SECONDARY RADIATION INFLUENCE ON LSF SHAPES IN RADIOGRAPHY

A. Notea, Y. Bushlin, and U. Feldman
Quality assurance and Reliability, Technion
Haifa 32000, Israel

INTRODUCTION

A radiographic image is generated by both primary and secondary radiations. In a previous study [1, 2] the influence of secondary radiation on the generated image was shown for square based blocks of finite dimensions (few mean free paths). The response to a step change in the block's thickness, varies drastically with the step location relative to the block's edges [3]. However, even when the radiographed object is large and the step response is studied far off the object's limits, the effect of the secondary radiation is still significant. This radiation distorts the "ideal" step response shape expected from the primary radiation.

The radiographic step response is applicable in the determination of the characteristic line spread function (LSF) [4]. The LSF is required for the radiographic image inverse problem solution [5].

The present study was dedicated to the analysis of the LSF shape as a function of the primary and secondary radiations ratio. The results show that the LSF changes with the thickness of the block. Hence, for processing of an image obtained from an object with considerable thickness or density variation, a single LSF is not sufficient.

The LSF in this study is expressed as a superposition of the primary and secondary radiations effects. This approach was verified experimentally and by computer simulation.

SECONDARY FLUX CONTRIBUTION

Photons interacting with the object in radiographic testing, undergo mainly two processes: absorption and scattering. The photons impinging on the film are either primary photons (passing through the object with no interaction) or scattered photons (assuming that scattering from the surrounding is negligible). Hence, the measured radiographic image \( O_m(x) \) may be considered as a superposition of an image generated by the primary flux \( O_m^P(x) \) and an image obtained from the scattered flux \( O_m^S(x) \):

\[
O_m(x) = O_m^P(x) + O_m^S(x)
\]
Fig. 1. Calculated primary (P) and secondary (S) fluxes emerging from a rectangular Lucite block as function of the block thickness.

The primary and secondary fluxes after transmission through Lucite blocks of various thicknesses is presented in Fig. 1 for a 300 kVp X-ray source. The curves were calculated using a model developed in a previous work [1]. The average energies required for the total attenuation and scattering coefficients appearing in the model, were determined by Monte Carlo simulation. In Fig. 1 it is seen that the primary flux (P) is decreasing exponentially with thickness while the scattered flux (S) is increasing up to a maximum and than decreasing.

On considering a step wedge of height \( h_1 \) and \( h_2 \), see Fig. 2, the following relations are obtained:

\[
\begin{align*}
P(h_1) &< P(h_2) \text{ for all } h_1, h_2, \ (h_1 > h_2) \\
S(h_1) &> S(h_2) \\
S(h_1) &= S(h_2) \\
S(h_1) &< S(h_2) \\
\end{align*}
\]

(2)

Fig. 2. Definition of \( h_1 \) and \( h_2 \) of a step wedge \((h_1 > h_2)\).
From Eq. (2) it is clear that three different shapes of the scattered flux profiles for a step wedge are possible. As the measured image is the summation of the primary and scattered contributions - three basic shapes for the step profiles are expected. The profiles shape is a function of $h_1$ and $h_2$ values and not only of the step height $h_1 - h_2$. Those three basic shapes are indicated by N, L and S [6]. In the following section, the mathematical description for these profiles is presented.

FORMULATION OF THE STEP RESPONSE

Under the assumption that radiography may be considered as a linear and shift invariant system, it is possible to express the primary flux $O_m^P(x)$ of Eq. (1) by a convolution of an ideal primary image $O_i^P(x)$ with a blurring function [7]:

$$O_m^P(x) = O_i^P(x) * LSF^P(x) \quad (3)$$

where $LSF^P$ represents the blurring operators affecting the primary flux image, such as internal film unsharpness and geometrical unsharpness. For the step wedge radiographed by a perpendicular primary X-rays, the ideal primary image is described by:

$$O_i^P(x) = k \{P(h_1) + [P(h_2) - P(h_1)]h(x)\} \quad (4)$$

where $h$ is the Heaviside step function and $k$ is a calibrating factor transforming flux units to film optical density (assuming a linear relation - see [1]).

The secondary flux image is also describable by a convolution of a step function with a characteristic blurring function $LSF^S$:

$$O_m^S(x) = k \{S(h_1) + [S(h_2) - S(h_1)]h(x)\} * LSF^S(x) \quad (5)$$

Note that $P(h_i)$ and $S(h_i)$ are the fluxes emerging from a block of thicknesses $h_1$ or $h_2$ far from the edges. The values for these functions are obtainable from Fig.1. According to Eq. (2) the value of the expression $[S(h_2) - S(h_1)]$ in Eq. (5) might be positive, negative or zero. This leads to the different shapes of the $O_m^S(x)$ profile. By inserting Eqs. (3) and (5) into Eq. (1), an expression for the measured image of the step wedge is obtained:

$$O_m(x) = O_0 + Hh(x) * LSF(x) \quad (6)$$

where:

$$O_0 = k[P(h_1) + S(h_1)] \quad (7)$$

$$H = k[P(h_2) - P(h_1) + S(h_2) - S(h_1)] \quad (8)$$

and:

$$LSF(x) = A \cdot LSF^P(x) + B \cdot LSF^S(x) \quad (9)$$

where $A, B$ are:

$$A = [P(h_2) - P(h_1)][P(h_1) - P(h_2) + S(h_1) - S(h_2)]^{-1}$$

$$B = [S(h_2) - S(h_1)][P(h_1) - P(h_2) + S(h_1) - S(h_2)]^{-1} \quad (10)$$

$$A + B = 1$$

$B$ may be positive [$S(h_1) < S(h_2)$], negative [$S(h_1) > S(h_2)$] or zero. Therefore different shapes of the total LSF, calculated from Eq. (9) are expected.
For a system where the blurring effects are negligible and the $LSF^P$ is describable by a $\delta(x)$ function, and the $LSF^S$ is taken to be exponential [8], then the total $LSF$ is given by:

$$LSF(x) = A\delta(x) + B\frac{\lambda}{2} e^{-\lambda|x|}$$

(11)

Where $\lambda$ is the characteristic parameter of $LSF^S$. Two of the possible $LSF$ shapes are demonstrated in Fig.3 for positive and negative $B$ values.

By substituting Eq. (11) into Eq. (6) the expected measured step response is obtained:

$$O_m(x) = O_0 + \frac{1}{2} H[1 + \frac{x - x_0}{|z - x_0|}(1 + Be^{-\lambda|x-x_0|})]$$

(12)

where $x_0$ is the edge location. Profiles calculated by Eq. (12) for values taken from Fig.1 are shown in Fig.4. Note that although the height difference ($\Delta h = h_1 - h_2$) for all the curves is the same, the profiles shapes are completely different. For profiles (a) and (b) $S(h_1) > S(h_2)$, overshoots are observed near the edge (the "N" shape [6]). For profiles (c) and (d) $S(h_1) < S(h_2)$, a regularly smoothed edge is obtained ("S" shape). The influence of the parameter $\lambda$ is demonstrated in all curves.

Fig.3. Plot of the LSF given in Eq. (11) for: $S(h_1) < S(h_2)$ ($B$ positive) and $S(h_1) > S(h_2)$ ($B$ is negative). The blurring parameter was: $\lambda = 0.2$ [mm]$^{-1}$. 

Fig.4. Profiles calculated by Eq. (12) for values taken from Fig.1.
Fig. 4. Calculated step response (Eq. (12)). a,d: $\lambda = 0.8$, b,c: $\lambda = 0.2$, a,b: $S(h_1) > S(h_2)$ ($h_1 = 9.6$, $h_2 = 5$ [mm]), c,d: $S(h_1) < S(h_2)$ ($h_1 = 74.6$, $h_2 = 70$ [mm]).

Fig. 5. Measured film density profiles from a Lucite step wedge radiographed at 275 kVp. Pixel size is 50\mu m, 400 lines averaged. a) $h_1 = 6.3$, $h_2 = 1.7$, b) $h_1 = 8.2$, $h_2 = 3.6$, c) $h_1 = 16.6$, $h_2 = 12.0$ [mm].
The above mathematical formulation was verified by experimental and
by Monte Carlo simulation results. The experimental setup consisted of
rectangular cross-section Lucite blocks of various thicknesses that
were used to build the step wedge with constant $\Delta h$ of 4.6[$mm$] and
various base thicknesses $h_2$. The step wedges were radiographed by 275
kVp X-ray machine - Andrex LSG 274 with Agfa Gevaert Structurix D4
film. The source - object distance was 3[$m$], i.e. almost a parallel
beam geometry and negligible geometrical unsharpness. Preliminary
experiments were done to establish the focal spot position, in which
the edge was placed, to eliminate any angle effect [9]. The exposure
conditions were varied according to the object thickness to ensure a
similar film density. The radiographs were digitized by a computerized
microdensitometer (Optronics - Photomotion 1700) with an aperture of
50$\mu$m. To reduce the signal to noise ratio, 400 lines were averaged.
Three of the measured profiles are presented in Fig.5 where two basic
profile shapes are clearly seen.

Fig.6 and 7 presents similar results obtained from Monte Carlo
simulation for step wedge with height difference $\Delta h$ of 1.5[$mm$]. The
simulation was performed with VIM code, using point detectors [1].
The Monte Carlo results demonstrates that the measured image is the
superposition of the primary and secondary fluxes. The results show
the variation of the secondary flux across the step wedge when the
difference $\Delta h$ is kept constant and the base thickness $h_2$ increases.
The contribution of this behavior to the total step wedge profile is
immediately evident. Note the resemblance between the calculated,
measured and simulated profiles.

![Monte Carlo simulated flux intensity profiles emerging from
Lucite step wedge radiographed at 275 kVp. $h_1 = 5.3, h_2 = 3.8[mm]$.
$\square$ - primary radiation ($P$), $\Delta$ - secondary radiation ($S$) and
* - total radiation intensity.](image_url)
Fig. 7. Monte Carlo simulated flux intensity profiles for Lucite step wedge radiographed at 275 kVp. $h_1 = 20.4$, $h_2 = 18.9 \text{[mm]}$. □ - primary radiation ($P$), ▲ - secondary radiation ($S$) and * - total radiation intensity.

The appearance of the overshoots near the edges in the simulation as well as in the radiographs, indicates that this effect is of physical meaning and should not be confused with the chemical film development effect described in [10].

DISCUSSION

It was shown that there are 3 basic shapes for the radiographic step wedge response: N, L and S. These shapes depend on the actual step wedge thickness values (not only on the step height) and are a direct consequence of the secondary radiation spatial distribution. The different step response shapes produce different types of LSFs.

The knowledge of the LSF is crucial for quantitative interpretation of the radiographs. For an object with wide variations in the density-thickness, the interpretation is to be based on several representative LSFs. These LSFs should be characterized by properly designed step wedges, that represent the object geometry and elemental composition.

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