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Wavelet Filter Based De-Noising of Weak Neutron Flux Signal for Dynamic Control Rod Reactivity Measurement

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Abstract

The measurement and validation of control rod bank (group) worths are typically required by the start-up physics test standard programs for Pressurized Water Reactors (PWR). Recently, the method of DCRM^{TM} (Dynamic Control rod Reactivity Measurement) technique is developed by KEPRI and will be implemented in near future. The method is based on the fast and complete bank insertion within the short period of time which makes the range of the reactivity variation very large from the below of the background gamma level to the vicinity of nuclear heating point. The weak flux signal below background gamma level is highly noise contaminated, which invokes the large reactivity fluctuation. This paper describes the efficient noise filtering method with wavelet filters. The performance of developed method is demonstrated with the measurement data at YGN-3 cycle 7.

1. INTRODUCTION

The Rod Swap Method (RSM) is widely used to estimate the control rod worth during low power physics test of PWRs. Because the RSM uses soluble boron in the determination of the reactivity of the reference control rod, it generates substantial waste RCS water and takes approximately 8-10 hours to complete. The DCRM^{TM} can measure the worth of each individual bank within 20 min. In other words, the measurement time can be greatly reduced to two hours. In addition, the rod shadowing effects can be avoided typically arising in RSM since only one bank is present in the core during the worth measurement. [1,4,5]

Since the DCRM^{TM} method is based on the complete bank insertion within the short period of time, the reactivity is fluctuating by sub-critical neutron multiplication after the insertion. The neutron signal is very weak but can greatly affect the reactivity calculation due to the noise contamination especially for the control banks with large reactivity worth. Figure 1 shows the typical variation of the flux signal during the DCRM™ test.

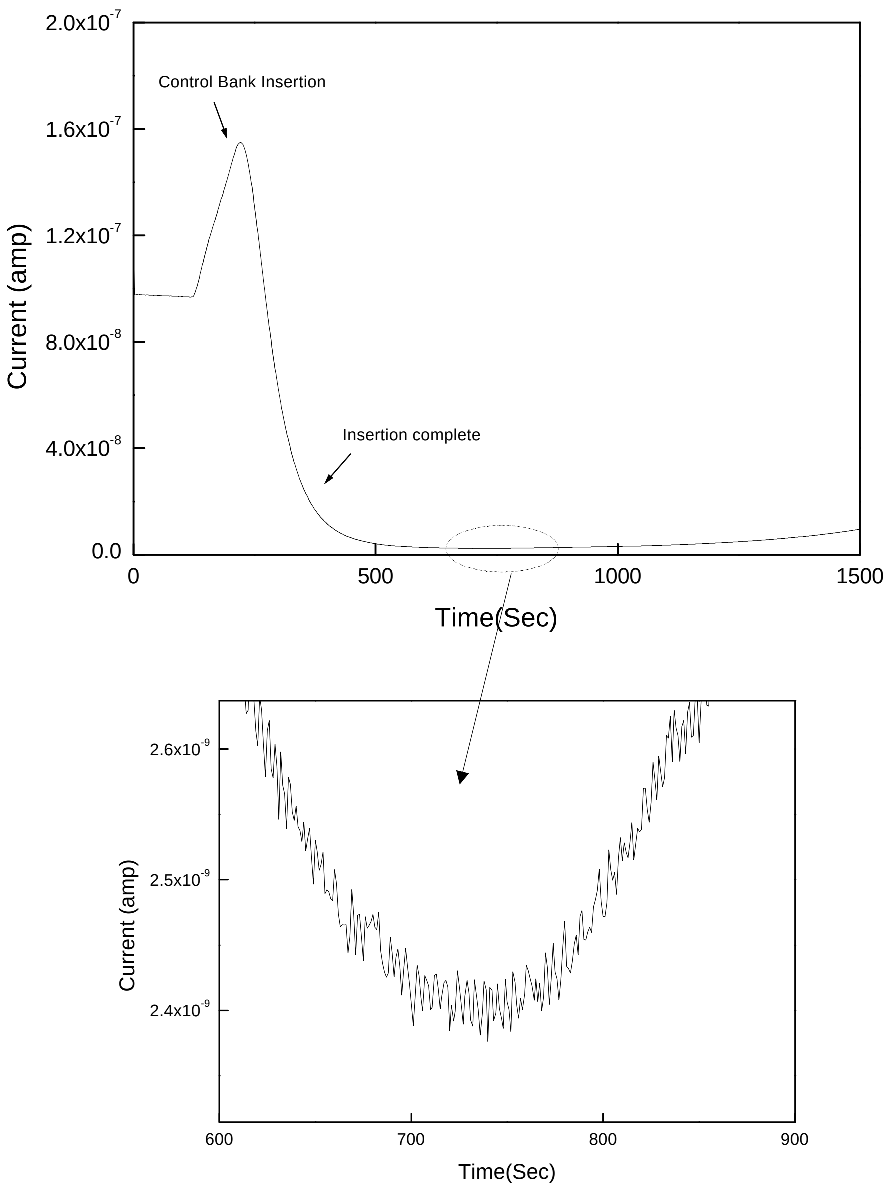

Figure 1. Typical variation of the neutron flux signal during DCRM™ test (YGN 3 Cycle 7)

2. BASIC THEORY OF WAVELET DE-NOISING

Wavelet is a waveform of effectively limited duration that has an average value of zero, which can be applied to non-stationary and transient signal. Wavelet analysis is the breaking up of a signal into shifted and scaled versions of the original (or *mother*) wavelet. Arbitrary functions can be expressed as the sum of sub-functions of level j which indicates the number of decomposition process of the time-domain signal. A brief but illustrative basic theory of wavelet transform can be found in [2] given as follows ;

Two basic functions, scaling function $f(x)$ and wavelet function $j(x)$ are defined which satisfy the following two-scale relations ;

$$\begin{aligned} f(x) &= \sum_k p_k f(2x-k), \\ j(x) &= \sum_k q_k f(2x-k), \end{aligned} \tag{1}$$

where p_k and q_k are given constants and k is an integer index. With the scaling function $f(x)$, sub-functions of level j are determined by

$$f_j(x) = f(2^j x - k). \tag{2}$$

Then an arbitrary function $f_j(x)$ can be expressed as

$$f_j(x) = \sum_k c_k^{(j)} f(2^j x - k). \tag{3}$$

And with the definition (1), an arbitrary function $g_j(x)$ can be expressed as

$$g_j(x) = \sum_k d_k^{(j)} j(2^j x - k). \tag{4}$$

Thus the following two-scale relation holds.

$$f_j(x) = f_{j-1}(x) + g_{j-1}(x). \tag{5}$$

In other word, the function $f_j(x)$ is decomposed to $f_{j-1}(x)$ and $g_{j-1}(x)$. This relation is used recursively and we can get the following relation

$$f_j(x) = g_{j-1}(x) + g_{j-2}(x) + ... + g_{j-n}(x) + f_{j-n}(x). \tag{6}$$

By using the above expressions, any function $f(x)$ can be expressed as a sum of functions $g_j(x)$ by infinite j. That is

$$f(x) \approx \sum_j g_j(x) = \sum_j \sum_k d_k^{(j)} j(2^j x - k). \quad (7)$$

The expansion coefficients $c_k^{(j)}$ and $d_k^{(j)}$ are given for various scaling functions and wavelet functions. In this paper, the Coiflet with level 2 is selected and the corresponding expansion coefficients can be found in [3]. Figure 2 shows the scaling function $f(x)$ and wavelet function $j(x)$ for the Coiflet with level 2.

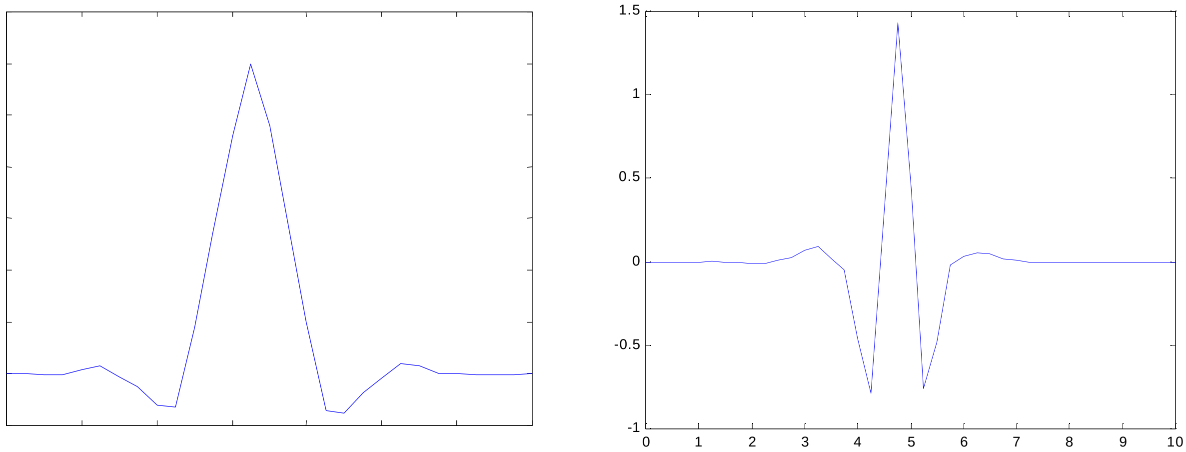

Figure 2. Scaling function $f(x)$ and wavelet function $j(x)$ for Coiflet with level 2

The de-noising procedure proceeds in three steps:

First Decompose :

Choose a wavelet and a level N. Compute the wavelet decomposition of the signal at level N.

Second Threshold coefficients :

For each order from 1 to N, select a threshold and apply thresholding to the coefficients.

Third Reconstruct signal :

Compute wavelet reconstruction based on the original approximation coefficients of level *N* and the modified coefficients of levels from 1 to N.

3. Application To DCRM™ Test

A demonstration calculation is performed using the noisy measurement data from the startup physics test of the YGN-3 cycle 7. During that test, 4 cycles of the reactivity measurement tests were performed for control banks #3,#4,#5 and #B7. The most severely noise contaminated case were bank #B7. Figure 3. shows the effective and smooth wavelet filtered result for weak neutron flux signal below the gamma background.

Using the inverse point kinetics equation, the measured re reactivity is calculated by

$$r(t) = \sum_k b_k \int_{-\infty}^{t} \frac{N'(t')}{N(t)} e^{-l_k(t-t')} dt' + \Lambda \frac{N'(t)}{N(t)} - \frac{s_{ext}(t)}{N(t)} \tag{8}$$

where, $r(t)$: total core reactivity

b_k: k-th group delayed neutron fraction

$N(t)$: core-averaged neutron density

Λ: prompt neutron generation time

l_k: k-th group delayed neutron decay constant

S_{ext}: external source strength

Equation (8) can be reduced easily from the traditional point kinetics equation. The first integral term of the right hand side represents the precursor term. By using the traditional assumption on the neutron density, that is varies exponential with time, the numerical solution of Equation (8) becomes

$$r(t_n) = \sum_k b_k \left(e^{-(l_k + w_n)\Delta t_n} B_{n-1,k} + A_{n,k} \right) + \Lambda w_n - s_{ext}(t) \frac{e^{-w_n \Delta t_n}}{N_{n-1}} \tag{9}$$

where $B_{n,k} = e^{-(\lambda_k + \omega_n)\Delta t_n} B_{n-1,k} + A_{n,k}$, $A_{n,k} = \frac{\omega_n}{\lambda_k + \omega_n}\left(1 - e^{-(\lambda_k + \omega_n)\Delta t_n}\right)$ and $w_n = \ln(\frac{N_n}{N_{n-1}}) / \Delta t$.

Figure 4 shows the control bank reactivity calculated with noisy neutron flux signal of bank #B7 for YGN 3 Cycle 7. After the bank insertion, it can be seen that the noise components are dominant during the control bank is in the core bottom region where only sub-critical multiplication exists. Since the reactivity calculation is very sensitive to the variation in neutron flux, the noisy signal should be appropriately filtered. Figure 5 is the final result of the calculated reactivity with wavelet filtered neutron flux signal. It clearly shows the effective noise filtering in the reactivity calculation. Thus the wavelet-based filter is proved to be applicable to estimate the reactivity variation during DCRM^{TM} test.

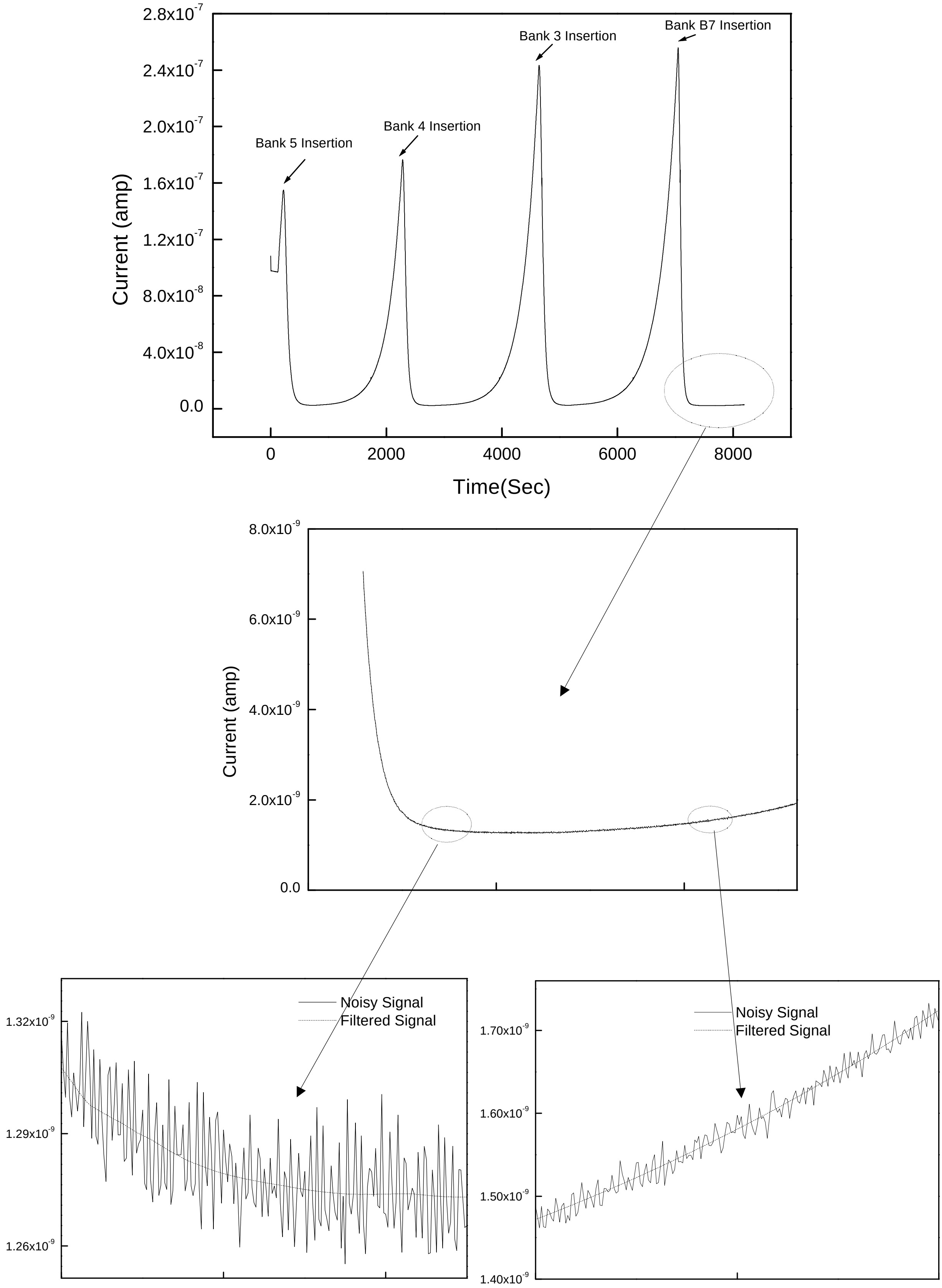

Figure 3. Wavelet filtered result for weak neutron flux signal (YGN 3 Cycle 7).

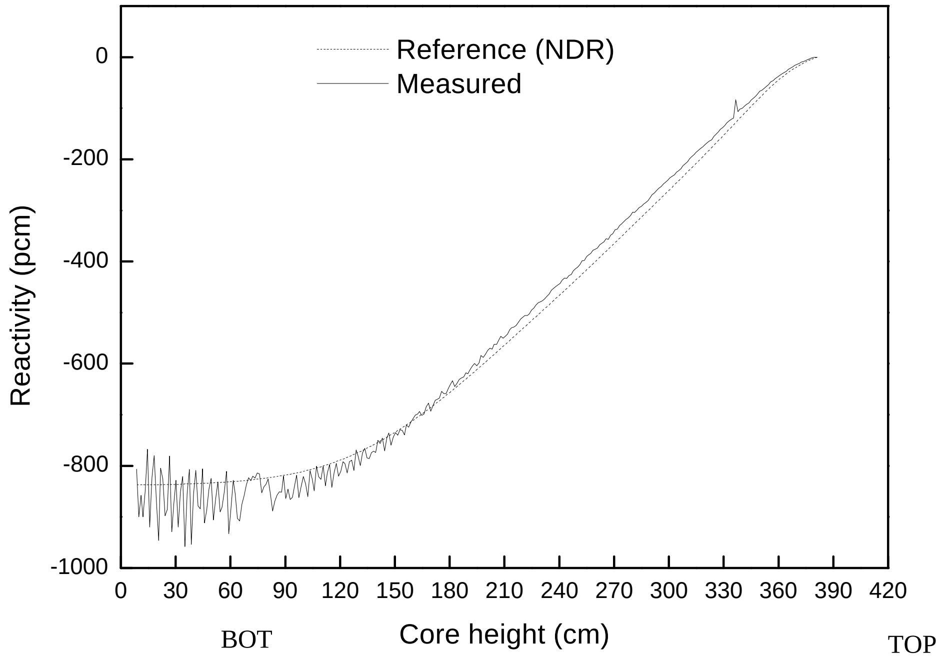

Figure 4. Reactivity calculated with noisy neutron flux signal (YGN 3 Cycle 7).

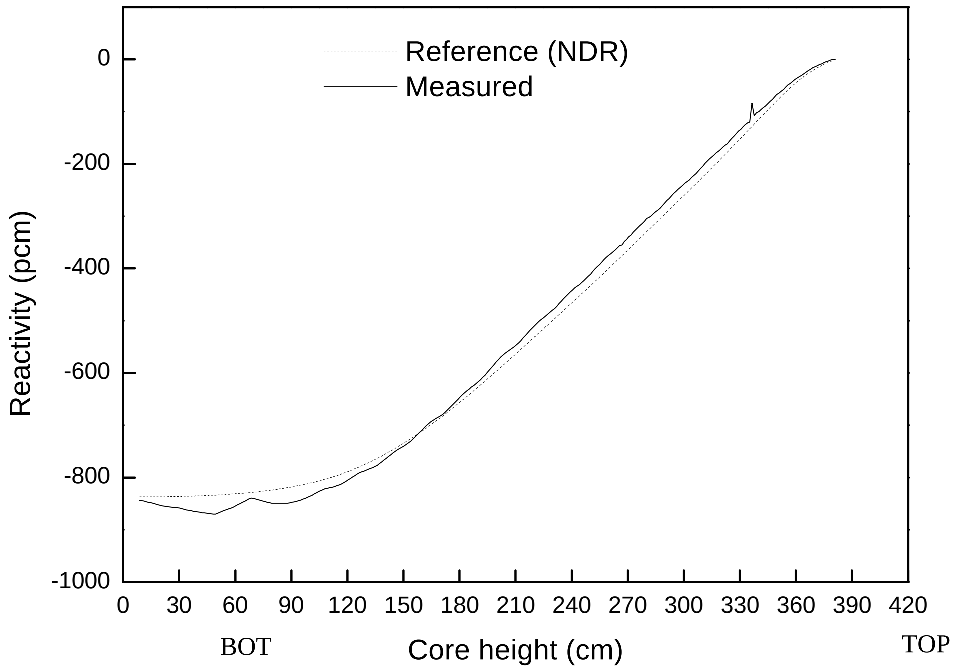

Figure 5. Reactivity calculated with wavelet filtered neutron flux signal (YGN 3 Cycle 7).

4. CONCLUSION

A new method using wavelet filter for the calculation of the reactivity is studied in order to apply to noisy and sensitive sub-critical state during dynamic control rod worth measurement. In the proposed method, the noisy transient neutron flux signal is decomposed with the wavelet basis and threshold of level 2 Coiflet is imposed. The reconstructed signal is shown to be smooth enough to calculate the dynamic reactivity. The developed filter algorithm is robust for large noise contamination and can be applied to various field of sub-criticality monitoring.

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