A LINEARIZATION BEAM-HARDENING CORRECTION METHOD FOR X-RAY COMPUTED TOMOGRAPHIC IMAGING OF STRUCTURAL CERAMICS*

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INTRODUCTION

Computed tomographic (CT) imaging with both monochromatic and polychromatic x-ray sources can be a powerful NDE method for characterization (e.g., measurement of density gradients) as well as flaw detection (e.g., detection of cracks, voids, inclusions) in ceramics. However, the use of polychromatic x-ray sources can cause image artifacts and overall image degradation through beam hardening (BH) effects [1]. Beam hardening occurs because (i) x-ray attenuation in a given material is energy dependent and (ii) data collection in CT systems is not energy selective. Without an appropriate correction, the BH effect prevents the establishment of an absolute scale for density measurement. Thus, quantitative density comparisons between samples of the same material but of different geometrical shape becomes unreliable [2].

Many different correction approaches are employed in medical CT systems to eliminate or reduce the BH effect. These range from the early "water bag" approach (i.e., prepatient beam filtering) to a dual-energy approach [3,4] and correction of the image after reconstruction [5,6]. The intensive correction effort undertaken for medical CT systems has reduced the BH for tissue and tissue-like material to less than a few Hounsfield units or to tenths of a percent. However, BH problems still exist for higher density bone and bone-like material.

For many industrial components made of relatively high-density materials, the BH effect is considerably greater than encountered in medical applications, but very little has been done to cope with this problem [7]. Rather, the BH effect is avoided in many industrial CT systems by using monochromatic isotope sources [8,9]. The main disadvantages of isotope-source CT systems are the low intensity (which leads to longer

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image data acquisition times) and the stringent safety measures required to protect personnel. The purpose of this paper is to present a linearization BH correction method applicable to the CT examination of ceramic materials with a polychromatic x-ray source.

**PRINCIPLE OF LINEARIZATION BH CORRECTION**

It has been recognized for some time [10] that the nonlinear CT image reconstruction process can be linearized if the material being scanned can be assumed to be homogeneous. This linearization process can be mathematically explained as follows: The intensity, \( I(x) \), of a polychromatic x-ray beam after penetrating a homogeneous material to a depth \( x \) is given by

\[
I(x) = \int S(E) e^{-\mu_L(E)x} dE,
\]

where \( S(E) \) is the spectrum of the polychromatic source and \( \mu_L(E) \) is the total linear attenuation coefficient (i.e., the total of the photoelectric, compton, and Rayleigh components). The polychromatic x-ray beam can be represented by an equivalent monoenergetic x-ray beam, by first substituting an effective total linear attenuation coefficient, \( \mu_L(\text{eff})(x) \):

\[
I(x) = \int S(E) e^{-\mu_L(\text{eff})(x)x} dE = I_o e^{-\mu_L(\text{eff})(x)x},
\]

where

\[
I_o = \int S(E)dE
\]

and \( \mu_L(\text{eff})(x) \) is the total effective linear attenuation coefficient obtained over the energy spectrum of interest. Having obtained \( \mu_L(\text{eff})(x) \), one can refer to the attenuation vs. energy plot and obtain an equivalent monoenergetic photon energy. Figures 1 and 2 illustrate this process for the case of \( \text{Si}_3\text{N}_4 \) and a typical polychromatic x-ray spectrum. Figure 1 shows the x-ray spectrum for a Siemens Somatom DR-H CT scanner operated at 125 kV. Figure 2 is a plot of the total linear attenuation coefficient as a function of photon energy for dense and green \( \text{Si}_3\text{N}_4 \) and for a fluorinated hydrocarbon, Freon TF. At each of 100 points on the x-ray energy spectrum curve, the relative flux was multiplied by the total linear attenuation coefficient at that energy. The weighted average of these 100 values is \( \mu_L(\text{eff}) \); this average was 0.901 for dense \( \text{Si}_3\text{N}_4 \). This total effective linear attenuation coefficient is independent of the depth of penetration, and thus the total attenuation becomes a linear function of \( x \). From the linear attenuation curve for dense \( \text{Si}_3\text{N}_4 \) (Fig. 2) and the \( \mu_L(\text{eff}) \) value of 0.901, the equivalent monoenergetic photon energy is found to be 60.6 keV.

Figure 3 shows this effect graphically by comparing the uncorrected attenuation coefficients with the corresponding \( \mu_L(\text{eff}) \) values for two \( \text{Si}_3\text{N}_4 \) densities. Note that the energy dependence of the uncorrected linear attenuation coefficient has a thickness dependence which is significant at specimen sizes of engineering interest (e.g., \( > 1 \text{ cm} \)). From Fig. 3, the BH correction value for specimens of different thickness can be determined. The relationship can be put into the CT reconstruction algorithm as a polynomial or as a look-up table. In order to calculate the BH correction values, one has to know accurately (1) \( \mu_L \) as a function of energy for the material being studied, at photon energies
relevant to commercial scanners (20-150 keV); and (2) the spectrum of the x-ray head. For medical CT imaging, extensive calculations of $\mu_e(E)$ have been done, and an accuracy of better than 0.5% has been claimed [12].

The $\mu_e(E)$ values presented here for Si$_3$N$_4$ compounds were calculated from attenuation coefficients for the corresponding elements [13]. The claimed accuracy of the attenuation coefficients of ref. 13 is better than 1% for the relevant energy range.

![Figure 1. Polychromatic X-Ray Spectrum of Siemens DR-H CT Scanner Operated at 125 kV [11].](image1)

![Figure 2. Total Linear Attenuation Coefficient for Dense and Green-State Si$_3$N$_4$ and Freon TF.](image2)
IMPLEMENTATION OF THE LINEARIZATION

Implementation of this linearization correction requires knowledge of the type of detector being used, the spectrum of the x-ray head, and the composition of the material being studied, as well as access to the raw detector data. Several excellent references [14] are available on CT detectors and we will not discuss detection here. In order to evaluate the accuracy of the effective linear attenuation coefficient method for a known x-ray spectrum and a homogeneous material, a theoretical calculation was completed and compared with an experimental measurement on a green-state Si₃N₄ specimen (\( \rho = 1.995 \) g/cm³) with dimensions of 5.7 x 4.3 x 3.1 cm. Figure 4 shows a comparison between the experimental data and theoretical calculations based on the x-ray head spectrum shown in Fig. 1. The excellent agreement between the experimental and theoretical results demonstrates that the BH effect can be calculated for ceramic materials. Figure 4 also shows how severe the BH effect can be.

The linearization BH correction method for ceramic materials was further experimentally verified with an Elscint Excel 2002 second-generation medical CT scanner. Access to the normalized detector data for this scanner was obtained. An approximate energy spectrum, \( S(E) \), was used to represent the polychromatic source. Freon TF was chosen as the test material because this fluid has a mass density (\( \rho = 1.565 \) g/cm³) and an electron density (\( z_{eff} = 14.4 \)) close to those of both green and dense Si₃N₄ (see Fig. 2). The test specimen was a 53-mm-diameter thin-walled polyethylene bottle filled with Freon TF and placed in the CT machine so as to produce a circular cross-sectional image. Figure 5 shows a plot of the uncorrected nonlinear attenuation and the linearization correction obtained by using \( \mu_{L}(eff) \) at equivalent monoenergetic photon energy (60.6 keV). The nonlinear polynomial-curve coefficients were empirically established during tests on the machine.
Figure 4. Comparison between Theoretically Calculated BH Effect and Experimentally Measured BH Effect for a Green-State Si₃N₄ Specimen.

Figure 5. Comparison of Theoretically Derived Uncorrected Linear Attenuation with Corrected Linear Attenuation for Estimated X-Ray Spectrum of Polychromatic Source from Elscint Excel 2002 CT Scanner.

Figure 6 shows the Freon TF CT image obtained with a standard "water equivalent" BH correction. The BH effect is about 10%. Figure 7 shows the CT image obtained when the linearization BH correction was implemented. In this case the BH was reduced to <1%.
Figure 6. CT Scan (10-mm Slice) of 53-mm-Diameter Polyethylene Bottle Filled with Liquid Freon TF, with Water BH Correction. BH effect is $\approx 10\%$.

Figure 7. CT Scan (10-mm Slice) of Same Specimen Shown in Fig. 6, with Linearization BH Correction. BH effect is $<1\%$. 
CONCLUSIONS

The results presented here show that a linearization BH correction procedure which takes into account the material composition of the specimen and the x-ray spectrum of the CT scanner can reduce the BH effect to less than 1%. Further reduction of the BH effect to the 0.1% level may not be possible, as scattering effects are present. Theoretically, a special BH calibration should be performed for the material of interest and for each density of this material. This presents a problem for ceramic components, as uniform ceramic calibration blocks may be difficult to produce. It would be very useful if the material mass-density/electron-density trade-off could be established so that calibrations could be done on known homogeneous substances such as the liquid Freon used in these experiments.

REFERENCES

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DISCUSSION

Mr. Ron Stripe, Lawrence Livermore: It seems to me that unless you know a priori the object size very accurately, that you are gaining a free variable from nowhere. You don't have the thickness or the internal structure of your object. How can you deconvolve the actual density on your radiograph or your C.T. from whether it's beam hardening or actual geometry effects? Also you looked at that first one, and you saw where you have that very light halo. How do you know, if you didn't know what was in your object, that that's not actually internal stress?

Mr. Segal: Well, here I know it isn't an actual internal structure because I have taken a liquid.

Mr. Stripe: But you have a priori knowledge of exactly what it contains.

Mr. Segal: Yes. So here I wanted to be sure that I am correcting the beam hardening and only the beam hardening.

Mr. Stripe: But the effect of beam hardening is a function of the thickness that the beam goes through, and if you don't know that thickness because you are trying to measure—that's one of the variables you are trying to evaluate. It seems you get back to the

Mr. Segal: This was your first question. If you are taking this picture (Fig. 3), we really should know the dimension of the sample. It depends on the geometry. But if we are implementing our correction at the stage of the normalized measure data, the correction will be independent of the thickness or geometry of the sample. The normalized measured data, or the preprocessed data

$$\ln \left( \frac{I_0}{I(X)} \right) = X \cdot \mu_{L(\text{eff})}(X)$$

is represented by the curved line in Fig. 5. At this stage we transfer this curve to a straight line. A straight line implies that the absorption coefficient $\mu_{L(\text{eff})}(X)$ is constant, i.e., a monochromatic beam.

Mr. Green, Johns Hopkins: Could you describe briefly, again, your specimen that you used for this?

Mr. Segal: My specimen was a plastic bottle filled with Freon T. F.

Mr. Green: And it's cylindrical, like a glass? And looking down?

Mr. Segal: Yes to both questions. It is quite heavy so there is some flatness.

Mr. Green: But the thickness is constantly going down the length. It's round?

Mr. Segal: It's just a plastic bottle.

Mr. William Friedman, Standard Oil: It seems like most of the beam hardening occurs in perhaps the outer 1 centimeter. Would it be possible to filter the beam so that you remove that soft component? And then get rid of most of these problems?

Mr. Segal: Yes. This was done for the human body. The patient was surrounded by a water bag. What it does, really, is it reduces the beam hardening from the edges where the slope is higher. The
equivalent here is surrounding the sample by a cylinder of the same material. Then most of the beam hardening will be taken out. However you will still have the central part.

This procedure reduces the beam hardening and also causes the beam hardening to be the same for all directions. Usually in a cylindrical object, the beam hardening will be different along different lines. However, it does not eliminate beam hardening.

Mr. R. Morris, Los Alamos National Laboratory: How did you derive your polychromatic beam hardening curve, experimentally or from first principles?

Mr. Segal: From first principles.

Mr. Morris: From tabulated cross-section values?

Mr. Segal: Yes.

Mr. Oliver: Just as a comment, the XIM system which Jeff described earlier used corrections essentially identical to yours. The corrections were made by taking real data from step blocks experimentally, externally, and that whole procedure can be automated because the correction can be put in essentially as a look up table. It is indeed dependent on material, but it is independent of thickness.

Mr. Segal: But here, measured data of the attenuation coefficient for ceramics is a real problem, due to the difficulty in preparing constant density samples having different thicknesses.