Applying Thermal Neutron Radiography to Non-Destructive Assays of Dynamic Systems

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Abstract. Dynamic processes or systems frequently can not have their behavior directly analyzed due to safety reasons or because they require destructive assays, which can not be always afforded when high-cost equipment, devices and components are involved. Under these circumstances, some kind of non-destructive technique should be applied to preserve the safety of the personnel performing the assay, as well as the integrity of the piece being inspected. Thermal neutrons are specially suited as a tool for this purpose, thanks to their capability to pass through metallic materials, which could be utterly opaque to X-rays. This paper describes the accomplishments achieved at the *Instituto de Engenharia Nuclear / CNEN*, Brazil, aiming at the development of an Image Acquisition System capable to perform non-destructive assays using thermal neutrons. It is comprised of a thermal neutron source provided by the Argonauta research reactor, a converter-scintillating screen, and a CCD-based video camera optically coupled to the screen through a dark chamber equipped with a mirror. The developed system has been used to acquire 2D neutron radiographic images of static devices to reveal their inner structure, as well as movies of running systems and working devices to verify its functioning and soundness. Radiographic images of objects taken at different angles would be later on used as projections to retrieve - through a proper unfolding software - their 3D images expressed as attenuation coefficients for thermal neutrons. A quantitative performance of the system has been assessed through its *Modulation Transfer Function – MTF*. In order to determine this curve, unique collimators designed to simulate different spatial frequencies have been manufactured. Besides that, images of some objects have been acquired with the system being developed as well as using the conventional radiographic film, allowing thus a qualitative comparison between them.

KEYWORDS: Real Time Neutron Radiography; 3D Neutron Tomography; Non Destructive Assay.

1. Introduction

Thermal neutrons have a great potential capability to perform non-destructive assays thanks to their, usually high, penetrability. This is specially true for heavy materials, which attenuate intensely X-rays, becoming hence opaque to them, precluding an inspection of their inner structure. Another remarkable characteristic of the thermal neutrons is that the absorption cross-section does not increase regularly with atomic number, as X-rays do. Such a behavior makes sometimes possible the differentiation between neighbor elements, a task ordinarily difficult or even impossible for X-rays.

The utilization of a CCD-based video camera in a image acquisition system presents several relevant advantages as follows. First, the exposure time is dramatically shortened, reaching up to 1% of that demanded by conventional film radiography. Such a short exposure time allows the image acquisition of moving objects in a *quasi* real time basis. Second, unlike systems employing radiographic films, the images are obtained already in the digital form, facilitating thus its treatment and storage.

This work presents some preliminary results obtained with the system being developed comprised of a CCD-based video camera - commercially available for conventional tasks such as surveillance and security - and a converter-scintillating. These results are then compared with equivalent ones obtained with systems employing radiographic films, when their advantages and limitations are analyzed and discussed.

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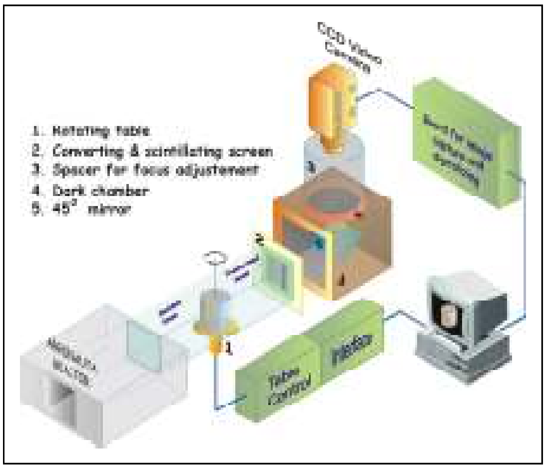
2. Methodology

The methodology employed to carry out neutron radiography of static objects and dynamic systems can be abridged in Fig.1. A broad thermal neutron beam emitted by a research reactor intercepted by the object, or system under inspection, hits a converter-scintillating screen, casting on it an image, which reveals the attenuation inner features of the object. This image is caught by a CCD-based video-camera and digitally stored in a computer. The arrangement shown in Fig.1 can be employed as well to obtain 3D tomographic images, if a sufficient number of projections are acquired under different object angles, as provided by the rotating table.

Figure 1: Brief scheme of the Image Acquisition System under development. A static 3D tomography of the object can also be obtained if several projections of it are taken at different angles.



2.1 Neutron Conversion and Detection

The thermal neutron beam used in this work were produced by the Argonauta Research Reactor installed at the *Instituto de Engenharia Nuclear*/CNEN – Brazil, and its main properties are presented on Table 1.

Table 1: Properties of the neutron beam at the main port of the Argonauta research reactor.

Thermal Flux	4.46×10^5 n.cm^{-2} s^{-1}
Epithermic Flux	6.00×10^3 n.cm^{-2} s^{-1}
L/D Ratio	63.25
Divergence (FWHM)	1^0 16'

The converter-scintillating screen acts as a transducer detecting the neutrons and emitting a visible bluish light with a peak at 450nm. It is constituted by a 15x10 cm thin plastic plate with a silver-activated $Li^6F(ZnS)$ layer deposit on its surface, being commercially known as NE426. Its luminescence decay time is short enough to allow the imaging of moving objects by using a suitable video camera. In this work a CCD-based AW-E650 model Panasonic video camera has been employed. It requires a minimum illumination threshold of 5×10^{-5} lx and allows a maximum integration time of 2 seconds. The optical coupling between the screen and the camera is performed by a dark chamber provided with a first surface mirror deflecting the light from the screen to the vertical direction where the camera axis is positioned. This arrangement prevents the direct incidence of neutrons to the camera which could damage it.

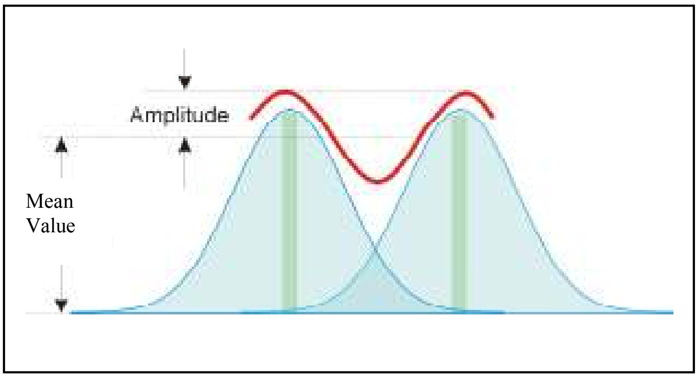
2.2 Image Quality

The *Modulation Transfer Function* - *MTF* [2] is an adequate tool to evaluate the performance of an imaging system. It shows how the capability of a system to resolve close features - close related to the modulation - is impaired by their spatial frequency. Relevant and useful information regarding the system can be inferred from this function, such as spatial resolution and contrast.

The MTF can be obtained by using special, and very expensive (when available at all), multi-slit collimators, or alternatively by a Fast Fourier Transform of the *Line Spread Function - LSF*. This function expresses the response of an imaging system to an ideal line source: a blurred strip instead of a single line. Methods to get the LSF can be found elsewhere [2,3].

Besides the resolution, the contrast plays an important role in the overall image quality. Among other factors, it depends mainly on the *modulation* - defined as the *Amplitude-to-Average Value* ratio - resulting from the overlap between neighbor LSF*s*. As one can infer from Fig.2, high spatial frequencies associated with low detector resolutions (broad LSFs) lead to low modulations and consequently to a poor image contrast. An image is considered of acceptable quality when the modulation reaches at least 10%. [2].

Figure 2: Overlap of two neighbor *Line Spread Functions*. High spatial frequencies and poor detector resolutions produce a low modulation degrading the image contrast.



2.3 Methodology to determine the MTF

In order to determine the MTF using the slit collimator approach, rather than FFT technique, it is necessary measure the modulation for several points of the spatial frequency domain. Since a single collimator of this kind, i.e., a piece containing constant-width slits at different gaps, was not available, several individual *three-slits* collimators have been manufactured. A photographic top view of one of these devices is shown in the Fig.3. Their slit width ranged from 0.0125 to 0.560 mm, covering thus the spatial frequency range 1.8 – 80 mm^{-1}. The modulation has been determined by mapping the optical density of neutrongraphic collimator images. A plot of the modulation against the spatial frequency defined by the slit widths furnishes the aimed MTF. Further details can be found elsewhere [4].

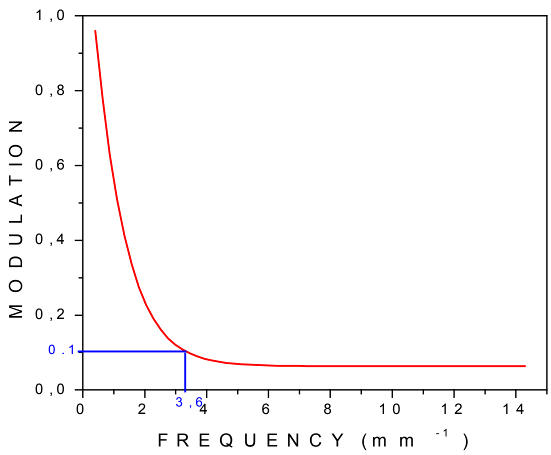
Figure 3: Photographic top view of a *three-slit collimator* with a 0.28mm slit gap. This device is actually a kind of *anti-collimator* in the sense that the slit is filled up with a material of higher attenuation coefficient than the main body.

3. Results

3.1. Quantitative Results

The obtained MTF for the developed system presented in Fig.4 exhibits a 10% cutoff-value at the spatial frequency of 3,6 mm^{-1}. Therefore the system is capable to distinguish features up to 0.28mm apart from each other.

Figure 4: MTF for the developed system. The cut-off at a modulation of 0.1, defines a spatial frequency of 3.6 mm^{-1} corresponding to a spatial resolution of 0.28 mm.



When compared with a conventional *radiographic film* imaging system, the developed system employing a converter-scintillating screen & video camera exhibits a much higher cutoff-value as shown on Table 2. Indeed, while the first system could resolve features up to 0.015mm apart [4], the second one only would succeed for a gap about 20 times larger. Nevertheless, the exposure time required by the conventional system surpasses that required by the developed system by a factor 1,200, excluding the time demanded for the chemical processing.

Table 2. Resolution and required acquisition times for the developed system and a conventional one employing radiographic films.

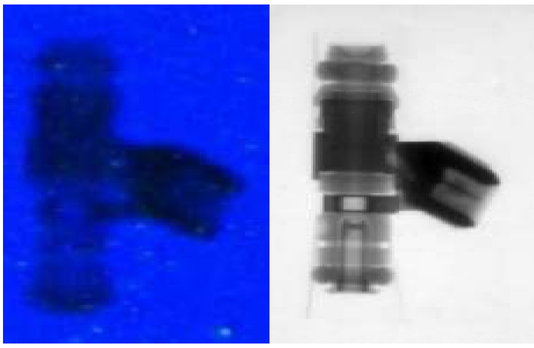
SYSTEM	Video Camera	Radiographic Film
Resolution (mm)	0.28	0.015
Acquisition Time	2 sec	40min + Development Time

3.2. Qualitative Results

A high resolution is solely one of the desirable properties that determine the overall performance of an imaging system. In some circumstances, specially for large objects, other characteristics may become more important as they could impact directly on the efforts and costs.

Although the ultimate goal of this work is the development of an imaging system capable to deal with moving objects, some images of static objects have been taken as well, addressing a proper system characterization. Within this frame, Fig.5 shows the images of an automobile fuel injector, taken with the developed system (a) and with a conventional one employing radiographic films (b).

Figure 5: Neutrongraphic images of an automobile fuel injector taken with the developed system (a) and with a conventional one employing radiographic films (b).



(a) (b)

The conventional system produces an image of superior quality. Yet, the developed system exhibits an image that can be regarded as acceptable, taking into account the contrast consistence with its companion.

The Fig. 6 shows images of an automotive oil pressure probe taken with both systems for comparison. As in the previous example, the higher image quality produced by the conventional system is evident. A very interesting feature of the imaging system employing a converter-scintillating screen optically coupled to a video camera is the possibility to study the kinetics of systems as those involving moving objects or materials. The Fig.7 for instance, shows some frames picked up from an actual *quasi* real-time movie of an ordinary lighter (placed upside down during the take), submitted to an intentional gas leakage. Thanks to the hydrogen contents of the hydrocarbon fuel, it is possible to get a high image contrast defining the fluid level.

Figure 6: Neutrongraphic images of an automotive oil-pressure probe obtained with the developed system (a), and with the conventional radiographic film system (b).

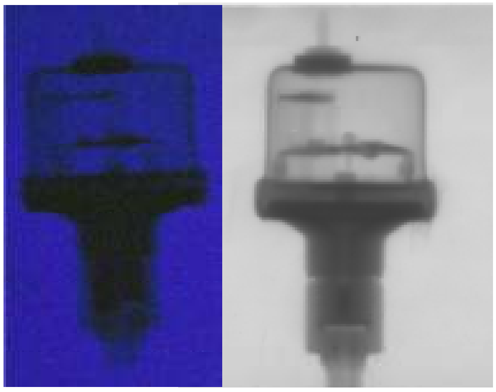
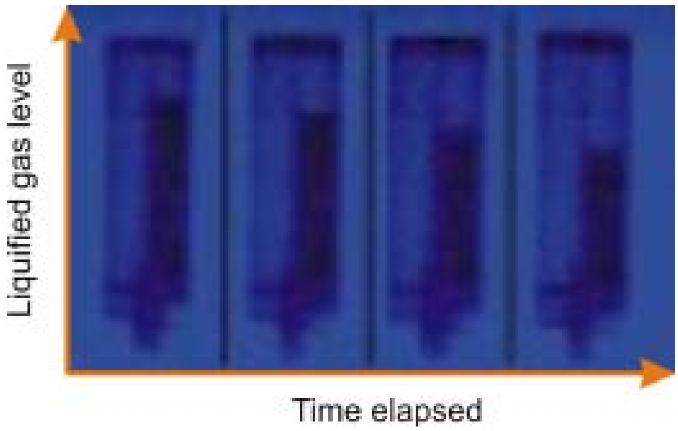
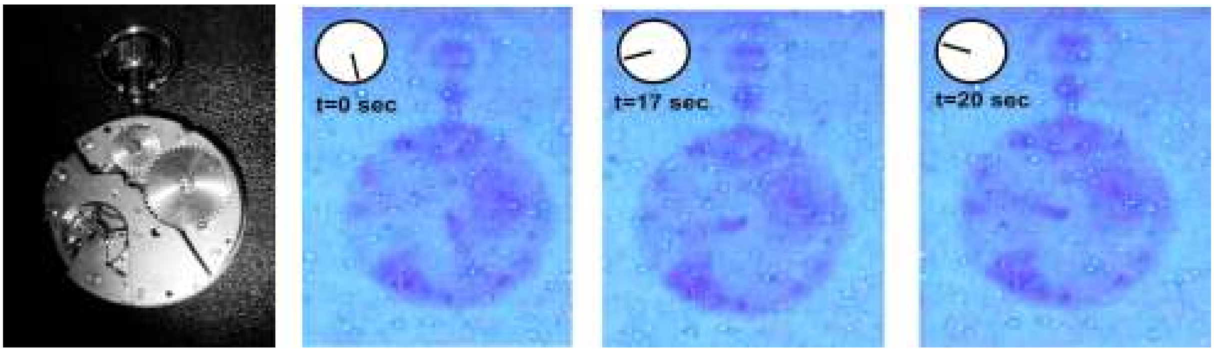

(a) (b)

Figure 7: Some frames picked up from the actual footage of an ordinary lighter, placed upside down during the take, with an intentionally caused gas leakage. The darker vertical strips correspond to the liquefied gas.



The faster movement of a mechanical chronometer has been recorded with the developed system as well. For this purpose, a thin cadmium strip has been glued up to its major pointer to increase its neutron attenuation. Three chosen frames corresponding to the elapsed times 0, 17 and 20 seconds are shown in the Fig. 8. The pointer appears somewhat blurred due to the long integration time (2 seconds) required to get a reasonable exposure. The utilization of a camera with a higher sensitivity or the employing of equipment to enhance the signal-to-noise ratio, such as light intensifiers or cooling devices would certainly improve the image quality.

Figure 8: Frames picked up from the actual footage of a mechanical chronometer. The time elapsed between the left and the right frame was 20 seconds. A conventional back view photograph of the open chronometer is also shown for reference.



4. Conclusion

A low-cost *quasi* real-time imaging system comprised of a converter-scintillating screen optically coupled to a general use video-camera has been assembled, tested and evaluated on both qualitative and quantitative aspects. The quality of the images produced by this system cannot compete with those given by a conventional imaging system employing radiographic films. However, it is capable to deal with moving objects, a task obviously impossible for the conventional system.
Moreover, it employs a reusable detector that furnishes end images already in the digital form and requires an exposure time several order of magnitude shorter than an conventional system.

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