30 LET NENE 2022
September 12-15
PORTOROŽ
SLOVENIA
31st International Conference Nuclear Energy for New Europe

Review of Application of FFTBM Method for Code Accuracy Quantification

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ABSTRACT

The fast Fourier transform based method (FFTBM) was proposed in the 1990s and is used for accuracy quantification of computer codes. FFTBM provides frequency-based measures for each single TH variables as well as the whole transient calculations. The measurement-prediction discrepancies in the frequency domain are assessed by the average amplitude (AA). An AA close to 0 indicates good agreement between measured and predicted results. AA is dependent to the proper selection of time windows, weighting factors, number of discrete data used. This paper summarized the application of FFTBM from publications in the last 30 years, including the relevant experimental tests, codes, number of selected parameters and AA_{tot}, etc. It attempts to provide some insights and guidelines for FFTBM application.

1 INTRODUCTION

The assessment of a thermal-hydraulic system code involves the comparison of calculated results against experimental data from separate effect tests and integral effect tests. The FFTBM is a well-established tool proposed in 1990s, already part of the Uncertainty Method based on the Accuracy Extrapolation (UMAE) [1], to quantitively evaluate the accuracy of system code calculations [2, 3]. It is applied to a set of time-dependent scalar quantities featuring the reactor thermal–fluid–dynamic behavior (such as primary and secondary pressure, coolant and cladding temperatures and flowrates) and for each of them provides quantification (by the "average amplitude") of the discrepancy to show the measurement–prediction discrepancies in the frequency domain. Moreover, each of such scalar quantities is assigned a weighting factor to account for their different relevance, and then all average amplitudes are averaged – with proper weighting – to obtain a single quantity that characterizes the overall discrepancy. This method has been successfully applied to the past international standard problems (ISPs) and standard problem exercises (SPEs) organized by CSNI and IAEA. The comparisons between the experimental data and calculated results were done for different transients and accidents on different experimental facilities.

The article by Prošek et al. [4] reviewed applications of FFTBM to the calculation analyses of ISPs and SPEs until the year 2002, i.e. ISP-21 [5], ISP-22 [6], ISP-27 [7], ISP-33 [8], ISP-35 [9], ISP-39 [10], ISP-42 [11], as well as Institut Jozef Stefan (IJS) calculations of IAEA-SPE-2 and IAEA-SPE-4, DCMN calculations of IAEA-SPE-1–4, participants to IAEA-SPE-4 calculations and SBLOCA database[12]. The first large FFTBM application was to the ISP-27 on BETHSY facility, where the FFTBM results showed differences between pre- and post-test calculations for the same user. The first application of FFTBM to containment code calculations was to ISP-35 performed on the NUPEC facility. The need for potential further efforts to refine the weighting factors was expressed. The application to ISP-39 performed on the FARO facility was the first application of FFTBM to severe accidents. The application confirmed the capabilities of the FFTBM method only in ranking generic calculation results. The application to ISP-42 performed on the PANDA facility showed that ten variables were not enough to completely characterize the transient. The application of FFTBM to the ISP-13 post-test calculations of the LOFT L2-5 test was performed in the frame of the BEMUSE program [13]. In addition, FFTBM has been applied to evaluate the code capability in the single variable prediction.

This paper investigates reports and articles published the last 30 years that include the FFTBM application to accuracy quantification, and summarizes the tests, codes and FFTBM results (AA_{tot}) over the years. The quantitative comparison between thermal–hydraulic code results and experimental measurements with qualitative evaluation may assist the decision whether or not the simulation needs to be improved. The results showed the maturity of the method and its usefulness to the thermal–hydraulic code analysis.

2 THE FAST FOURIER TRANSFORM BASED METHOD (FFTBM) METHOD

The simplest formulation about the accuracy of a given code calculation, with reference to the experimental measured trend, is obtained by the difference function:

$$\Delta F(t) = F_{calc}(t) - F_{\exp}(t) \tag{1}$$

The FFTBM characterizes each calculation through two values:

· A dimensionless average amplitude, AA:

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

· A weighted frequency, WF:

$$WF = \frac{\sum_{n=0}^{2^m} \left| \tilde{\Delta} F(f_n) \right| \cdot f_n}{\sum_{n=0}^{2^m} \tilde{\Delta} F(f_n)} \tag{3}$$

The most significant information is given by AA, which represents the relative magnitude of the discrepancy deriving from the comparison between the addressed calculation and the corresponding experimental trend (AA=1 means a calculation affected by a 100% of error). The WF factor characterizes the kind of error, because its value emphasizes whether the error has more relevance at low or high frequencies, and depending on transient, high frequency errors can be more acceptable than low frequency ones (in other words, analyzing thermal-hydraulic transients, better accuracy is generally represented by low AA values at high WF values [14].

Trying to give an overall picture of the accuracy of a given calculation, average indexes of performance are obtained by defining:

$$(AA)_{tot} = \sum_{i=1}^{N_{\text{var}}} (AA) \cdot (w_f)_i \tag{4}$$

With

$$\sum_{i}^{N_{\text{var}}} (w_f)_i = 1 \tag{5}$$

Where N_{var} is the number of analyzed parameters and $(w_f)i$ are weighting factors (Table 1) that take into account the different importance of each parameter from the viewpoint of safety analyses.

Table 1: Weighting factor components for the analyzed quantities

Quantity	w_{exp}	w_{saf}	w_{norm}
Pressure drops	0.7	0.7	0.5
Mass inventories	0.8	0.9	0.9
Flow rates	0.5	0.8	0.5
Primary pressure	1.0	1.0	1.0
Secondary pressure	1.0	0.6	1.1
Fluid temperatures	0.8	0.8	2.4
Clad temperatures	0.9	1.0	1.2
Collapsed levels	0.8	0.9	0.6

Following the quantitative evaluation of accuracy, the Quantitative Assessment (QA) can be managed by means of the application of the FFT method. Obviously, the most suitable factor for the definition of an acceptability criterion is the average amplitude AA. With reference to the accuracy of a given calculation, we can define the following acceptability criterion:

$$(AA)_{tot} < K \tag{6}$$

Where K is an acceptability factor that is valid for the whole transient. It’s noted that $AA_{tot} \leq 0.3$ characterize very good predictions; $0.3 < AA_{tot} \leqslant 0.5$ characterize good code predictions; $0.5 < AA_{tot} \leqslant 0.7$ characterize poor code predictions and $AA_{tot} > 0.7$ characterize very poor code predictions. The difficulty in getting the value $AA_{tot} = 0.3$ (e.g. very good knowledge of boundary conditions and a very detailed nodalization are necessary), led to the decision of assuming $K = 0.4$ as reference threshold value identifying acceptable accuracy of a code calculation. The same criterion can be used to evaluate the code capability in the single variable prediction. In particular, acceptability factor $AA= 0.1$ has been fixed for the primary pressure, because of its importance.

3 FFTBM APPLICATIONS

3.1 Loss of coolant accidents (LOCA)

A best-estimate safety analysis methodology for small break LOCAs including the DVI line and cold leg break accidents needs to be developed to identify the uncertainties involved in the safety analysis results. Such a best-estimate safety analysis methodology will contribute to defining a more precise specification of the safety margin, and will thus lead to a greater operational flexibility. However, such an effort is lacking because the available integral effect test data are not sufficient.

There were five SBLOCA ISP exercises based on four integral test facilities, LOBI, SPES, BETHSY, ROSA IV/LSTF and the recorded data during a steam generator tube rupture transient in the DOEL-2 PWR (Belgium) [15]. SBLOCA was investigated in IAEA SPE-2 and IAEA SPE-4. FFTBM was applied to code accuracy quantification, which could be found in the comparison reports of each exercise and review papers [4, 12]. In addition, LOCA has been investigated in other tests including PKL I2.2 test, BETHSY 6.2TC test, etc [16]; [17]; [18][19][4]. Table 2 presented the AA_{tot} for each calculation. The FFTBM results of ISP could be found in the review paper by Prošek et al. [4]. The minimum AA_{tot} in table 2 is 0.164 by ATHLET code, although with 12 selected parameters. While the calculation with 7-pipe steam generator nodalization results in the largest AA_{tot} of 0.4663.

Table 2 summary of FFTBM applied to LOCA tests

Ref.	Tests	Code	AA_{tot}	N_{var}	Notes
[20]	IAEA SPE-2	TRACE	0.233-0.315	17	
		RELAP5	0.211-0.302		
		APROS	0.237-0.268		
[21]	IAEA SPE-4 SBLOCA experiment	APROS	0.335	12	New models
		RELAP5	0.289		
		TRACE	0.369		
[16]	PKL I2.2	ATHLET	0.164	12	
[17]	SB-CL-32 test	SOCRAT/V1	0.38	--	
[18]	SBLOCA	RELAP5/MOD3.2	0.3884 0.3995 0.4663 0.4086 0.3776	25	SG nodalization with 5 pipes, 3 pipes, 7 pipes, 12 pipes, 12 pipes-A
[19]	RD-14M large LOCA test B9401	FIREBIRD-III MODI-77	0.295; 0.264	23; 24	Blind; open quantitative analysis
		CATHENA 3.5d Rev. 0	0.277; 0.229		
		RELAP5/MOD3.2	0.357; 0.361		
		RELAP5/MOD3.2.2g	0.312; 0.273		
		RELAP5/CANDU	0.313; 0.26		
		FIREBIRD-III MODI-77	0.392; 0.318		
[22]	0.7% SBLOCA	RELAP5	0.2195	21	
[23]	BETHSY 9.1b	RELAP5/MOD3.2	0.34	21	
	BETHSY 4.1a TC		0.17	--	
[4]	BETHSY 6.2TC	RELAP5	0.28	23	

The ATLAS program is closely related with the development of the APR1400 reactors and the SPACE code. The multiple roles of ATLAS testing are emphasized in very close conjunction with the development, licensing and commercial deployment of these reactors and their safety analysis codes (Song et al., 2015). The role of ATLAS for nuclear safety enhancement is also introduced by taking some examples of its contributions to voluntarily lead to multi-body cooperative programs such as domestic and international standard problems. [24] overviewed the ATLAS Standard Problem (ASP) exercises, namely two domestic standard problem (DSP) exercises, with DSP-01 launched in 2008, and one international standard problem (ISP) exercise ISP-50, investigated small break LOCA including the DVI line and cold leg break accidents. Each standard problem had more than 10 participants, and the FFTBM results of accuracy quantification were presented in Table 3 [25]. Most of the calculations are acceptable with $AA_{tot} < 0.4$, except 2 cases both calculated by MARS-KS that the AA_{tot} are 0.777 and 0.523.

Table 3 FFTBM results in ATLAS Standard Problem (ASP) exercises

Ref	Tests	Code	AA_{tot}	Time window	Cut frequency	N_{var}	Notes
[26]	ATLAS DSP-01	MARS-KS	0.282	0-1000s	1.02Hz	22	100% DVI line break
		MARS-KS	0.333				
		MARS-KS	0.278				
		RELAP5-ME	0.237				
		RELAP5/MOD3.3	0.249				
		RELAP5/MOD3.3	0.269				
		MARS-KS	0.276				
		MARS-KS	0.204				
		MARS-KS	0.316				
		MARS-KS	0.777				
[27]	ATLAS DSP-02	MARS-KS	0.280	0-1000s	1.02Hz	22	6-in. CL SB-LOCA
		MARS-KS	0.268				
		RELAP5/MOD3.3	0.290				
		MARS-KS	0.523				
		RELAP5/MOD3.3	0.303				
		RELAP5-ME	0.298				
		MARS-KS	0.313				
		MARS-KS	0.226				
		MARS-KS	0.324				
		MARS-KS	0.337				
		MARS-KS	0.320				
[28]	ISP-50	MARS-KS	0.322	0-2000s	1.02Hz	22	50% DVI line break
		MARS-KS	0.359				
		TRACE 5.0 p. 02	0.353				
		TRACE 5.0 p. 02	0.348				
		R5/M3.3	0.201				
		R5/M3.3	0.302				
		RELAP-ME	0.372				
		R5/M3.3	0.262				
		R5/M3.3	0.278				
		CATHARE2V1.5Bmod3.1	0.265				
		KORSAR	0.324				
		KORSAR	0.379				
		KORSAR	0.352				
		ATHLET M2.2	0.310				
		ATHLET	0.316				
		APROS	0.298				

3.2 FFTBM applied to other tests

Table 4 presented the investigated tests that used FFTBM for code accuracy quantification. The accidents include MCP trip, natural circulation, loss of heat sink, station black-out (SBO), total loss of feed-water (TLOFW), reflood and burnup calculations. In which the burnup calculations were carried out by WIMSD5 and ORIGEN-2 codes, and the accuracy quantification was between the calculated results. In table 4, RELAP5/MOD3.2.2 had a good prediction in MCP trip in VVER Mochovce VVER 440/213 nuclear power plant (NPP). It concluded in the paper that the simpler is the transient the higher code accuracy is generally achieved [29]. The AA_{tot}s are close to 0 in the cases of natural circulation and LOFT LP-FW-1. The number of selected parameters in LOFT LP-FW-1 is far less than the suggested 20. The same is to the unblocked FLECHT SEASET reflood tests that selected 5 parameters for code evaluation. The C2 V2.5_3 code had a good performance in ACHILLES test, while the AA_{tot} are larger than 0.87 by C3 V1.3 3-field code.

Fig. 1 presented the AA_{tot}s that are less than 0.7. The data are from table Table 2, 3, 4, as well as the review paper by Prošek et al. [4] and ISP comparison reports. Different legends are used to distinguish LOCAs and other accidents. Most AA_{tot}s are less than 0.4, representing acceptable code predictions, since the year 1995. The models and codes have better performance (more obvious on SBLOCAs) in 2020s than in 1990s.

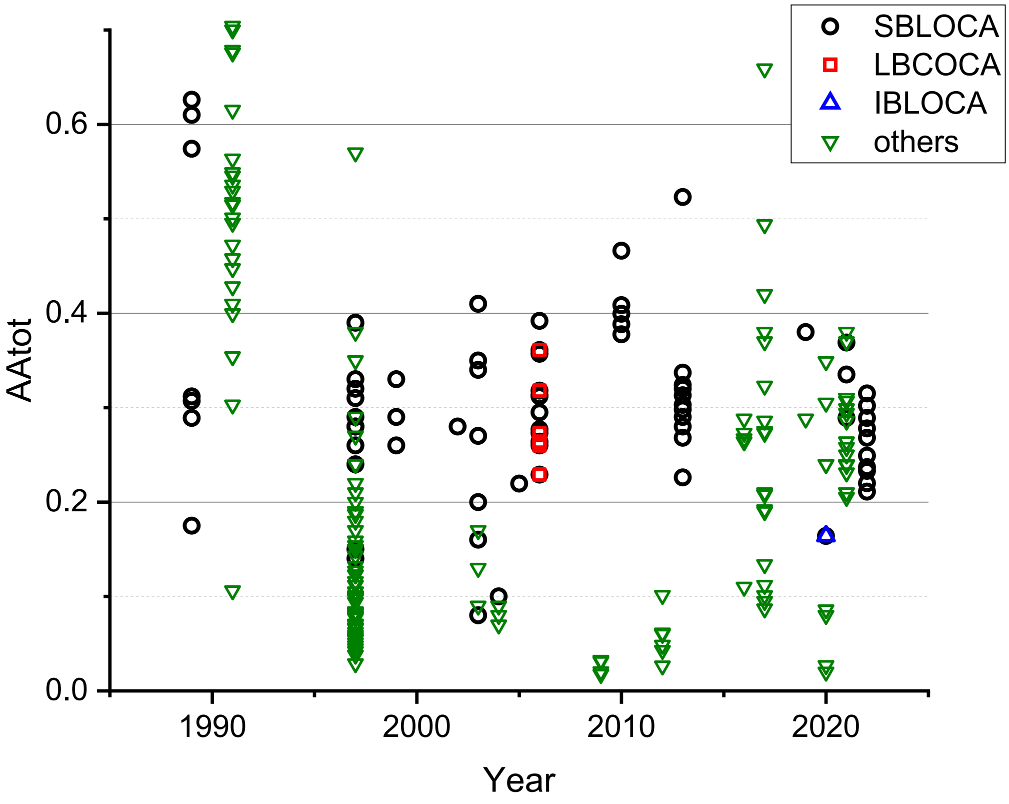

Fig. 1 Summary of AA_{tot} over the years

Table 4 Application of FFTBM and AA_{tot}

Ref.	Tests	Code	AA_{tot}	N_{var}
[29]	MCP trip	RELAP5/MOD3.2.2	0.09	19
[30]	Natural circulation in VVER-1000	RELAP5/MOD3	0.09	--
[31]	PKL III E3.1	RELAP5/MOD3.3	0.4	18
[32]	loss of heat sink transients	RELAP5/MOD3.2	0.1012; 0.0486	11
[33, 34]	Station Black-Out (SBO) test in PSB-VVER facility	MELCOR	0.273	28
[35]	Ingress of coolant event	TRACE	0.24	5
[36]	LOFT LP-FW-1 (total loss of feed-water (TLOFW))	SPACE	0.086 0.027	2
[37]	PERSEO Test 7 Part 2	RELAP5/MOD3.3	0.66	12
		RELAP5-3D	0.21	
[38]	PERSEO Test 9	RELAP5-3D	0.39	14

[39]	Unblocked FLECHT SEASET reflood tests	FS - 31021	SPACE	0.205	5
		FS - 31302		0.264	
		FS - 31504		0.231	
		FS - 33849		0.258	
		FS - 34103		0.286	
		FS - 34316		0.299	
		FS - 34420		0.239	
		FS - 34711		0.307	
		FS - 35050		0.294	
[40]	Reflood FEBA test 214 and 216		CATHARE2	0.18	10
	ACHILLES test A1R030		C2 V2.5_2	0.208	
			C2 V2.5_3	0.21	
			C3 V1.3 2-field	0.323	
			C3 V1.3 3-field	0.992	
			C2 V2.5_3	0.112	
	ACHILLES test A1R047		C2 V2.5_2	0.273	
			C2 V2.5_3	0.286	
			C3 V1.3 2-field	0.42	
			C3 V1.3 3-field	1.026	
			C2 V2.5_3	0.101	
	ACHILLES test A1R048		C2 V2.5_2	0.37	
			C2 V2.5_3	0.38	
			C3 V1.3 2-field	0.659	
			C3 V1.3 3-field	0.883	
			C2 V2.5_3	0.095	
[40]	Burnup calculations for BNPP fuel assemblies		WIMSD5; ORIGEN-2	0.0176-0.0324	14

3.3 FFTBM applications in single variable predictions

There are FFTBM applications provided with only average amplitudes of single variable predictions (Table 5) for the evaluation of both the original and newly-proposed models, for example the flashing model [42], subcooled boiling model [43] and reflood model [39]; [44]. Moreover, FFTBM was applied to evaluate the calculation of other types of plant, e.g. suppression tank for fusion plant [45] and in-box LOCA in Water-Cooled Lead Lithium Breeding Blanket [46, 47].

Table 5 FFTBM applications in single variable predictions

Ref.	Code	Tests
[45]	TRACE	Suppression tank for fusion plant
[46]	SIMMER-III (Modified version)	In-box LOCA in WCLL-BB
[47]	SIMMER-III	
[43]	MARS KS-1.4	Subcooled boiling
[44]	SPACE	Reflood
[42]	TRACE	flashing

Multi-dimensional FFT was proposed to the accuracy quantification for the multi-dimensional transient data, such as space and time distributions obtained from CFD calculations and experiments, by directly providing a single scalar quantity to characterize the overall deviation. A 3D FFT approach was applied to the CFD simulation of in-vessel flow. The 3D-AAs for selected parameters are larger than 0.6. It was suggested by the authors that the mathematical aspects of multi-dimensional FFT be carefully investigated [48].

4 CONCLUSION

FFTBM has been applied to code accuracy quantification for more than 30 years. The total average amplitude (AA_{tot}), which is used for acceptability criterion, is decreasing compared to 2000s.

The quantitative comparison between thermal–hydraulic code results and experimental measurements with qualitative evaluation may assist the decision whether or not the simulation needs to be improved. The results showed the maturity of the method and its usefulness to the thermal–hydraulic code analysis.

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