Performance evaluation of a photon counting detector for high energy NDT applications

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Abstract

The use of digital detectors as an alternative of film radiography is still an open issue in NDT community. The application of Digital Detectors Arrays (DDA) was supported by ASTM (2010) and CEN (2013). More specifically, the EN ISO 17636_2 standard treats both computed radiography and DDA usage for NDT of welds.
In this paper, we present image quality assessment of a photon-counting detector (PCD), which operates in the direct x-ray converting mode; and it was designed using latest CdTe-CMOS sensor hybrids. The pixel size is of 100µm, which makes the PCD suitable for controlling parts with thickness > 40mm for class B (parts with lower wall thickness may be also controlled if compensation principle II can be applied).
An important PCD characteristic concerns the sensor thickness: 2mm of CdTe. This value permits increasing quantum efficiency of about a factor five in respect to DDA based on GOS scintillator (200µm thick). The PCD was investigated with an Iridium 192 and Cobalt 60 gamma sources; and with a linear accelerator (6MeV). Image quality has been assessed in terms of EN ISO 19232 IQI (wire and hole). In addition, also the Signal to Noise Ratio and the basic spatial resolution (via the duplex IQI) have been measured according to the EN ISO 17636_2. For the Iridium 192 gamma source, performance evaluation has been completed by means of a qualification mock-up containing artificial flaws. A comparison with film radiography will be also presented.

1. Introduction

The use of digital detectors as an alternative of film radiography is still an open issue in NDT community (1). The application of Digital Detectors Arrays (DDA) was supported by ASTM (2010) and CEN (2013). More specifically, the EN ISO 17636_2 standard (2) treats both computed radiography (CR) and DDA usage for NDT of welds. Besides indirect detection of X-rays using CR and DDAs with scintillation layers (e.g. GOS), the direct detection by DDAs based on semiconductor technology (e.g. Si, Se or CdTe) is gaining more and more importance in NDT applications. If equipped with fast read-out electronics (ASICs) and low noise CMOS read-out, direct detecting DDAs can operate in photon counting mode, which allows detecting single photons and even determining their energies (3). Compared to indirect detecting DDAs, photon counting detectors (PCDs) offer several advantages. SNR limited only by quantum noise, low image unsharpness and high contrast sensitivity are the most noticeable. PCDs have been proved to function with energies up to 400keV (3). Here, image quality assessment of a PCD is presented for energies up to few MeV. The investigated detector (4) was designed using latest CdTe-CMOS sensor hybrids. The pixel size is of 100µm, which makes the PCD suitable for controlling parts with thickness > 40mm (class B in (2)). However, parts with lower wall thickness may be also controlled if compensation principle II can be applied. An important PCD characteristic concerns the sensor depth: 2mm of CdTe. This is the largest value available today and it has been selected in order to maximise quantum efficiency in NDT high energy range [100 keV < E < few MeV].

2. Experimental Conditions

As test object, different uniform steel blocks varying in thickness from 30mm and up to 150mm have been considered. Test object was placed in contact with detector, which was equipped with appropriate shielding. Image Quality Indicators (IQI) were positioned on the source side of the object as depicted in Figure 1, except for the duplex IQI, which is used to measure the system basic spatial resolution (SR_b) and it was positioned directly on the detector without any object between the source and the latter. Three types of sources were used: Iridium 192 (Ir192), Cobalt 60 (Co60) and a 6-9MeV linear accelerator (LA), for which the 6MeV mode has been selected. The source activity was 90 Ci and 13 Ci for Ir192 and Co60, respectively. The source-to-detector distance (SDD) has been selected accordingly to (2) (min value + 5%).

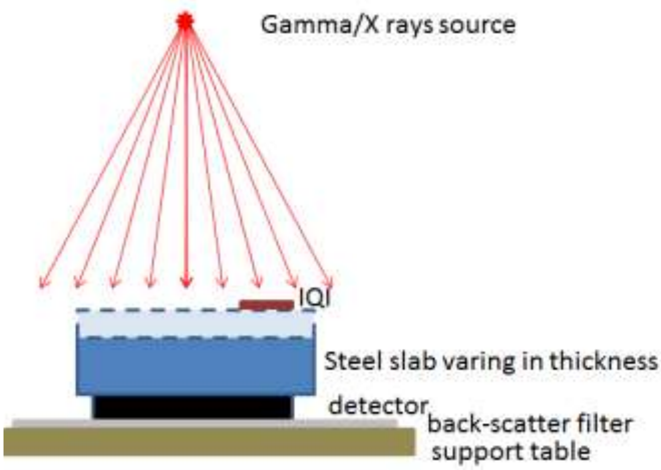

Figure 1. Schematic (not to scale) set-up representation.

The detector under investigation was the XCounter FLITE FX15.1.256.200.IP67 model. This is a compact dual energy, photon-counting and direct converting X-ray detector, whose active area dimensions are 153.6×25.6 mm^2. The term "dual energy" means that two images are simultaneously acquired. Each image contains photons whose energy is larger than a pre-selected threshold. The operator can choose the values for the two thresholds in the energy range [20-130 keV]. The values of 45keV and 100keV were retained for PCD performance evaluation.

3. Image Evaluation

Image quality has been assessed by means of the following IQI (5,6,7):
- Wire IQI reference FE W6 and W10 in conformity with (5)
- Hole IQI reference FE H5 and H9 in conformity with (6)
- Duplex IQI in conformity with (7)

IQI visibility was compared to (2) requirements and also to those of French RCC-M code (8). Accordingly to (2), image signal to noise ratio (SNR) and the detector basic spatial resolution (SR_b) have been measured and used to compute the normalized signal to noise ratio (SNR_N):

$$SNR_N = SNR \times (88{,}6\mu m/SR_b) \quad (1)$$

As it concerns SR_b, the latter was computed according to procedure described in (2), which considers interpolation from modulation depth analysis, i.e. interpolated SR_b (iSR_b) corresponds to the 20% dip (difference in peak).
For IQI detection, images have been evaluated according to the monitor viewing conditions described into (2). In particular, no processing of original data was allowed; only the contrast/brightness has been adjusted by the operator. The latter has to be qualified for the radiographic image interpretation accordingly to (9). For original data, however, we mean images that have undergone allowed correction/calibration procedures in conformity to (2).
In our case, the calibration procedure recommended by the manufacturer was applied. In particular, flat field images (without IQI) have been acquired at every object thickness for the pixel non-uniformity correction.

4. Results

Before presenting the results, some explanations/definitions concerning the symbols used in the following tables need to be introduced. When scoring the IQI values, it has been noted if the obtained value was equal to the minimum required by a standard (Y), and also if it was larger (Y(+1), Y(+2), …), or it was less (N(-1), N(-2), …).
Results obtained with the 100keV energy threshold only are reported since no remarkable difference in IQI detectability was observed between the two set of images; though the fact that with 100keV threshold, images were somewhat sharper than that with 45keV threshold.

4.1 Image Quality with Ir192 gamma source

Images acquired with the PCD satisfied ISO 17636_2 (class B) IQI requirements for the investigated steel thickness range. The same holds for the RCC-M code, whose requirements are even less strict.

Test #	Test Object	Wire IQI seen	Hole IQI seen	Conformity to ISO:CEN 17636 W/H	Conformity to RCCM W/H	iSRb meas	SNR_N mesured	Conformity to ISO:CEN 17636 $iSRb/SNR_N$	Exposure Time (min)	SDD
Ir_01	33 mm steel	0,20mm/W13	0,40mm/H6	Y(+2)/Y(+2)	Y(+3)/Y(+4)	123µm	265	Y/Y	3	520mm
Ir_02	43 mm steel	0,32mm/W11	0,50mm/H7	Y(+1)/Y(+2)	Y(+2)/Y(+3)	123µm	151	Y/Y	5	620mm
Ir_03	63 mm steel	0,50mm/W9	0,80mm/H9	Y/Y(+1)	Y/Y(+1)	123µm	94	Y/Y	10	820mm
Ir_04	83 mm steel	0,50mm/W9	,00mm/H1	Y(+1)/Y(+1)	Y(+1)/Y(+2)	123µm	116	Y/Y	60	1000mm
Ir_05	93 mm steel	0,50mm/W9	,25mm/H1	Y(+1)/Y	Y(+1)/Y(+1)	123µm	122	Y/Y	120	1000mm

Table 1. PCD image quality results with an Ir192 gamma source. Activity of 90 Ci.

For the 33mm case (Ir_01) two up to four IQI more than that required were detected. This allowed the application of compensation principle II: the obtained iSR_b value was considered respecting standard requirements thanks to wire IQI results. Note that in the 33mm case, the SNR was very large, 450 (with only 3min of exposition). For thicker samples, the exposure time was adjusted as to obtain lower SNR values.

4.2 Image Quality with Co60 gamma source

For the Co60 gamma source, we would like to explore larger thicknesses, but we disposed of 13 Ci activity source, which limited the number of tests and exposure time. Anyway, wire/hole IQI requirements (ISO 17636_2 (class B) and RCC-M) were respected for the investigated thicknesses. As it pertains iSR_b and SNR_N, they were nearly respected (43mm and 63mm of steel) since iSR_b has to be larger than 130µm and SNR_N has to be larger than 100. A slightly longer exposure time would have solved this as it was the case for the 83mm thick object.

Test #	Test Object	Wire IQI seen	Hole IQI seen	Conformity to ISO:CEN 17636 W/H	Conformity to RCCM W/H	iSRb meas	SNR_N mesured	Conformity to ISO:CEN 17636 $iSRb/SNR_N$	Exposure Time (min)	SDD
Co_01	43 mm steel	0,40mm/W10	),80mm/H9	Y/Y	Y(+1)/Y(+1)	140µm	92	Y/Y	8	620mm
Co_02	63 mm steel	0,50mm/W9	,00mm/H1	Y/Y	Y/Y	140µm	94	Y/Y	24	820mm
Co_03	83 mm steel	0,50mm/W9	,00mm/H1	Y(+1)/Y(+1)	Y(+1)/Y(+2)	140µm	104	Y/Y	80	1000mm

Table 2. PCD image quality results with a Co60 gamma source. Activity of 14 Ci.

4.3 Image Quality with a LA (6MeV)

With the LA, detector response was quickly saturated since the flux impinging on the detector (N° of quanta per unit time) was too large to be correctly handled (pile-up effect). As a consequence an important pixel cross talk was observed: the signal of one pixel was spread out to neighbours and vice versa.
With 83mm of steel thickness, with a SDD of 5m and an exposure time of 10min, no IQI was discernible. So it was decided to put in front of the detector all steel slabs we disposed: 165mm. An additional filtration (0,5mmTa + 0,2mmW) was added and, finally, an exploitable image has been acquired. IQI results for 165mm of steel are in conformity with ISO 17636_2 (class B) and RCC-M requirements.

Test #	Test Object	Wire IQI seen	Hole IQI seen	Conformity to ISO:CEN 17636 W/H	Conformity to RCCM W/H	iSRb meas	SNR_N mesured	Conformity to ISO:CEN 17636 $iSRb/SNR_N$	Exposure Time (min)	SDD
LA_01	165 mm steel	0,80mm/W7	,60mm/H1	Y/Y(+1)	Y(+1)/Y(+2)	140µm	112	Y/Y	10	5000mm

Table 3. PCD image quality results with a 6MeV LA.

4.4 Spatial resolution

As it concerns detector iSR_b, for the Ir192 case, it was possible to distinguish two iSR_b corresponding to the two detector energy thresholds; iSR_b for 100keV threshold was slightly better (123µm) than iSR_b for 45keV threshold (130µm). These values are both

larger than nominal pixel size of 100µm. The reason probably relies on detector internal scatter due to high energy radiation. However, the application of compensation principle II allows the use of the PCD also for thicknesses lower than 40 mm as it was pointed out for the 33mm case.
With the Cobalt60 source we did not distinguish a significant difference in iSR_b between the two energy thresholds. Probably, they were both much smaller than Co60–rays energies (1.17 and 1.33 MeV). An iSR_b of 140µm was outlined for the two cases.
The Co60 detector iSR_b was used to compute the SNR_N of LA images since iSR_b was not measured for the LA.

4.5 Comparison to film radiography

For the Ir192 gamma source case and for the 83mm thickness of steel, one acquisition has been performed with film. The cassette composition respected RCC-M prescriptions (film class C2, double film technique, …).
The same image quality as that obtained with the PCD was reached with an exposure time multiplied by a factor 12. This result was confirmed with a mock-up containing artificial flaws 20mm × 6mm × 0.1mm in size and positioned in the transition region of a bi-metallic weld in an 84mm thick pipe.

5. Conclusions

The most important result of this study is the fact that the investigated PCD allows easily satisfying RCCM and the more strict ISO 17636_2 standard (class B) image quality requirements (wire and hole IQI) for the steel thickness range and source types being tested. IQI values larger than the minimum requested were obtained in the majority of the experienced configurations.
It has to be stated that it was the first time that a photon counting detector from XCounter was tested with a LA. We learned that images respecting quality standard requirements are achievable at the condition that photon flux is sufficiently low as to avoid pile-up effects.
This PCD, with 2mm thick CdTe layer, presents an important improvement in the quantum efficiency ; it allows a gain in exposure time of a factor 12 if compared to film radiography.
Differently from previous tests (10), where a GOS-based flat panel detector was evaluated, there was no particular need to use an external metal screen filter. (with the LA, a filter was added just to reduce beam flux to detector in order to avoid pile-up).
In fact, PCD offers the possibility to filter scattered radiation via software by applying an energy threshold to detected photons.
In general, images obtained with the largest energy threshold were sharper and provided a better IQI visibility, even if the corresponding SNR was lower than that computed from images acquired with the smallest energy threshold.

6. Perspectives

PCD behaviour with very large photon flux has to be deeper investigated and understood in order to define PCD use with pulse sources such as LA and betatrons.

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