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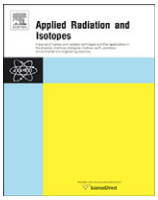

Implementation and characterisation of new neutron imaging system for dynamic processes investigation at the Es-Salam research reactor

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A R T I C L E I N F O

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A B S T R A C T

Neutron imaging is a powerful method for non-destructive investigations where high penetration through metals and in particular high contrast for hydrogenous materials maybe exploited. Due to the complexity of digital neutron static or video image formation, image capture conditions and parameters must be accurately selected. In this work, implementation of a new neutron imaging system based on CCD camera and LiF–ZnS scintillator is presented. The image characteristics in terms of contrast, noise and dynamic range and investigation limits of this new imaging system were studied as a function of the neutron source properties.

1. Introduction

The work in the field of neutron radiography at the Nuclear Research Centre of Birine has the goal of developing neutron radiography non-destructive control techniques for various scientific studies and industrial applications. This technique is helpful for the improvement of quality assurance in high level activities of research and development in the nuclear field and industry. Dynamic process imaging using a neutron beam is a very powerful and interesting investigative tool so far as light materials, elements and substances such as hydrogen, water lubricants and some other relevant materials are concerned (Domanus, 1992; Harms, 1986; Lehmann et al., 2005; Wagner et al., 2006). The neutron imaging system that is most commonly used is based on a CCD camera (charged coupled device) and scintillator screen. Because of the complexity and large number of operations necessary for capturing dynamic processes with any digital neutron imaging system (neutron camera), specific optimum experimental conditions and procedural accuracy are required. The sequence of events required to capture a single image with a full-frame CCD camera is summarised in Scientific Imaging Technologies (1994). In order to promote the neutron radiography applications around the Es-Salam research reactor, a new neutron imaging system was implemented in addition to the conventional film method (Kharfi, 2002; Kharfi et al., 2005). Because it is our first experience with such electronic neutron imaging systems, we decided to start up with inexpensive CCD camera and LiF–ZnS scintillator based neutron imaging system. When the implementation feasibility is well demonstrated and proved, and the process mastered, we proposed to implement a more sophisticated system like those produced and assembled at the Paul Scherrer Institute (PSI, Switzerland) or NeutronOptics (France). This new system uses the same reactor beam channel and the same neutron collimator as the film method. In this work, the implementation phases and characterisation procedures are presented. The main characteristics and the investigation capabilities and limits were studied.

2. Neutron source and geometrical facility characteristics

The new imaging system is placed at the radial channel of the Es-Salam research reactor and will enlarge applications of neutron radiography, will diversify applied methods and will make neutron radiography easier, in comparison with older film based methods (Fig. 1). The available neutron beam intensity at the sample position varies from 1.6×10^6 to 2.4×10^7 n/cm^2/s, with a cadmium ratio of 82.93. The L/D ratio is $\sim$125 depending on the position of the object on the exposure table. The divergent angle of the collimator is $\sim1.5^\circ$. The neutron beam at the sample position has a diameter of 210 mm at the actual detection position. The beam uniformity is 6% from 0 to 9 cm and 9% outside. The sample holder is designed to support objects from 1 to 20 kg and assure 30 cm vertical movement. A major step in the improvement of the neutron radiography activity is the implementation of a neutron imaging system for static and

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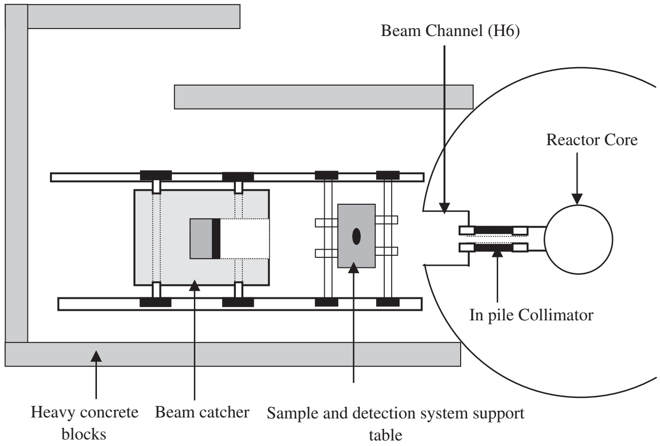

Fig. 1. General layout of the actual Neutron Radiography Facility.

dynamic processes. The use of an imaging system based on a scintillator, a front coated mirror, lenses and a CCD camera is a guarantee of more reliable and accessible images and an improvement for neutron radiography imaging (Lehmann et al., 2004; Lehmann and Vontobel, 2004; Cocking, 1987; Martin, 1987; Anderson, 2009).

3. Description of the imaging system

The neutron detection system was manufactured and assembled by NeutronOptics, France. The components of this imaging system are placed in an aluminium light tight box (175 mm × 105 mm × 120 mm) positioned vertically by a holder fixed on the metallic table of the neutron radiography facility. The camera consists of 250 μm LiF–ZnS scintillator, a front-surfaced Al/SiO$_2$ mirror and a high sensitivity Sony CCD camera with 2×10^{-5} l× (at f1.4) as the minimum required illumination (Fig. 2) (www.NeutronOptics.com). Because the detection area (field of view) is 12 cm (H[1]) × 10 cm (V) and the number of effective pixels is 752 (H) × 582 (V), this system has as an intrinsic spatial resolution of ~171 μm. In most cases, the effective resolution will be limited by the relatively low L/D ratio rather than the camera. In order to limit the neutron beam from the reactor channel, originally 21 cm in diameter, to the field of view of 12 cm × 10 cm, we use a Cadmium window.

The main characteristics of the different components of this imaging system are presented in Table 1.

4. Characterisation procedures of the imaging system

To characterize this new imaging system in terms of its video capture capabilities, taking into account the neutron source properties especially its intensity, the intrinsic characteristics of the CCD chip and geometrical exposure conditions, we applied a severe test procedure. The test procedure was based on video capture of a dynamic process. The dynamic process that we chose is the examination of hot water behaviour inside a coffee machine. Then the high contrast for hydrogenous based substances and materials for neutron imaging can be exploited. Therefore, we have studied the influence of the most important acquisition parameters, namely, frame rate and gain, on neutron imaging video sequence quality, and capture of time-lapse sequences of this dynamic process. Several video sequences were captured under the same experimental neutron exposure conditions and different acquisition parameters of the dynamic process. Details and conditions of the video sequence captures are presented in Table 2.

The system being studied was characterised in terms of contrast, noise and dynamic range on the basis of the following approaches:

1. Contrast: a histogram can also describe the amount of contrast, which is the difference in brightness between light and dark areas in a frame. In this work, the maximum contrast is estimated according to the Michelson formula given by Michelson (1927):

   $$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

   I_{max} and I_{min} represent the highest and lowest luminance of the analysed image.

   Because contrast is proportional to the camera gain (G) and the frame exposure time (τ), it can be studied as a function of $G\tau$.
2. Noise: thermally excited electrons in the Silicon lattice of the CCD chip are counted as signal. This dark current noise is measured in units of electrons per second per pixel. It can be reduced very significantly by cooling the CCD chip. The specification of thermal noise always refers to the full CCD chip. Pixels with noise greater than the average are called as hot pixels. The total noise σ_N is the sum of thermal noise (σ_{th}), read out noise (σ_R) and shot noise (σ_{shot}) (Andor Technology plc., 2011; Kristin, 2007).

   $$\sigma_N = \sqrt{\sigma_R^2 + \sigma_{th}^2 + \sigma_{\text{shot}}^2} \tag{2}$$

   The shot noise is unavoidable and caused by a fundamental law of nature—the quantum nature of light. It is important to remember that shot noise is dependent on the signal, not additive and Poison distributed. The read out noise is additive Gaussian distributed and independent of the signal. For our imaging system, we expect that the major contribution to the total noise comes from the shot and the thermal noise (dark current and hot spots) with read out noise negligible. Thermal and shot noise are frame exposure time (e.g., integration time) dependent. Therefore, we tried to study the noise as a function of $G\sqrt{\tau}$ in this work. To quantify the thermal noise on the video sequences, we propose a method based on the calculation of statistical grey level deviations from the mean value for identical regions selected on different frames taken from the video sequences obtained. Frame subtraction and filtering are efficient techniques to reduce or eliminate some kinds of noise such as dark current and hot spots. These techniques were used after noise estimation to improve the frame quality of the best neutron video obtained.
3. Dynamic range: the dynamic range of a CCD camera is defined as the full well capacity divided by the total noise:$D_R = fullwell/\sigma_N$ (Kodak Application Note, 2005). Since thermal noise is exposure time dependant, the dynamic range is a function of frame exposure time as well (Kodak Application Note, 2005). It is very important to mention that in order to be able to fully exploit the dynamic range, the A/D converter has to have enough bit depth (Cannistra, 1998). In our case the CCD camera bit depth is 8 bits (256 levels). The study of dynamic range variation as a function of frame exposure time (frame rate) allow us to determine the frame rate (temporal resolution) that must be selected to permit the capture of a video sequence with an optimum grey level scale. The measurement of the effective dynamic range is not an easy task and required the use of electron spectroscopy techniques and special signal metric instruments (van Vliet et al., 1998). In its simplest terms, dynamic range refers to the

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[1] H : horizontal, V : vertical.