Equivalent Penetrameter Sensitivity (EPS) for Performance Evaluation of Computed Radiography Systems

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Abstract

To obtain radiographic images which are adequate for non-destructive inspection requirements, methods are required to evaluate the performance of the imaging technique. Although visual observation of radiographs can meet part of the quality assessment of radiographic technique, this method is neither a sufficient nor a reliable way for quantitative assessment of image quality. Image quality indicators (IQI) are used in film-based industrial radiography as means to determine if the quality of the radiographic technique is satisfactory. Visualization of a specific IQI in a production radiograph measures the sensitivity or effectiveness of a radiographic technique in detecting small density changes in the evaluated specimen. The sensitivity of radiographic technique is usually represented by ability to visualize a percentage change of some parameters with respect to the test piece thickness, where smaller percentage means better radiographic sensitivity.

For computed radiography (CR), the primary metrics for establishing the performance are signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR), and basic spatial resolution (SR_b). However, SNR, CNR or SR_b do not provide enough information for a quick quantitative performance evaluation of the CR technique [1]. Moreover, in CR often the required IQI hole can be seen in the radiograph even when the computed radiography system's performance, in terms of SNR or CNR, is inadequate for the application. To address these limitations, the concept of equivalent penetrameter sensitivity (EPS) is being used in CR. The EPS is a measure of the intrinsic (inherent) contrast sensitivity of an imaging system and gives an indication of how well small density changes in objects can be detected at a given exposure level. Instead of a single IQI hole, an EPS test requires a plate with a series of holes and evaluates the number of holes visible using the CR technique. Although the EPS test is subjective, it is considered to be a reliable means to establish and monitor a critical performance metric of CR systems [2].

This paper discusses the EPS concept for CR systems, the reasons behind the EPS measurements and how it can be used to evaluate the performance of a CR system and imaging plate. A case study that was performed during the qualification of a CR system, using the EPS concept is also discussed in this paper.

Keywords: non-destructive testing, computed radiography, image quality indicator, equivalent penetrameter sensitivity, industrial radiography.

1. Introduction

In industrial radiography, quality assurance technique is required to determine if the quality of the produced radiograph is satisfactory. Radiograph's quality is assessed in terms of the radiographic sensitivity, which refers to the smallest detail that can be seen on the radiograph. Sensitivity of flaw detection is a complex function of the size, shape, position, absorption coefficient of flaw, type of film/imaging plate (IP) used and parameters of the computed radiographic imaging system such as: signal-to-noise ratio (SNR), contrast-to-noise (CNR), sharpness of image (SR_b). Therefore, it is not possible to easily calculate or find the sensitivity of flaw detection from any of these measured parameters alone for both film and digital radiography.

In CR, SNR is the ratio of the mean pixel values (signal) to the standard deviation of the pixel values (noise). Signal term is used for the mean pixel/gray values of a digital image with linear response to radiation dose in a homogeneous exposed area. The noise term used for statistical fluctuation of gray values or pixel values and measured quantitatively as the standard deviation of the mean pixel value in a projected area of constant object thickness. Contrast term is used to quantify the difference of the radiation signal intensity (measured as pixel value) between the base material and the discontinuity (replicated using an IQI). CNR is defined as the ratio of the difference of signal intensities of two regions of interest to the background noise (standard deviation of the pixel values). Basic spatial resolution or sharpness of image (SR_b) is the ability to distinguish between small objects that are close together in digital image or ability to clearly see abrupt changes in an object. The higher the SNR, CNR or smaller the SR_b, the better the quality of finished radiographic image is.

There is no direct relationship between radiographic sensitivity and flaw size; however, the sensitivity of a radiograph is an indirect indication of overall quality measure of the radiographic system and process parameters, and its ability to reveal flaws or thickness changes in the specimen being examined. Sensitivity is measured using a device known as an IQI and expressed numerically in terms of smallest detectable variation in specimen thickness as a percentage of total thickness [3].

There are three common types of IQI used in industrial radiography such as: (i) wire type (ii) step hole, and (iii) plaque hole as shown in Figure 1. The wire type of IQI consists of a series of metal wires mounted in a flexible plastic holder. The wires, which are 60 mm, long are mounted parallel to each other about 5 mm apart and are available in steel, copper and aluminium (Figure 1a) [4]. ISO standard 19232-1 and its equivalence British and European standard BS 462-1 specify a device and a method for the determination of the image quality of radiographs using wire-type image quality indicators [5-6]. The step hole IQI consists of a series of steps in increasing thicknesses, each having one or more circular holes of a diameter equal to the thickness of the step and drilled at right angles to the surface of the step. European standard EN 462-2 specifies a device and a method for the determination of the image quality of radiographs using step-hole type image quality indicators. This type of IQI is normally available in steel [6].

(a) Wire type IQI (b) Step hole type IQI (c) Plaque hole type IQI

Figure 1: Conventional three types of IQI [7-8]

The plaque hole type of IQI consists of a number of uniform thickness strips, or “plaques”, each containing three holes drilled through the thickness at right angles to the surface. Hole diameters are one, two and four times the IQI plaque thickness (T), and therefore we referred to them as 1T, 2T, and 4T holes. The perceptibility (degree of ability to see the holes in finished radiograph) is dependent on both the diameters of the holes and the thickness of the plaque, as well as image contrast and noise. The plaque hole type IQI used in the United States are called penetrameters, which are different than the European wire or step/hole type IQI.

The best known penetrameters is the American society of testing materials (ASTM) design, which consists of uniform-thickness plaque containing three drilled holes and identification letters, as shown in Figure 1(c) [9]. ASTM standards E1025-05 specifies the design and manufacturing of the penetrameters, which are used to indicate the quality of the radiographic technique but not intended to be used as a measure of size of discontinuity shown on the radiograph [10]. Contrast sensitivity using a plaque type penetrameter is also quantitatively assessed in terms of equivalent penetrameter sensitivity (EPS). The EPS plaques are used because they allow the radiographer to discern subtle differences in image quality as radiographic parameters are changed. According to the ASTM E1316 definition, the EPS is the thickness of penetrameter, expressed as percentage of the section thickness radiographed, in which a 2T hole would be visible under the same radiographic condition” [11].

In another definition for EPS, is the contrast sensitivity 2-2T which is 2% of the thickness of the material with a hole diameter of two times the plate thickness (2T) is just discernible in the radiograph [12]. Therefore, a 2-2T call-out would mean that the plaque thickness should be two percent of the material thickness and that a hole that is twice the IQI thickness must be detectable on the radiograph. This presentation of a 2-2T IQI in the radiograph verifies that the radiographic technique is capable of showing a material loss of 2% in the area of interest [13]. 2-2T quality requirements is most commonly required for routine radiography; however, critical components may require more rigid such 1-2T or 1-1T [14].

The EPS value is defined for hole type IQIs in ASTM E1025-11 as [15]:

$$EPS\ (\%) = \frac{100}{t_{material}}\sqrt{\frac{T_{IQI}d_{hole}}{2}} \qquad (1)$$

Where, EPS - Equivalent Penetrameter sensitivity in % of material thickness

$t_{material}$ - Thickness of penetrated material

T_{IQI} - Thickness of IQI

d_{hole} - Diameter of IQI hole

The primary metrics for establishing a digital radiography system's performance are its SNR, CNR and SR_b [16]. In film applications, these metrics are typically evaluated indirectly (no quantitative measurement) using the previously mentioned conventional IQI. If the required IQI hole for a specific application is visible, the SNR and CNR are considered acceptable.

The use of conventional IQI as described in Figure 1(c) in CR, demonstrated that the required IQI hole can be readily seen in the radiograph even when the CR system's performance, in terms of SNR or CNR, is inadequate for the application [1]. Additionally, current plaques type penetrameters may provide go/no-go type of information whether the achieved sensitivity meets the requirements (e.g. 1-2T or 2-2T) but can't quantitatively specify the system's sensitivity. To address these limitations, the concept of robust equivalent penetrameter sensitivity (EPS) method conforming to ASTM practice E746 and ASTM E1735-07 using EPS plaques also called relative image quality indicator (RIQI) is being used in CR [15].

EPS can't be measured using a phantom (a test object containing major CR quality indicators together) and requires special type of EPS plaques which contain 14 different arrays of penetrameter-type hole sizes designed to render varied condition of threshold visibility ranging from 1.92 % to 0.94%. Therefore, the method provides inherently greater sensitivity and accuracy than possible with a standard hole-type penetrameter [2]. EPS performance curve allows establish the minimum exposure required and acceptable exposure ranges for a specific CR system and imaging plate.

The purpose of the EPS testing is to determine the exposure levels (exposure charts for CR in analogy to film radiography) necessary to ensure an adequate SNR. The EPS process control tests check the present plateau and compare it with the baseline plateau to ensure that it is stable over time and to determine if a system is getting "noisier" with age. Therefore, it is not only the contrast but also noise and EPS could be consider as an alternative way to measure SNR. Although the EPS test standard contains holes similar to a standard hole-type penetrameter, by incorporating multiple holes over an area, the effect of image noise is more robustly assessed. For systems with a linear relationship between pixel value and exposure received, improved visibility corresponds to a low EPS, so in essence a low EPS is analogous to a high SNR and CNR. Although the identification of number of visible hole is subjective to the judgement of the viewer, this practice is generally accepted in industrial radiography and has been demonstrated to be a reliable means to establish and monitor a critical performance metric of computed radiography systems [2].

2. Methodology

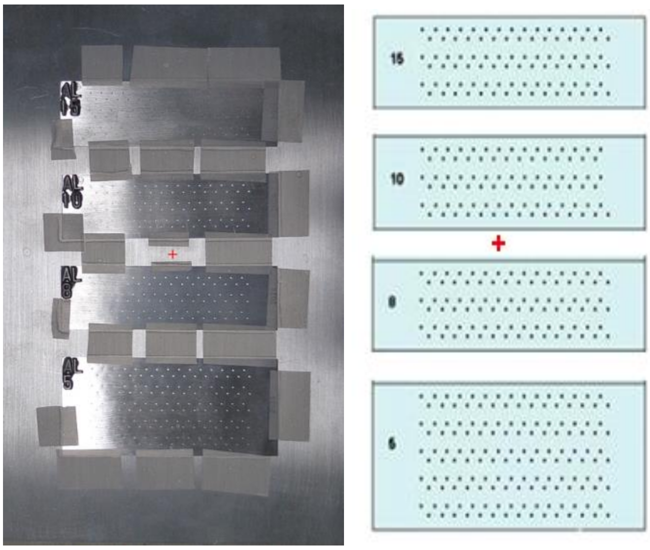
An EPS measurement of a commercially available table-top flatbed CR system and high resolution IP (small particle size phosphor) was performed using the testing guideline provided in ASTM E2445 with the EPS plaques and absorber plate manufactured in accordance with ASTM E746 standards [15,17]. Other key specification of the CR system are; 16bit image scanner, selectable 35 or 70 microns resolution, inline erasing, contactless (magnetic) plate transport mechanism, direct laser contact, scan width 35 cm (14 inch) and no gain setting or photomultiplier adjustments required when exposing various thicknesses. ASTM DICONDE compliant system was previously certified as highest system class IP/1 40 in accordance to EN14784-1 and ISO 16371-1. The objective of this study is to assess the baseline EPS performance under different exposure setting conditions. The exposure (in mA-s) corresponding to start of plateau of EPS curve is considered as the minimum exposure required for achieving optimum contrast in the image.

ASTM E746 presented a practice called relative image quality response aimed to generate a curve which is similar to a probability of detection (POD) for relative degree of image quality assessment of different imaging systems or radiographic processes. In this approach, plaques EPS value for each holes array counted as data in x-axis “a” and percentage of visible hole (no. of visible holes / total no. of holes) counted as data in y-axis “a-hat” [15]. From the curve, the EPS value (on the horizontal axis) derived from 50% visible hole (vertical axis) is considered as 50% POD.

3. Experimental Setup

The EPS test consists of four EPS plaques and an absorber plate as shown in Figure 2. The plaques which also called relative image quality indicator (RIQI), contain several rows of duplex holes. Based on the thickness of the plaques and diameter of the holes, each duplex row represents an EPS in accordance to equation 1 (values shown in Figure 2), when placed on the absorber plate. For lower energy CR systems (under 160kV), 2024 aluminum is used for both the EPS plaques and the 0.75 inch thick absorber plate and was selected for this study considering the target applications of the investigated CR system which are low energy radiographic inspection of airframe structural components primarily made from aluminum alloy.

The EPS plaques were placed on the absorber plate, arranged according to the thickness, with the thickest plaque on the top of the absorber. The edges of the plaques were placed at least 1.5 inches away from any edge of the absorber plate. The plaques were affixed to the absorber plate with tape so that the plaques are flat and do not cover any holes. X-ray radiation source was aligned in the approximate center of the plate between #8 and #10 EPS plaques (+ sign in the images presented in Figure 2). The kiloVoltage setting was set at 65 kV and Focal Detector Distance (FDD) was maintained at 39 inches (or 1 meter) from the X-ray source focal spot in accordance with ASTM E2445 guideline. A CR plate was exposed at series of exposure (mA-s) settings aimed to produce pixel value (PV) distributed within 10% to 90% of maximum PV or 6554 – 58982 (16 bit image processor) of the CR system under investigation.



EPS Rows	Step Thickness		Hole Diameter		EPS
#	mm	inch	mm	inch	%
1	0.38	0.015	0.71	0.03	1.93
2	0.38	0.015	0.64	0.03	1.83
3	0.38	0.015	0.58	0.02	1.75
4	0.25	0.010	0.79	0.03	1.66
5	0.25	0.010	0.71	0.03	1.58
6	0.25	0.010	0.64	0.03	1.49
7	0.20	0.008	0.71	0.03	1.41
8	0.20	0.008	0.64	0.03	1.33
9	0.20	0.008	0.58	0.02	1.28
10	0.13	0.005	0.81	0.03	1.19
11	0.13	0.005	0.71	0.03	1.12
12	0.13	0.005	0.64	0.03	1.05
13	0.13	0.005	0.58	0.02	1.01
14	0.13	0.005	0.50	0.02	0.94

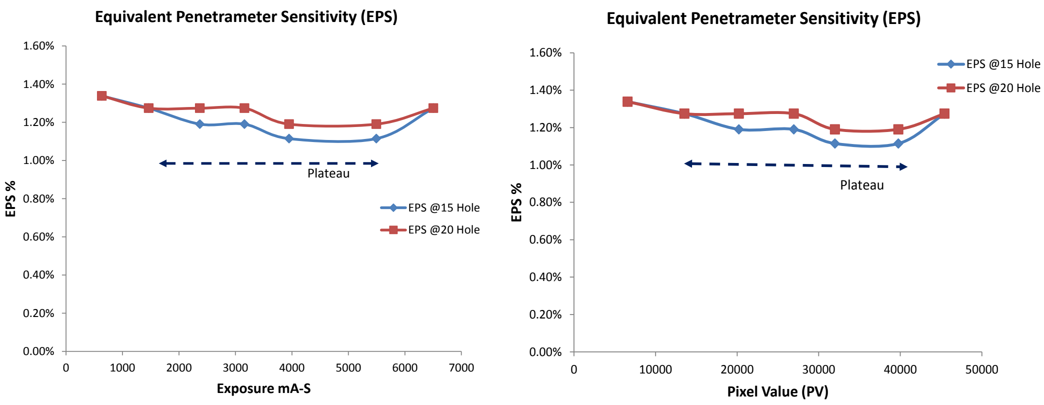
Figure 2: EPS and aluminium (Al) absorber plate setup

All CR system processing parameters, energy level, and exposure data were recorded and maintained throughout the tests. For each exposure, the EPS performance was recorded by determining the duplex row where a minimum of 15 or 20 holes (out of 30 holes in each duplex row) are clearly visible and the corresponding pixel value (PV) is measured for that image, on an unobstructed area (+ position in Figure 2) of the plate. Graphs were generated for the exposure and PV versus EPS value.

4. Results

The resulting images were evaluated for EPS, with each duplex row of holes corresponding to EPS as shown in Figure 2. The EPS using high resolution imaging plate with respect to X-ray exposure or PV is shown in Figure 3. EPS is determined by the smallest sensitivity row in which the required number of holes can be discerned. In the ASTM standard and published CR literature two minimum number of visible holes requirement were found (15 or 20 out of 30 holes) and therefore EPS curves were constructed considering both 15 (general requirement) and 20 (more stringent requirement) visible holes out of overall 30 holes in each duplex row.

From the EPS curves (Figure 3) as expected, a distinguishable increase in EPS (inferior EPS) at low exposure with improving EPS as exposure increases and yield a relatively flat plateau. The plateau range was identified that provided a consistent EPS value (variation of ≤15%). The result showed that plateau yield 1.2% (minimum value) EPS value within the exposure range from 1465 to 5495 mA-s or within pixel value ranging from 13546 to 39774. The end of curve showed slight increase of EPS value which is unusual compare to the example EPS curve showed in the ASTM standard. However, the primary purpose of the EPS test is to find the start of the plateau which is visible in the EPS curve, as shown in Figure 3.

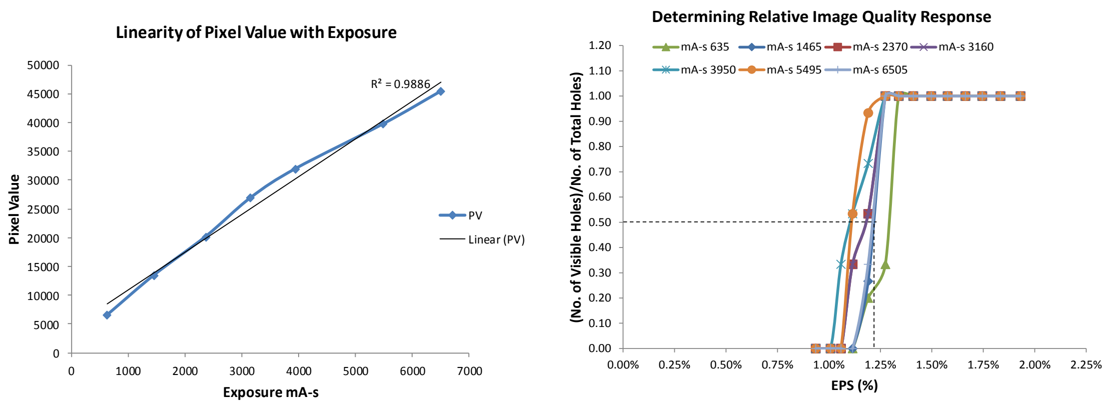


(a) EPS vs Exposure (b) EPS vs pixel value

Figure 3: Equivalent penetrameter sensitivity (EPS) vs exposure (a); pixel value (b)

The signal value of a picture element (pixel) of a digital radiographic image is proportional to the radiation dose or exposure (i.e. the linearized signal intensity is zero, if the radiation dose is zero) and should be linearly related. In addition, a graph was generated for the PV versus exposure level and determine if the system exhibits a linear relationship for any exposure level range. The exposure/PV relationship was considered as linear since each data point is within ± 10% of a straight line best fit of the data as shown in Figure 4. This meets the requirement of exposure/PV linearity which is prerequisite for SNR calculation.

Accordingly, relative image quality response for different exposure conditions are plotted in Figure 4 (b) which provides EPS values of 1.25% at 50% POD in accordance to this method. The value is similar to the minimum EPS % found in Figure 3.



(a) Pixel value with exposure (b) Relative image quality response

Figure 4: Linearity of pixel value with exposure (a) relative image quality response (b)

5. Conclusion

The primary purpose of the EPS test is to find the start of its plateau, when EPS based on number of visible holes, is plotted against different exposure. A plateau was found in this study although the complete EPS curve is not similar to the example given in the ASTM standard. EPS plaques are used because they allow the radiographer to discern subtle differences in image quality as radiographic parameters are changed and also provide an acceptable exposure range for CR imaging plates. Like CNR, SNR and SR_b, EPS is a measure of the image quality and varies with different CR systems and imaging plates. EPS is analogous to SNR but is a visual interpretation and is independent of system software. Like SNR, EPS increases with exposure therefore a series of exposure is required to find the EPS 'plateau". Only one exposure, from the plateau region, is required for subsequent periodic performance monitoring. For system qualification, the user needs the required EPS value and for process control a baseline EPS performance is required.

EPS testing generates the acceptable gray value working range of the CR system and imaging plate combination, which will provides the optimum thickness sensitivity. The linearity of signal or pixel value with radiation dose or exposure is required. Although it is not a new concept, evaluation of radiography systems using the EPS has rarely been used until now. Subjectivity of the measurements (human factor), variation of test standards among different manufacturers or inappropriate test protocols are the factors that effects the EPS measurements. In addition, expensive EPS test specimens also limit its wider application or usefulness in the film radiography. However, the EPS method provides inherently greater sensitivity and accuracy than a standard hole-type penetrameter as demonstrated in this work.

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