끝점 신호 보존을 위한 적응 커널 필터를 이용한 중성자 신호 잡음 제거

Neutron Signal Denoising using Edge Preserving Kernel Regression Filter

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Abstract - A kernel regression filter with adaptive bandwidth is developed and successfully applied to digital reactivity meter for neutron signal measurement in nuclear reactors. The purpose of this work is not only reduction of the measurement noise but also the edge preservation of the reactivity signal. The performance of the filtering algorithm is demonstrated comparing with well known smoothing methods of conventional low-pass and bilateral filters. The developed method gives satisfactory filtering performance and edge preservation capability.

Key Words : Neutron, Noise, Filter, Edge, Kernel

1. Introduction

Nuclear reactor power deviation from the critical state is a parameter of specific interest defined by the reactivity measuring neutron population. Reactivity is an extremely important quantity used to define many of the reactor startup physics parameters. The time-dependent reactivity is normally determined by solving the using inverse neutron kinetics equation. The reactivity computer is a device to provide an on-line solution of the inverse kinetics equation. The DDRCS™ (Direct Digital Reactivity Computer System) is presently used in Korean nuclear power plants during initial plant startup and for recurrent physics tests. The input signal to DDRCS™ is provided by the excore neutron detectors. The measurement signal of the neutron density is normally noise corrupted since the measurement system has no provision for a neutron distribution which neutrons are generated from fission or non-fission process. Therefore the neutron signal or the calculated reactivity should be filtered properly to give sufficiently large signal-to-noise ratio to prevent a high degree of interpretational uncertainty. This paper describes a kernel regression based noise smoother for that purpose.

Kernel based methods are most popular non-parametric estimators which can uncover structural features in the data which a parametric approach might not reveal.

In this paper, the performance of the kernel regression smoothing method is demonstrated for the measured reactivity signal contaminated with noise. The results show the developed smoother can be applied not only the noise smoothing but also bumpless follow of the signal with non-smooth edges.

2. Filter Algorithms

In this section some of the mathematical techniques in kernel regression are described.

2.1 Gaussian Kernel Regression Filter

Kernel regression is an old method for smoothing data still new work continues at a rapid pace. Kernel regression of statistics was derived independently by Nadaraya[1] and Watson[2]. Kernel regression[1,2] is the estimation of the functional relationship $y(t)$ between two variables y and t. Measurement produces a set of random variables $\{t_i, y_i; i=1,\dots,N\}$ on the interval $\{0 \le t_i \le T\}$. It is assumed that

$$y_i = y(t_i) + \varepsilon \tag{1}$$

where ε is a random noise variable with the mean equal to zero. The Nadaraya-Watson kernel regression estimate $y(t)$ of at $t=\tau$ from this random data is defined as the estimator $\hat{y}(\tau)$ as

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$$\hat{y}(\tau) = \frac{\sum_{i=1}^{N} y_i k(\tau - t_i)}{\sum_{i=1}^{N} k(\tau - t_i)} \quad (2)$$

The function $k(\tau - t_i)$ is the kernel function which can be chosen from a wide variety of symmetric functions. In this paper, the Gaussian density function is used, i.e.,

$$k(t) = \exp(-D(t_i, t_q)^2 / \sigma^2) \quad (3)$$

where D is the distance metric and Euclidean distance is used here defined by

$$D(t_i, t_q) = \|t_i - t_q\| = \sqrt{(t_i - t_q)^2} \quad (4)$$

t_q is the query point where the smoothed signal is to be generated in the interval of time series data $\{0 \le t_i \le T\}$.

σ^2 is the bandwidth of the kernel. σ^2 is a scaling factor which controls how wide the influencing measurements are spread around a query point. Bandwidth can also control the smoothness or roughness of a density estimate. Increasing the kernel width σ^2 means further away points get an opportunity to influence the query point. As $\sigma^2 \to \infty$, the smoothed signal tends to the global average. In this paper an adaptation algorithm is introduced to modify the bandwidth which can be reduced appropriately to preserve the edge signal as an inverse of the local distance as follows :

$$\sigma(\tau) = 1 / \sum_{i=1}^{N} (x(\tau) - x(t_i))^2. \quad (5)$$

2.2 Bilateral Filter

The bilateral filter is a technique proposed by Tomasi and Manduchi[3]. This technique preserves edges by mixing a moving average technique with a nonlinear system of weights. It relies on an assumption that any noise is more uniformly distributed, and that signals have distinct edges or steps that can be detected by examining local differences. Each neighboring value is weighted on its proximity in space or time (a domain weight). But then, a second weighting factor gives some measurement of local difference (a range weight). Often, these two weights are expressed as a pair of Gaussian distributions in a summation. In the time domain, this is expressed as:

$$k(t) = \exp(-D(t_i, t_q)^2 / \sigma_S^2) \cdot \exp(-D(x_i, x_q)^2 / \sigma_R^2) \quad (6)$$

where $\exp(-D(x_i, x_q)^2 / \sigma_R^2)$, $D(x_i, x_q) = \|x_i - x_q\|$, σ_S^2, σ_R^2 are the variance of the spatial distances for noise rejection and feature preservation, respectively. The weighting factor $\exp(-D(x_i, x_q)^2 / \sigma_R^2)$ plays a role with local difference information for edge preservation.

2.3 Illustrative Examples

Figure 1 shows the comparison of overall filter performance for noise corrupted stepwise reactivity signal. Figure 2 shows the noise filtering performance of each filters.

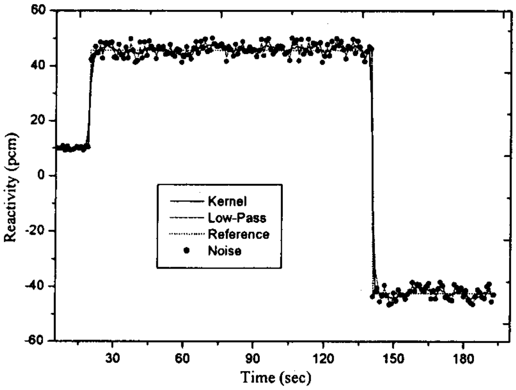

Figure 1. Comparison of filter performance

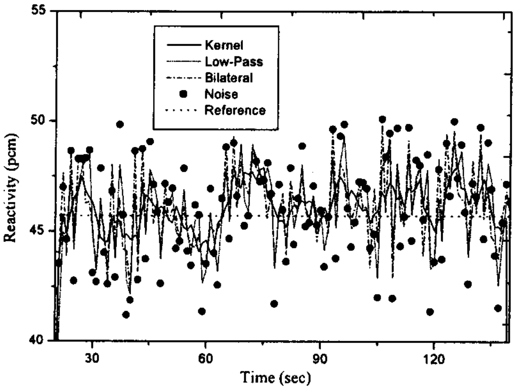

Figure 2. Noise filtering performance

Kernel regression filter with adaptive bandwidth shows the best performance compared with conventional low-pass and bilateral filters.

Figure 3 is the variation of bandwidth for kernel regression filter which gives minimum value (1.0) at the edge area.

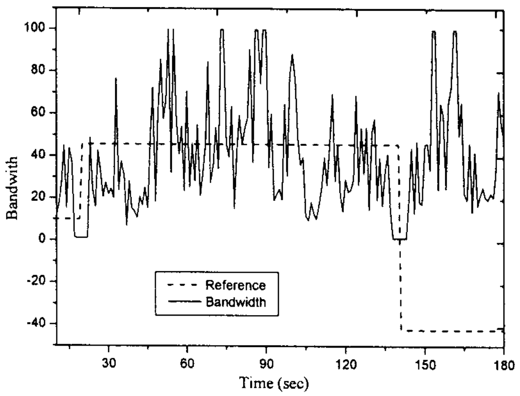

Figure 3. Variation of bandwidth for kernel regression

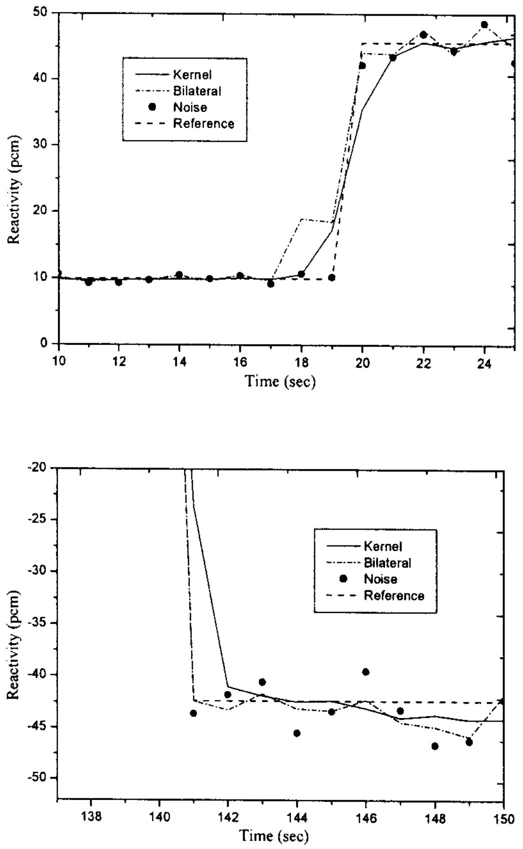

Figure 4. Filter performance at edge area

Figure 4 shows the magnified view of the filter performance at edge area. The bilateral filter gives excellent edge preserving property but shows not always bumpless transfer. Kernel regression filter with adaptive bandwidth gives not only powerful noise reduction and reliable edge preservation capacity.

This kind of stepwise variation of reactivity is frequently found during reactor startup physics test from movement of control rods. Therefore the reconstruction capability of the edge points is an important characteristic of the reactivity smoother.

3. Conclusion

Kernel based noise smoothing technique is developed and successfully applied to digital reactivity meter. Introducing the adaptive filter bandwidth, the reactivity estimation error can be minimized and signal edge is appropriately preserved. The performance of the algorithm is demonstrated comparing with well known smoothing methods including low-pass and bilateral filters.

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