray interaction cross-sections for aluminum.

$$E' = \frac{E}{1+\left(1-\cos\theta\right)E/m_e}, \tag{1}$$

where m_e is the mass of the electron. The Klein-Nishina formula[4] predicts the probability for scattering at an angle θ into a solid angle dΩ,

$$\frac{d\sigma}{d\Omega} = \frac{e^4}{2m_e^2}\left(\frac{E'}{E}\right)^2\left(\frac{E'}{E}+\frac{E}{E'} - \sin^2\theta\right), \tag{2}$$

where e is the charge of the electron. The relative scattering probability is indicated in Fig. 2 for a range of incident energies. It can be seen that especially at lower energies there is significant scattering in the backward (θ > 90) direction.

At low energies coherent interactions also contribute to the scattering of x-rays. As the name implies, the radiation interacts coherently with all the electrons in an atom according to the formula

$$\frac{d\sigma}{d\Omega} = \frac{e^4}{2m_e^2}\left(1+\cos^2\theta\right)\ |\ F(q)\ |^2, \tag{3}$$

where F(q) is the atomic form factor[5], and q = 2Esinθ/2. This process can be distinguished from Compton scattering by the fact that the energy of the scattered x-ray is the same as that of the incident x-ray. Scattering occurs predominately in the forward direction due to the strong influence of the form factor. An additional structure factor is needed to account for interference effects from neighboring atoms. In the extreme case of crystalline material, strong interference conditions result in Bragg scattering.

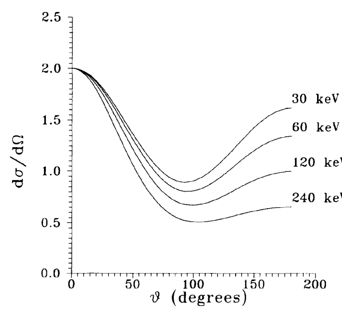

Fig. 2. Angular dependence of Compton scattering for several incident energies.

Most studies of backscatter for nondestructive inspection have used a conventional bremsstrahlung x-ray source[6]. This tends to obscure the fine points evident in the scattering equations described above. We have approached this problem by using a monochromatic x-ray source, which allows us to quantitatively compare scattering measurements with predictions from Eqs. 1-3. We describe below a Monte Carlo model of the x-ray backscatter process and a comparison with experimental measurements. Based on these preliminary results we discuss the potential for applying backscatter measurements to the detection of corrosion in airplane structures.

MONTE CARLO MODEL

There exist several general purpose Monte Carlo codes for describing the interaction of radiation with matter. For our studies we have implemented the EGS4 code[7] developed at SLAC. This code has been used extensively for predicting the response of nuclear detectors to different types of radiation, and for calculating radiation doses in nuclear medicine. This code contains the scattering information of Eqs. 1-3 as well as the cross sections for photoelectric absorption in all of the elements. Each photon is traced through the material until it is either absorbed via the photoelectric effect or is scattered out of the object. Thus, multiple interactions are properly accounted for. However, each scatter is considered to occur on a free isolated atom, so the effects of the structure function on coherent scattering will not be accounted for.

We have set up this model to simulate a 60 keV point source located 1.27 cm from an aluminum plate and collimated so as to produce a 3.5 mm diameter spot at the surface of the plate. For different thicknesses of aluminum we have evaluated the radiation which scatters back through the incident surface.

The Monte Carlo technique allows one to probe details of the scattering process that would be difficult or impossible to measure experimentally. One such example is illustrated in Fig. 3 where we show a profile of the depth in the material at which the first Compton scattering occurred. This is a measure of the ability to probe a given region in the object. The upper curve indicates the response obtained when backscattered radiation between 105 and 135 degrees is measured. The gradual falloff in intensity with depth is

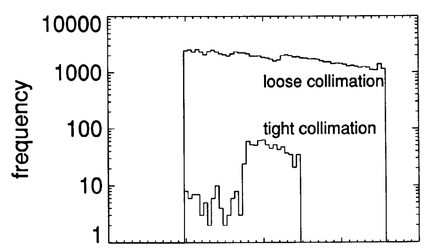

Fig. 3. Monte Carlo prediction for the rate of backscatter of 60 keV x-rays from aluminum as a function of the depth at which the first scatter occurs. The loose collimation accepts x-rays scattered at angles from 105 to 135 degrees, whereas tight collimation restricts scattering to the range from 119 to 121 degrees.

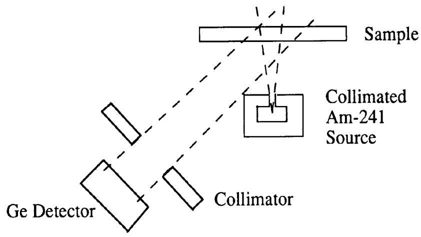

Fig. 4. Diagram of experimental setup for backscatter studies.

due to the attenuation of both the incident and scattered beam. When radiation from a restricted angular region is admitted we can focus on a small slice of the object, obtaining the response indicated by the lower curve in Fig. 3. In this case the overall intensity is dramatically reduced, thus requiring longer inspection time. We also see that there is a background from other regions which is admitted to the detector because it has undergone multiple scattering. By varying parameters in the Monte Carlo model one can optimize the arrangement of source, detector and collimators for a specific problem.

COMPARISON WITH EXPERIMENT

To test the predictions of the Monte Carlo model we have set up the simple experiment sketched in Fig. 4. Americium-241 has a prominent emission at 59.5 keV and very little additional background. Integration times of several hours were required because the source strength was only 10 μCi. The arrangement of detector and collimator corresponds to the loose collimation condition indicated in Fig. 3, so our results should be sensitive to the total thickness of the aluminum sample.

Figure 5 shows the backscatter energy spectra measured for two different thicknesses of aluminum. In each case a background spectrum obtained with no sample present has been subtracted from the data. The background results mostly from scattering

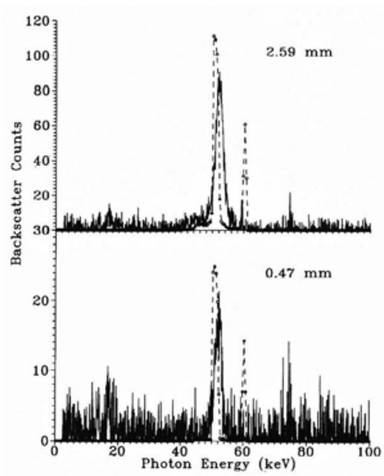

Fig. 5. Examples of backscatter spectra for different thicknesses of aluminum as measures experimentally (solid lines), and predicted by EGS4 Monte Carlo (dashed lines).

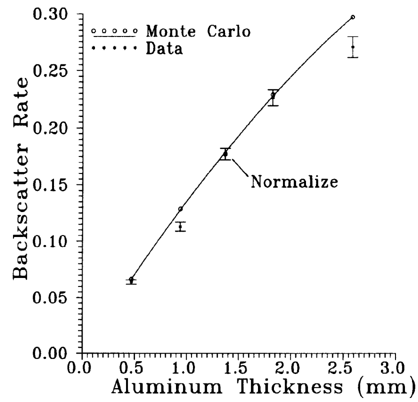

Fig. 6. Comparison of Monte Carlo predicted and experimentally measured backscatter rate as a function of sample thickness.

in the lead shielding of x-rays with energy > 100 keV emitted at very low rates by the ^{241}Am source. The Monte Carlo predictions are plotted on top of the data. A very clear Compton shifted peak is present in both data sets and agrees quite well with the Monte Carlo predictions. However the coherent scattering peak is greatly suppressed in the experimental data relative to the Monte Carlo prediction. This is likely due to the fact, as mentioned in the previous section, that the Monte Carlo model does not account for the structure function describing correlations between atoms in bulk material.

Integrating over the Compton peak we calculate the backscatter rate plotted in Fig. 6 as a function of aluminum thickness. This is compared with the Monte Carlo predictions normalized to one of the data points. The error bars represent the statistical uncertainty in the measurements. In addition, there is a systematic uncertainty (not shown) due to the lack of reproducibility in positioning the sample in this proof-of-principle experiment. Keeping this in mind, the results are in very good agreement with the Monte Carlo predictions. Based on the statistical errors we calculate an uncertainty in thickness measurement of better than 100 μm for aluminum sheet up to 3 mm thick.

CONCLUSION

We have demonstrated that the Compton backscatter technique has the sensitivity needed to measure airplane skin thickness. Furthermore, a Monte Carlo model of the backscatter process has been shown to be in good agreement with experimental results for Compton scattering. This model should prove valuable in designing a device optimized to detect corrosion in aluminum 1-2 mm thick. Additional Monte Carlo calculations and experimental studies will be carried out to take into account the effect of different aluminum alloys and corrosion products. Finally the technique will be tested on more realistic structures containing joints, rivets, and curved surfaces.

ACKNOWLEDGMENT

This work was sponsored by the FAA-Center for Aviation Systems Reliability, operated by the Ames Laboratory, USDOE, for the Federal Aviation Administration under Contract No. W-7405-ENG-82 with Iowa State University.

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