DEVELOPMENT OF A HIGH RESOLUTION X-RAY RADIOGRAPHIC TECHNIQUE, OPTIMIZED FOR ON-SITE TESTING IN RADIOACTIVE ENVIROMENTS

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Abstract:A high resolution x-ray radiographic system has been developed, based upon scintillation fibre optics. One of the goals in the design process was to achieve as high overall system resolution as possible. Another was to restrict the size of the components. Hence the system is optimized for sizing and characterization of cracks in nuclear power plants.

The first part of this paper describes the components of the system. Such as the high resolution x-ray image detector and how the parameters of the system has been chosen during the design process.

The system is able to scan the test object from different directions and angles. The second part of the paper describes a mathematical model for the two separate, manipulating robots that handles the x-ray tube and the x-ray image detector. It is a general model that is applicable to any arbitrary configurations. A technique to calibrate theirs absolute positions relative to each other has been developed and is also included.

The third part is highlighting the problems associated with scintillating fibre optics and how to solve this problem.

The last section is about a method to use filters, based on statistical methods, to remove noise induced from the radioactive environment.

Introduction:A radiographic system optimized for crack characterization in nuclear power plats has been developed. One common type is inter-granular stress corrosion cracking (IGSCC) [Fig. 1]. This kind of cracks characterized by quiet narrow width and it contains of major part with branches. A typical 5 mm deep crack has a crack opening width in the range of 25-50 µm.

The main idea in the design process was achieve as high radiographic sensitivity in the system as possible. To make the system suitable for on-site testing it had to have a limited physical size. The NDT-system (x-ray machine, x-ray image detector and the manipulating robot) was optimized as follows. The first step was to develop a suitable x-ray image detector. The requirements were high spatial resolution and dynamics at high energies to make it suitable for object thicknesses equivalent to 60 mm steel. Next step was to choose a radiation source. In an early stage isotopes were excluded due to their lack of intensity. A 450 kV x-ray machine with a small focus size found to be the optimum for our needs. The x-ray tube was then equipped with a diaphragm to restrict the primary beam in order to only radiate the imaging area of the detector. To be able to take exposures in different angles around cracks, demands on the manipulating system concerning stiffness and relative position accuracy were postulated.

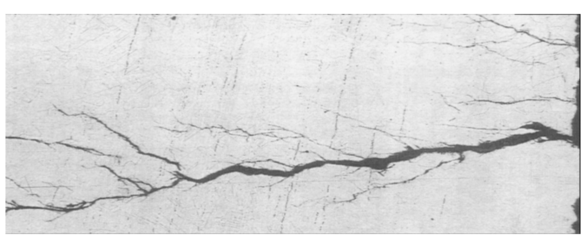


Fig. 1 Cross section of an typical IGSCC.

Results:1. X-ray image detector optimization

In traditional x-ray converters as phosphor, spatial resolution and detection efficiency are in conflict. An improvement is to use structured CsI(Tl). The best approach to achieve high spatial resolution and high detection efficiency is to utilise a scintillating glass fibre optic faceplate

(FOP) [1]. It is obvious that a traditional phosphor can't combine resolution and detection efficiency.
How a columnar CsI(Tl) is compared with scintillating FOP is not highlighted in this paper but interesting result has been achieved with 700 µm thick CsI(Tl)-screens [2]. When our system was designed (1995) there were only earlier versions of FOP available commercially. Since then both CsI(Tl) and FOP have been improved. There is also a difference between those two in light yield. Normally it is an advantage with high light yield, but if the lens is effective it produce too much light and will saturate the CCD-chip without reaching maximum contrast. In our solution a low light yield is preferable. To produce an x-ray image with high contrast is it the number of detected photons that is important (not to detect light only). To optimize the image detector we have tried to tune the light yield to the A/D-converter. As we use a 12-bit A/D-converter, full well capacity in the CCD should correspond to the amount of the available digitization levels. As we use a 12-bit (4096 levels) A/D-converter a saturated CCD correspond to about 4000 detected photons/pixel.
First we decided to optimize the system for an object thickness equal to 60 mm steel. Calculations of x-ray output and attenuation coefficients were made with software [3] to simulate filtered spectrum from a 450 kV x-ray tube. The diagram shows the filtered x-ray spectrum after a 60 mm thick steel object. The simulation is with maximum power of a 450 kV constant potential x-ray tube (Philips MG451).

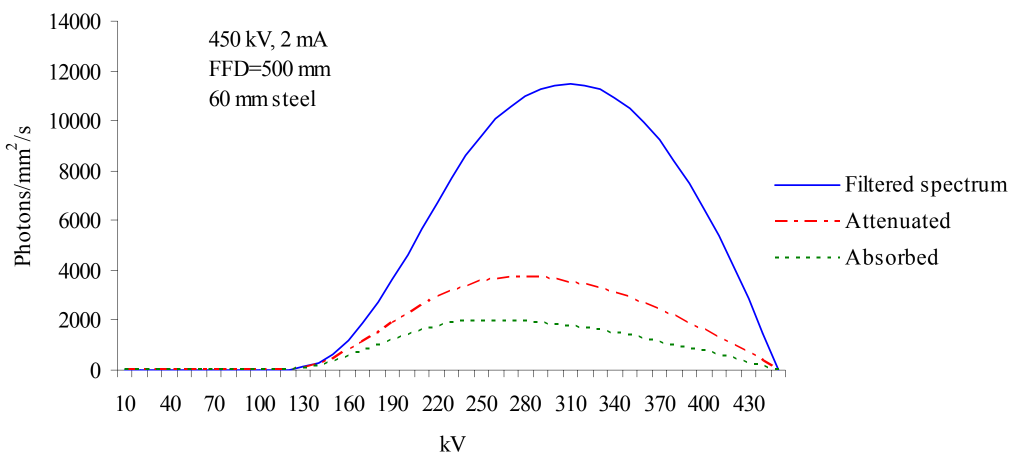


Fig. 2 Simulated filtered spectrum and detection efficiency of a 10 mm scintillating FOP.

The detection efficiency is about 33% and corresponds to 73 000 detected photons in the diagram [Fig. 2]. Data to simulate the detection efficiency for our scintillating FOP (a glass material named LG9) were available in reference [1].

$$DE = T_a \cdot T_c \cdot T_t \qquad (1)$$

DE = scintillating output energy / photon input energy
T_a = 0,33 (absorbed photon energy / incident photon energy)
T_c = 0,09 (generated scintillating light / absorbed photon energy)
T_t = 0,04 (output scintillating light / generated scintillating light)

If equation (1) is modified it will calculate the amount of light photons for each detected photon rather then the detection efficiency it can be used for optimizing the hole chain from the input scintillating FOP to the signal to the A/D-converter.

$$CE = \frac{Ph_e \cdot T_c \cdot T_t \cdot F_r^2 \cdot QE_{ccd}}{3,6} \qquad (2)$$

CE = number of electrons / incident photon energy
Ph_e = 300 [keV] (incident photon energy)
F_r = 0,7 (Fresnel losses in coupling interfaces)
QE_{ccd} = 0,25 (quantum efficiency in CCD)

As a pixel size of 22,5·22,5 μm^2 is used is 35 photons are detected (/pixel/s). The final solution for the x-ray image detector was then ordered after discussion with the delivering company, Photonic Science [4]. The ordered x-ray image detector was a modified standard image detector (XIOS 1:1) with an interchangeable scintillating FOP as input screen. The material in the FOP is a Tb_2O_3 activated, fused glass fibre optic, with 20 μm fibre diameter. The FOP is connected to a fibre optic lens with a length of 100 mm and 6 μm fibre diameter. The fibre optic lens is manufactured from a heavier glass material then the FOP to protect the CCD from primary radiation. In the end of the lens is the CCD-chip mounted. It is a full frame CCD (EEV-0530 MPP) of 1:th grade with a size of 1320 ·1150 pixels. The full well capacity is 300 000 e$^-$. The readout circuit works at 200 kHz and the read out time for a full image is 7 s.

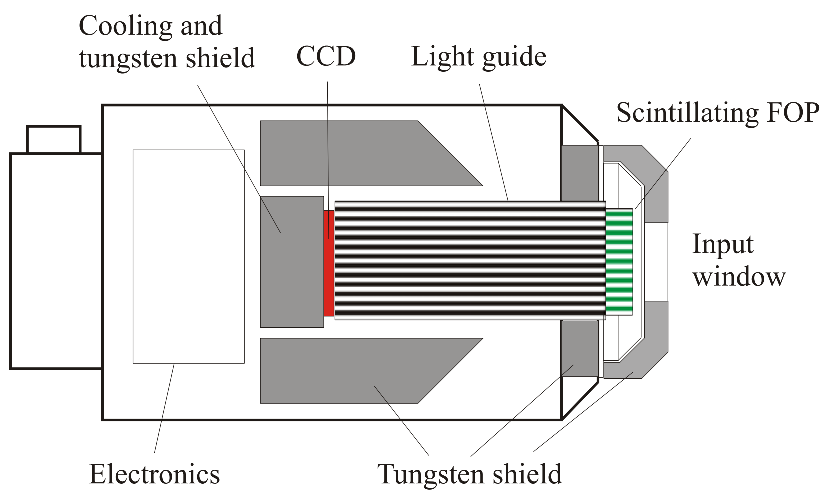


Fig. 3 Schematic sketch of the x-ray imaging detector.

The CCD-chip is cooled with two stage (Peltier) cooling. The CCD-chip and the readout electronics is also protected from background radiation with wolfram blocks. The front is covered with tungsten shielding with an input window with an area of 28·26 mm^2. The overall length of the is 240 mm and the diameter is 120 mm. Tests to measure the resolution of the system at 400 kV was carried out according to EN 462-5. The result is in figure below [Fig. 4]. The image quality indicator is made of platinum and the diameter of the smallest wires is 50 μm with the same distance between them.

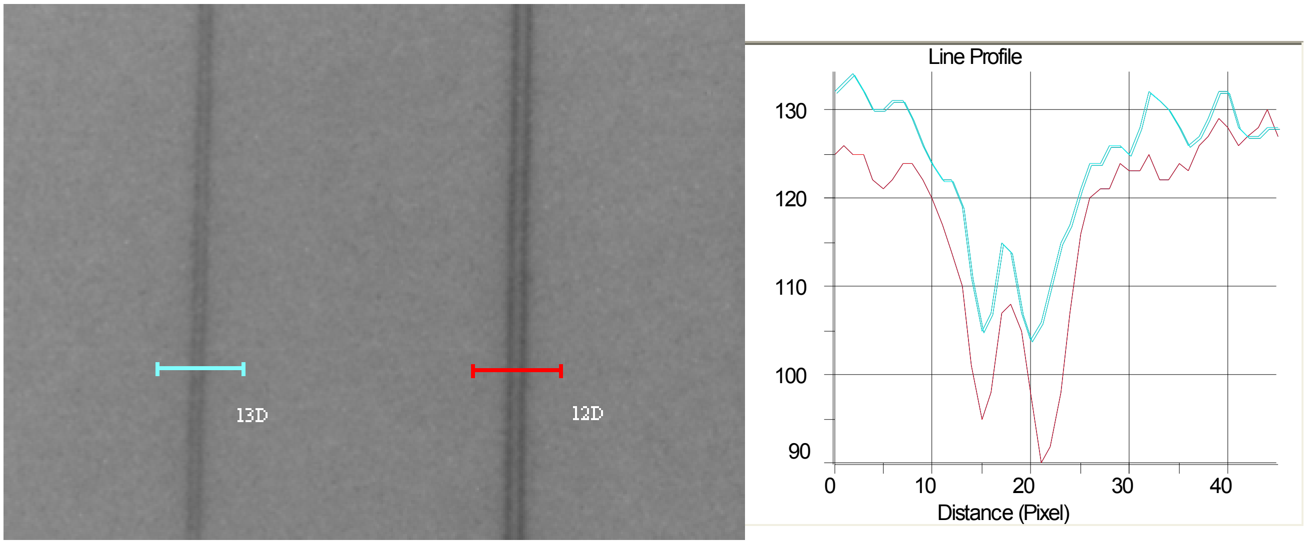


Fig. 4 Resolution measured according to EN 462-5 (400 kV, 20 mm steel)

2. Positioning equipment

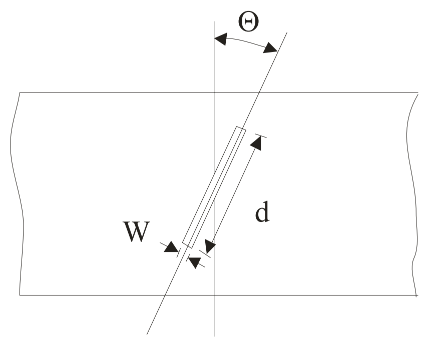
To be able to detect cracks with an x-ray system, the x-ray beam has to be fairly parallel to the crack. The relationship between the depth and width of a crack with the viewing angle and the performance of the x-ray system can be analyzed. A classical formula [5] has been used for traditional film radiography and is a useful tool to predicting crack sensitivity.

$$d \cdot W = Const \cdot \left(d \sin(\Theta) + W \cos(\Theta) + U_T\right)\left(1 + \frac{I_S}{I_D}\right) \tag{3}$$

I_D = Primary radiation
I_S = Scattered radiation
μ = Attenuation coefficient
U_T = Total un-sharpness

$$U_T \geq \sqrt{U_F^2 + (tf / SFD)^2}$$

U_f = Inherent un-sharpness
f = Focus spot size
SFD = Source to film distance
t = Object thickness



To optimize each parameter in equation (3), best possible result can be achieved. Some factors are not relevant to digital x-ray system, but relationship between width and depth to the angle is the same. The constant on right hand in equation (3), is only available for film radiography and should be replaced by a corresponding factor for the contrast sensitivity of the image detector.
To be sure that a crack will be detected it is necessary to make a series of exposures with a small displacement in angle between each exposure. From our experience a serie of exposures from -15º to +15º with an angular displacement of 1º is very effective to be shore that most parts of a crack, including sub-branches in the case of IGSCC, will be detected. Based on this theoretically considerations the positioning equipment was developed [Fig. 5].

To make the system easy to use we decided in an early stage to make the manipulating in two, separate units. The reason was to make it more versatile and avoid specially designed, object specific, manipulating units. A very important aspect with NDT examinations in nuclear environments is the background radiation level. The time for NDT technicians to stay in the radioactive environments has to be minimized. To minimize that time a technique to calibrate the relative positions of each manipulating unit is developed. A hair-cross like device is mounted in the front of the image detector during calibration procedure. By moving the x-ray tube into a numbers of positions and line up the image detector so that the hair-cross verifies that the focus of the x-ray tube is on the vector in the centre of the x-ray image detector. When this is done it is possible to transform the coordinate system of the manipulating unit for the x-ray tube into the coordinate system of the x-ray image detector. When the internal calibration is done it is possible to rotate around any arbitrary point with high accuracy e.g. the opening of a crack inside the object to be examined.

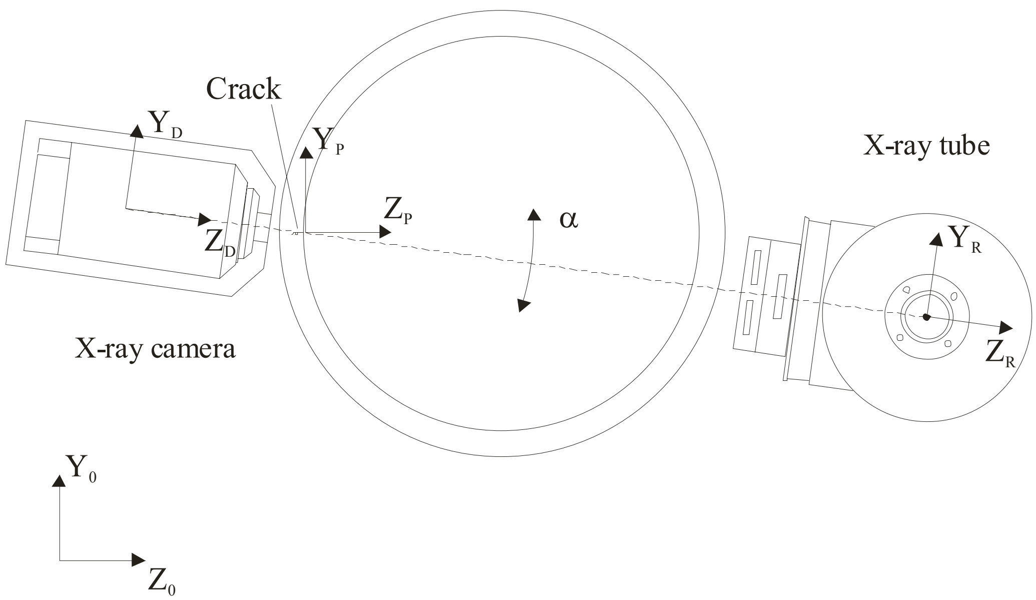


Fig. 5 X-ray system in position for a scanning sequence.

3. Scintillating fibre optics

The fibre scintillating fibre optics used is non-uniform in the sense that the individual fibre has different conversion efficiency. A “chicken- wire” pattern is visible in the raw image. To compensate for this effect a standard image operation, background compensation, is used (4). An exposure with a background image is made from the same material and thickness as the object of interest. To avoid negative values a zero-image with no radiation is also needed since the zero-level in the A/D-converter is adjusted slightly over zero.

$$C_{X,Y} = \frac{I_{X,Y} - Z_{X,Y}}{B_{X,Y} - Z_{X,Y}} \cdot M \qquad (4)$$

$B_{X,Y}$ = Background image
$Z_{X,Y}$ = Zero image
M = Mean value of $B_{X,Y}$ - $Z_{X,Y}$

4. Statistical filtering

There are two sources of radiation induced noise in the x-ray image detector. One is of course background radiation when it is used in radioactive environments such as nuclear power plants. The other is radiation from the primary beam that goes in by the input window in the x-ray image detector and then travels trough the fibre optic lens [fig. 3] and hits the chip directly. The CCD is assumed to have a 20 μm Si, epitaxial region where all the charge is collected and a 1 mm thick backing of Si from which no charge is collected [6]. The probability that a photon from the primary beam hits the CCD is very little, but the charge it creates is very large compared to a photon that's detected in the scintillating fibre optics in the front. Most of the background radiation in a nuclear power plant, when it is accessible for non destructive examinations, consists of radiation from ^{60}Co contaminations. The background radiation gives the same effect as from the photons from the primary beam. It is complicated to simulate the deposition of charge from an attenuated x-ray in the CCD. The photons from the primary beam that's hit the CCD has high energy due to the filtration trough the test object (usually 40-60 mm of steel) and the fibre optic lens. The dominant attenuation process at that energy in Si is the Compton-effect. There is only a part of the energy that will absorb the rest of the energy will scatter away. The dominate direction is forward and the energy that will be deposit is from the Compton electron. If the radiation originates from ^{60}Co it will have higher energy when it hits the CCD. Instead of simulate the process a series of test has been done to measure the energy that will be deposit in the pixels. The mean range from a secondary electron in the CCD is short. It means that when a pixel is hit by an x-ray it deposit most of the energy in one single pixel and its neighbours.

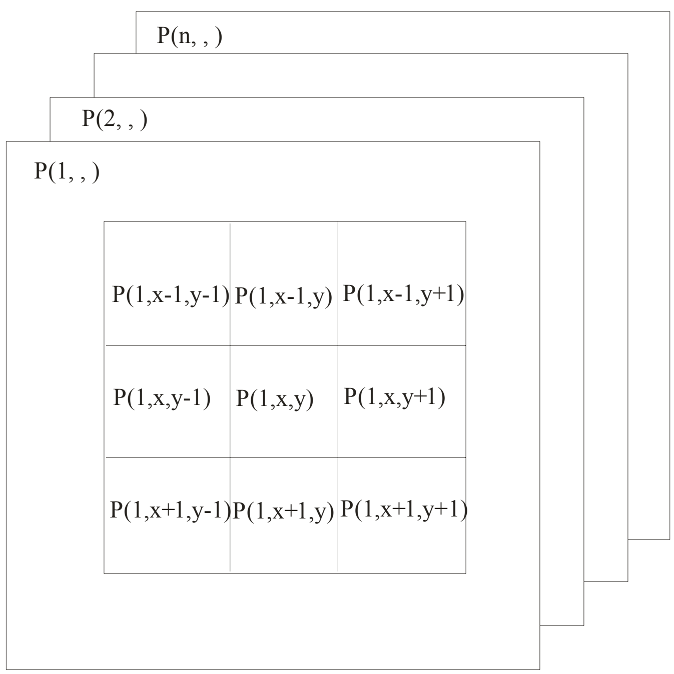


Fig. 6 Pixel notation in sub-images.

By dividing each exposure in sub-exposures with identical exposures data can they be compared pixel by pixel. To distinguish between light generated in the scintillating FOP and charge directly deposited n the CCD a special type median filter has been developed (5). By sorting the data with the same pixel from each sub-image, in a vector and then take the median value from the vector, can a criterion be used to separate values originated from primary radiation and radiation induced noise in the CCD.

$Max(P_{X,Y}(1,2,...,n))$ will be rejected if

$$Max(P_{X,Y}(1,2,...,n)) - Median(P_{X,Y}(1,2,...,n)) > Const \cdot \sqrt{Median(P_{X,Y}(1,2,...,n))} \quad (5)$$

then it continues with

$$Max(P_{X,Y}(1,2,...,n-1)) - Median(P_{X,Y}(1,2,...,n)) > Const \cdot \sqrt{Median(P_{X,Y}(1,2,...,n))}$$

until no more values will be rejected. The pixel value ($P_{X,Y}$), is the mean value of all accepted values from the sub-images. The constant (*Const*) is the confidence interval of the normal distribution.

Const = 1,96 (95% confidence)
Const = 2,58 (99% confidence)

Instead of simulating the phenomenon a series of tests has been carried out. The tests were done without the scintillating FOP, with the energy set to 400 kV and a steel object with 50 mm in thickness, were used. From our test it was obvious that about 0,1% of the values from the sub-pixels, were rejected. To make the algorithm more efficient, the neighbour pixel [Fig. 6] to those how are rejected are also excluded.

Discussion: The system have been working well and despite that the image detector have been heavily exposed for more than 1000 hours at high energies, the CCD have not been damaged. In the next version of the image detector, a new construction will be used in order to avoid exposure of the CCD with primary radiation. The scintillating fibre optic will also be replaced with one with improved quality alternatively with a thicker CsI(Tl) if this gives better resolution [3]. The image sequences from the scanning around the cracks have given a new dimension to crack characterisation. It is planned to be developed refined methods for sizing of crack by using spatio-temporal filtering methods. The needs for filtering methods [7] to eliminate problems from variations of thicknesses and attenuations in objects has been highlighted when it is difficult to present image with more than 8 bits.

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