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Image Enhancement for High frame-rate Neutron Radiography

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Abstract

High frame rate neutron radiography has been utilized to investigate two-phase flow in a metallic duct. However, images obtained by high frame-rate neutron radiography suffered from severe statistical noise due to its short exposure time. In this study, a spatio-temporal filter was applied to reduce the noise in the sequence images obtained by high frame-rate neutron radiography. Experiments were performed at the B4-port of the Research Reactor Institute, Kyoto University, which has a thermal neutron flux of 5.0×10^7 n/cm^{2}s. Results were also compared with those obtained at the JRR-3, the Japan Atomic Energy Institute, with a thermal neutron flux of 1.6×10^8n/cm^{2}s.

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Keywords:

1. Introduction

Flow visualization is indispensable to understand the dynamics in thermal hydraulics. Since a non-intrusive measurement method with high spatial and temporal resolution is desirable, numerous efforts have already been made to develop a method for measuring flow with better signal quality. Neutron radiography is one of the radiographic techniques that make use of the difference in the attenuation characteristics of neutrons in various materials, whose characteristics complementary to those of X-ray radiography has many advantages for fluid flow in a metallic duct [1]. Thermal neutrons easily penetrate most dense metals, whereas they are attenuated by such

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materials as hydrogen, water, boron, gadolinium, and cadmium. Therefore, neutron radiography is more suitable for visualizing and measuring a multiphase flow in a metallic duct or a liquid metal flow than x-rays [2].

However, the temporal limit of neutron radiography depends on the neutron flux emanated from a neutron source. The short exposure in neutron radiography causes severe noise due to the statistical variation of the neutron flux [3]. Generally, time averaging can be applied to reduce such statistical noise from the original images. However, such time averaging cannot be used for motion pictures, which may cause image blurring in the filtered images. Spatial filters can be used for high frame-rate neutron radiography, however, if the S/N ratio (signal to noise ratio) is really poor, the spatial noise cannot be removed just by applying such spatial filters. Thus, it is indispensable to reduce noise from an original image by applying a temporal and spatial filter at the same time. The purpose of this study is to apply such a spatio-temporal filter to high frame-rate neutron radiography to enhance the image quality and to compare the effect of neutron flux numbers from the different neutron sources.

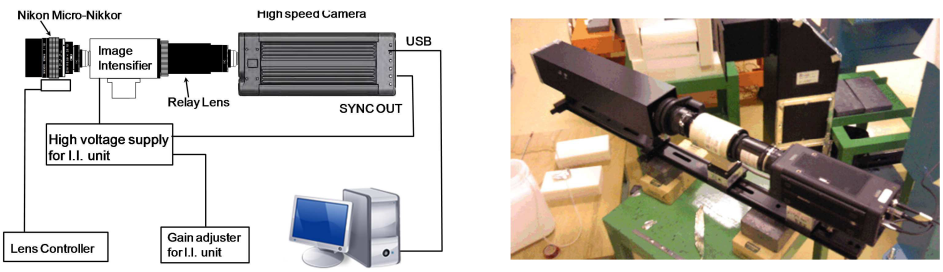
Nomenclature

B	gray level in the filtered image
E	Statistical error
F	Neutron fluence
g	Gaussian function
p	position
s	position
t	exposure time
R	spatial resolution
Σ	macroscopic cross section
ϕ_{th}	thermal neutron flux
δ	Object thickness

2. Experiments

2.1. Imaging System

The block diagram of the imaging system for high frame-rate neutron radiography is shown in Fig.1. The experiments were performed by using the B4-port of the Research Reactor Institute, Kyoto University [4]. A high-speed video camera (MotionPro Y4 Lite, IDT Co.Ltd.) was tested to achieve high spatial resolution (1014×1014 pixels). A high-gain, fast gated image intensifier (Single MCP (GaAsP)+Booster) by HAMAMATSU was employed to amplify the light intensity of phosphorescent images from a fluorescent converter (^{6}LiF/ZnS:Ag)[5]. The exposure time can be adjusted by a pulse generator connected to the camera sync out. The light shielding box equipped with no optical mirror to reduce light decay and the optical axis was inclined at 45° to the neutron beam to avoid radiation damage.



(a) Detail of imaging system (b) light shielding box

Fig. 1. (a) Detail of imaging system; (b) layout of the light shielding box

2.2. Experimental setup

The experimental apparatus consists of a small stainless steel tube, a tube pump and a reservoir tank. Three different diameter tubes (1.0, 2.0, and 4.0mm) were tested. Air-water two-phase mixture was pumped by the tube pump and recorded by the above mentioned imaging system.

3. Image degradation in neutron radiography

Generally image degradation in neutron radiography can be influenced by a number of system components here are specific examples [6].

a) Object scattering degradation
b) Geometric unsharpness due to divergence of neutron beam
c) Motion unsharpness due to object motion
d) Statistical noise due to short exposure time

The first two contributions a) and b) should be taken into account for static and dynamic neutron radiography. Last two contributions c) and d) should be considered, in particular, for high frame-rate neutron radiography, where rapid fluid motion should be observed. Since the measurement of neutrons generated by a random process is affected variation, the measurement error increases with recording speed. As the measurement error is usually given by the standard deviation, the relative measurement error E is given as a function of the neutron fluence F by the equation [1]:

$$E = \sqrt{F} \big/ F \tag{1}$$

The neutron fluence per pixel area in the image sensor is given by

$$F = \phi_{th} \exp(-\Sigma\delta) \cdot R^2 \cdot t \tag{2}$$

Where R is the spatial resolution of the image, namely the real scale projected in a pixel, and t is the measuring time or exposure time. Measuring time should be adjusted depending on the fluid flow conditions, where the statistical noise can increase. The temporal resolution of dynamic neutron radiography is determined by both the light decay characteristics of the converter and the measurement error of neutrons caused by the statistical fluctuation of neutron flux. However, both of the temporal and spatial resolutions would be insufficient for practical application to the rapid two-phase flow phenomena. Therefore, noisy images with short exposure time should be enhanced by applying some filtering methods.

4. Spatial and temporal filter

In general, the value of the filtered image at a given location is a function of the values of the input image in a small neighborhood of the same location. Gaussian low-pass filtering computes a weighted average of pixel values in the neighborhood, in which the weights decrease with distance from the neighborhood center [7]. Spatial filter and temporal filters are widely used in image processing and signal processing. In particular, Gaussian low-pass filtering computes a weighted average of pixel values in the neighborhood, in which, the weights decrease with distance from the neighborhood center. However, the assumption of slow spatial variations in such filtering fails at edges, which are consequently blurred by low-pass filtering. Many efforts have been devoted to reducing this undesired effect. Anisotropic diffusion [8] is a popular filtering method and the diffusion methods average over extended regions by solving partial differential equations, and are therefore inherently iterative. Iteration may raise issues of stability and depend on the computational architecture. On the other hand, bilateral filtering smoothes images while preserving the edge, it is none iterative, local and simple [9]. The filtered image can be calculated using the following equation:

$$B(s) = \frac{\sum_{p \in N_s} g(|p-s|, \sigma_d) g(I(p) - I(s), \sigma_i) I(s)}{\sum_{p \in N_s} g(|p-s|, \sigma_d) g(I(p) - I(s), \sigma_i)} \tag{3}$$

$$g(x, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-x^2/2\sigma^2\right) \tag{4}$$

$$N_s = \begin{bmatrix} p_x = [s_x - k, s_x + k] \\ p_y = [s_y - k, s_y + k] \end{bmatrix} \tag{5}$$

Where, I is the original gray level, B the filtered gray level, respectively. $p(p_x,p_y)$ and $s(s_x, s_y)$ are positions. In Eq.(3), two Gaussian functions appear and the first denotes a similarity function in the distance, and the second denotes a similarity function in the gray level.

Bennett [10] proposed a modification of the bilateral filter for motion video image to take the motion in the images into account. At the present study, we propose a similar simple modification to the original bilateral filter as follows:

$$B(s,t) = \frac{\sum_{t_p} \sum_{p \in N_s} g(|(p,t_p) - (s,t)|, \sigma_d) g(I(p,t_p) - I(s,t), \sigma_i) I(s,t)}{\sum_{t_p} \sum_{p \in N_s} g(|(p,t_p) - (s,t)|, \sigma_d) g(I(p,t_p) - I(s,t), \sigma_i)} \tag{6}$$

$$N_s = \begin{bmatrix} p_x = [s_x - k, s_x + k] \\ p_y = [s_y - k, s_y + k] \end{bmatrix} \tag{7}$$

$$t_p = [t - m, t + m] \tag{8}$$

Where t_p is the time domain for smoothing in the time, which was assumed to have the same weight in the spatial domain. If we input zero to the time domain m, we can obtain the original equation of the bilateral filter as written in Eq.(3).

5. Results

The proposed spatio-temporal filtering method (Eq.(5)) has been applied to images obtained at the B4-port of KUR and at the JRR-3 of JAEA. Figure 2 shows the original and filtered images of two-phase mixture flowing images in a small diameter tube obtained at the B-4 port of the KUR. The exposure time was 5ms, and the successive images are shown at every 20ms. As shown in these images, it is recognized that the severe noises could be removed from the original images by applying the modified bilateral filter, while preserving the edge information.

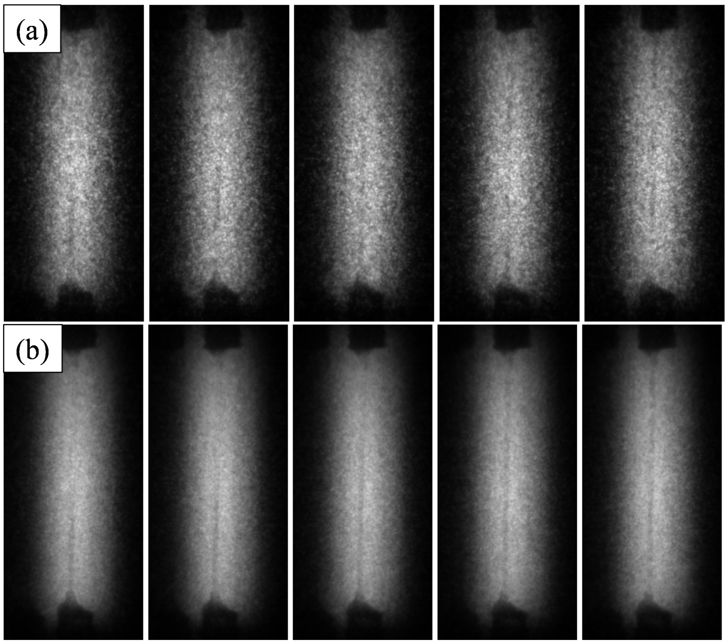


Fig. 2. (a) Original two-phase flow images (b) Filtered images.(Exposure time:5ms, tube diameter:1mm)

Figure 3 shows the filtered and original processed images obtained at the JRR-3M of the JAERI. The exposure time was 2ms, and the successive images are shown at every 60ms. A single water droplet evaporates in a heated motel metal pool. As shown in these images, severe signal noise in the darker region around the evaporating bubble due to the neutron attenuation in the liquid phase. Such severe signal noisy images can be also enhanced by applying the proposed filtering method.

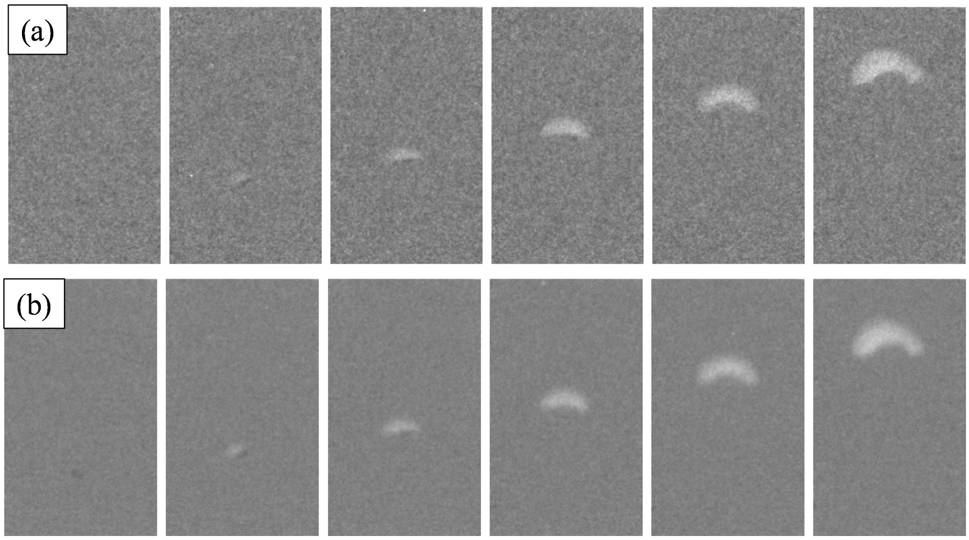


Fig. 3. Water droplet evaporating in a liquid metal (a) Original images (b) Filtered images.(Exposure time:2ms)

6. Conclusions

Spatio-temporal filter was proposed for high frame-rate neutron radiography by modifying the bilateral filter [6]. Experiments were performed at the B4-port of the Research Reactor Institute, Kyoto University, which has a thermal neutron flux of 5.0×10^7 n/cm^{2}s and at the JRR-3M, the Japan Atomic Energy Institute for thermal neutron with a flux of 1.6×10^8n/cm^{2}s. It is confirmed that the noisy images can be clearly enhanced by applying a modified bilateral filter as expressed by Eq.(6)

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