International Conference
Nuclear Energy for New Europe 2006
Portorož, Slovenia, September 18-21, 2006
http://www.djs.si/port2006

# Quantitative Assessment with Improved FFTBM by Signal Mirroring

**Andrej Prošek, Matjaž Leskovar**
"Jožef Stefan" Institute
Jamova 39, SI-1000 Ljubljana, Slovenia
andrej.prosek@ijs.si, matjaz.leskovar@ijs.si

## ABSTRACT

In the last years the number of quantitative comparisons between experimental and calculated data in the area of nuclear technology has increased. The most widely used was the Fast Fourier Transform Based Method (FFTBM) for accuracy quantification of thermal-hydraulic code calculations, which is being continuously improved. However, when preliminary applying the original FFTBM to a severe accident test in 2005 the need for further optimization was identified. It was observed that FFTBM favours certain trends (e.g. monotonic increasing function). The purpose of the present study was therefore to improve the FFTBM in this respect. This was achieved by signal mirroring. Signal mirroring was proposed for eliminating the edge effect from the signal. The edge effect is present in the signal when the first and the last data point of the time signal are different and the aperiodic signal is treated like a periodic signal in the fast Fourier transform. For the demonstration of the improved FFTBM by signal mirroring the LOFT L2-5 test (large break loss-of-coolant accident) calculations performed in the frame of the Best-Estimate Methods Uncertainty and Sensitivity Evaluation (BEMUSE) programme were used. The results of the quantitative assessment showed that with the improved FFTBM by signal mirroring the analyst can get a better picture how much each discrepancy contributes to the accuracy as assessed by FFTBM.

## 1 INTRODUCTION

For years the Fast Fourier Transform Based Method (FFTBM) has been used for accuracy quantification of code calculations. The FFTBM shows the measurement-prediction discrepancies - accuracy quantification - in the frequency domain. It assists in answering how to conduct objective comparison and how many improvements to the input model are needed.

Recently FFTBM was applied to the severe accident International Standard Problem ISP-46 (Phebus FPT1) [1] and the need for the optimization of FFTBM was identified. Namely, it was observed that when calculating the accuracy trend the accuracy changes very much when the experimental signal sharply increases or decreases (e.g. triangular shape of cladding temperature). When the signal starts to return to its previous value, the accuracy also follows this trend. It is not logical that the still present discrepancy decreases the accuracy instead of increasing it. This problem was not evident when applying FFTBM to a few time windows and/or a time interval. However, when FFTBM with the capability to calculate the time dependent accuracy was developed [2] and applied, this was observed. Also it was observed that for monotonically increasing or decreasing functions the original FFTBM normally gives high accuracy. The purpose of the present study was therefore to improve the FFTBM in this respect. It was found out that the reason for above observations in FFTBM applications is the edge effect. Namely, if the values of the first and last data point of signal differ, then there is a step function present in the periodically extended time signal when performing the fast Fourier transform (FFT). This step function gives several harmonic components in the frequency domain, thus increasing the sum of the amplitudes. Therefore it is first described how the problem of the edge effect was resolved by signal mirroring and then the demonstration application is presented.

## 2 IMPROVED FFTBM BY SIGNAL MIRRORING

In order to make original FFTBM applicable for all variables and transients the signal mirroring was proposed to eliminate the edge effect in calculating the accuracy. For more information on FFTBM the reader is referred to [3].

### 2.1 Original FFTBM

For calculation of measurement-prediction discrepancies the experimental signal $F_{\mathrm{exp}}(t)$ and error function $\Delta F(t)$ are needed. The error function in the time domain is defined as $\Delta F(t) = F_{\mathrm{cal}}(t) - \widetilde{F}_{\mathrm{exp}}(t)$, where $\widetilde{F}_{\mathrm{cal}}(t)$ is the calculated signal. The code accuracy quantification for an individual calculated variable is based on the amplitudes of the discrete experimental and error signal obtained by FFT (frequency domain) at frequencies $f_n$, where $n=0,1,...,2^m$ and m is the exponent defining the number of points $N=2^{m+1}$. The average amplitude (AA) is defined:

$$\mathrm{AA} = \sum_{n=0}^{2^m} \left| \widetilde{\Delta F}(f_n) \right| \Big/ \sum_{n=0}^{2^m} \left| \widetilde{F}_{\mathrm{exp}}(f_n) \right|, \tag{1}$$

where $\left| \widetilde{\Delta F}(f_n) \right|$ is the error function amplitude at frequency $f_n$ and $\left| \widetilde{F}_{\mathrm{exp}}(f_n) \right|$ is the experimental signal amplitude at frequency $f_n$. The AA factor can be considered a sort of average fractional error and the closer AA value is to zero, the more accurate is the result. For more information on weighting factors refer to [3]. Typical values of AA are from 0 to 1. For primary pressure the acceptability factor was set to 0.1. For total AA (total accuracy), calculated from weighted AA of selected variables, the acceptability factor was set to 0.4.

### 2.2 Signal mirroring

If we have a function $F(t)$ where $0 \le t \le T_d$ and $T_d$ is transient time duration, its mirrored function is defined as $F(-t)$, where $-T_d \le -t \le 0$. From these functions a new function is composed which is symmetrical in regard to the y-axis: $F(t)$, where $-T_d \le t \le T_d$. By composing the original signal and its mirrored signal, a signal without the edge between the first and the last data sample is obtained, and is called symmetrized signal. To explain this different signals are shown on Figure 1, i.e. the original signal (LOBI L2-5 test measured primary pressure) together with the shifted original signal [Figure 1 (a)], the mirrored original signal [Figure 1 (b)], two periods of the original signal [Figure 1 (c)] and the symmetrized signal combined from one period of the mirrored signal and one period of the original signal [Figure 1 (d)]. We see that only the symmetrized signal is without edge when treating aperiodic signal as one period of the periodic signal. Please also note that the edge is not visible in the plotted signal, when the signal is not shifted or not plotted as a periodic signal [see Figure 1 (c)]. However, when performing FFT, the aperiodic signal is treated as periodic signal and therefore the edge is part of the signal which is not physical.

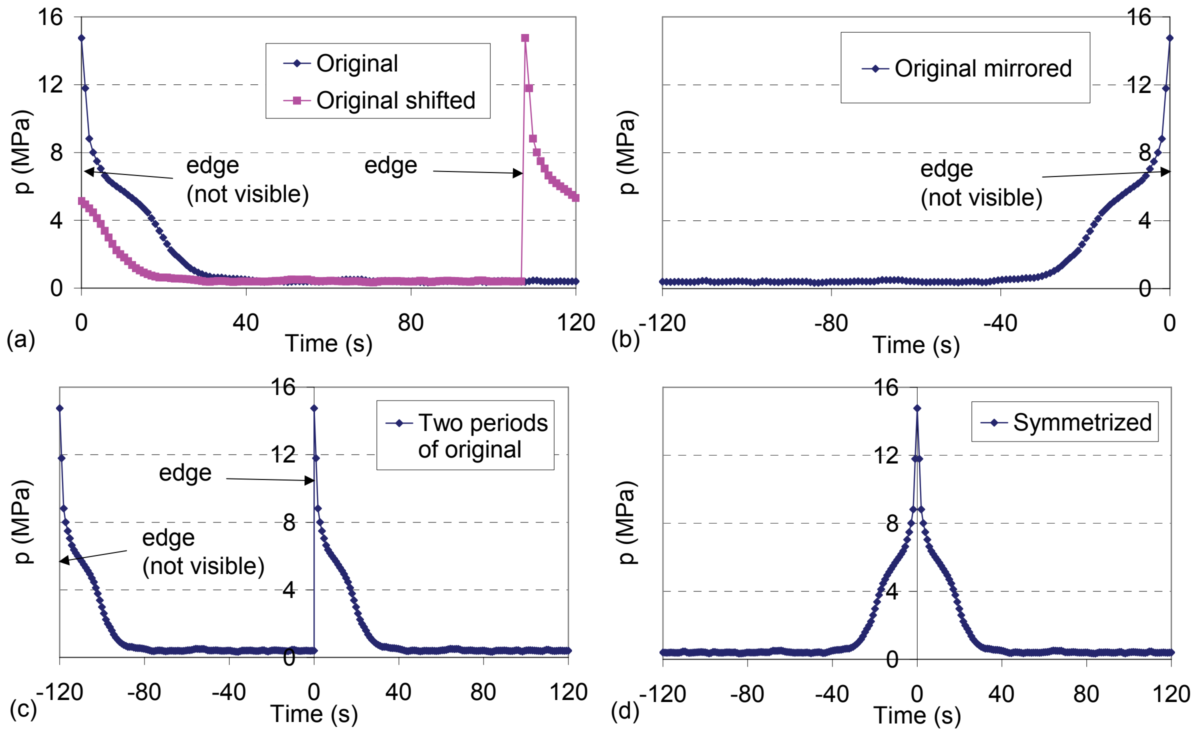



Figure 1: Different signals composed from the original LOBI L2-5 test primary pressure signal.

## 2.3 Calculation of $AA_m$

For the calculation of average amplitude by signal mirroring ($AA_m$) the same expression is used as for AA except that, instead of the original signal, the symmetrized signal is used. The reason to symmetrize the signal was to exclude the edge from the signal. As already mentioned, the edge has no physical meaning, but FFT produces harmonic components because of it. By mirroring the shape of the experimental and error signal is symmetric and the spectrum is different from original signal spectrum, because it is without unphysical edge frequency components. Because of different spectrum the sum of the amplitudes changes both in numerator and denominator of Eq. (1). However, when original and error signal are without edge, the same result is produced by original FFTBM and improved FFTBM by signal mirroring. The signal is automatically symmetrized in the program for improved FFTBM by signal mirroring what is more described in [4].

# 3 FACILITY, TEST AND PARTICIPANTS DESCRIPTION

For demonstration of the improved FFTBM by signal mirroring the calculations from Best-Estimate Methods Uncertainty and Sensitivity Evaluation (BEMUSE) programme were used. In the phase II of the BEMUSE project [5], which is the re-analysis of the ISP-13 exercise, post-test calculation of the LOFT L2-5 test, 14 participants provided their calculations. The objective of the ISP-13 test (LOFT L2-5 test) was to simulate a Loss of Coolant Accident (LOCA) caused by a double-ended, off-shear guillotine cold leg rupture coupled with a loss of off-site power in the nuclear LOFT test facility. Delayed initiation of the high pressure injection system (HPIS) and the low pressure injection system (LPIS) [6] were assumed.

### 3.1 Facility description

The LOFT Integral Test Facility is a scale model of a pressurized water reactor (PWR). The intent of the facility is to model the nuclear thermal-hydraulic phenomena that would take place in a PWR during a LOCA. The general philosophy in scaling coolant volumes and flow areas in LOFT was to use the ratio of the LOFT core [50 MW(t)] to a typical light PWR core [3000 MW(t)]. For some components, this factor is not applied; however, it is used as extensively as practical. In general, components used in LOFT are similar in design to those of a PWR. Because of scaling and component design, the LOFT LOCA is expected to closely model a PWR LOCA. The LOFT Emergency Core Cooling System (ECCS) simulated the ECCS of a commercial PWR. It consisted of two accumulators, a HPIS, and a LPIS.

### 3.2 Test description

The experiment was initiated by opening the quick opening blowdown valves in the broken loop hot and cold legs. The reactor scrammed on low pressure at 0.24 s. Following the reactor scram, the operators tripped the primary coolant pumps at 0.94 s. Accumulator injection of emergency core coolant (ECC) to the intact loop cold leg began at 16.8 s when the system pressure dropped below 4.2 MPa. Delayed ECC injection from the HPIS and LPIS began at 23.90 s and 37.32 s, respectively. The fuel rod peak cladding temperature of 1078 K was attained at 28.47 s. The accumulator emptied at 49.6 s. The cladding was quenched at 65 s, following the core reflood. The LPIS injection was stopped at 107.1 s, after the experiment was considered complete.

### 3.3 Participants description

The information about participants performing calculations is shown in Table 1. In total 14 calculations from 13 organizations were performed using 6 different codes (9 different code versions) [5]. The most frequently code used was RELAP5/MOD3.3.

Table 1: Information about participants performing LOFT L2-5 test calculations.

| Organisation | Calculation ID | Code used |
|---|---|---|
| Commissariat à l'Energie Atomique (CEA), France | CEA | CATHARE 2.5 |
| EDO "Gidropress“ (GID), Russia | GID | TECH-M-97 |
| Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS), Germany | GRS | ATHLET1.2C |
| Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France | IRSN | CATHARE 2.5 |
| Japan Nuclear Energy Safety (JNES), Japan | JNES | TRAC-P 5.5.2 |
| Korea Atomic Energy Research Institute (KAERI), South Korea | KAERI | MARS 2.3 |
| Központi Fizikai Kutató Intézet (KFKI), Hungary | KFKI | ATHLET 2.0A |
| Korean Institute of Nuclear Safety (KINS), South Korea | KINS | RELAP5/MOD3.3 |
| Nuclear Research Institute (NRI), Czech Republic | NRI-K (Kyncl) | RELAP5/MOD3.3 |
| Nuclear Research Institute (NRI), Czech Republic | NRI-M (Macek) | ATHLET 2.0A |
| Paul Scherrer Institute (PSI), Switzerland | PSI | TRACE 4.05 |
| Türkiye Atom Enerjisi Kurumu (TAEK), Turkey | TAEK | RELAP5/MOD3.3 |
| Universitat Politècnica de Catalunya (UPC), Spain | UPC | RELAP5/MOD3.3 |
| University of Pisa (UPI), Italy | UPI | RELAP5/MOD3.2 |

## 4 QUANTITATIVE RESULTS

The calculated and experimental data were received from the University of Pisa, the lead organisation of phase II. A quantitative analysis was then performed by original and improved FFTBM with signal mirroring. The obtained results are not part of the BEMUSE phase II final report [5]. However, some interesting results were found by using improved FFTBM by signal mirroring. In Table 2 signal mirroring is demonstrated for experimental signal [denominator in Eq. (1)] and Figure 2 show the accuracy for primary pressure calculations. Figure 3 show experimental and calculated signals for cladding temperature, and the error signals. In Figure 4 the corresponding AA and $AA_m$ are shown. Based on Figures 2 and 3 it is explained how both the experimental signal [denominator in Eq. (1)] and the difference signal [numerator in Eq. (1)] are influenced by the edge effect. Finally, the results for total accuracy are shown in Figure 5. For more detailed information on results please refer to [4].

### 4.1 Example of mirroring for primary pressure signal

As example of mirroring for signals from Figure 1 the FFT was performed. Table 2 shows that the sum of amplitudes of the original, the original shifted, and the mirrored signal are the same for the transient duration interval. The sum of amplitudes of two periods of the original signal is also the same. This is true also for the sum of amplitudes of two periods of the original shifted and mirrored signal. However, when making the FFT of the symmetrized signal, the sum is less then in the case of the signals where the edge is present. In this way the edge contribution to the sum can be directly quantified. The sum of amplitudes of the symmetrized signal has to be extracted from the sum of amplitudes of the signal composed from two periods of the original signal. In our example this contribution is 7.220459071 [(23.19970969 - 15.41356232) = 7.220459071]. This means that the sum of amplitudes of the experimental signal [denominator) in Eq. (1)] is 31% less when the edge effect is not considered, which gives an almost 45% larger value of AA. This means that all integral variables (integrated break flow, ECCS injected mass) and variables dropping to zero value (power, primary pressure during LOCA) exhibit lower AA values because of the edge in the experimental signal. This also partly explains the, in general, very high accuracy of these variables comparing to other variables and acceptability factor for primary pressure (dropping during small break LOCAs) to be set to 0.1.

Table 2: The sum of amplitudes [denominators in Eq. (1)] of signals shown in Figure 1.

| Type of signal | Sum of amplitudes of FFT |
|---|---|
| original signal | 23.19970969 |
| shifted original signal | 23.19970969 |
| mirrored signal | 23.19970969 |
| two periods of original signal | 23.19970969 |
| symmetrized signal | 15.97925061 |

How symmetrization of signals influences the results is shown in Figure 2. Figures 2(a) and 2(b) show AA and $AA_m$ for primary pressure signal, respectively. Because the denominator for primary pressure signal is smaller in the case of symmetrized signal (see Table 2) and this contribution is larger for error signal, the values of $AA_m$ are larger than AA for approximately a factor of 2. For this case,s this also means that acceptability criterion for $AA_m$ is not satisfied for any calculation.

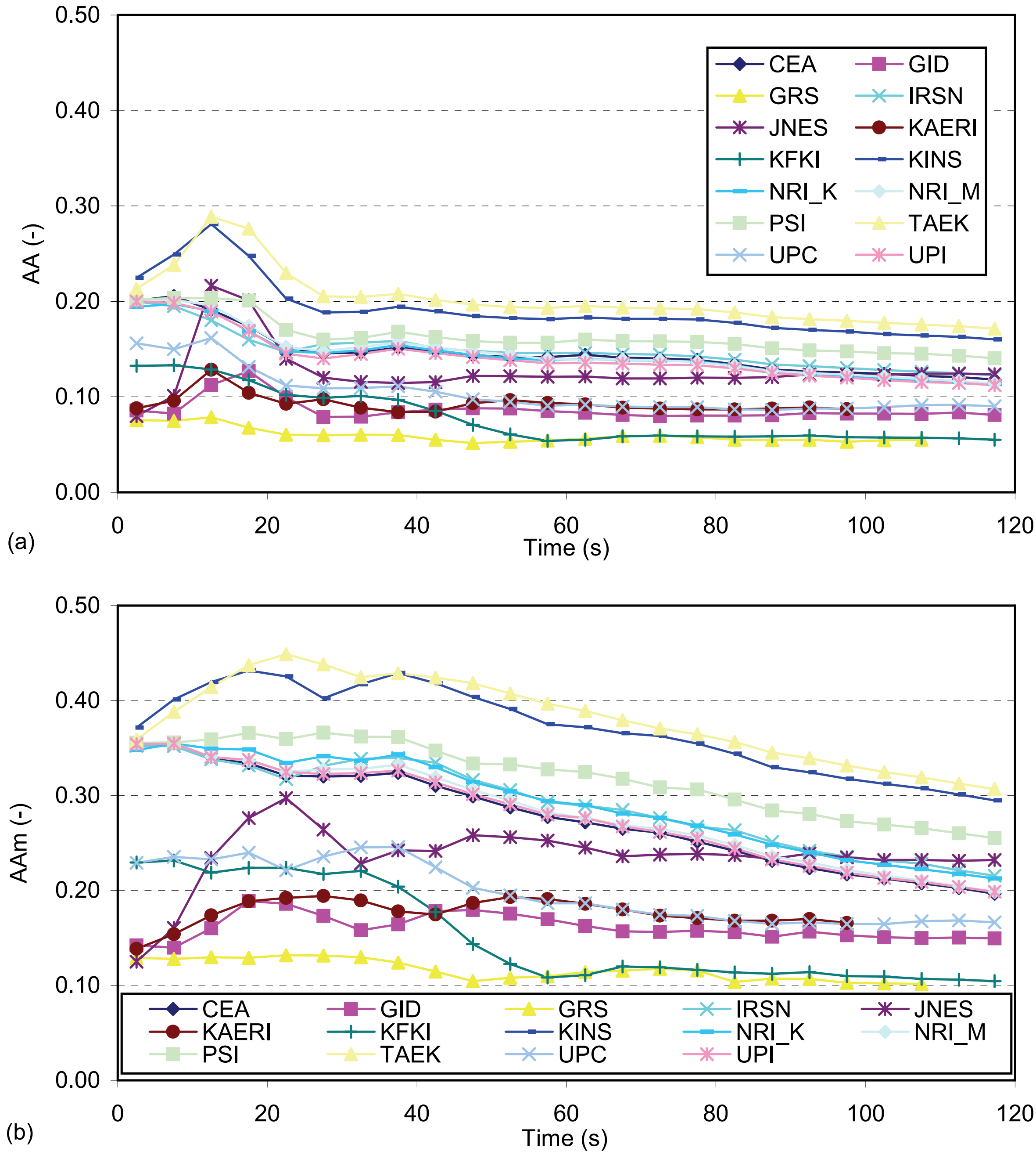
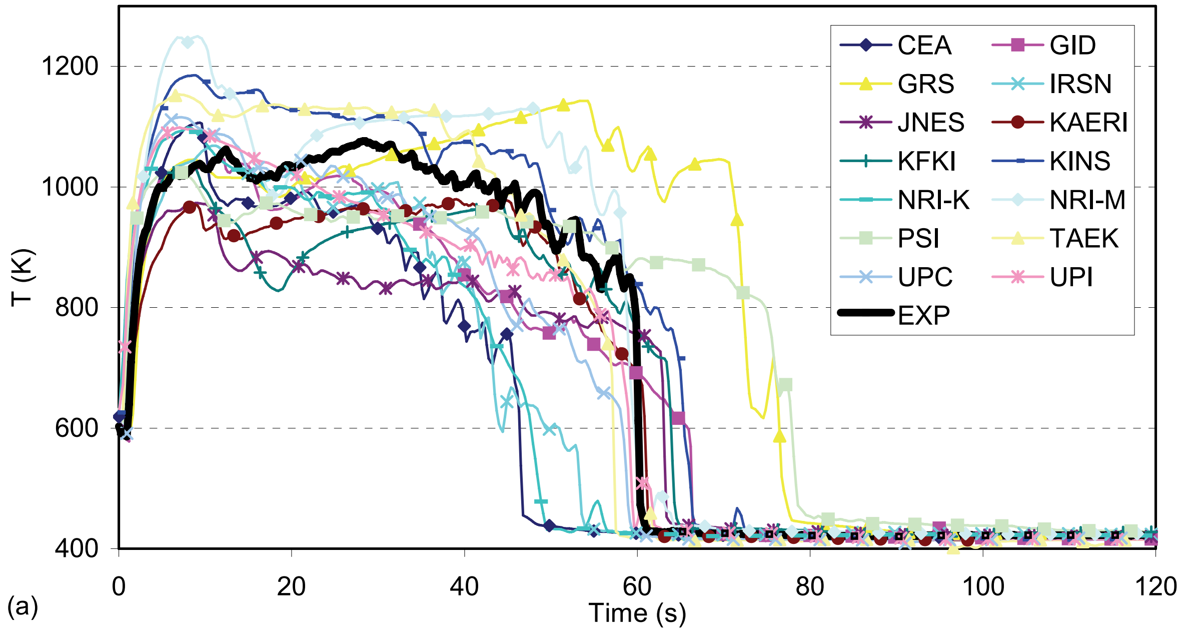


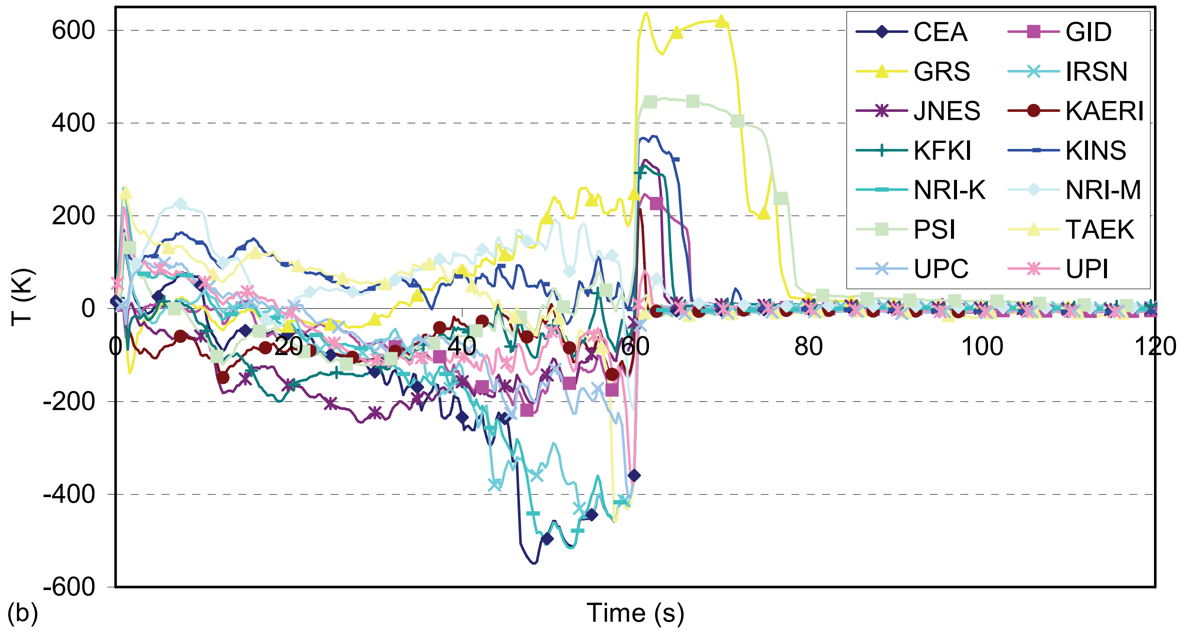

Figure 2: Time trend of average amplitude for primary pressure for 14 participants in BEMUSE: (a) AA and (b) $AA_m$.

## 4.2 Results for cladding temperature

In Figure 3(a) the calculated cladding temperatures in the middle of the core are compared to experimental data. As for ranking of participants only the error signal is relevant (experimental signal has no influence on ranking because it is used for normalization) it is shown in Figure 3(b). The larger is the error and the longer is lasting, the larger is the discrepancy and this should be confirmed by quantitative results. The symmetrization of experimental and error signal slightly increases the value of $AA_m$ comparing to AA as can be seen from Figure 4. The edge effect of the signals distorts AA not to be monotonic increasing



(a)



(b)

Figure 3: Signals used for AA calculation of cladding temperature at 2/3 core height for 14 participants in BEMUSE: (a) Experimental signal (please note that calculated signals are also added to chart for comparison of calculated and experimental signals), (b) Error signals.

[see Figure 4(a)] while $AA_m$ shown in Figure 4(b) increases with progression into transient for all calculations. Nevertheless, at the end of transient the edge effect is small for all calculations. The symmetrization of error and experimental signal increases average amplitude around 15% where approximately 10% is because of experimental signal symmetrization.

This example shows the need to make FFTBM universal for all calculated cases (not depending on the edge of the error signal) and for all kinds of variables (not depending on the edge of the experimental signal). Only in this way the accuracy assessment performed with FFTBM becomes objective.

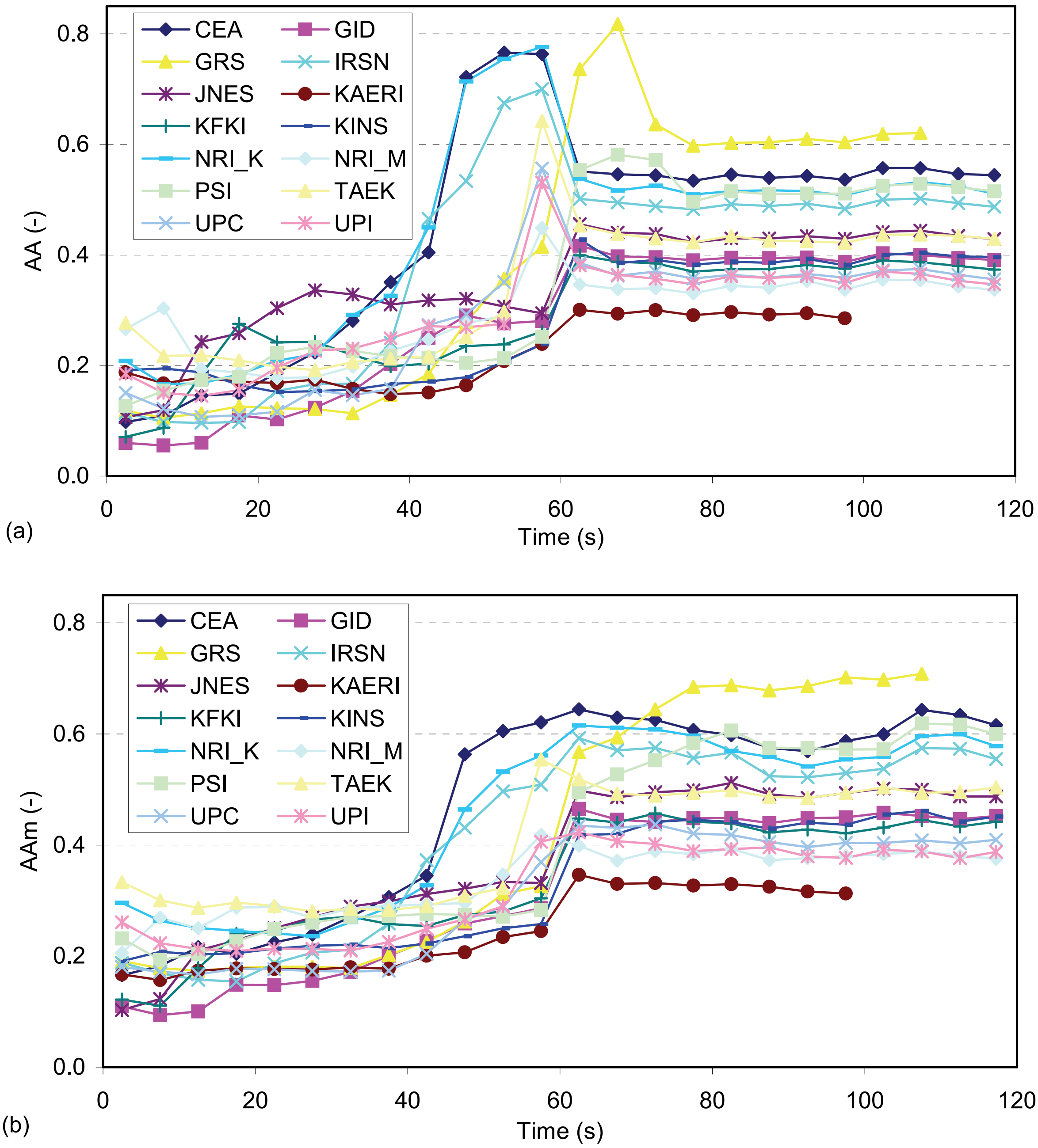



Figure 4: Time trend of average amplitude for cladding temperature at 2/3 core height for 14 participants in BEMUSE: (a) AA and (b) $AA_m$.

## 4.3 Results for total accuracy

The total accuracy time trends obtained by the original and the improved FFTBM by signal mirroring are shown in Figures 5(a) and 5(b), respectively. It total 18 variables were selected for AA total calculation [5]. It can be seen that practically all calculations satisfy acceptability criterion 0.4 except the GID calculation. The reason is the varying pressure drop that oscillated in the beginning of the transient around the experimental trend. When the signal was treated with moving average [see GID1 on Figure 5(a)], this calculation also satisfies the acceptability criterion. A more detailed discussion on this is provided in [4].

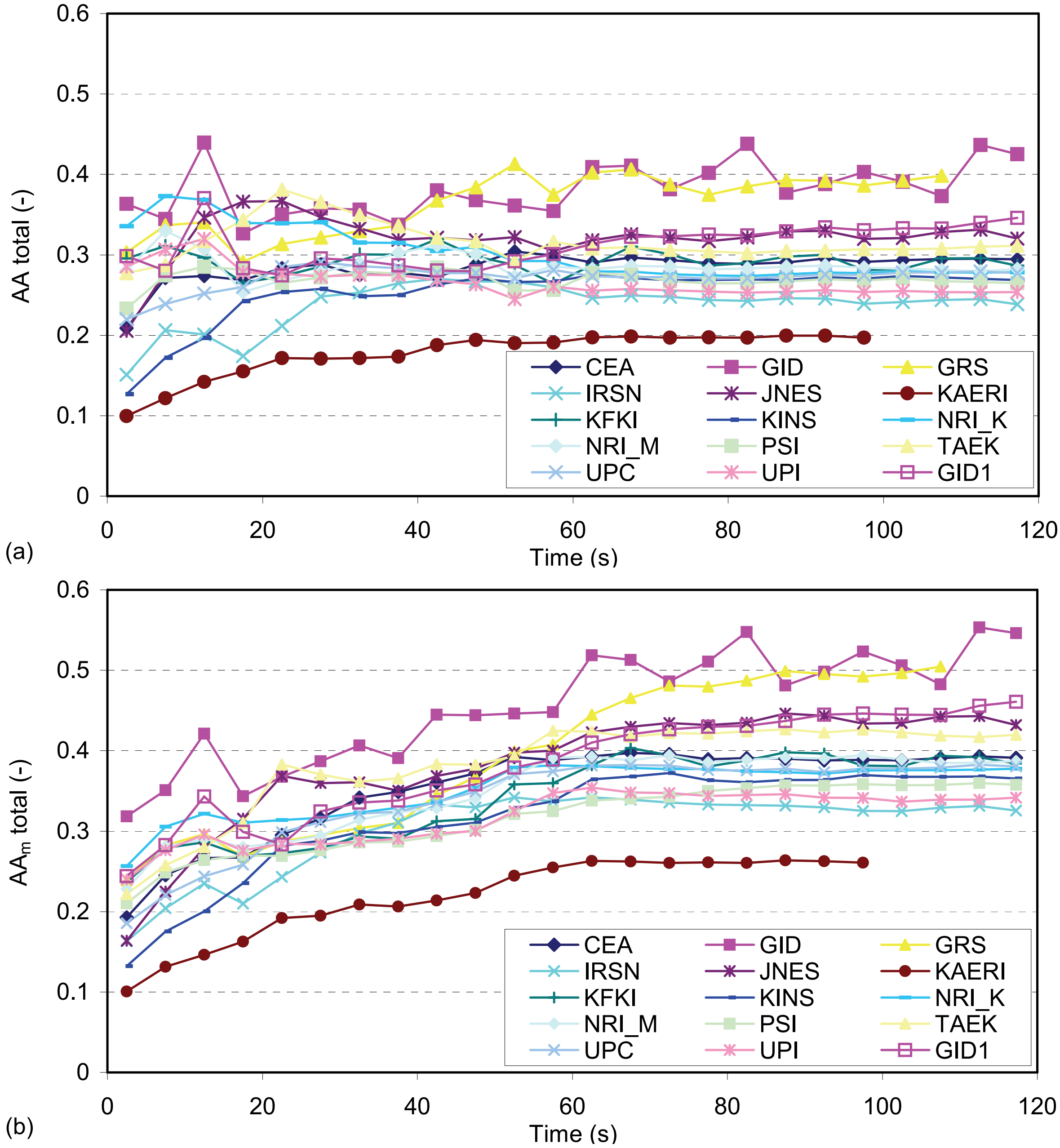



Figure 5: Total accuracy trend obtained by: (a) original FFTBM, (b) improved FFTBM by signal mirroring.

Figure 5(a) shows that the total accuracy obtained by original FFTBM is, for most calculations, rather constant during the transient because of compensating edge effects, while Figure 5(b) shows that, in the case of improved FFTBM by signal mirroring, the trend is monotonic. In the example for cladding temperature, it was shown that $AA_m$ is a more objective measure for calculating time dependent accuracy than AA because the edge effect is eliminated from signals. In the case of the LOFT L2-5 test, after core quench, the transient is more or less over and therefore the differences are small resulting in flat AA total. The total accuracy trends obtained with original FFTBM and improved FFTBM by signal mirroring become same when there is no edge in the error signal. Please remember that only the error signal influences the ranking of calculations and both methods give the same result when the deviation is terminated or when there is no edge in the error signal. However, when values are compared with acceptability criteria, the ranking is not solely. Namely, absolute values of AA are influenced by both the edge effect in the error signal and the experimental signal.

Therefore, the improved FFTBM by signal mirroring gives better quantitative assessment than original FFTBM. Nevertheless, when the transient is over, the edge effects are normally smaller, therefore the applications in the past seems appropriate for ranking of participants. However, when comparing results of different tests where absolute values of AA total are compared, care must be taken because of edge effects.

## 5 CONCLUSIONS

In the study, the signal mirroring was proposed to eliminate the edge effect when calculating accuracy. The original FFTBM and improved FFTBM by signal mirroring were applied to large break LOCA test L2-5 calculations performed in the frame of BEMUSE programme, phase II.

The results show that when calculating time-dependent accuracy, the accuracy was varying very much during fast variable increase or decrease in the case of original FFTBM. The reason was the edge effect, which produces several harmonic amplitudes, which are then also used for average amplitude calculation. It was shown that the improved FFTBM by signal mirroring may be used regardless of the edge effects. It was demonstrated to be very useful in studies of the same test with several different calculations as in BEMUSE phase 2. Its primary purpose is not to mark the calculations, as this can be done also by visual observation, although very time consuming, but rather to help the analyst to rank calculations, to detect the variables, which need further improvement, to easily detect time shifts of the signals etc. The analyst can then look in more detail the identified trends.

## ACKNOWLEDGMENTS

The authors acknowledge the support of Ministry of higher education, science and technology of the Republic of Slovenia within the program P2-0026 and the research projects J2-6542 and J2-6565.

## REFERENCES

[1] A. Prošek, M. Leskovar, Application of FFTBM to Severe Accidents, *Int. Conf. Nuclear Energy for New Europe 2005*, Bled, Slovenia, September 5-8, 2005, pp. 013.1-013.10.

[2] A. Prošek, B. Mavko, Quantitative assessment of time trends: Influence of time window selection, *Proc. 5th Int. Conf. on Nuclear Option in Countries with Small and Medium Electricity Grids*, Dubrovnik, Croatia, May 16-20, 2004, pp. 1-9.

[3] A. Prošek, F. D'Auria, B. Mavko, Review of quantitative accuracy assessments with fast Fourier transform based method (FFTBM), *Nuclear Engineering and Design*, vol. 217, (1-2), 2002, pp. 179-206.

[4] A. Prošek, M. Leskovar, Improved FFTBM by signal mirroring, IJS-DP-9336, Jožef Stefan Institute, Ljubljana, Slovenia, March 2006.

[5] OECD/NEA, BEMUSE Phase 2 Report: Re-Analysis of the ISP-13 Exercise, Post Test Analysis of the LOFT L2-5 Test Calculation, NEA/CSNI/R(2006)2, Paris, France, May 2006.

[6] OECD/NEA, CSNI INTERNATIONAL STANDARD PROBLEMS (ISP), Brief descriptions (1975-1999), NEA/CSNI/R(2000)5, Paris, France, 2000.