Simulating the x-ray image contrast to set-up techniques with desired flaw detectability

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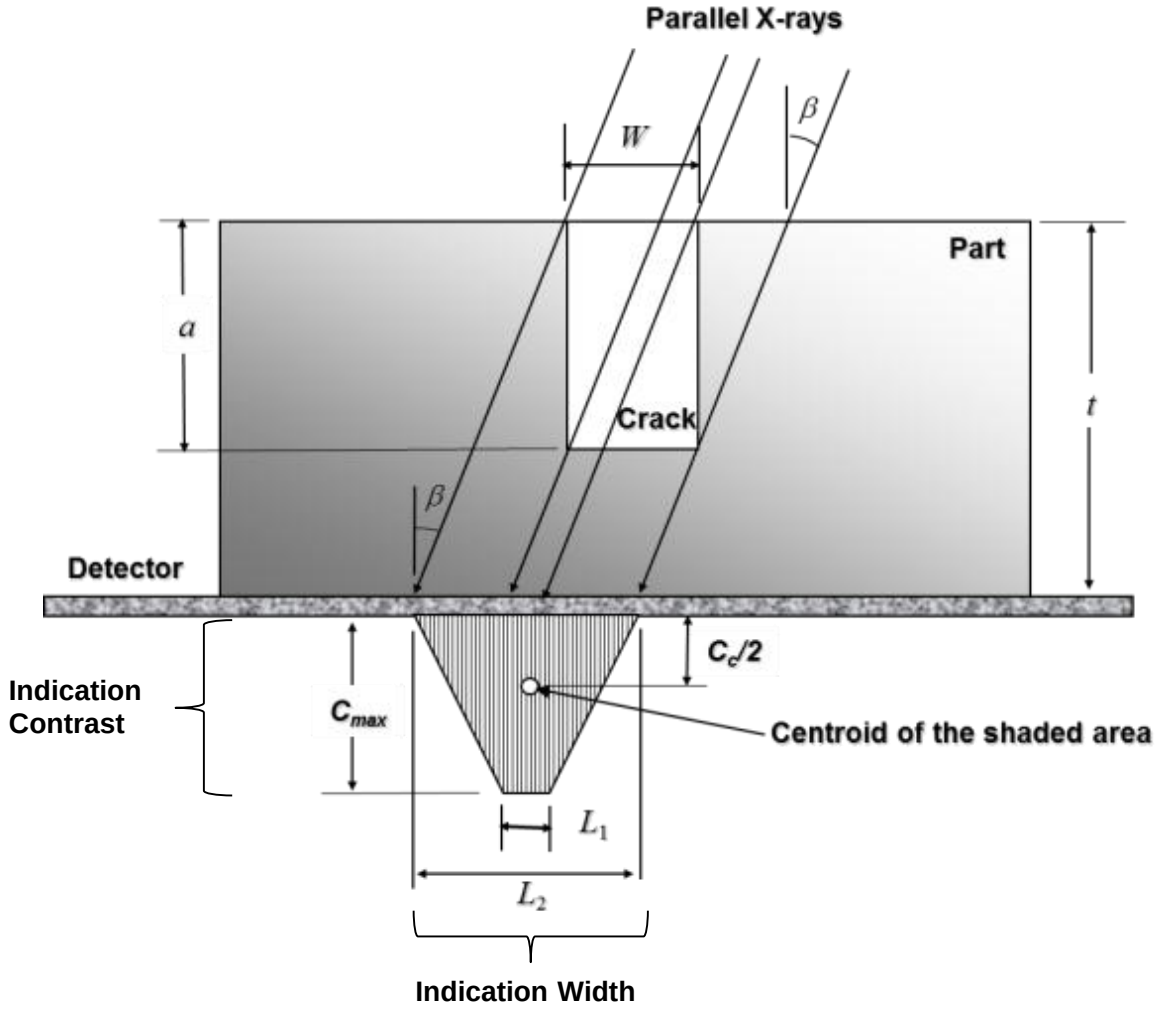
Background and Objective

- The paper provides simulation data of previous work by the author in developing a model for estimating detectability of crack-like flaws in radiography.
- The methodology is being developed to help in implementation of NASA Special x-ray radiography qualification, but is generically applicable to radiography.
- The paper describes a method for characterizing X-ray detector resolution for crack detection. Applicability of ASTM E 2737 resolution requirements to the model are also discussed.
- The paper describes a model for simulating the detector resolution. A computer calculator application, discussed here, also performs predicted contrast and signal-to-noise ratio calculations.
- Results of various simulation runs in calculating x-ray flaw size parameter and image contrast for varying input parameters such as crack depth, crack width, part thickness, x-ray angle, part-to-detector distance, part-to-source distance, source sizes, and detector sensitivity and resolution are given as 3D surfaces.
- These results demonstrate effect of the input parameters on the flaw size parameter and the simulated image contrast of the crack.
- These simulations demonstrate utility of the flaw size parameter model in setting up x-ray techniques that provide desired flaw detectability in radiography. The method is applicable to film radiography, computed radiography, and digital radiography.

Cross Sectional Geometry of Part, Slot, and X-ray Shadow Profile on the Detector



Visual detection of a fine flaw like a crack is based on contrast magnitude

The rectangular cross sectional area of the crack is mapped as a trapezoidal area

Figure 1: Cross Sectional Geometry of Part, Slot, and X-ray Shadow Profile on the Detector

Flow Chart of the Analytical Model Development

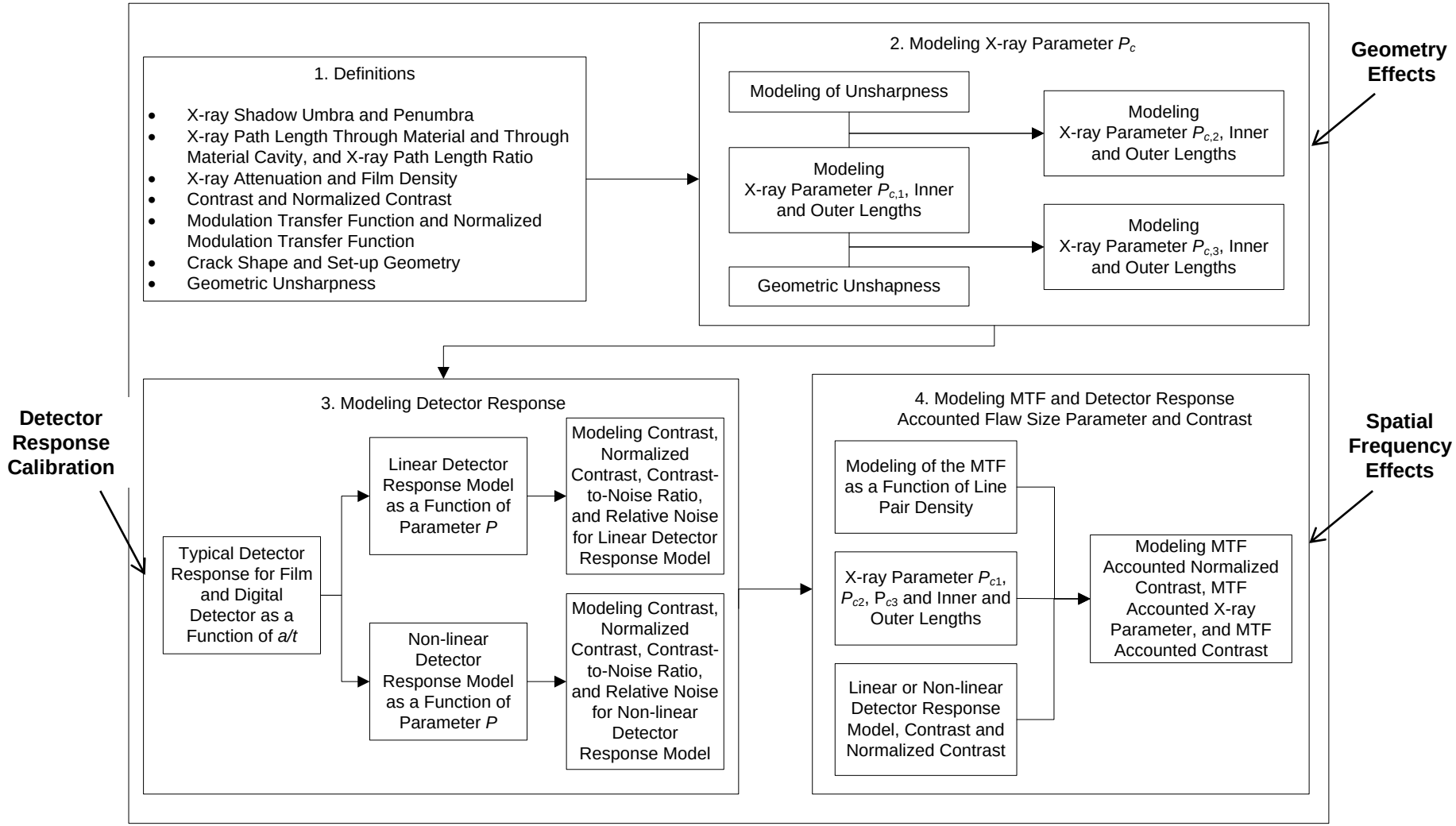


Figure 2: Flow Chart of the Model Development

X-ray Parameter Analytical Model 1

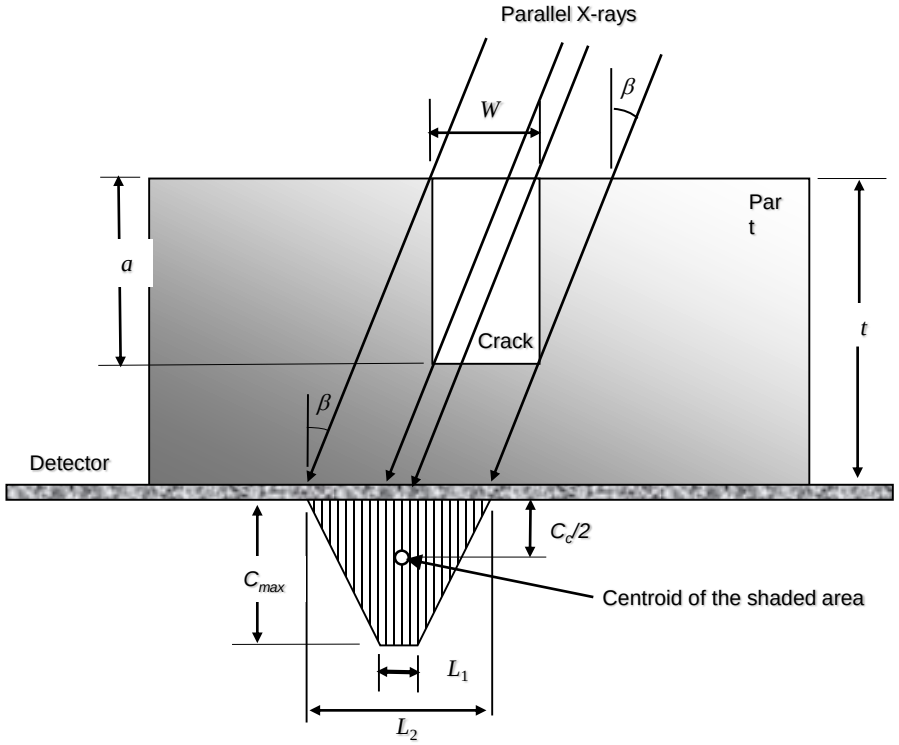


Figure 3: Schematic of Cross Section of a Crack

- Above image shows normal component of the X-ray beam angle
- Vertical hatched shaded area indicates relative change in thickness in path-length of X-ray
- X-ray parameter and the equivalent indication width are used in computing the simulated contrast.

$$P_{c,x}L_{e,x} = aW/t \qquad x = \text{model number } 1, 2, 3$$

- Model 1 is used to derive models 2 and 3.

Assumptions

- Image density proportional to ray length in material
- Parallel rays in the plane of figure

Inner Width $L_{1,1} = |W - a\tan\beta|$

Outer Width $L_{2,1} = W + a\tan\beta$

Equivalent Indication Width $\boxed{L_{e,1} = \frac{aW}{t}\frac{1}{P_{c,1}}}$

Mode 1: $W \geq a\tan\beta$

X-ray Parameter

$$\boxed{\begin{aligned} P_{\max,1} &= a/t \\ P_{c,1} &= \frac{2}{3}(a/t)\left(\frac{2L_{1,1}+L_{2,1}}{L_{1,1}+L_{2,1}}\right) \end{aligned}}$$

Mode 2: $W \leq a\tan\beta$

X-ray Parameter

$$\boxed{\begin{aligned} P_{\max,1} &= \frac{W}{t\tan\beta} \\ P_{c,1} &= \frac{2}{3}\left(\frac{W}{t\tan\beta}\right)\frac{2L_{1,1}+L_{2,1}}{L_{1,1}+L_{2,1}} \end{aligned}}$$

Model 3 with Geometric Unsharpness

Geometric Unsharpness

$$U_g = \frac{Sd_2}{d_1}$$

Inner Width

$$L_{1,3} = \left| \frac{L_{x,3}\left(d_1 + d_2\right)}{d_1} - U_g \right|$$

Outer Width

$$L_{2,3} = \frac{L_{x,3}\left(d_1 + d_2\right)}{d_1} + U_g$$

Where, $L_{x,3} = \frac{3}{4}\frac{\left(L_{1,1} + L_{2,1}\right)^2}{\left(2L_{1,1} + L_{2,1}\right)}$

Equivalent Indication Width

$$\boxed{L_{e,3} = \frac{aW}{t}\frac{1}{P_{c,3}}}$$

Mode 1 and 2 X-ray Parameter

$$\boxed{P_{c,3} = \frac{2}{3}P_{\max,3}\frac{2L_{1,3} + L_{2,3}}{L_{1,3} + L_{2,3}}}$$

Where, $P_{\max,3} = P_{\max,1}\frac{L_{1,1} + L_{2,1}}{L_{1,3} + L_{2,3}}$

Calibrating Detector Response Function f_n to Step Wedge a/t

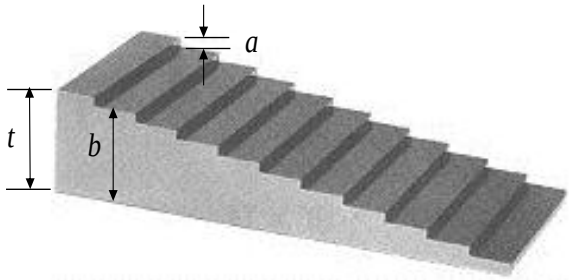


Figure 4: An Example of An Aluminum Step Wedge

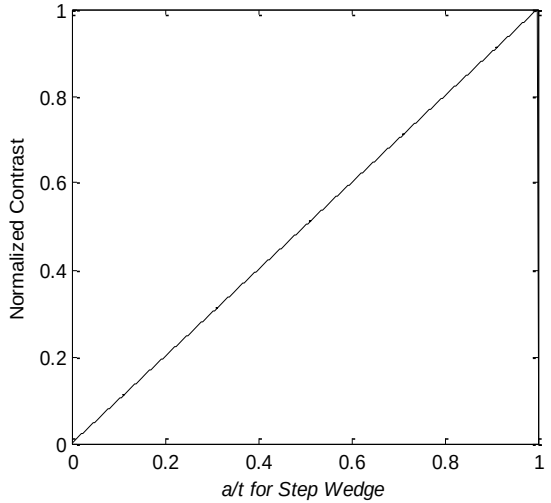


Figure 5: Normalized Detector Response Function for a Digital Detector

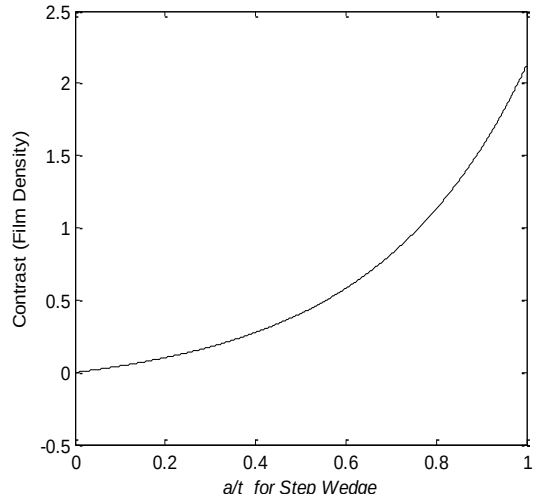


Figure 6: Detector Response Function for a Film

Modulation Accounted X-ray parameter $P_{c,M} = g_n\left(1/L_{lp}\right)P_c$

Normalized Contrast $C_{f(P_c),M} = M_n \dfrac{f_n(P_c)}{f_n(1)} = g_n\left(L_{lp}\right)\dfrac{f_n(P_c)}{f_n(1)}$

Image Contrast $S_{f(P_c),M} = M_n f_n(P_c) = g_n\left(1/L_{lp}\right) f_n(P_c)$

X-ray parameter P_c is used in place of a/t when using the calibration curves to calculate simulated contrast.

Equivalent Indication Width, L_e is used in place of L_{lp} when applying function g_n to calculate simulated contrast

Custom Slotted Shim IQI

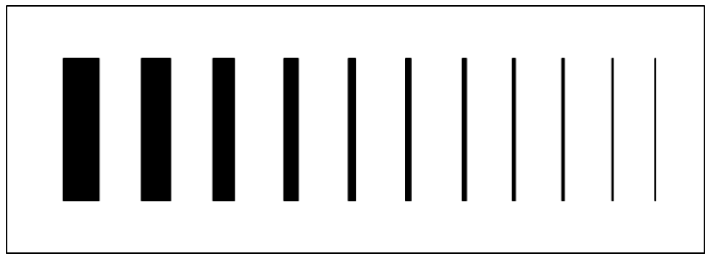


Figure 7A: Slotted Shim IQI

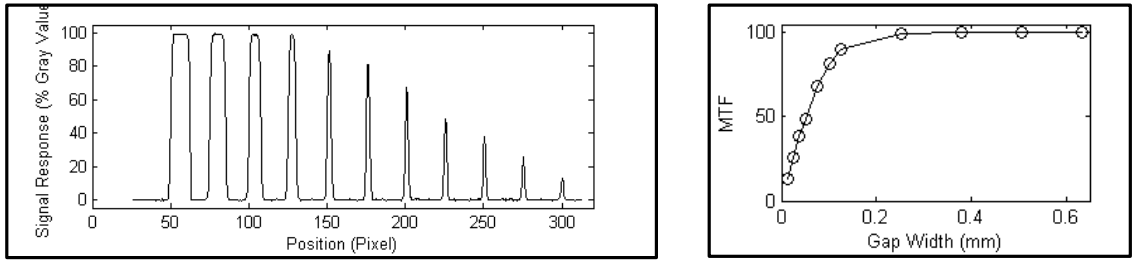


Figure 7B: Signal Response and MTF

- Since the slot directly simulates a surface crack, a slotted shim IQI is preferred.
- Black areas are through slots.
- Spacing between slots is relatively large causing no effect on modulation of slot response from the space around each slot.
- The modulation is solely affected by the slot gap.

- An example of the signal response from the slotted shim IQI and the MTF calculated as the maximum response on a slot area divided by the response outside shim. MTF function is plotted versus slot (or gap) width.
- Equivalent length computed by the x-ray parameter application can be directly substituted as the input variable to the MTF curve to get value of the modulation.

Duplex Wire IQI and Shim Type Line Pair IQI

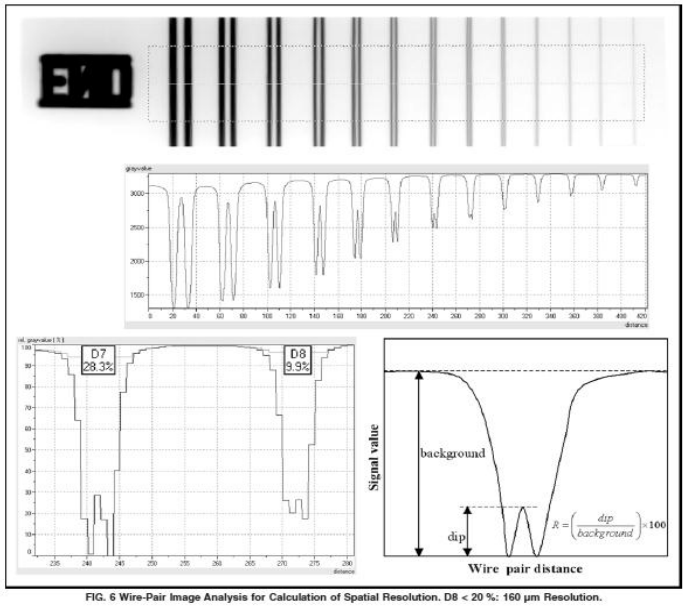


FIG. 6 Wire-Pair Image Analysis for Calculation of Spatial Resolution. D8 < 20 %: 160 µm Resolution.

Figure 8A: ASTM 2597 duplex wire IQI measurements

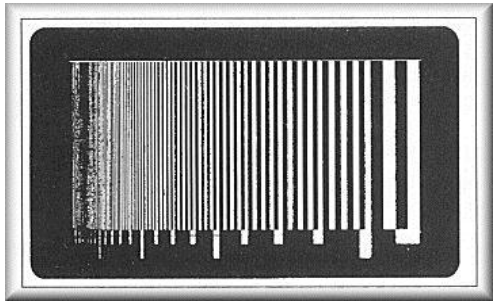


Figure 8B: A Shim Type Line Pair IQI Made from a 0.05 mm thick lead shim

- Since slotted shim IQI is custom made, a shim type line pair IQI or the ASTM duplex wire IQIs can be used as a substitute.
- For the shim type IQI and duplex wire IQI, MTF is plotted as a function of line pair width.
- Note that for the shim line pair and duplex wire IQI, modulation is defined as dip between the two wire indications due the gap between the wires. For duplex wire IQI, the modulation is also affected by the wire diameter, not just by the gap.
- The duplex wire IQI image derived MTF is most conservative and is used as an approximation to the slotted shim IQI MTF.
- The shim type line pair IQI image derived MTF is also conservative and can used as an approximation to the slotted shim IQI MTF.
- However, the gap response can be defined relative to the thickest metal wire response. This definition is similar to the slotted IQI response and the MTFs measured using the slotted IQI and the duplex wire IQI would be close.

Modulation Transfer Function, g_n

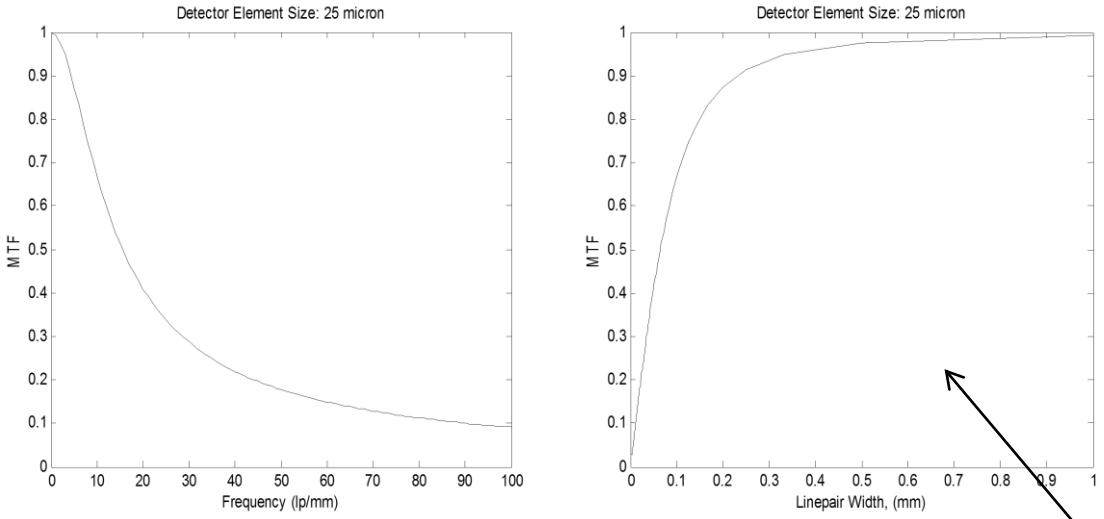


Fig. 9A: MTF Used for the Film in the Simulation

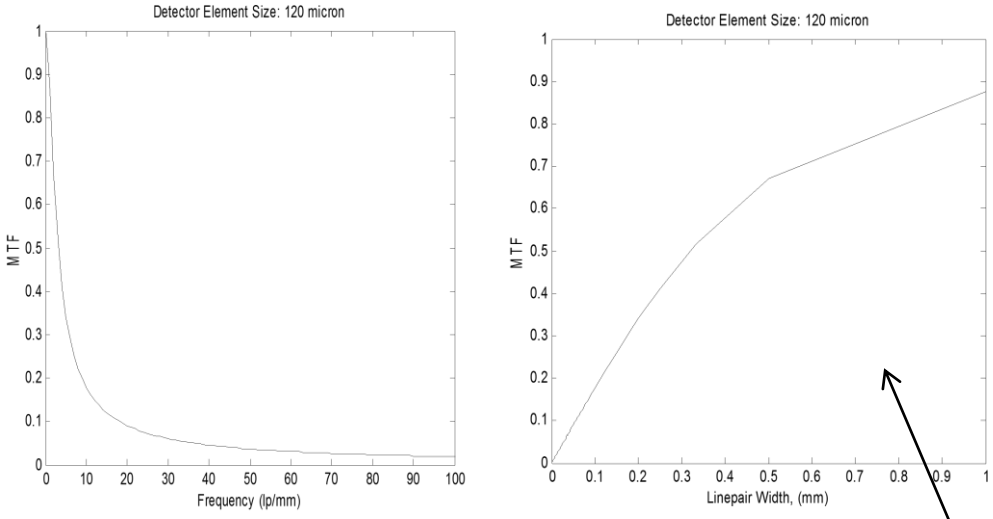


Fig. 9B: MTF Used for a Digital Detector in the Simulation

Equivalent Indication Width, L_e is used in place of L_{lp} when applying function g_n to calculate simulated contrast

Equivalent Indication Width, L_e is used in place of L_{lp} when applying function g_n to calculate simulated contrast

X-ray Parameter Calculator Application

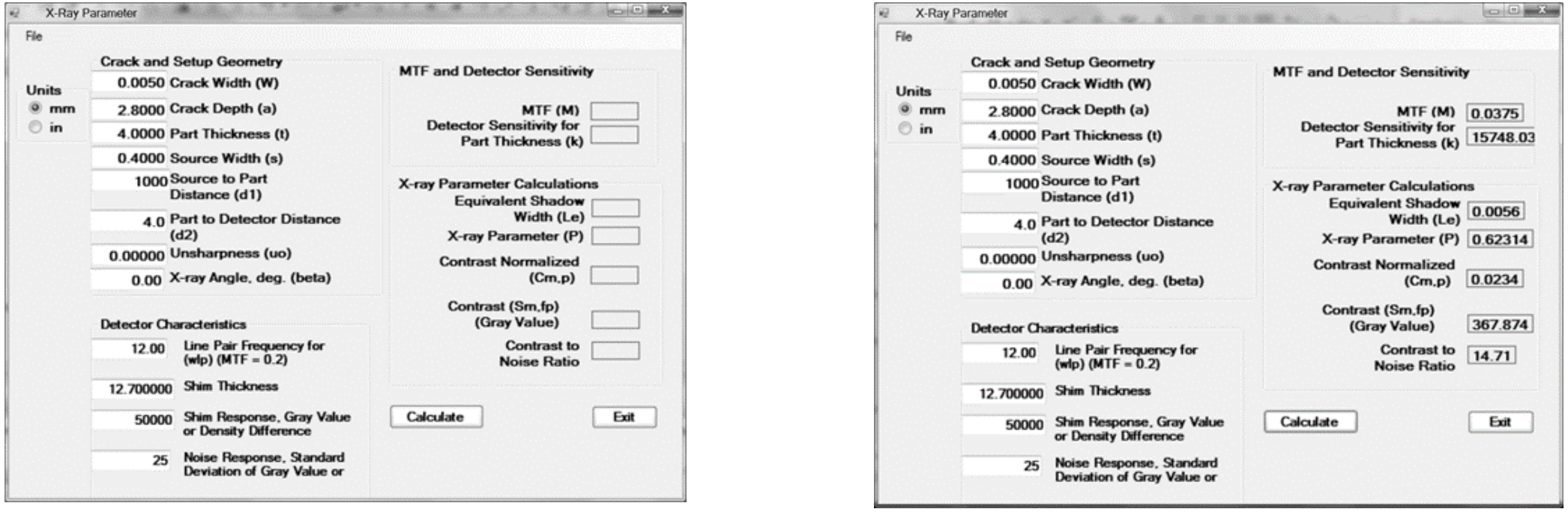


Figure 10. X-ray parameter calculator application, left panel: input only, right panel: input and output

- Under the block named "X-ray Parameter Calculations", equivalent indication width (L_e), x-ray parameter (P), normalized contrast ($C_{M,p}$), gray value contrast ($S_{M,f(p)}$), and contrast to noise ratio are given.
- A 70% through crack is chosen with 0 degree angle of incidence for x-rays.
- The x-ray parameter is 62.3% which is expected to be less than or equal to a/t = 70%.
- The crack width of 0.005 mm casts a shadow with equivalent width of 0.0056 mm which is expected to be slightly larger than the crack width.
- The normalized contrast is 2.34% which compares favorably with the 2% contrast sensitivity typically used in film radiography. The contrast to noise ratio is 14.71, which is much greater than 2, indicating reliable crack detection.

X-ray Parameter $P_{c,3}$ Calculation Example

Source to part distance = 60 cm
Part to detector distance = 10 cm

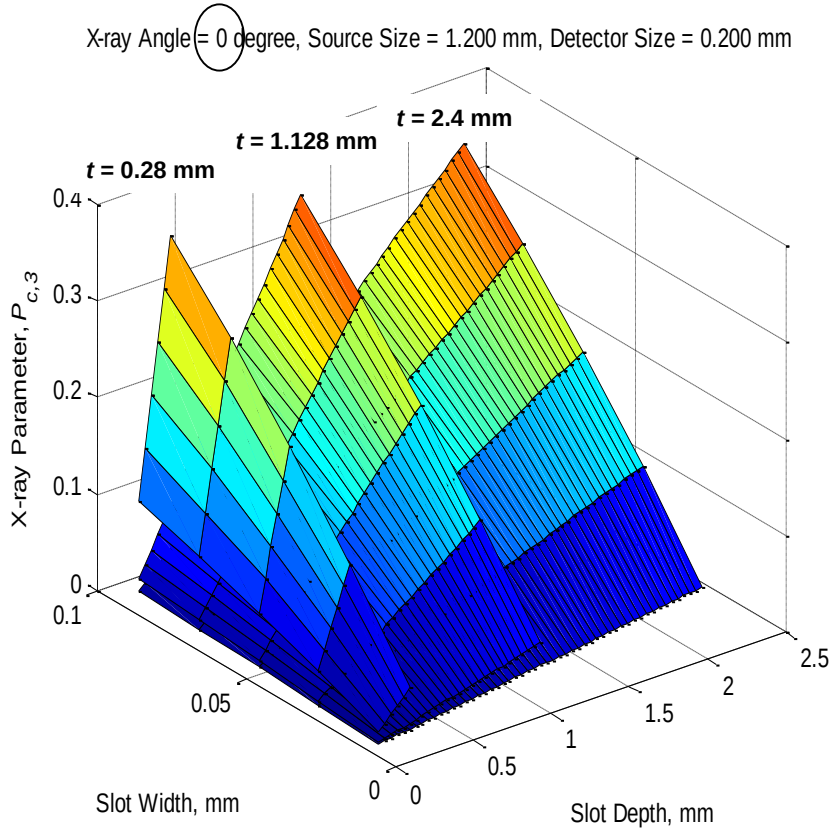


Fig. 11: X-ray parameter, source = 1.2 mm

X-ray parameter P_c increases with slot depth and width.
X-ray parameter P_c for a given a/t is same for varying plate thicknesses for X-ray angle of 0 degree to part normal.

X-ray Parameter $P_{c,3}$ Calculation Example

Source to part distance = 60 cm
Part to detector distance = 10 cm

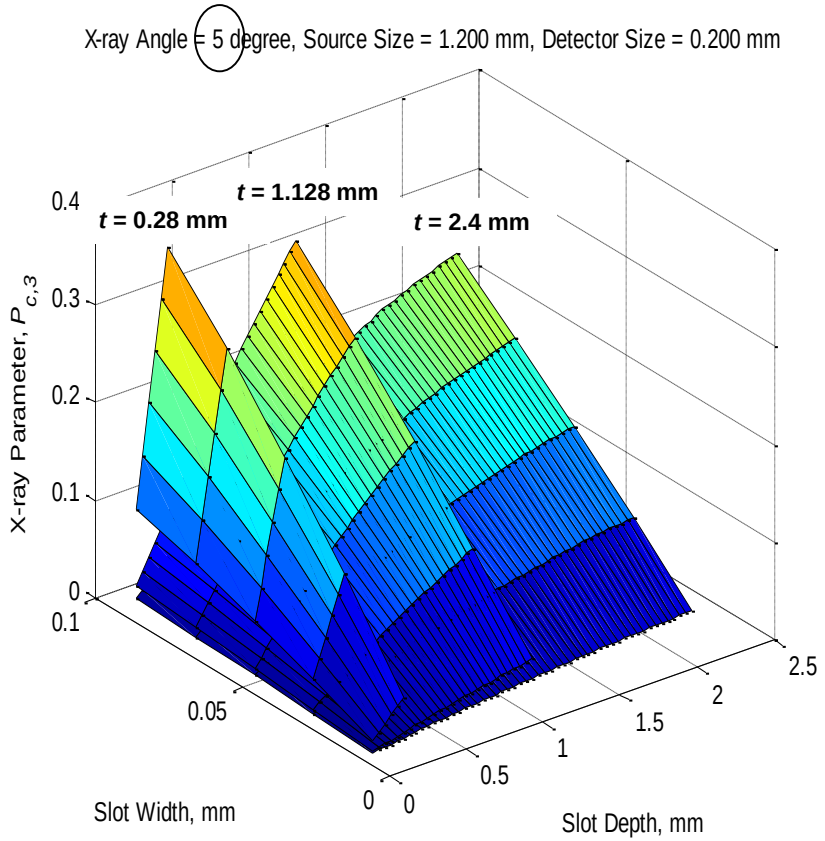


Fig. 12: X-ray parameter, source = 1.2 mm

X-ray angle is different between simulation data of Fig. 11 (angle = 0) and Fig. 12 (angle = 5 deg.).
Higher X-ray angle reduces the X-ray parameter. The effect is higher for thicker parts.

X-ray Parameter $P_{c,3}$ Calculation Example

Source to part distance = 60 cm
Part to detector distance = 10 cm

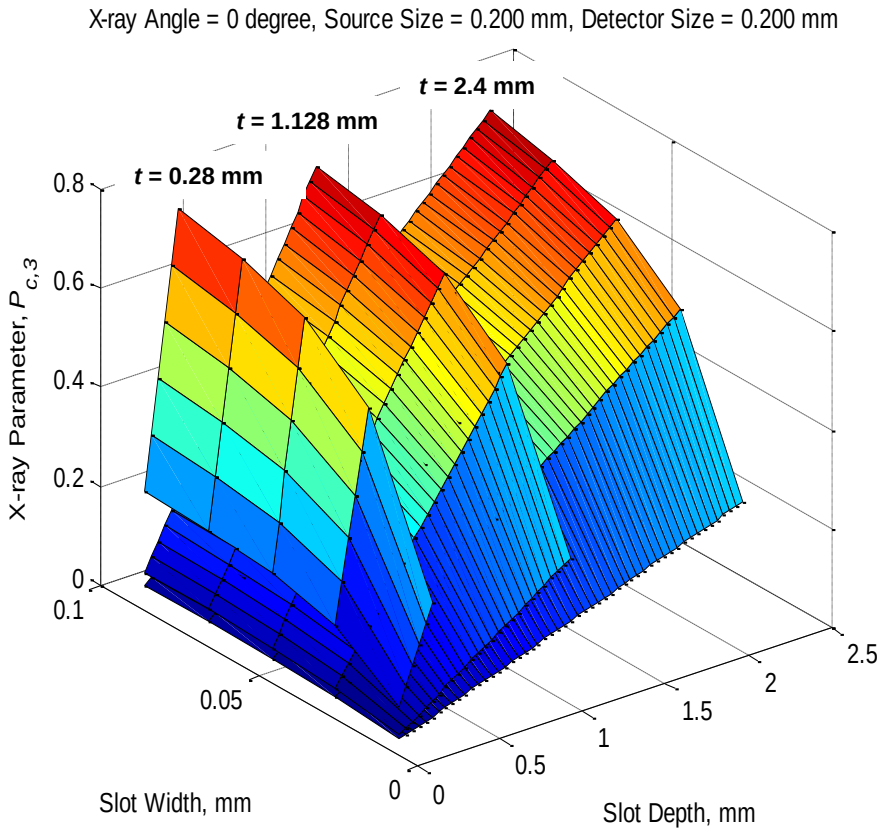
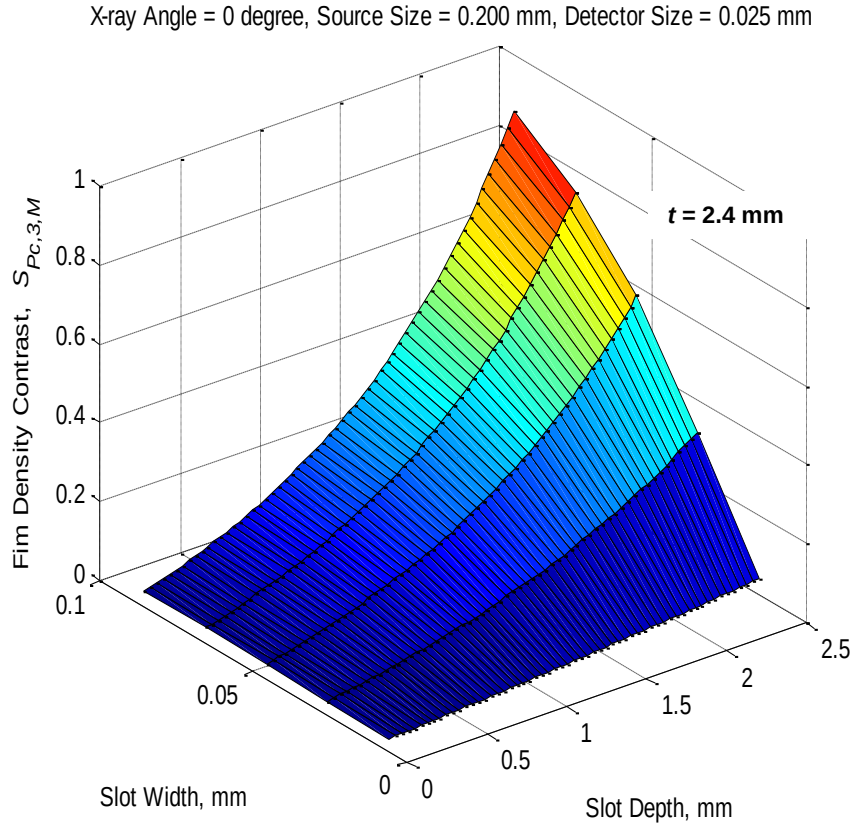


Fig. 13: X-ray parameter, source = 0.2 mm

Source size is different between Simulation Data of Fig. 11 (Source Size = 1.200 mm) and Fig. 13 (Source Size = 0.200 mm). Smaller source size in Fig. 13 gives higher values of the flaw size parameter.

Contrast $S_{pc,3,M}$ Calculation Example

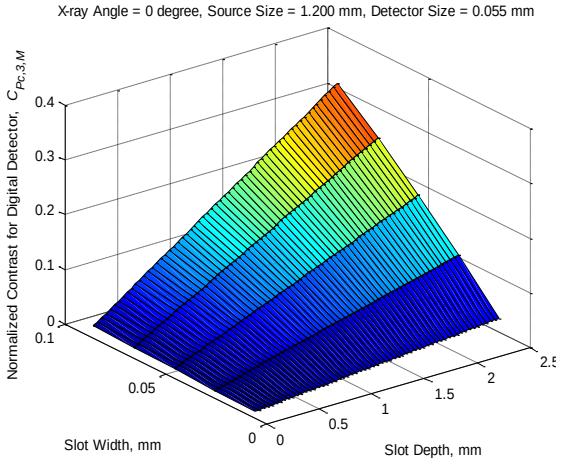
Source to part distance = 60 cm
Part to detector distance = 10 cm



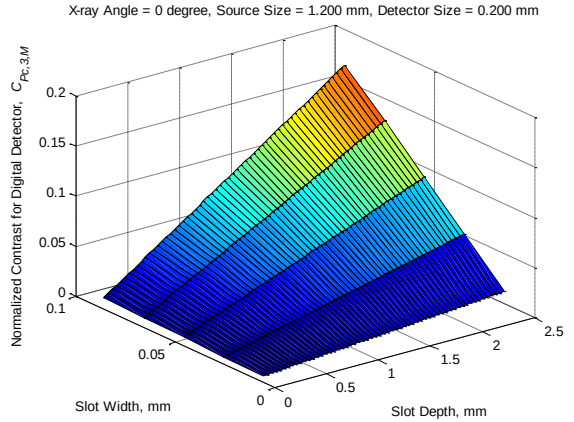
Uses calibration curve of Fig. 6

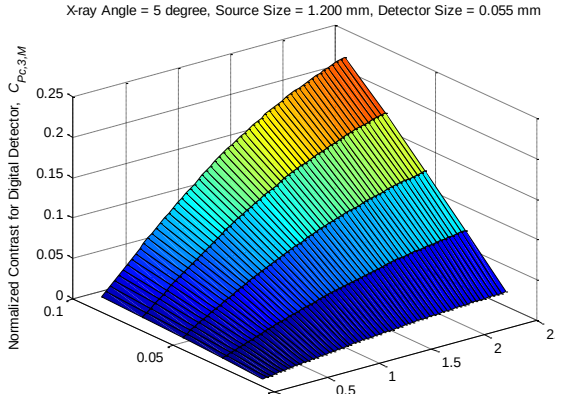
Fig. 14: Simulated equivalent contrast for film, detector resolution 20 lp/mm, source size 0.2 mm

Normalized Contrast $C_{pc,3,M}$ Calculation Example

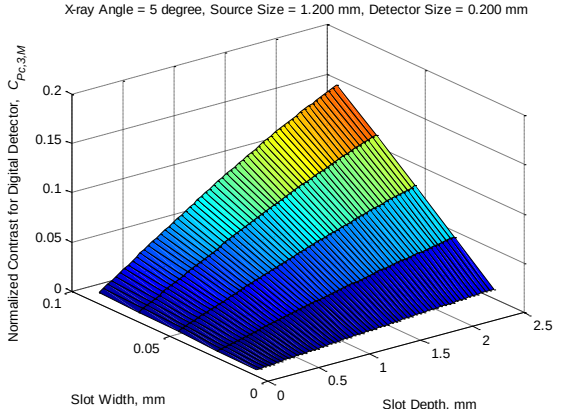


As detector size increases normalized contrast decreases





As x-ray angle increases normalized contrast decreases



Source to part distance = 60 cm
Part to detector distance = 10 cm
t = 2.4 mm
Uses calibration curve of Fig. 5

Fig. 15: Simulated equivalent normalized contrast for digital detectors

Conclusions

- The paper provides examples of use of the model previously published by Koshti[8,9] to compute
  - x-ray parameter,
  - simulated normalized contrast,
  - image contrast, and
  - contrast-to-noise ratio from a given cracklike flaw.
- The approach uses measurement of
  - Modulation Transfer Function of the detector,
  - detector sensitivity in the set-up as well as
  - detector noise.
- These estimations are recommended to be correlated with actual data such as contrast from an Reference Quality Indicator (RQI) so that Probability of Detection analysis can be performed using the model estimated x-ray parameter, simulated normalized contrast, image contrast as measures of flaw size and actual measured contrast as signal response.
- Some of the limitations of the method are
  - X-ray scatter is not modeled. It is assumed to be low, uniform and controlled by the technique, material, and detector requirements.
  - There is certain amount of scatter due to the crack faces for incident angles less than 1 degree. The scatter results in internal reflection of x-rays between the faces of the crack enhancing the crack detection. The effect would be more pronounced for thicker parts due to deeper (depth a) crack faces. This effect is not accounted in the model. Therefore, results of this simulation should be correlated with actual results on the RQI for a given part thickness.