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Ocenjevanje natančnosti napovedi termohidravličnih programov

The Accuracy Quantification of Thermal-Hydraulic Code Predictions

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V zadnjem času je velika pozornost namenjena vprašanju natančnosti napovedi termohidravličnih programov pri računanju dinamičnih odzivov sistemov jedrskih reaktorjev. Kljub velikemu napredku je zelo malo zanesljivih in splošnih orodij za ocenjevanje natančnosti računalniških izračunov. Za merljivost natančnosti programa je predlagana nova metoda na temelju naključnostne stopnje aproksimacije (NSA - SARBM). Namen študije je bil tudi raziskati in dokazati primernost predlagane metode.

V postopku kvalifikacije metode NSA z metodo na podlagi hitre Fourierjeve preslikave (HFP - FFTBM) so bili uporabljeni izračuni termohidravličnega računalniškega programa RELAP5/MOD3.2 in eksperimentalni podatki iz naprave BETHSY.

Z grafično primerjavo potekov in primerjavo natančnosti izračunov, dobljenih z metodama NSA in HFP smo pokazali, da metoda NSA dobro napove natančnost izračunanih potekov prehodnih pojavov. Da bi bil izračun natančnosti z metodo NSA podoben postopku z metodo HFP, smo predlagali novo mero za oceno natančnosti, imenovano količnik natančnosti (KN - AF). Dobljeni rezultati za natančnost izbranih BETHSY poskusov kažejo, da je bolje združiti metodi NSA in HFP za oceno natančnosti, kakor pa metodo NSA uporabljati samostojno.

(Ključne besede: natančnost izračunov, programi termohidravlični, NSA - SARBM, BETHSY)

Recently, significant attention has been paid to code accuracy issues in predicting the dynamic responses of nuclear reactor systems. Though significant progress has been made, only a few reliable and general tools to quantify code accuracy are available. A new Stochastic Approximation Ratio Based Method (SARBM) was proposed for accuracy quantification. The objective of this study was to investigate and qualify the proposed method.

The RELAP5/MOD3.2 thermal-hydraulic code calculations and the BETHSY experimental data were used in the process of qualifying the SARBM with a Fast Fourier Transform Based Method (FFTBM).

The obtained results showed that the SARBM was able to satisfactorily predict the accuracy of the calculated transient trends when visually comparing plots and comparing the results with the results obtained by the qualified FFTBM. A new figure of merit for code accuracy, called the accuracy factor (AF), was proposed instead of the stochastic approximation ratio to make the total accuracy calculation with the SARBM more like the FFTBM approach. The accuracy results obtained for the selected BETHSY tests suggest combining the SARBM with the FFTBM for accuracy quantification rather than using it independently.

(Keywords: code accuracy, thermal hydraulic code, SARBM, BETHSY)

0 UVOD

Namen postopka za ocenjevanje velikih termohidravličnih programov z najboljšo oceno (NO - BE) je preveriti njihovo kakovost s primerjanjem računalniških izračunov in izmerjenih podatkov, dobljenih na pomanjšanih eksperimentalnih napravah za jedrske elektrarne. Sistemski termohidravlični programi z najboljšo oceno napovedo prehodne pojave v reaktorjih stvarno, kakor je to najbolj mogoče, tako da fizikalno obnašanje ponazarjajo z določeno natančnostjo. Informacijo o nenatančnosti napovedi dobimo iz postopka ocenjevanja in overitve

0 INTRODUCTION

The assessment process of large thermal-hydraulic best-estimate (BE) computer codes aims principally at verifying their quality by comparing code predictions against experimental data obtained mainly from tests performed on scaled plant experimental facilities. The best-estimate thermal-hydraulic system codes predict reactor transient scenaria as realistically as possible by approximating the physical behaviour with some accuracy. The information on the inaccuracy of the predictions comes from the code assessment and validation process. The first widely računalniškega programa. Prva široko uporabljena metoda za ocenjevanje natančnosti računalniškega programa je bila metoda na podlagi hitre Fourierjeve preslikave (HFP) [1]. To je integralna metoda v frekvenčnem prostoru, ki uporablja hitro Fourierjevo preslikavo (HFP). Uporabljena je bila za številne standardne probleme ([2] do [4]).

Pred kratkim so v Združenih državah Amerike temeljito pregledali tehnike za analizo podatkov, uporabnih za samodejno oceno natančnosti, ter razvili programsko opremo za njihovo uporabo [5]. Za oceno natančnosti časovnih potekov so poleg metode HFP priporočili še nekaj drugih mer natančnosti. Sočasno je Islamov [6] za primerjavo dveh inačic programa RELAP5 v izračunu posamezne spremenljivke predlagal postopek z naključnostno aproksimacijo. V naši študiji je bila vzeta naključnostna aproksimacija in po njej smo razvili metodo NSA za oceno natančnosti programa.

Glavni namen dela je bil metodo NSA kvalificirati z metodo HFP s primerjavo natančnosti izračunov, dobljenih za poskuse na BETHSY (Glej 2.1). V preteklosti smo namreč zelo intenzivno proučevali poskuse z eksperimentalne naprave BETHSY ([7] do [10]), ter jih že tudi ocenili z metodo HFP ([11] do [13]). V nadaljevanju so po kratkem pregledu metod in opisu načina modeliranja predstavljeni glavni rezultati študije.

used methodology suitable to for quantifying the code accuracy was the Fast Fourier Transform Based Method (FFTBM) [1]. This is an integral method in the frequency domain using the Fast Fourier Transform (FFT). It was applied to several standard problems ([2] to [4]).

Recently, a review of data-analysis techniques for applications in automated, quantitative accuracy assessments was done in the United States of America and software was developed to deploy the recommended techniques [5]. For accuracy quantification the FFTBM was adopted and a few other accuracy measures were recommended. At the same time, Islamov [6] proposed a stochastic approximation approach to a comparative analysis of the closeness of two RELAP5 calculation models for single variables. In our study the stochastic approximation was adopted, and based on this approximation the SARBM for code accuracy quantification was developed.

The main purpose of the paper was to qualify the SARBM with the FFTBM by comparing the accuracy obtained for BETHSY (Cfr. 2.1) experiments. In the past the BETHSY experiments were intensively studied ([7] to [10]), and some experiments were also quantitatively assessed with the FFTBM ([11] to [13]). After a brief review of the methods used and the modelling description the main results are discussed.

1 UPORABLJENE METODE

1.1 Mera natančnosti na temelju naključnostne aproksimacije

Stopnja naključnostne aproksimacije (SNA - SAR) kot mero negotovosti modela *Y*, uporabljeno v metodi NSA, je definiral Islamov [6] kot: “Naj so X_1, X_2,…, X_n opazovane naključne spremenljivke in opazovana spremenljivka *Z* z njimi deterministično povezana tako, da velja $Z(X_1, X_2,…, X_n)$. Pri tem so X_1, X_2,…, X_n vstopne spremenljivke modela *Y*, odziv modela $Y(X_1, X_2,…, X_n)$ pa naj pomeni pričakovano aproksimacijo spremenljivke *Z*. Stopnjo naključnostne aproksimacije kot merilo negotovosti modela *Y* tedaj lahko zapišemo z naslednjo enačbo:

1 THE METHODS USED

1.1 An accuracy measure based on the stochastic approximation ratio

The Stochastic Approximation Ratio (SAR) measure of the uncertainty of a model *Y* adopted in the SARBM was defined by Islamov [6] as: “Let X_1, X_2,…, X_n be the observed random parameters, and the observed variable *Z* is presumed to be somehow deterministically related to the input parameters $Z(X_1, X_2,…, X_n)$. Parameters X_1, X_2,…, X_n are considered as the input data for the model *Y*, and a model response $Y(X_1, X_2,…, X_n)$ is considered as an anticipated approximation of the variable *Z*. The Stochastic Approximation Ratio measure of the uncertainty of a model *Y* can be written as:

$$SAR = \left(1 - \frac{\sqrt{A_{Y-Z}}}{\sqrt{A_Y} + \sqrt{A_Z}}\right)^2 \qquad (1),$$

kjer so A_{Y-Z}, A_Y in A_Z drugi momenti – srednje kvadratne vrednosti:

where A_{Y-Z}, A_Y and A_Z are second-order moments:

$$A_{Y-Z} = \int \left[y(x) - z(x) \right]^2 f(x)dx \qquad (2)$$

$$A_Y = \int \left[y(x) \right]^2 f(x)dx \qquad (3)$$

$$A_Z = \int \left[z(x) \right]^2 f(x)dx \qquad (4),$$

kjer *f(x)* pomeni gostoto verjetnosti.” Za nadaljnje podrobnosti in izpeljavo izraza naj si bralec ogleda [6].

and *f*(*x*) is density function.” For further details and the derivation the reader is referred to [6].

Izvirno predlagan izraz SNA je bil prilagojen za uporabo v istoimenski metodi NSA. V primeru primerjave izračuna s preizkusom je vhodni parameter čas ($x=t$), izračunani signal $y(t)$ in eksperimentalni signal $z(t)$, medtem ko je gostota verjetnosti $f(t)$ v skladu s [6] UNKNOWN, kar pomeni, da je ne upoštevamo. Enačbe od (2) do (4) integriramo v območju [0,T], kjer je zgornja meja integracije T časovni korak, v katerem ocenjujemo natančnost. Ker so eksperimentalni in izračunani podatki diskretni, je v algoritmu SARBM uporabljena diskretna integracijska shema.

Vrednost SNA je v območju [0, 1]. Vrednost $SNA \cong 1$ pomeni, da se eksperimentalni in izračunani signal dobro ujemata. Če je vrednost $SNAR << 1$, pomeni, da se eksperimentalni in izračunani signal razhajata in je nenatančnost velika. Ker pri metodi HFP manjše vrednosti povprečne amplitude pomenijo večjo natančnost, smo definirali novo mero natančnosti, imenovano *količnik natančnosti* (*KN - AF*):

The originally proposed SAR was adopted for use in the SARBM. In the case of a code–experiment comparison the input parameter is time ($x=t$), the calculated signal is $y(t)$, the experimental signal is $z(t)$, while the density function $f(t)$ is, according to [6], UNKNOWN, which means that it is not taken into account. The Eqs. 2 to 4 are integrated over [0, T], where the upper limit T is the time interval for which the accuracy is quantified. Because of the discrete experimental and calculated data a discrete integration scheme is used in the developed SARBM algorithm.

The SAR is located in the interval [0, 1]. If $SAR \cong 1$ it means that the experimental and calculated signals are very close. If $SAR << 1$ it means that the experimental and calculated signals are not close and that the inaccuracy is very high. Because in the FFTBM lower values of the average amplitude mean higher accuracy, a new accuracy measure, called the accuracy factor (*AF*), was defined:

$$AF = 1 - SAR \qquad (5).$$

Ta mera natančnosti je bolj praktična za primerjavo rezultatov metode NSA z rezultati metode HFP in za določanje ene same mere za natančnost na podlagi kombinacije več statističnih mer za natančnost.

This accuracy measure is more practical for comparing the results with the FFTBM results and constructing a single measure of the code accuracy from several statistical accuracy measures.

1.2 Mera natančnosti na podlagi povprečne amplitude

Metoda na podlagi hitre Fourierjeve transformacije uporablja za mero natančnosti povprečno amplitudo. Za podrobnosti razvoja in uporabe naj si bralec ogleda ([1] do [4]).

Poglavitna značilnost Fourierjeve transformacije je, da splošno zvezo, veljavno v časovnem prostoru, lahko analiziramo tudi v frekvenčnem prostoru, ne da bi pri tem izgubili informacijo. Ko uporabljamo funkcije, vzorčene v digitalni obliki, lahko uporabimo hitro Fourierjevo preslikavo (HFP), to je algoritem za hitro računanje diskretne Fourierjeve preslikave. Da bi jo lahko uporabili, mora biti število diskretnih vrednosti enako potenci števila 2 in izpolnjen stavek o vzorčenju.

Metoda HFP v frekvenčnem prostoru kaže odstopanje računalniških napovedi od meritev. Za izračun teh odstopanj potrebujemo eksperimentalni signal $F_{exp}(t)$ in razliko signalov $\Delta F(t) = F_{calc}(t) - F_{exp}(t)$ kjer je $F_{calc}(t)$ izračunani signal.

Natančnost programa za posamezno izračunano spremenljivko določimo z uporabo amplitud diskretnega eksperimentalnega signala in signala razlik, dobljenih s HFP pri frekvencah $f_n = n/T_d$, kjer sta ($n=0,1,...,2^m$) in T_d čas trajanja prehodnega pojava vzorčenega signala. Te amplitudne spektre skupaj s frekvencami uporabimo za izračun povprečne amplitude (*PA - AA*), ki označuje natančnost programa pri izračunu posamezne spremenljivke:

1.2 An accuracy measure based on the average amplitude

The FFTBM uses the average amplitude as a measure of the accuracy. For details of its development and use the reader is referred to ([1] to [4]).

A fundamental property of the Fourier transform is that a generic relationship valid in the space identified by its variables can be analysed in a different space identified by different variables without a lack of information. When using functions sampled in digital form, a FFT can be used, i.e. an algorithm that rapidly computes the discrete Fourier transform. To apply it, functions must be identified by a number of values, i.e. a power with a base equal to 2, and the sampling theorem must be fulfilled.

The FFTBM shows the measurement-prediction discrepancies in the frequency domain. To calculate these discrepancies the experimental signal $F_{exp}(t)$ and the error function $\Delta F(t) = F_{calc}(t) - F_{exp}(t)$ are needed, where $F_{calc}(t)$ is the calculated signal.

The code accuracy quantification for an individual, calculated parameter is based on the amplitudes of discrete experimental and error signals obtained with a FFT at frequencies $f_n = n/T_d$, where ($n=0,1,...,2^m$) and T_d is the transient time duration of the sampled signal. These spectra of amplitudes, together with the frequencies, are used for calculating the average amplitude (*AA*) that characterizes the code accuracy in predicting a single variable:

$$AA = \frac{\sum_{n=0}^{2^m} \left| \tilde{\Delta} F(f_n) \right|}{\sum_{n=0}^{2^m} \left| \tilde{F}_{\exp}(f_n) \right|} \qquad (6),$$

kjer sta $\tilde{\Delta}F$ amplitudni spekter razlike signalov in $\tilde{F}_{\exp}$ amplitudni spekter eksperimentalnega signala.

where $\tilde{\Delta}F$ and $\tilde{F}_{\exp}$ are the amplitude spectra of the error function and the experimental signal, respectively.

1.3 Opis metode NSA

Za skupno natančnost izračuna je bila predlagana nova metoda NSA po vzoru metode HFP [7]. Namesto skupne povprečne amplitude je bil za mero natančnosti predlagan skupni količnik natančnosti:

1.3 Overview of SARBM

The SARBM was proposed following the FFTBM approach [2] to get an overall picture of the accuracy for a given code calculation. Instead of the total average amplitude the total accuracy factor was used for the accuracy measure:

$$AF_{tot} = \sum_{i=1}^{N_{\mathrm{var}}} AF_i \cdot \left(w_f \right)_i \quad \text{z / with} \quad \sum_{i=1}^{N_{\mathrm{var}}} \left(w_f \right)_i = 1 \qquad (7)$$

kjer je N_{var} število analiziranih spremenljivk, AF_{i} in $(w_{\mathrm{f}})_{\mathrm{i}}$ pa sta količnik natančnosti oziroma utežni faktor za *i*-to analizirano spremenljivko. Običajno za opis prehodnega pojava zadostuje 20 do 25 spremenljivk. Vsak utežni količnik $(w_{\mathrm{f}})_{\mathrm{i}}$ upošteva natančnost preizkusa, pomembnost spremenljivke za jedrsko varnost in njeno zvezo s primarnim tlakom. Utežni količnik za *i*-to spremenljivko je definiran kot [2]:

where N_{var} is the number of variables analysed, and AF_{i} and $(w_{\mathrm{f}})_{\mathrm{i}}$ are the accuracy factor and the weighting factor for *i*-th analysed variable, respectively. Normally 20 to 25 variables are sufficient to represent the transient. Each $(w_{\mathrm{f}})_{\mathrm{i}}$ accounts for the experimental accuracy, the safety relevance of particular variables and its relevance with respect to pressure. The weighting factor for the *i*-th variable is therefore defined as [2]:

$$(w_f)_i = \frac{\left(w_{\exp} \right)_i \cdot \left(w_{saf} \right)_i \cdot \left(w_{norm} \right)_i}{\sum_{i=1}^{N\ \mathrm{var}} \left(w_{\exp} \right)_i \cdot \left(w_{saf} \right)_i \cdot \left(w_{norm} \right)_i} \qquad (8),$$

kjer w_{exp} upošteva natančnost preizkusa, w_{saf} pomembnost spremenljivke za jedrsko varnost in w_{norm} normalizacijo na primarni tlak. Npr.: na natančnost preizkusa vplivajo negotovosti instrumentov, merilnih postopkov in različnih postopkov, uporabljenih za primerjavo meritev in izračunov. Preglednica 1 kaže, da večja ko je negotovost meritve, manjša je utež w_{exp}, s čimer se rezultatu pripiše večjo natančnost. Podobno velja, da bolj ko je parameter pomemben za jedrsko varnost, večja je utež w_{saf}. Uteži se med primerjavami za isto vrsto prehodnega pojava ne smejo spreminjati.

Da bi presodili kakovost izračuna, so bile za $\mathrm{KN_{tot}}$ - $\mathrm{AF_{tot}}$ na podlagi umetnih podatkov in inženirske presoje določene meje sprejemljivosti [14]. Preglednica 2 kaže meje sprejemljivosti za metodo NSA v primerjavi z mejami za metodo HFP. Za overitev same metode NSA in njenih mej sprejemljivosti so bili uporabljeni preizkusi na BETHSY, opisani v naslednjem poglavju.

Primer, ki kaže razlike v delovanju metode NSA in metoda HFP, je prikazan na sliki 1. Med seboj primerjamo različne stalnice z razmerjem med izračunanim in preizkusnim signalom y(t)/z(t) med 0,5 in 2. Slika kaže različne mere natančnosti spremenljivke v odvisnosti od razmerja y(t)/z(t). Metoda NSA da enak rezultat, če je izračunani signal dvakratnik

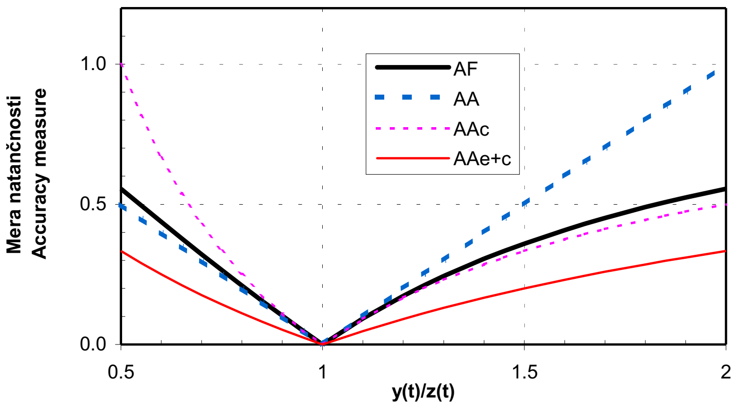
where w_{exp} is the contribution related to the experimental accuracy, w_{saf} is the contribution that expresses the safety relevance, and w_{norm} is the contribution of primary pressure normalization. For example, experimental accuracy is influenced by uncertainty due to the intrinsic characteristics of the instruments, the measurement method and the various evaluation procedures used to compare the experimental measures and the code predictions. Table 1 shows that the more uncertain is the measurement the lower is the weight w_{exp}, resulting in a higher calculation accuracy. Similarly, the more relevant is the parameter to safety the higher is the weight w_{saf}. The weights must remain unchanged during each comparison between code results and experimental data concerning the same class of transient.

To judge the quality of the calculation the acceptability limits for $\mathrm{AF_{tot}}$ were defined based on artificial data and engineering judgement [14]. Table 2 shows the acceptability limits for the SARBM compared to the limits for the FFTBM. For a validation of the SARBM and its acceptability limits the BETHSY experiments described in the next section were used.

An example to show the differences in how the SARBM and the FFTBM work is shown in Figure 1. Different constant functions with ratios between the calculated and experimental signal y(t)/z(t) ranging from 0.5 to 2 were compared. In the figure the different single-variable accuracy measures are shown as a function of the ratio y(t)/z(t). The SARBM gives the same

Preglednica 1. *Utežni količniki za analizirane spremenljivke [2]*
Table 1. *Weighting factor components for the analysed variables [2]*

	w_{exp}	w_{saf}	w_{norm}
padci tlakov pressure drops	0,7	0,7	0,5
količine mas mass inventories	0,8	0,9	0,9
pretoki flowrates	0,5	0,8	0,5
primarni tlak primary pressure	1,0	1,0	1,0
sekundarni tlak secondary pressure	1,0	0,6	1,1
temperature kapljevine fluid temperatures	0,8	0,8	2,4
temperature srajčk clad temperatures	0,9	1,0	1,2
sesedna raven collapsed levels	0,8	0,9	0,6
moč sredice core power	0,8	0,8	0,5



Sl. 1. *Mere natančnosti primerjave stalnic v odvisnosti od njunega razmerja*
Fig. 1. *Accuracy measures as a function of the ration between constant functions*

eksperimentalnega signala ali nasprotno, KN pa je omejen med 0 in 1, ker je izraz v enačbi (1) normaliziran tako na izračunani kakor na eksperimentalni signal. Pri metodi HFP je AA normaliziran na eksperimentalni signal. Zato smo raziskali primera, ko je PA - AA normaliziran na izračunani signal (primer PA_c - AA_c) in na vsoto izmerjenega in preizkusnega signala (primer PA_{e+c} - AA_{e+c}).

Zanimivo je, da se krivulja KN - AF tesno pokriva z levim delom krivulje PA - AA, ko je izračunani signal manjši od eksperimentalnega, in desnim delom krivulje PA_c - AA_c, ko je izračunani signal večji od eksperimentalnega. Ko pa je PA - AA normalizirana na vsoto obeh signalov, je težnja za PA_{e+c} - AA_{e+c} podobna težnji za KN - AF. To odkritje pojasnjuje nekatere razlike med metodama HFP in NSA pri razlagi rezultatov. Pri majhnih odstopanjih (manj ko 20%) so krivulje za mere natančnosti precej linearne in se ujemajo dobro, saj ima normalizacija manjši vpliv. Pri večjih odstopanjih pa se metodi HFP in NSA zaradi različnega načina

result when the calculated signal is two times the experimental signal or vice versa, and AF is limited between 0 and 1, because the fraction in Eq. 1 is normalized to both the calculated and experimental signals. In the case of the FFTBM the AA is normalized to the experimental signal. Therefore, the average amplitude was investigated for the cases with AA normalised to the calculated signal (case AA_c) and to the sum of the calculated and experimental signals (case AA_{e+c}).

What is interesting is that the AF curve closely matches with the left-hand part of the AA curve when the calculated signal is smaller than the experimental signal and right-hand part of the AA_c curve when the calculated signal is larger than the experimental signal. When the AA is normalized to the sum of both signals the trend for case AA_{e+c} was similar to the AF trend. This finding explains some of differences between the FFTBM and the SARBM when interpreting the accuracy results. At smaller discrepancies (less than 20%) the accuracy-measure curves are rather linear and agree well. At larger discrepancies the FFTBM and normalizacije med seboj dopolnjujeta. Primer takega dopolnjevanja je bil pokazan v študiji [14] za primer padca signala razlike tlakov v tlačniku.

1.4 Postopek za določitev natančnosti izračuna

Ko sta že kvalificirana uporabnik in vhodni model, postopek ocenjevanja izračunov poteka v treh delih. V prvem delu izberemo eksperiment po overitvenih matrikah Komiteja za varnost jedrskih naprav (Committee on the Safety of Nuclear Installations - CSNI) [15] (ali prehodni pojav elektrarne), zatem izračun ocenimo kakovostno in nato še kolikostno.

Kakovostna ocena z vizualno primerjavo izračunanih in eksperimentalnih potekov ter primerjavo posameznih parametrov da prve ocene o izračunu. Kakovostna analiza je potrebni predpogoj kolikostni analizi, ki ji sledi.

Kakovostna analiza temelji na subjektivnih ocenah, te dobimo z ovrednotenjem in razvrstitvijo odstopanj med merjenimi in izračunanimi parametri, ki si jih izberemo za popis pojava. Te ocene so:

– **Odlično**: računalniški program napove parameter v okviru nezanesljivosti eksperimenta.
– **Sprejemljivo**: računalniški program splošno napove vse pojave, časovno obnašanje in usmeritve.
– **Komaj sprejemljivo**: računalniški program ne napove pojava ali parametra, vendar je vzrok znan in ga lahko pojasnimo.
– **Nesprejemljivo**: računalniški program ne napove parametra, in vzrok ni znan.

Kolikostno oceno lahko napravimo z metodama NSA in HFP. Povedati je treba, da metodi NSA in HFP pri kolikostni oceni ne omogočata razpoznave izvora napake (tj. vpliv uporabnika, napačen začetni pogoj, pomanjkljivost vhodnega modela itn.) ali neposredno upoštevata časovni odmik določenih pojavov. Časovni odmik se bolje oceni s kakovostno analizo, ki spremlja kolikostno analizo.

2 OPIS MODELIRANJA

2.1 Opis naprave BETHSY

BETHSY je celostna eksperimentalna naprava, katere namen je bil raziskovati prehodne pojave in nezgode tlačnovodnih lahkovodnih reaktorjev. Naprava je pomanjšava trizančne jedrske elektrarne, proizvajalca Framatome s toplotno močjo 2775 MW. Prostornina je pomanjšana v razmerju blizu 1:100, medtem ko so geodetske višine in tlaki ohranjeni [16]. Moč sredice je omejena na raven zaostale toplote, zato na napravi ni bilo mogoče simulirati prehodnih pojavov, v katerih ne pride do zaustavitve sredice.

the SARBM, due to the different normalization, complement each other. Such an example was shown in [14] for pressurizer differential pressure drop.

1.4 The methodology for quantifying the code accuracy

Given a qualified user and a qualified nodalization scheme, the code assessment process of the calculations involves three steps: the first is the selection of an experiment from the Committee on the Safety of Nuclear Installations (CSNI) validation matrices [15] (or a plant transient), the second is a qualitative assessment, and the last is a quantitative assessment.

The qualitative assessment with visual observation gives the first indications about the calculated predictions. The qualitative assessment phase is a necessary prerequisite for a subsequent quantitative phase.

The qualitative analysis is based on subjective judgement marks obtained by evaluating and ranking the discrepancies between the measured and calculated parameters that describe the phenomena. These marks are:

– **Excellent**: the code predicts the parameter within the experimental uncertainty band;
– **Reasonable**: the code generally predicts the phenomena, the time behaviour and the trends;
– **Minimal**: the code does not predict the parameter or the phenomenon, but the reason for this is understood and predictable;
– **Unqualified**: the code does not predict the parameter, and the reason is not understood.

The subsequent quantitative assessment can be managed by applying the SARBM and the FFTBM. It should be noted that the SARBM and the FFTBM do not allow the identification of the error origin (i.e. the user effect, the wrong initial condition, the nodalization model deficiency, etc.) or to take into account directly the time shift of certain phenomena in the quantitative analysis. The time shift is better characterized through the necessary qualitative assessment that must be associated with the quantitative assessment.

2 A DESCRIPTION OF THE MODELLING

2.1 A description of the BETHSY facility

BETHSY is an integral experimental facility whose purpose was to investigate pressurized-water reactor (PWR) accident transients. The reference plant is a three-loop 2775 MWt Framatome PWR plant. The volume scaling is close to 1:100, while the elevations and pressures are preserved [16]. The core power has been limited to decay heat levels. This obviously implies that accident transients without scram could not be investigated.

2.2 Opis vhodnega modela za RELAP5

Razviti splošni vhodni model BETHSY za RELAP5 je bil optimiran na temelju predhodnih modelov ([7], [9], [17] in [18]). Potem je bil potrjen [20] v skladu z mednarodnimi priporočili (geometrijska oblika, ustaljeno stanje, itn.). Vsako od treh zank smo modelirali posebej ne da bi upoštevali majhno asimetrijo, ki vlada med zankami. Modelirali smo vse pomembne dele reaktorskega hladilnega sistema: cevovode reaktorskega hladilnega sistema, črpalko reaktorskega hladiva, sredico, povratni kanal v reaktorski posodi in uparjalnike. Sekundarna stran sestoji iz uparjalnikov in cevovodov. Vhodni model BETHSY za RELAP5 vsebuje 398 vozlišč, 408 spojev in 402 toplotni telesi s 1573 mrežnimi točkami.

2.3 Izbrani poskusi BETHSY

Za kvalifikacijo metode NSA z metodo HFP so bili izbrani poskusi, izvedeni na poskusni napravi BETHSY (Boucle d'Études Thermohydrauliques de Systemes)*. Prvi izbrani poskus je bil BETHSY 6.2 TC, to je 15,24 cm (6-palčni) zlom v hladni veji brez visokotlačnega in nizkotlačnega varnostnega vbrizgavanja (dvojnik poskusov, izvedenih na Veliki poskusni napravi (Large Scale Test Facility - LSTF), na Zanki za preučevanje neobičajnega obnašanja (Loop for Off-normal Behaviour Investigation (LOBI) in Simulatorju za varnostne preskuse (Simulatore per esperienze di sicurezza - SPES)).

Drugi izbrani poskus je bil BETHSY 9.1b, 5,08 cm (2-palčni) zlom v hladni veji z zamujenim končnim posegom, znan tudi kot mednarodni standardni problem št. 27.

Tretji izbrani poskus je bil BETHSY 4.1a TC, kjer so simulirali naravno pretakanje (dvojnik s poskusom na LSTF).

Eksperimentalne podatke smo dobili skupaj s pripadajočimi nezanesljivostmi. Npr.: negotovosti za tlak in temperaturo poskusa BETHSY 9.1b, ki ju prikazuje slika 2, sta 0,18 MPa oz. 4 K [19].

3 REZULTATI

Uporabljen je bil postopek za določitev natančnosti izračuna, opisan v 1. poglavju. V kakovostni fazi ocene z vizualnim opazovanjem grafično prikazanih rezultatov smo prehodne pojave najprej razdelili v časovna okna. Potem smo vizualno opazovali rezultate in jih kakovostno ocenili. Da bi dobili vtis o poteku prehodnih pojavov, slika 2 kaže primarni tlak in temperaturo grelne palice v vrhnjem delu sredice za izmerjene eksperimentalne podatke in rezultate, izračunane z RELAP5/MOD3.2 za izbrane poskuse na BETHSY. Primer subjektivne ocene kot del kakovostne analize je prikazan v preglednici 3. Zaradi kratkosti so grafi za druge spremenljivke in

2.2 A description of the RELAP5 input model

The developed universal RELAP5 input model for BETHSY was optimised based on previous models ([7], [9], [17] and [18]). Then it was qualified [20] according to the international guidelines (geometry, steady-state etc.). Each of the three loops was represented explicitly without taking into account the small asymmetry between the loops. All major reactor coolant system components were modelled: reactor coolant system piping, reactor coolant pumps, core section, reactor vessel downcomer and steam generators. The secondary side consists of steam generators and steamlines. The RELAP5 input model of the BETHSY facility contains 398 volumes, 408 junctions and 402 heat structures with 1573 mesh points.

2.3 Selected BETHSY experiments

For qualification of the SARBM with the FFTBM three experiments performed on the Boucle d'Etudes Thermohydrauliques de Systemes (BETHSY) were selected. The first selected experiment was BETHSY 6.2 TC, a 15.24-cm (6-inch) cold leg break without a high- and low-pressure safety-injection system (counter-part test with Large Scale Test Facility (LSTF), Loop for Off-normal Behaviour Investigation (LOBI) and Simulatore per esperienze di sicurezza (SPES)).

The second selected experiment was BETHSY 9.1b, 5.08-cm (2-inch) cold leg break without a high-pressure injection system and with a delayed ultimate procedure, also known as the international standard problem ISP-27.

The third experiment selected was the BETHSY 4.1a TC natural circulation test (counter-part test with LSTF).

The experimental data were obtained with associated measurement uncertainties. For example, the uncertainty of the pressure and the temperature for BETHSY 9.1b, shown in Figure 2, are 0.18 MPa and 4 K, respectively [19].

3 RESULTS

The methodology for quantifying the code accuracy described in Section 1 was used. In the qualitative assessment phase, including a visual observation of the plotted results, the transients were first subdivided into time windows. Then a visual observation with a qualitative assessment was performed. To give a picture of the transient progression, Fig. 2 shows the primary pressure and the heater-rod temperature at the top of the core for experimental and RELAP5/MOD3.2 calculated results for the selected BETHSY transients. An example of subjective judgement as part of the qualitative analysis is shown in Table 3. For brevity, the other plots and all

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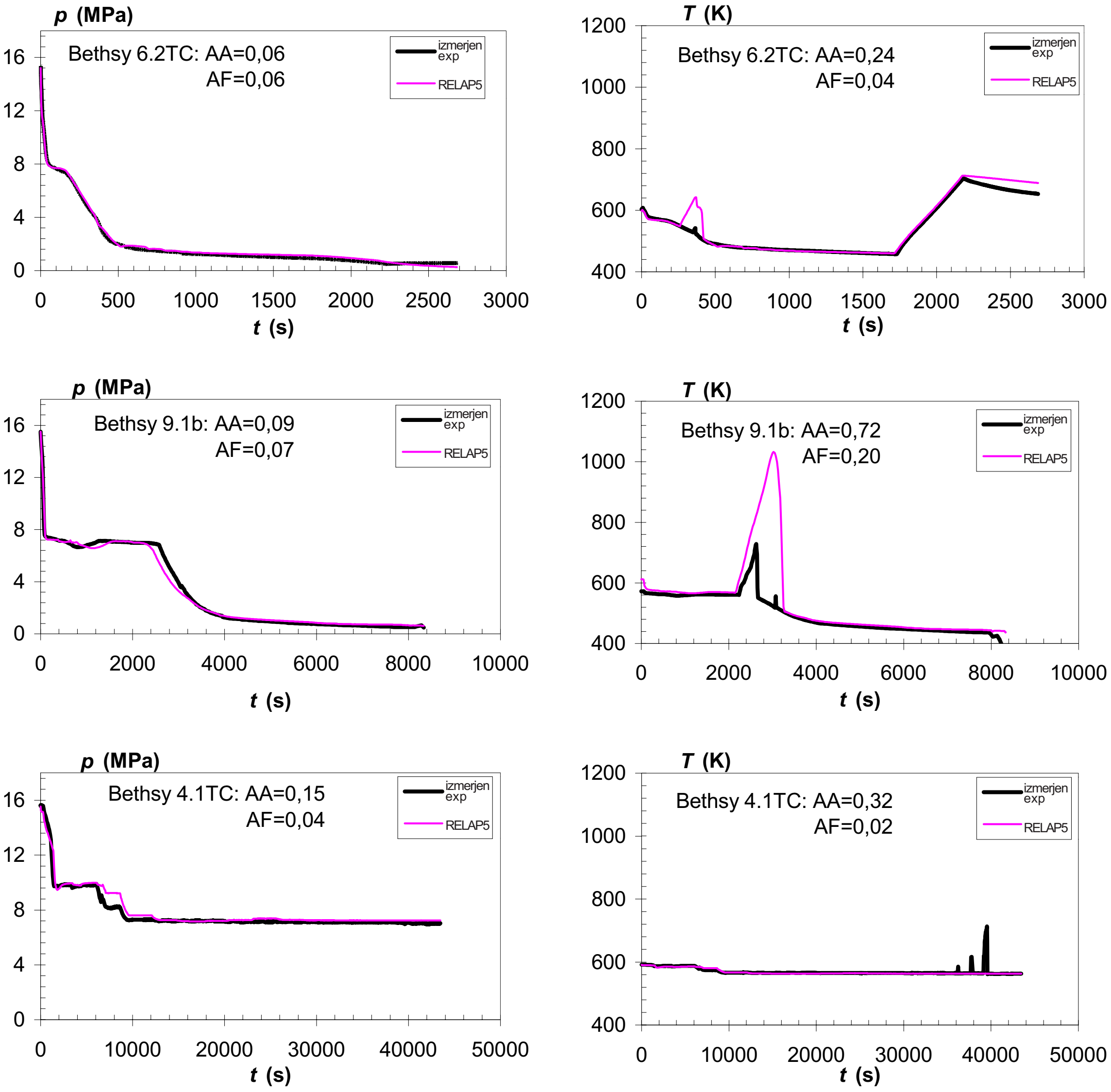
* Zanka za toplotnohidravlično preučevanje sistemov



Sl. 2. *Primarni tlak in temperatura srajčke za poskuse BETHSY*

Fig. 2. *Primary pressure and cladding temperature for BETHSY experiments*

vse podrobnosti kakovostnih analiz na tem mestu izpuščeni – bralec naj se obrne na [20].

Za kakovostno analizo so bila uporabljena časovna območja, določena na temelju časovnih oken. Za poskus na BETHSY 6.2 TC so bila za analizo natančnosti uporabljena štiri časovna območja: od odprtja zloma do časa izpraznjenja sifona (0 do 140 s), do časa vklopa akumulatorjev (0 do 350 s), do konca vbrizgavanja akumulatorjev (0 do 980 s), in do konca prehodnega pojava (0 do 2687 s). Za poskus BETHSY 9.1b so bila za analizo izbrana tri časovna območja: od trenutka zloma do časa vklopa akumulatorjev (0 do 2962 s), do časa vklopa nizkotlačnega varnostnega vbrizgavanja (0 do 5177 s) in do konca prehodnega pojava (0 do 8330 s). Za poskus BETHSY 4.1a TC so bila za analizo natančnosti ponovno uporabljena tri časovna območja: od začetka prehodnega pojava do konca pojava enofazne naravne cirkulacije (0 do 4380 s), do konca pojava dvofazne naravne cirkulacije (0

the details of the qualitative assessment are not provided in this paper – the reader is referred to [20].

For the quantitative analysis, time intervals were determined based on the time windows. For BETHSY 6.2 TC four time intervals were chosen for the accuracy analysis: from the time of the opening of the break to the time of loop-seal clearance (0 to 140 s), to the time of accumulators start (0 to 350 s), to the end of accumulator injection phase (0 to 980 s), and to the transient end (0 to 2687 s). For BETHSY 9.1b accuracy analysis, three time intervals were selected: from the break occurrence to the time of accumulator injection start (0 to 2962 s), to the time of the low-pressure injection system start (0 to 5177 s), and to the transient end (0 to 8330 s). For the BETHSY 4.1a TC accuracy analysis also three time intervals were selected: from the beginning to the end of the single-phase natural circulation (0 to 4380 s), to the end of the two-phase natural circulation phase (0 to

Preglednica 2. *Meje sprejemljivosti za natančnost izračuna [2]*
Table 2. *Acceptability limits for calculation accuracy [2]*

NSA - SARBM	**Mera Measure**	**HFP - FFTBM**
$AF_{\mathrm{tot}} \leq 0{,}1$	zelo dobro very good	$AA_{\mathrm{tot}} \leq 0{,}3$
$0{,}1 < AF_{\mathrm{tot}} \leq 0{,}25$	dobro good	$0{,}3 < AA_{\mathrm{tot}} \leq 0{,}5$
$0{,}25 < AF_{\mathrm{tot}} \leq 0{,}45$	slabo poor	$0{,}5 < AA_{\mathrm{tot}} \leq 0{,}7$
$AF_{\mathrm{tot}} > 0{,}45$	zelo slabo very poor	$AA_{\mathrm{tot}} > 0{,}7$

Preglednica 3. *Subjektivna ocena izračuna za eksperiment na BETHSY 9.1b [20]*
Table 3. *Subjective judgement of code calculation of BETHSY 9.1b experiment [20]*

Pojav Phenomenon	**Parameter, ki opisuje pojav Parameter describing phenomenon**	**preskus exp.**	**R5**	**Ocena Judgement**
1. okno: 0 do 2962 s 1st window: 0 to 2962 s				
praznjenje tlačnika pressurizer emptying	tlačnik izpraznjen (s) pressurizer empty (s)	116	125	E
obnašanje primarnega tlaka primary pressure behaviour	primarni tlak (PT) v 2900. s (MPa) primary pressure (PP) at 2900. s (MPa)	4,5	3,66	R
obnašanje sekundarnega tlaka secondary pressure behaviour	sekundarni tlak (ST) v 2900. s (MPa) secondary pressure (SP) at 2900. s (MPa)	4,4	3,52	R
iztok hladiva skozi zlom break flow	povprečen iztok hladiva skozi zlom (kg/s) average break flow (kg/s)	0,53	0,51	E
2. okno: 2962 s do 5177 s 2nd window: 2962 s to 5177 s				
obnašanje akumulatorjev accumulators behaviour	čas vklopa akumulatorjev (s) accumulator injection start (s)	2966	2800	R
	čas izklopa akumulatorjev (s) accumulator injection stop (s)	3856	3900	R
iztok hladiva skozi zlom break flow	čas, ko se PT izenači s ST (s) the time PP equals SP (s)	2366	2275	E
	povprečen iztok hladiva skozi zlom (kg/s) average break flow (kg/s)	0,097	0,112	R
praznjenje sifonov loop seal clearing	čas izpraznitve sifona (s) time of loop seal clearing (s)	-	1975	M
izsušitev sredice core dryout	čas izsušitve sredice (s) time of core dryout (s)	3036	2800	R
	najvišja temperatura srajčke (K) peak cladding temperature (K)	734	1103	M
3. okno: 5177 s do 8330 s 3rd window: 5177 s to 8330 s				
delovanje nizkotlačnega varnostnega vbrizgavanja (LPIS) low pressure injection system (LPIS) intervention	čas vklopa LPIS (s) LPIS start (s)	5184	5775	R
	količina dovedenega hladiva z LPIS (kg) total mass delivered by LPIS (kg)	3077	2049	M

E – odlično, R – sprejemljivo, M – komaj sprejemljivo, R5 – RELAP5
E - excellent, R - reasonable, M – minimal, R5 – RELAP5

do 29375 s) in do konca pojava povratne kondenzacije (0 do 43461 s).

Za analizo natančnosti so bile uporabljene iste spremenljivke, skupno 23 (21 v primeru poskusa 9.1b). Preglednica 4 kaže rezultate kolikostne analize za poskus BETHSY 9.1b za izbrana časovna območja. Izbrane spremenljivke so bile: primarni tlak (PP), sekundarni tlak (P47), tlak v akumulatorju (PSM2), vstopna temperatura v sredico (TF012A), izstopna temperatura iz sredice (TF0304), temperatura hladiva

29375 s), and to the end of reflux condensation mode (0 to 43461 s).

The same set of 23 variables (21 in the case of the 9.1b test) was selected for calculating the code accuracy. Table 4 shows the results of the quantitative analysis for the BETHSY 9.1b test in the three selected time intervals. The selected variables were: pressurizer pressure (PP), secondary pressure (P47), accumulator pressure (PSM2), core inlet temperature (TF012A), core outlet temperature (TF0304), upper-v glavi reaktorske posode (TF042), integrirani pretok skozi zlom (INTQMB), temperatura v povratnem kanalu uparjalnika (SG) št. 1 (TF454C), masni iztok hladiva (QMB), integrirani pretok sistema za zasilno hlajenje sredice (INTQMS), temperatura srajčke (sredina sredice) (TS0215), temperatura srajčke (vrh sredice) (TS0228), sesedna raven hladiva v sredici (ZT0200), tlačna razlika v ceveh U uparjalnika št. 1 (tok navzgor) (DP426), tlačna razlika v uparjalniku št. 1 (DP4), moč sredice (W02), tlačna razlika v sifonu št. 1 (tok navzdol) (DP12VG), tlačna razlika v sifonu št. 1 (tok navzgor) (DP12VP), tlačna razlika v tlačniku (DPP1), tlačna razlika na vstopu v uparjalnik št. 1 (DP41) in tlačna razlika v glavi reaktorske posode (DP050). Za primarni tlak se pri metodi HFP zahteva večja natančnost (PA - AA=0,1) kakor za druge spremenljivke, saj tlak narekuje potek prehodnega pojava. Razen za poskus BETHSY 4.1a TC je bil kriterij za tlak izpolnjen, kar se vidi na sliki 2. Kljub temu lahko vidimo, da je za poskus BETHSY 4.1a TC količnik natančnosti boljši kakor v preostalih dveh primerih. Do razlike pride zaradi različnih značilnosti metod NSA in HFP. Ko si vizualno pogledamo poteke tlakov na sliki 2, lahko sklenemo, da je ujemanje za primarni tlak zelo dobro.

Preglednica 5 kaže skupno natančnost za izbrane prehodne pojave v različnih časovnih območjih. Ko med seboj primerjamo metodi (na podlagi mej sprejemljivosti za skupno natančnost), se rezultati ujemajo zelo dobro. Edina izjema je BETHSY 6.2 TC, kjer je metoda HFP dala oceno zelo dobro (rahlo pod mejo za zelo dobro) in NSA oceno dobro (rahlo nad mejo za zelo dobro) v prvem in četrtem časovnem območju. Izračun BETHSY 9.1b je bil z obema metodama ocenjen kot dobro v vseh časovnih območjih, medtem ko je bil izračun poskusa BETHSY 4.1a TC ocenjen kot zelo dobro v vseh časovnih območjih. S tem smo pokazali, da NSA daje primerljive rezultate kot preverjena metoda HFP. Ko metodi dasta različne rezultate, je potrebna podrobna analiza z vizualnim opazovanjem, da presodimo pomembnost razlike.

4 SKLEPI

V študiji je bila predstavljena nova razvita metoda NSA za oceno natančnosti. Za njeno preveritev smo uporabili tri različne poskuse, izvedene na eksperimentalni napravi BETHSY. Dobljene ocene smo primerjali z rezultati ocenjevanja z metodo HFP.

Prvi pomemben rezultat raziskave je bila ugotovitev, da je natančnost, izračunana z metodo NSA, v časovnem prostoru primerljiva z izračuni natančnosti z metodo HFP v frekvenčnem prostoru. Izračuni z računalniškim programom RELAP5/MOD3.2 za različne poskuse so bili ocenjeni kot zelo dobri ali dobri. Rezultati kažejo, da je bolje združiti metodi NSA in HFP za oceno natančnosti kakor pa metodo NSA

head top temperature (TF042), integrated break mass flow (INTQMB), steam generator (SG) no. 1, downcomer bottom temperature (TF454C), break flow (QMB), integrated emergency core cooling system mass flow (INTQMS), cladding temperature (middle) (TS0215), cladding temperature (top) (TS0228), core collapsed level (ZT0200), SG no. 1 U-tube upflow differential pressure (DP426), SG no. 1 U-tube inlet to outlet differential pressure (DP4), core power (W02), loop seal 1 downflow differential pressure (DP12VG), loop seal 1 upflow differential pressure (DP12VP), pressurizer differential pressure (DPP1), SG no. 1 inlet plenum differential pressure (DP41) and downcomer to upper head differential pressure (DP050). For primary pressure the FFTBM method requires higher accuracy (AA=0.1) than for other variables as the pressure determines the sequence of events for a transient. Except for BETHSY 4.1a TC this criterion was achieved, which can be seen in Figure 2. However, when looking at the accuracy factor, the highest accuracy was obtained for the BETHSY 4.1a TC test. This is because of the different characteristics of the methods. When visually observing the pressure trends in Figure 2 it can be concluded that the agreement for the primary pressure is very good.

Table 5 shows the total accuracy obtained for the selected transients for different time intervals. When comparing the methods (based on the acceptability limits for total accuracy) the results agree very well. The only exception was BETHSY 6.2 TC, where the FFTBM gave very good (slightly below the limit for very good) and the SARBM gave good (slightly above the limit for very good) in the first and fourth time intervals. The BETHSY 9.1b calculation was quantified with both methods as good for all the time intervals, while the BETHSY 4.1a TC calculation was quantified as very good for all time intervals. With this it was shown that the SARBM gives results comparable to the qualified FFTBM. When the methods give different results, a detailed analysis with visual observation is needed to judge the importance of the difference.

4 CONCLUSIONS

In this study the developed SARBM for accuracy quantification was presented. For its validation three different tests performed on the BETHSY facility were used. The obtained accuracy was compared against the results of accuracy quantification by the FFTBM.

The first key result of the investigation was that the calculation accuracy obtained with the SARBM in the time domain is comparable to the calculation accuracy obtained with the FFTBM in the frequency domain. The RELAP5/MOD3.2 calculations of various experiments were quantified as very good or good. The results suggest combining the SARBM with the FFTBM for accuracy quantifica-

Preglednica 4. *Rezultati kolikostne analize za poskus BETHSY 9.1b*
Table 4. *Results of quantitative analysis of BETHSY 9.1b experiment*

Št. No.	**Parameter Parameter**	**Časovno območje - Time interval**					
		0 do/to 2962 s		**0 do/to 5177 s**		**0 do/to 8330 s**	
		AA	***AF***	***AA***	***AF***	***AA***	***AF***
1	PP	0,13	0,07	0,08	0,07	0,09	0,07
2	P47	0,20	0,07	0,10	0,07	0,10	0,07
3	PSM2	0,36	0,03	0,11	0,05	0,12	0,06
4	TF012A	0,05	0,01	0,03	0,01	0,09	0,02
5	TF0304	0,34	0,05	0,37	0,05	0,36	0,04
6	TF042	0,30	0,04	0,25	0,06	0,22	0,05
7	INTQMB	0,05	0,07	0,05	0,04	0,20	0,16
8	TF454C	0,10	0,03	0,07	0,03	0,08	0,02
9	QMB	0,69	0,32	0,69	0,34	0,85	0,45
10	INTQMS	0,00	0,00	1,00	1,00	0,35	0,44
11	TS0215	1,10	0,20	0,69	0,19	0,58	0,16
12	TS0228	1,37	0,20	0,79	0,23	0,72	0,20
13	ZT0200	0,23	0,12	0,32	0,11	0,39	0,12
14	DP426	0,63	0,31	0,63	0,31	1,41	0,31
15	DP4	0,56	0,65	0,55	0,65	0,58	0,64
16	W02	0,09	0,06	0,09	0,05	0,12	0,05
17	DP12VG	1,33	0,46	0,99	0,47	0,67	0,34
18	DP12VP	0,87	0,18	0,88	0,21	1,08	0,20
19	DPP1	0,13	0,14	0,12	0,14	0,14	0,16
20	DP41	1,16	0,68	1,16	0,68	1,30	0,79
21	DP050	0,83	0,94	0,83	0,94	0,88	0,95
	skupaj total	**0,41**	**0,20**	**0,35**	**0,16**	**0,34**	**0,14**

Preglednica 5. *Ocena skupne natančnosti izračunov s HFP in NSA*
Table 5. *Total accuracy obtained by FFTBM and SARBM*

Časovno območje time interval	**BETHSY 6.2 TC**		**BETHSY 9.1b**		**BETHSY 4.1a TC**	
	AA_{tot}	AF_{tot}	AA_{tot}	AF_{tot}	AA_{tot}	AF_{tot}
1.	0,08	0,13	0,41	0,20	0,09	0,04
2.	0,20	0,09	0,35	0,16	0,13	0,05
3.	0,16	0,08	0,34	0,14	0,17	0,06
4.	0,27	0,11	-	-	-	-

uporabljati samostojno, ker se njuni oceni dopolnjujeta in združeni povečujeta zaupanje v rezultate.

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tion rather then using it independently. Namely, the results complement each other and when combined they increase confidence in the results.

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