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Nuclear Instruments and Methods in Physics Research A 542 (2005) 123–128
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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Characterization of the image quality in neutron radioscopy

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Available online 5 March 2005

Abstract

Neutron radioscopy, or dynamic neutron radiography, is a non-destructive testing method, which has made big steps in the last years. Depending on the neutron flux, the object and the detector, for single events a time resolution down to a few milliseconds is possible. In the case of repetitive processes the object can be synchronized with the detector and better statistics in the image can be reached by adding radiographies of the same phase with a time resolution down to 100 μs. By stepwise delaying the trigger signal a radiography movie can be composed.

Radiography images of a combustion engine and an injection nozzle were evaluated quantitatively by different methods trying to characterize the image quality of an imaging system. The main factors which influence the image quality are listed and discussed.

PACS: 07.85.Y; 87.59.B; 42.79.L; 42.30.V

Keywords: Neutron radioscopy; Dynamic neutron radiography; Image quality; Modulation transfer function; Combustion engine

1. Introduction

Going to short exposure times a lot of parameters can determine the quality of a neutron radiography (NR). In order to compare NR images taken at different facilities with different detector systems the images should be characterized quantitatively by image processing. By systematical listing, understanding and filtering of the image artefacts a further improvement of the image quality can be achieved.

For NR imaging three components are necessary, of which every single one influences the image quality: the neutron source including beam collimators, the object and the detector. Four parameters are useful in considering the image quality: the spatial resolution Δ_x, the time resolution Δ_t, the noise σ and the contrast C. The spatial

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0168-9002/$ - see front matter
doi:10.1016/j.nima.2005.01.296

resolution Δ_x can be defined as the distance at which two structures can be distinguished, and the time resolution Δ_t is the exposure time of the image. The noise σ is the mean grey level amplitude of the statistical fluctuations of a homogeneous area. The contrast C is the grey level difference between two areas and determines if we recognize a detail or not.

Several measurements were carried out [1–3] at the thermal neutron imaging facilities Neutra, PSI [4], and at the Neutrograph, ILL [5]. The comparison between the images shows how an image characterization is possible and how the imaging system can be further improved.

2. Measurements

For the first time a running combustion engine was investigated with neutrons. The engine, a four stroke and 0.5 kW model air craft engine of the OS company (see Fig. 1), running at 4800 rpm, was investigated at Neutra, PSI. The cycle of 12.5 ms was subdivided in 50 frames with 250 μs exposure time each. By synchronizing the detector and the combustion engine for each frame 4000 images were acquired and summed up by software afterwards. The intensified Princeton Instruments Camera PI-Max from PSI was used in combination with a Li^6ZnS scintillator from the AST company.

Fig. 1. Running four-stroke model aircraft engine.

An induction sensor registering a screw on the rotating rotor blade was used as trigger. The delay of the trigger signal leading to a different time point was done by the camera software.

In a series of NR experiments a common rail diesel injection nozzle (Fig. 2) with a single central hole of 0.2 mm diameter and a pressure up to 1000 bar was inspected. Instead of injecting diesel a non-flammable oil was used and propagation and form of the injection cloud were observed in 5 steps of 100 μs at Neutrograph, ILL. The injector was triggered with about 20 Hz, and the camera accumulated 12,000 images synchronous to the injection process. The detector system at ILL consists of a Sensicam, an Interline Transfer CCD camera of the company PCO with a fast shutter option. The visualization of the injection cloud was first seen in the third try because the attenuation of the oil is only 1‰ and the right point in time was not yet known. Thus, it is an ideal sample for a check of the NR image quality.

At the beam line H9 at ILL, the very high flux of $3.2 \times 10^9\ \mathrm{n/cm^2\,s}$ gives optimal conditions for short exposure times. Otherwise working with such a high flux needs some special precautions. The activation level must be controlled continuously and before starting a long time measurement of a few hours, an estimation of the decay times should be done. At ILL for the first time scintillator degradation was observed. The scintillation intensity sinks about 3% after 300 min in the high-flux neutron beam [6].

3. Evaluation methods

A good measurement of the spatial resolution Δ_x is the determination of the modulation transfer function (MTF) by a knife edge profile [7] with the same distance to the detector as the object, the so-called edge spread function ESF (Figs. 3 and 4).

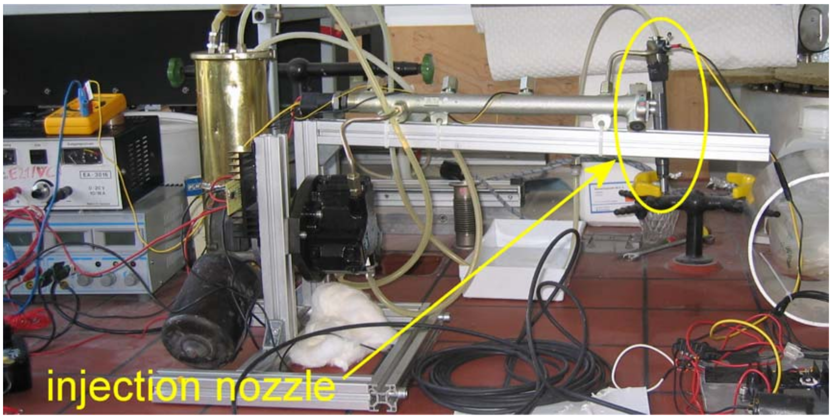

Fig. 2. The diesel injection setup for neutron radioscopy.

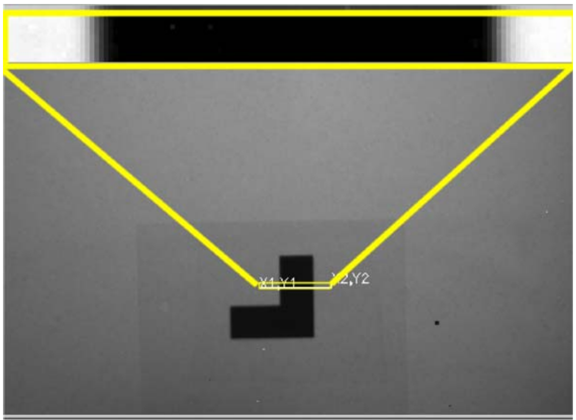

Fig. 3. NR image at FRM-II of a Cd plate with magnification of the Cd-edges.

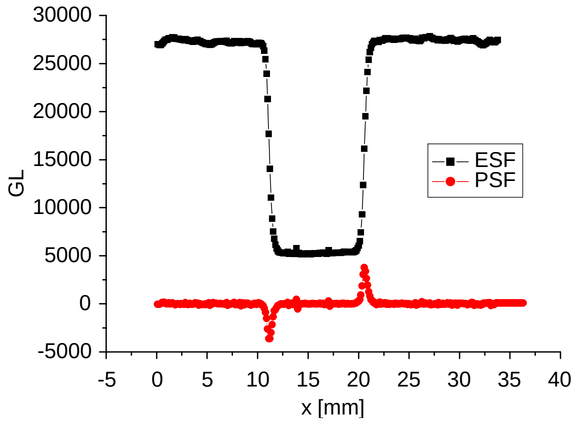

Fig. 4. The grey level profile of the edge above, also called edge spread function ESF, and its derivation the PSF.

This kind of evaluation was done with one of the first NR at the Antares facility [8] at FRM-II, Munich. As knife edge a Cd plate of 2 mm thickness was used. Using a defined width of 1 cm the conversion of pixel in real distance was much easier. By IDL program the edge can be extracted and the data are immediately fitted, the resolution is calculated and the profiles and fit parameters are exported to a log file for further processing. If an edge is not perfectly sharp, a lower estimation of the spatial resolution is possible. In the case of strong neutron absorbers like Gd, Cd, B and negligible fraction of scattered neutrons this method is exact.

The derivation of the ESF, taken as long as possible, is the line spread function LSF and in the case of a homogeneous isotropic beam also the point spread function PSF. The PSF is the detector response of a perfect point source independent of its position. The determination of the PSF is normally done with an ESF because it is quite difficult to measure the PSF directly using an exact pinhole of a strong absorber. The PSF in Fig. 5 was extracted from the derivation of the profile in Fig. 4.

In most cases the PSF will have a gauss-like shape because of the beam divergency, the scintillator spot size and the zoom optics of the

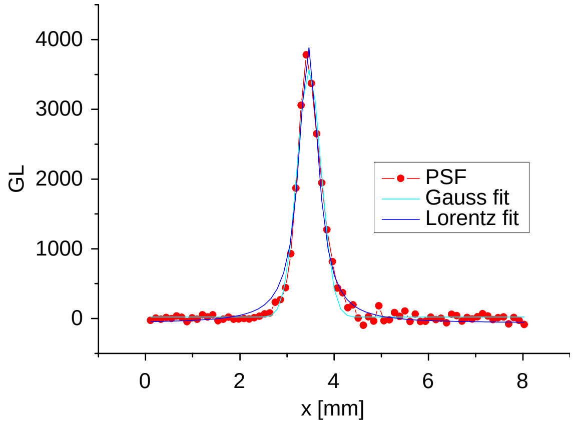

Fig. 5. Point spread function PSF (derivation of the ESF).

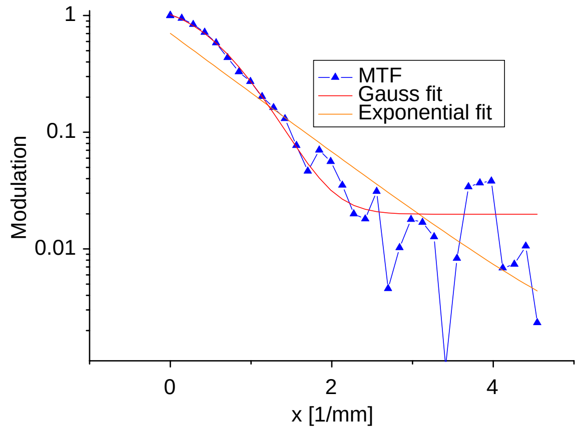

Fig. 7. Semilog plot of the modulation transfer function with a gauss and a lorenzian fit.

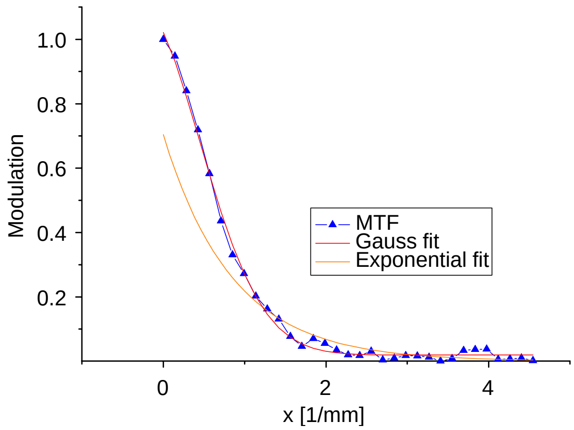

Fig. 6. Modulation transfer function (MTF) of the imaging system.

camera. In Fig. 5 the PSF was fitted with a gauss curve with a FWHM of 0.6 mm.

The normalized Fourier transform of the data in Fig. 5 is the MTF (Fig. 6).

The MTF is a more precise description of the spatial resolution than the distance of two resolvable structures and tells us which spatial modulation amplitude in the object causes what modulation amplitude in the image vs. the spatial modulation frequency. The higher the spatial frequency at which the MTF drops to zero and the steeper the drop, the better the image quality.

In the semilog plot in Fig. 7 the MTF was fitted with a gaussian and an exponential function. The gauss fit is slightly better. However, if the PSF can be fitted well by a gaussian or the ESF well by an error function, the FWHM of the gaussian or the distance from 10% to 90% of the ESF Δ_x are both used as a measure for the spatial resolution prediction. The FWHM of the gauss curve is by the factor of 0.91 smaller than Δ_x.

The time resolution Δ_t in neutron radioscopy corresponds to the exposure time of the CCD. A lower limit is set by the scintillation decay time of the used scintillator.

Besides the spatial resolution the noise characteristics are crucial if one wants to see small contrasts. A reasonable quantity is the relative background or open beam noise σ. The measurement of the noise is very simple if the object does not cover the total beam. A region of interest extracted from an area of homogeneous neutron flux can deliver the ratio of standard deviation/mean. Normalizing the image with an open beam NR improves the relative noise σ. If the beam is not homogeneous, σ may differ in different positions also in normalized images and more radiographies must be taken in order to characterize $\sigma(x, y)$. The noise in the radiography has many components, but the most relevant one for short exposure times is the neutron quantum noise, which is proportional to the square root of the neutron fluence. That was confirmed well at PSI during a beam breakdown. The noise behaviour

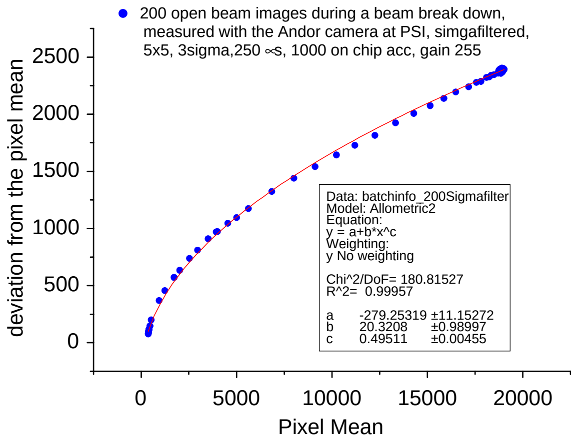

Fig. 8. Noise σ (pixel deviation) dependent on the neutron flux (pixel mean), measured at PSI during a beam breakdown.

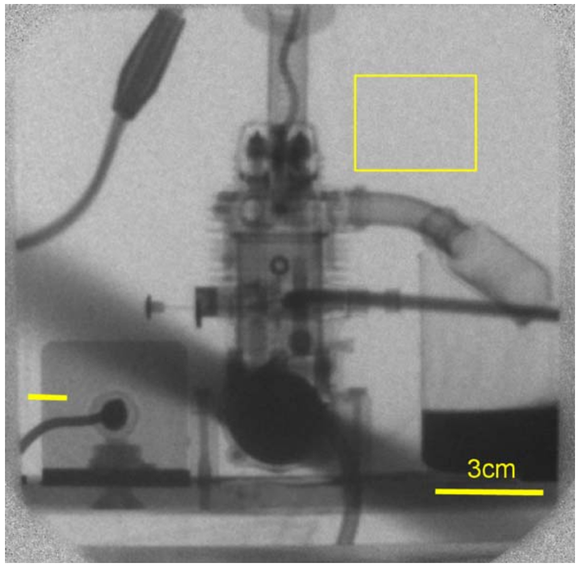

Fig. 9. One single frame of an NR movie of the model air craft engine in Fig. 1, $t = 250\,\mu s$ with 4000 accumulations, $\Delta_x = 0.75\,mm$, $\sigma = 3\%$.

follows perfectly the square root dependence as visible in Fig. 8.

By smoothing an NR the relative noise σ can be reduced by scarifying spatial resolution.

In non-destructive testing the typical question is: Can I see a certain detail in the image? There, additional to the spatial and time resolution and the noise also the contrast of that detail becomes relevant. The object itself determines that contrast by its size, its attenuation and scattering properties. Additionally the contrast sensitivity of the human eye has its limits and only with sophisticated visualization tools special tasks can be performed well.

4. Results

For the first time a combustion engine running by its own was imaged by neutron radioscopy. In Fig. 9 one single frame of the neutron radiography movie is visible. 4000 images of the same phase with an exposure time of $250\,\mu s$ were summed up and normalized with an open beam image. After the summation the image exceeds the dynamic range of 16 bit and the 32 bit floating point data type must be used for processing. A gamma filter with a kernel size of 5×5 pixel and a deviation of 3σ was applied. The relative noise σ in the open beam was measured in the rectangle in the right upper image region. It is 3% high and the spatial resolution measured by the edge spread function ESF is 0.75 mm.

The profile was extracted from the mounting plate of the sensor (Fig. 3, line near the left image border). The image size is $15\,cm \times 15\,cm$ (1058×1038 pixel).

The fast injection process of a high-pressure nozzle was observed with neutrons (Fig. 10). The lack of a sharp edge in the image allows only a rough estimation of the spatial resolution. From the profile of the cylindrical nozzle the spatial resolution is estimated to be 1 mm, at a time resolution Δ_t of $100\,\mu s$. This agrees with the PSF estimation based on the L/D ratio of 150 of the neutron beam and a distance object detector of about 150 mm. The 12,000 accumulations were done in a special manner. The camera was triggered with double the frequency of the nozzle.

In alternation images of the injection cloud and open beam images for normalization were taken and finally each image was normalized with the following open beam image. That way the relative background noise σ was reduced drastically to 4.4‰ and oil drops or oil fog completely

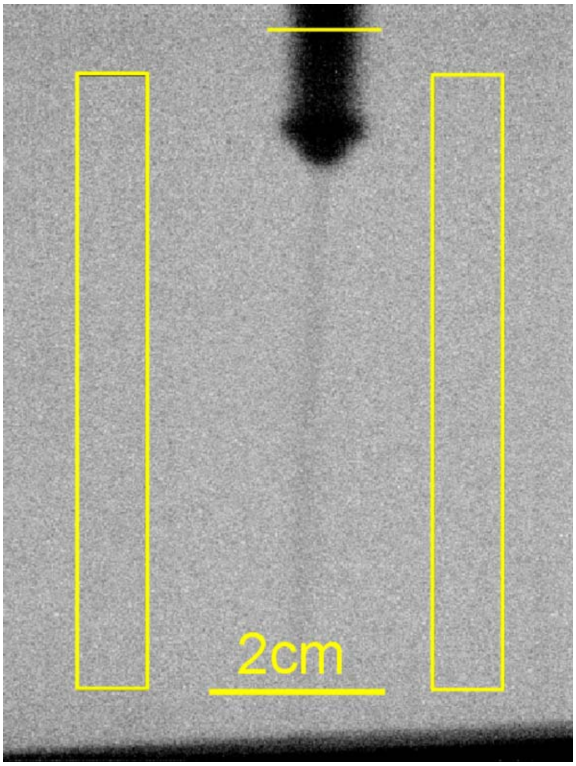

Fig. 10. NR image of the injection nozzle (Fig. 2) in action, $t = 100\,\mu s$ with 12,000 accumulations, $\Delta_x = 1\,mm$, $\sigma = 4.4‰$.

disappeared. The two yellow boxes in the image were used for the calculation of σ. The size of Fig. 10 is $6.2\,cm \times 8.3\,cm$ and 640×480 pixel.

Acknowledgements

The present study is supported by the Technische Universität München, Physik E21 and the new high flux neutron source FRM-II, Garching, Germany [8]. Thanks also to our supporters from Institut Laue Langevin, Grenoble, France and from Paul Scherrer Institut, Villigen, Switzerland.

The model aircraft engine was provided by courtesy of Markus Axtner and the injection test stand by courtesy of the Robert Bosch GmbH.

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