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Technical Note

Modification of the fast fourier transform-based method by signal mirroring for accuracy quantification of thermal-hydraulic system code

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A B S T R A C T

A thermal–hydraulic system code is an essential tool for the design and safety analysis of a nuclear power plant, and its accuracy quantification is very important for the code assessment and applications. The fast Fourier transform-based method (FFTBM) by signal mirroring (FFTBM-SM) has been used to quantify the accuracy of a system code by using a comparison of the experimental data and the calculated results. The method is an improved version of the FFTBM, and it is known that the FFTBM-SM judges the code accuracy in a more consistent and unbiased way. However, in some applications, unrealistic results have been obtained. In this study, it was found that accuracy quantification by FFTBM-SM is dependent on the frequency spectrum of the fast Fourier transform of experimental and error signals. The primary objective of this study is to reduce the frequency dependency of FFTBM-SM evaluation. For this, it was proposed to reduce the cut off frequency, which was introduced to cut off spurious contributions, in FFTBM-SM. A method to determine an appropriate cut off frequency was also proposed. The FFTBM-SM with the modified cut off frequency showed a significant improvement of the accuracy quantification.

1. Introduction

The assessment of a thermal–hydraulic system code involves a comparison of calculated results against experimental data from separate effect tests and integral effect tests. The fast Fourier transform-based method (FFTBM) is a tool to quantitatively conduct such comparisons [1]. The method can show a discrepancy between experimental data and calculated results in the frequency domain and is known to be effective at assessing the code accuracy.

Many improvements to the FFTBM have been made since its first development. For a more complete picture of thermal–hydraulic code accuracy, Prošek and Mavko [2] devised an FFTBM with new accuracy measures. In another study by Prošek and Mavko [3], the capability to calculate a time-dependent accuracy was described. These improvements were used to quantify the accuracy of the code calculations for a large-break loss-of-coolant accident in the RD-14M facility [4]. Prošek and Leskovar [5] showed how FFTBM, with the capability to calculate time dependent code accuracy, could be successfully adapted for use within a severe accident field. Prošek et al. [6] proposed an FFTBM by signal mirroring (FFTBM-SM). By eliminating the so-called edge effect related to the discontinuity in FFTBM, the method significantly improved the capability to calculate code accuracy. It is known that the FFTBM-SM judges the accuracy in a more consistent and unbiased way.

However, in some applications, quantitative results obtained by raw experimental signal are considerably different from those obtained by noise-reduced experimental signal, although the obtained quantitative results are expected to be similar because the two signals are almost the same to code users. This reveals that, in the FFTBM-SM application, the accuracy quantification is dependent on whether noise exists in the experimental signal. In this study, it is identified that accuracy quantification by FFTBM-SM, as well as by FFTBM, is dependent on the frequency spectrum that is obtained by FFT of the experimental and error signals, meaning the difference between the experimental data and the calculated results. If the signals include a lot of noise as well as sharp changes or discontinuities, the frequency spectrum determined by FFT of the signals involves a lot of high-frequency components. Then, the high-frequency components have significant influence on the accuracy quantification, leading to frequency-dependent evaluation.

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So far, by using signal mirroring to eliminate the discontinuity causing the high-frequency components, FFTBM-SM has solved this problem in terms of the discontinuity only. Therefore, a further improvement is needed.

The objective of this work is to reduce the frequency dependent evaluation feature of FFTBM-SM. It is shown that, by reducing the cut off frequency, which has generally been set at 0.5 Hz, the problem could be mitigated by eliminating spurious high-frequency components. In this study, a method to determine an appropriate cut off frequency is proposed and its effect is demonstrated using the advanced thermal-hydraulic test loop for accident simulation (ATLAS) tests [7–9] calculations.

2. FFTBM for accuracy quantification

2.1. FFTBM

In FFTBM, the FFTs of the experimental and the error signals are performed first. The accuracy of a single variable is assessed by using the average amplitude (AA), which is defined by

$$AA = \frac{AA_{error}}{AA_{\exp}} = \frac{\sum_{n=0}^{2^m}\left|\tilde{\Delta F}(f_n)\right|}{\sum_{n=0}^{2^m}\left|\tilde{F}_{\exp}(f_n)\right|} \quad (1)$$

where $\left|\tilde{\Delta F}(f_n)\right|$ is the amplitude obtained by the FFT of the error signal at frequency f_n (where n=0,1, …,2^m and m is the exponent defining the number of points $N=2^{m+1}$ where m=8, 9, 10, 11) and $\left|\tilde{F}_{\exp}(f_n)\right|$ is the amplitude obtained by the FFT of the experimental signal at f_n [10]. AA in Eq. (1) means the ratio of the sum of the amplitudes of the error signal to the sum of the amplitudes of the experimental signal. If the experimental and calculated signals are equal (i.e., the error signal is zero), AA becomes zero, which means perfect agreement. Inversely, if the calculated signal is zero, AA becomes 1.0, which means 100% error.

A cut-off frequency (COF) has been introduced to cut off spurious contributions, generally negligible. When calculating AA in Eq. (1), amplitudes above COF are neglected. Generally, the COF has been set at 0.5 Hz [11] because, in most cases, AA fully converges to AA at the highest (maximum) frequency within 0.5 Hz. The maximum frequency is defined by:

$$2f_{max} = \frac{2^{m+1}}{T_d} = \frac{N}{T_d} \quad (2)$$

where N is the number of sampled points, equally spaced, which is a power with base 2 (N range from 2^9 and 2^{12}) and T_d is the selected time window. In this study, N is determined such that f_{max} is > 0.5 Hz for each FFTBM application.

2.2. FFTBM-SM

FFTBM-SM was proposed by Prošek et al. [6] to improve a deficiency of FFTBM. For example, the integrated break flow signal, which is an experimental signal of the main steam line break experiment at the ATLAS facility [9], is presented in Fig. 1A. According to the periodic nature of the discrete Fourier transform (DFT) [12], the signal is considered as the periodically extended signal infinitely in DFT, as shown in Fig. 1B. Then, when the first data point differs from the last one in the original signal, a discontinuity is observed. The discontinuity yields several harmonic components in the frequency domain. Thus, the sum of amplitudes increases and AA is affected by this.

FFTBM-SM uses the symmetrized signal as presented in Fig. 2A rather than the original signal shown in Fig. 1A. FFTBM using a symmetrized signal that is a combination of the original signal and its mirrored signal; this signal does not result in the discontinuity when the symmetrized signal is periodically extended, as can be seen in Fig. 2B. Because of this, FFTBM-SM can judge the accuracy of a single variable in a more consistent and unbiased way than FFTBM [6].

3. Modification of FFTBM-SM

3.1. Frequency-dependent evaluation feature of FFTBM-SM

In this study, the limitation of FFTBM-SM is found; it can be described by the following example. Using a lag compensator, the signal in Fig. 2 can be processed into a noise-reduced signal. Fig. 3 shows the symmetrized signal and the noise-reduced symmetrized signal. Assume that the two signals are quantitatively assessed. Then, we would probably judge that the accuracy quantification obtained by FFTBM-SM should be almost the same as the area below the curve is almost the same. However, a different assessment based on the sum of the amplitudes, which is an index for accuracy quantification in FFTBM-SM, was obtained as shown in Table 1.

The Parseval relationship [13], which is one of the properties of DFT, states that the energy or power in the time-domain representation is equal to the energy or power in the frequency-domain representation:

$$\frac{1}{N}\sum_{n=0}^{2^{m+1}}|x[n]|^2 = \sum_{n=0}^{2^{m+1}}\left|\tilde{F}(f_n)\right|^2, \quad (3)$$

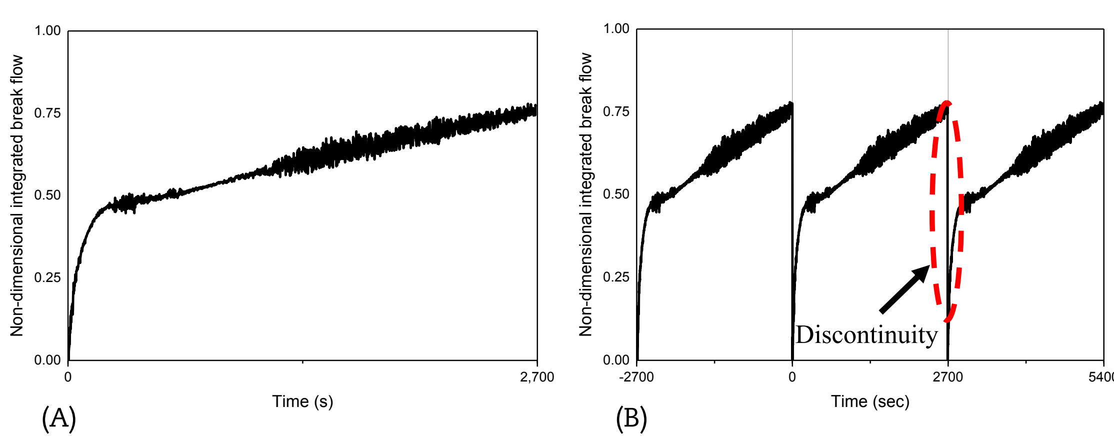

Fig. 1. Original signal and its periodically extended signal. (A) Symmetrized signal; (B) periodically extended signal.