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Software Package for Three-Dimensional Visualization of the Behavior of Neutron Fields and Archived Parameters During the Operation of the RBMK-1000 Reactor

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Abstract

This paper describes the calculation algorithm, software package and visualization of the three-dimensional neutron field deformation according to the archive of the RBMK (high-power pressure-tube reactor) reactor operational parameters. The determination of the field deformation is based on finding "natural" functions for approximating the readings of in-reactor control discretely located sensors. This paper considers the use of generally accepted harmonic functions and "natural" functions for describing the spatial deformation of the neutron field. It is shown that to describe the deformation of the neutron field, it is sufficient to use only a few "natural" functions, in contrast to the use of all harmonic functions from a given set. This, in turn, opens up new possibilities, in particular, for solving the problems of predictive diagnostics of in-reactor control sensors.

Keywords: nuclear reactor, neutron flux density, natural functions, energy release control sensors, scientific visualization.

1. Introduction

The RBMK nuclear reactor (high-power channel reactor) is a physical object, which state is described by a set of spatially distributed parameters - physical fields that require constant monitoring and control [1].

One of the most important fields is the three-dimensional neutron field. Despite the developed control and regulation system [2], the impact of many random factors leads to deformation of the neutron field, i.e. changes in the neutron field in space and time.

The traditional theoretical approach to the conditions for occurrence and description of the nature of the neutron field deformations is based on the solution of the spatial dynamics equations with feedback on the temperature of the fuel, coolant, moderator, coolant void fraction, etc. [9,10]. In this case, the solution of the problem is represented in the form of a Fourier series:

$$\delta\varphi(\vec{r},t) = \sum_{i}^{n} A_i\,(t)\psi_i(\vec{r}) \tag{1}$$

where $A_i(t)$ – is the amplitude factor responsible for the time behavior of the function $\psi_i(\vec{r})$; $\psi_i(\vec{r})$ – are the known eigenfunctions of the stationary reactor problem (2).

$$\hat{L}\psi_i(\vec{r}) = \lambda_i\psi_i(\vec{r}) \qquad \psi_i(\vec{r})|_S = 0 \tag{2}$$

where $\hat{L}$ - operator of the stationary reactor problem. For example, in the diffusion one-group approximation having the form:

$$\hat{L} = \Delta + \varkappa_0^2(\vec{r}) \tag{3}$$

where Δ – Laplace operator; $\varkappa_0^2(\vec{r})$ – function describing the multiplying properties of a medium.

When describing the deformation of the neutron field in practice, such an approach inevitably encounters the problem that the function $\varkappa_0^2(\vec{r})$ - is not exactly known due to the presence of many random perturbing factors [7, 8]. Consequently, the real eigenfunctions $\{\psi_i\}$ by which the deformation of the field (1) is represented are also unknown. Moreover, the function $\delta\varphi(\vec{r},t)$ itself is a random function.

If we consider a nuclear reactor as an object with random parameters, then it allows a new approach to the choice of a set of coordinate functions $\{\psi_i\}$, namely, using the theory of canonical expansions of a random function [3]. It is shown in [4] that the functions of the canonical expansion of the neutron flux density, obtained as a result of processing the archive of operating parameters, are the eigenfunctions of a really operating reactor. Further in this paper, these functions will be called "natural" functions, in contrast to the generally accepted eigenfunctions of the boundary value problem (2). It is clear from physical considerations that if "natural" functions are used as coordinate functions in expansion (1), then the deformation of the field can be described by a smaller number of terms of the series. It was shown in [11] that when determining the deformation of the neutron flux density distribution over the height of the RBMK reactor, two natural functions are sufficient. In this case, the initial information for the search for high-altitude "natural" functions was the readings of the sensors for monitoring the energy release in height (ERCS), which consisted of four measuring sections. Note that the results obtained in this work, firstly, make it possible to restore the lost measurement information even in the event of failure of two measuring sections, and secondly, they open up opportunities for diagnosing the operability of individual sections of the ERCS. At the same time, the disadvantage of this work is the fact that the height deformations were considered isolated from the deformation of the three-dimensional field as a whole, although they should be only "sections" of the three-dimensional deformations of a single neutron field in a nuclear reactor [6].

In this paper, with the help of "natural" functions, three-dimensional deformations of the neutron field are determined from the readings of in-core control sensors discretely located in the volume of the reactor.

2. Algorithm for calculating "natural" three-dimensional deformation functions of the neutron field

In the RBMK reactor, 76 four-section ERCS sensors are installed to monitor the neutron field in the core volume [5]. Thus, in the core volume, the neutron field is measured at 304 points. From the mathematical point of view, the problem of determining the deformation of the neutron field is reduced to the problem of approximating point measurements by a set of known continuous functions. The most important step in the approximation is the choice of the approximating dependence. In this case, the form of the approximating dependence is determined empirically, taking into account physical considerations, from which it follows that the deformation of the field can be described by a set of smooth functions, in contrast to the neutron field itself, which has a sharply inhomogeneous character. In this work, deformation means the deviation of the neutron field at time t from a certain initial field at time t = 0. In accordance with the method for determining the "natural" functions of the reactor [4, 12, 13], at the first stage, a standard Fourier expansion in terms of the eigenfunctions of a known boundary value problem is set, for example, for a homogeneous cylinder-shaped reactor. In order to simplify calculations in this work, the initial set is taken in the form

$$\delta\varphi(\theta,r,h) = \sum_{i=1}\sum_{j=1}\sum_{k=1} A_{ijk} cos\,(i\theta) cos\,(j\frac{\Pi r}{R}) sin\,(k\frac{\Pi h}{H}) \qquad (4)$$

where, instead of the Bessel functions, the trigonometric functions are used to describe the radial dependence.

Later on, the algorithm is divided into the following stages:

- A time interval is selected for calculating field deformations.
- From the archive of operational parameters, readings of sensors are read and their deviations from the initial value are calculated.
- The obtained values are approximated by harmonic functions by the least squares method and the coefficients are found A_{ijk}.
- The statistical characteristics of the coefficients are determined A_{ijk}.
- A well-known procedure is used to search for new expansion functions for which the coefficients turn out to be uncorrelated.

3. Software package for visualization of field deformation

The algorithm described above is implemented in a software package designed to study the dynamics of neutron fields in nuclear reactors based on data from archived operational parameters, computational and experimental determination and visualization of the "natural" functions of the reactor during operation. This program was developed in the C ++ programming language in the Qt Creator 5.15 development environment (a cross-platform free development environment for developing programs in C, C ++ and QML).

Currently, there is already one software package for visualization of archived data of the RBMK reactor, described in [14]. This program is intended for the analysis of archived data and visualization of various parameters of a nuclear power unit with a RBMK-type reactor. The archive data there is visualized in two-dimensional form. The software package described in this paper visualizes the data in three-dimensional form, allowing the user to fully interact with the rendered three-dimensional scene, and also calculates and visualizes the neutron field deformation by applying the algorithm for calculating "natural" functions described above.

The software package is functionally divided into three modules (Figure 1):

- data extraction module (designed to extract data from the operational archives of the «SKALA-MICRO» system);
- data processing module (designed to process the extracted data);
- data visualization module (designed for three-dimensional visualization of the extracted data and operations performed on them).

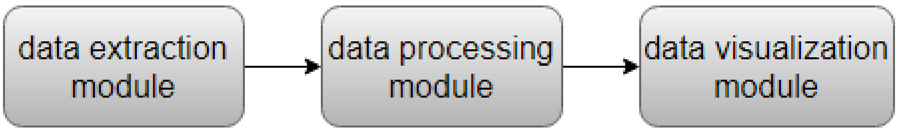

Figure. 1. Block diagram of the software package.

Figure 2 shows the software package operation diagram.

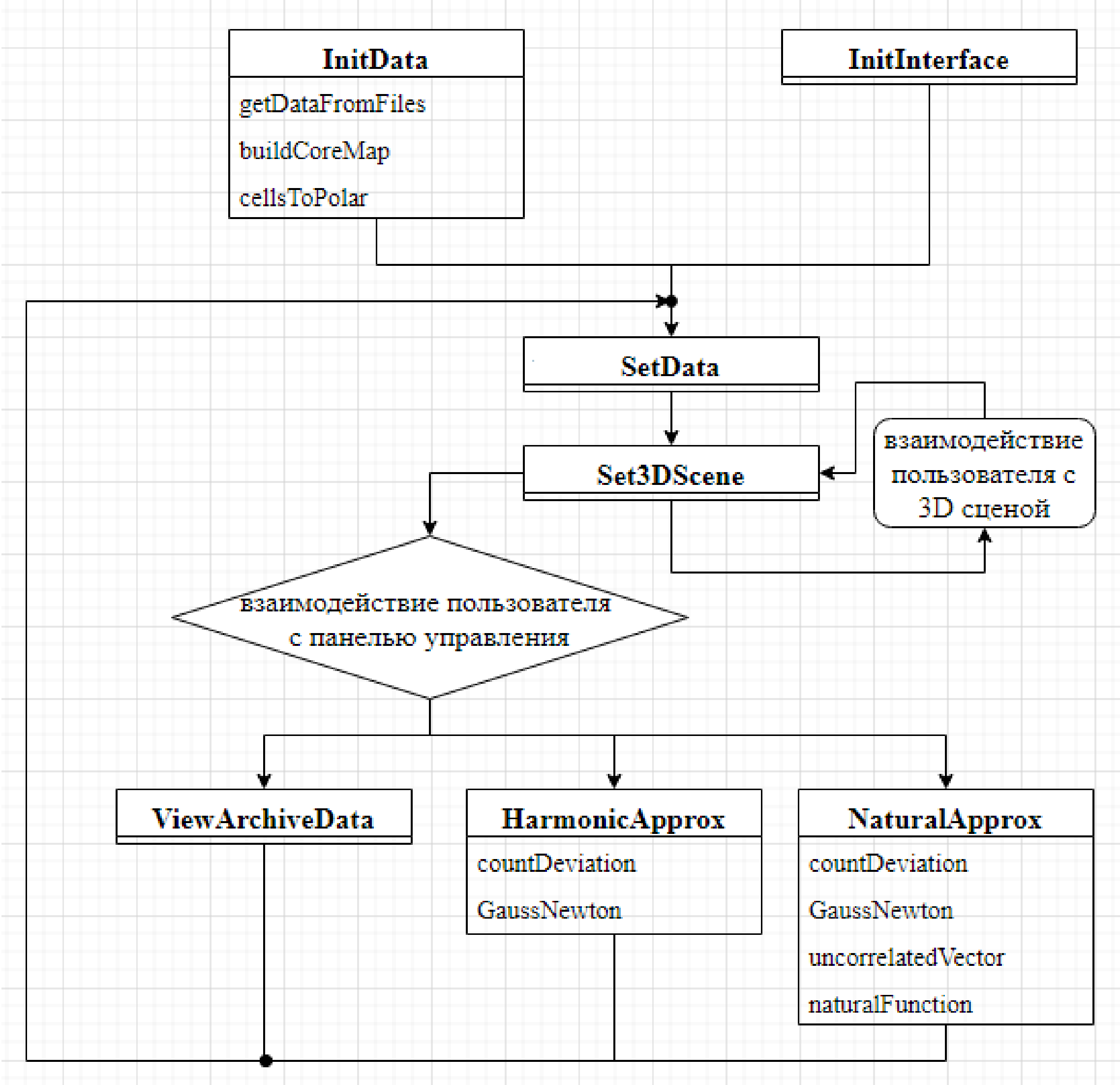

Figure. 2. Software package operation diagram.

InitInterface and InitData are methods that are called when the program starts. InitInterface is responsible for creating a general program interface (initializing and displaying all widgets, in particular the user control panel, with the exception of the 3D scene - it is drawn separately). InitData is responsible for initializing constants and arrays of processed data:

- getDataFromFiles - data extraction from the operational archives of the «SKALA-MICRO» system (data extraction occurs as follows: the PostgreSQL database parameters are loaded from the config.xml file, after which a connection is created using the loaded configuration with the database; the connection is asked for a list of dates for which there are time slices in the database, after which, when sequentially enumerating each slice, the data itself for the current slice is requested directly);
- buildCoreMap – building a cartogram of the core;
- cellsToPloar – the coordinates of the core cells are converted to polar coordinates (θ, r).

SetData - fills data arrays with values of parameters or functions, which will later be rendered by the Set3DScene method and displayed.

Set3DScene is a method responsible for rendering a 3D scene (a rendered scene representing a three-dimensional model of a cartogram of the nuclear reactor core). The method is called when the user interacts with the control panel, or directly with the scene itself.

When interacting with the control panel, depending on the user's choice, the following events are possible:

- ViewArchiveFiles – the method is called to display the system parameters in the selected time slice;
- HarmonicApprox – builds approximating three-dimensional harmonic functions. At runtime, calls the countDeviation methods (calculating the deviations of the ERCS sensors of the selected time slice from the initial one), GaussNewton (Gauss-Newton algorithm for calculating the coefficients of the approximating function by nonlinear least squares method);
- NaturalApprox – builds a 3D natural function. At runtime, it calls the methods countDeviation, GaussNewton, uncorrelatedVector (transition from correlated coefficients A_i to uncorrelated V_i), naturalFunction (calculation of natural functions themselves).

Then the program calls the SetData and Set3DScene methods again to re-render the 3D scene.

Figure 3 shows the user interface of the developed software package.

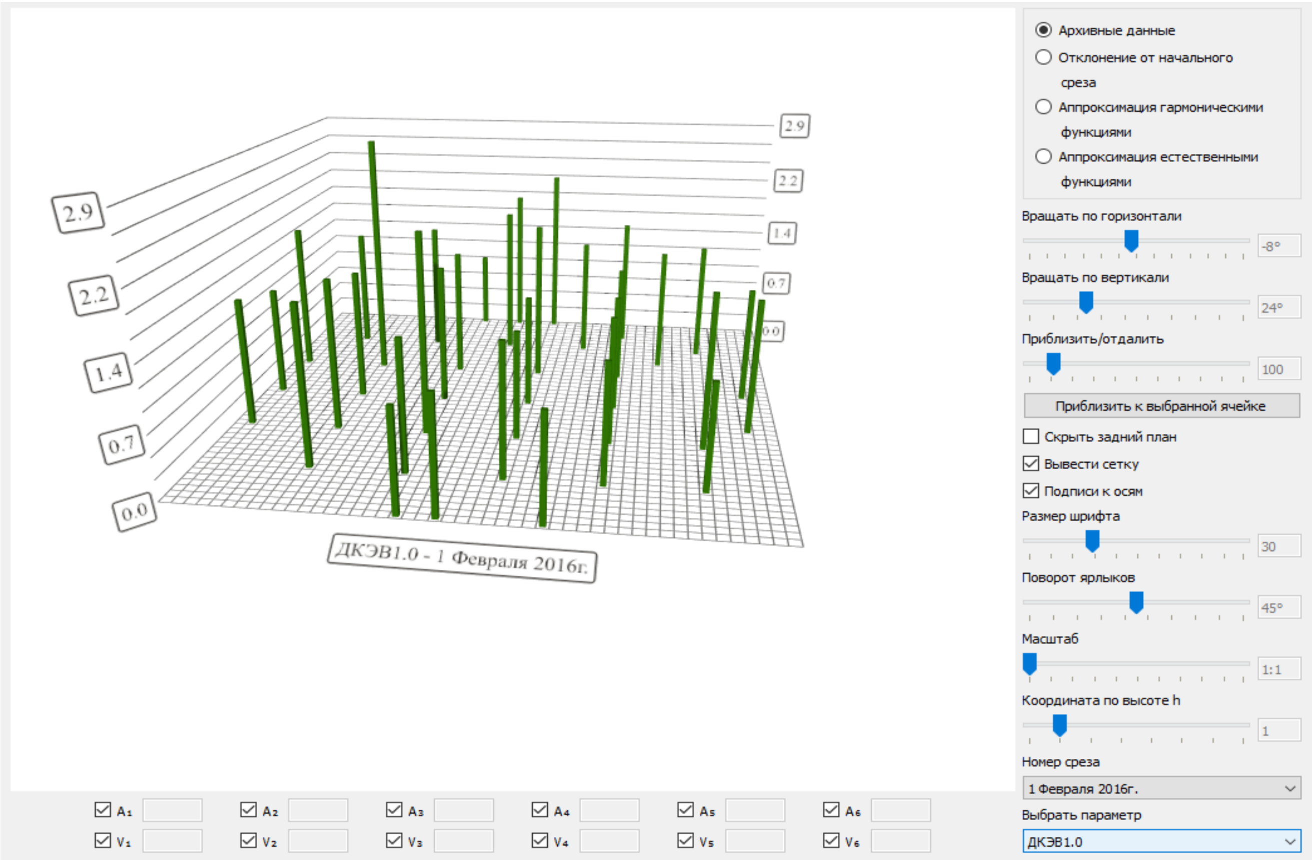

Figure 3: User interface of the software package

In the center of the window there is a visualized scene representing a three-dimensional model of the nuclear reactor core cartogram. The plane (x, y) corresponds to the cross-section of the core, divided into cells of equal size. By height, the value of any parameter or function is displayed in the cell for the corresponding coordinate along the height of the core. Depending on the selected visualization mode (output of archived data, output of deviations from the initial time slice, approximation of ERCS values by harmonic functions and approximation of ERCS values by natural functions), the scene displays either the values of the selected parameters in the form of three-dimensional rods (bars), or smooth three-dimensional functions.

User interaction with the rendered scene is mainly achieved by using the control panel located on the right side of the window. With its help, user can control the interface (font, scale, etc.), the position of the camera, select the visualization mode, access and process the archived data of the «SKALA-MICRO» information system. In addition to using the control panel, user can zoom in / out the camera using the mouse wheel. Left mouse button click on the rendered scene calls the corresponding method that determines exactly where the click was made. If the click was made on a cell of the nuclear reactor core cartogram, then coordinates of the cell and its selected parameter value are displayed on the screen. If the parameter value in the cell is zero or the click was made not on the cell of the cartogram, then the selection does not occur. There is a detailed description of the user control panel below.

In the upper right corner, user can select one of the data visualization modes:

- archived data - displays the archived data of the «SKALA-MICRO» system in the form of three-dimensional bars, the coordinate of the bar on the plane (x, y) corresponds to the coordinate of the core cell, and the height corresponds to the value of the selected parameter for the corresponding cell;
- deviation from the initial slice - displays the difference between the values of the archived data in the selected time slice for the corresponding parameter and the values of the initial slice, the resulting values are displayed as three-dimensional bars, the bar height corresponds to the deviation value for the corresponding core cell;
- approximation by harmonic functions - displays on the screen a smooth three-dimensional graph of a set of approximating harmonic functions $\{\Psi_k\}$, corresponding to the selected coordinate along the height of the core h for the corresponding number of the time slice;
- approximation by natural functions - displays on the screen a smooth three-dimensional graph of the set of approximating natural functions $\{\widetilde{\Psi}_k\}$, corresponding to the selected coordinate along the height of the core h for the corresponding number of the time slice;

The control panel allows the user to control the camera by moving the corresponding sliders responsible for rotating the camera horizontally and vertically and for zooming in and out. The button "zoom in to the selected cell" brings the camera to the selected cell as close as possible, if any cell is selected. If there is no selection, the camera moves to its original position, i.e. to the position of the camera when starting the program.

Among other things, the control panel allows user to adjust the user interface by changing the font size of the labels, the scale of 3D bars, the display of the grid, etc.

The “height coordinate” button is responsible for choosing a coordinate along the height of the core. Each coordinate has its own harmonic and natural approximating function (the distribution of the neutron flux density φ(θ, r, h) depends on the cell coordinate (θ, r) and on the coordinate along the core height h).

The "time slice number" button is responsible for choosing a time slice in the considered period of time. For example, this paper considers archive data for the month of February 2016 with a one-day frequency.

The "select parameter" button is responsible for selecting a parameter (for example, power generation, power, ERCS, etc.), for which, depending on the visualization mode, a three-dimensional model will be built.

At the bottom of the screen there is a panel responsible for the approximation coefficients of the harmonic and natural functions A_i and V_i. When the mode "approximation by harmonic functions" is selected in the control panel, the program displays calculated coefficients A_i for the corresponding time slice. When the mode "approximation by natural functions" is selected, the program displays the calculated coefficients V_i. With the help of checkboxes, user can select the numbers of harmonic and natural functions $A_i\Psi_i$ and $V_i\widetilde{\Psi}_i$, which will be displayed on the rendered 3D scene.

As an example of the archived operational data visualization, we took data from the archive of the Smolensk NPP (nuclear power station) for February 2016 with a data recording frequency of 1 day. The initial state refers to 02.01.2016 and the field deformations are determined at any time slice up to 02.29.2016.

Figures 4, 5 show the field deformation on 29.02.2016 in relation to 01.02.2016 depending on the number of harmonic and "natural" functions used for approximation.

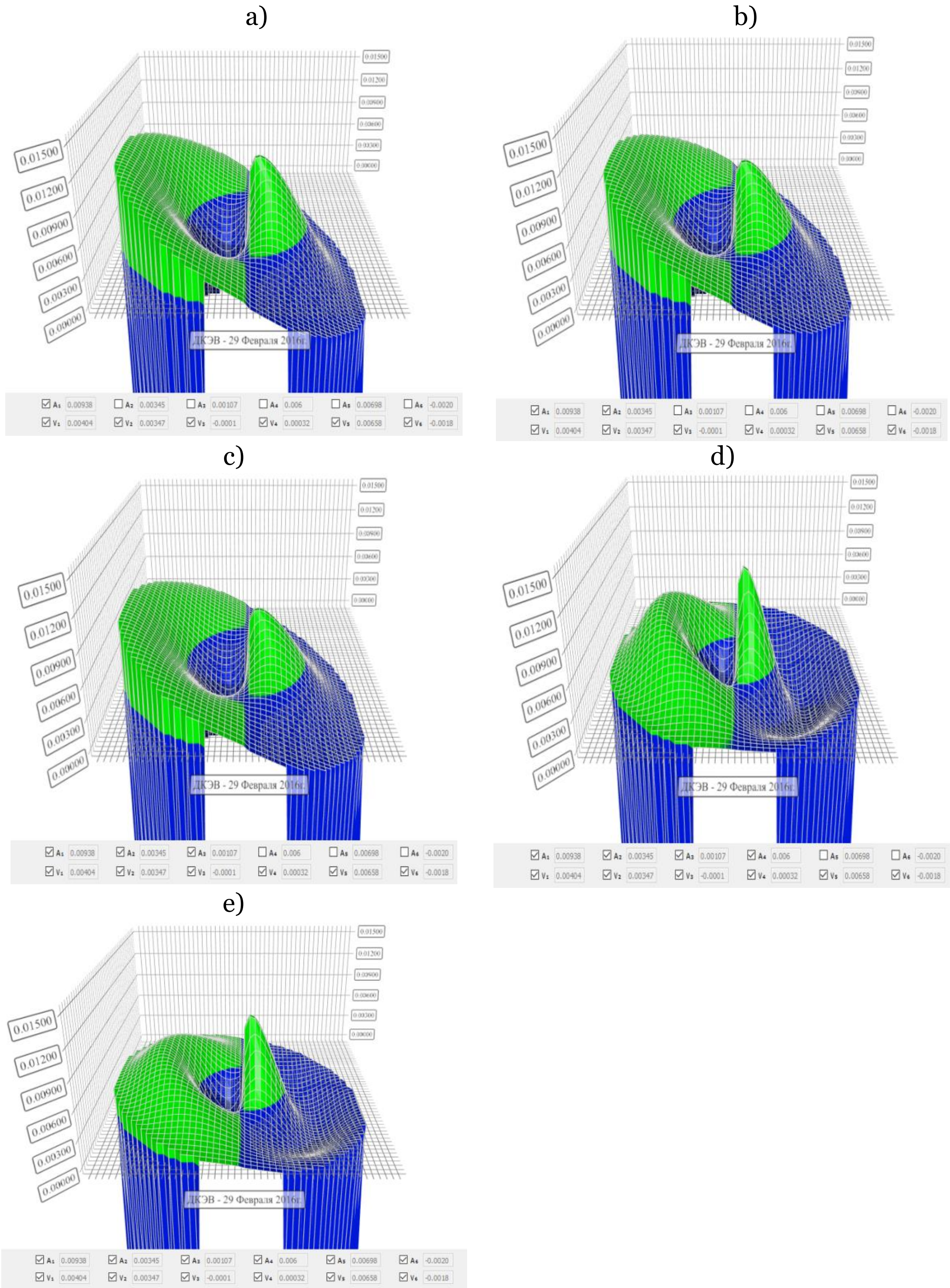

Figure 4: Approximation of the ERCS deviations values from the initial time slice by a set of harmonic functions: a) only 1st harmonic function is used; b)1st and 2nd functions are used; c)1st, 2nd, and 3rd functions are used; d) 1st, 2nd, 3rd and 4th functions are used; e) all 6 functions are used

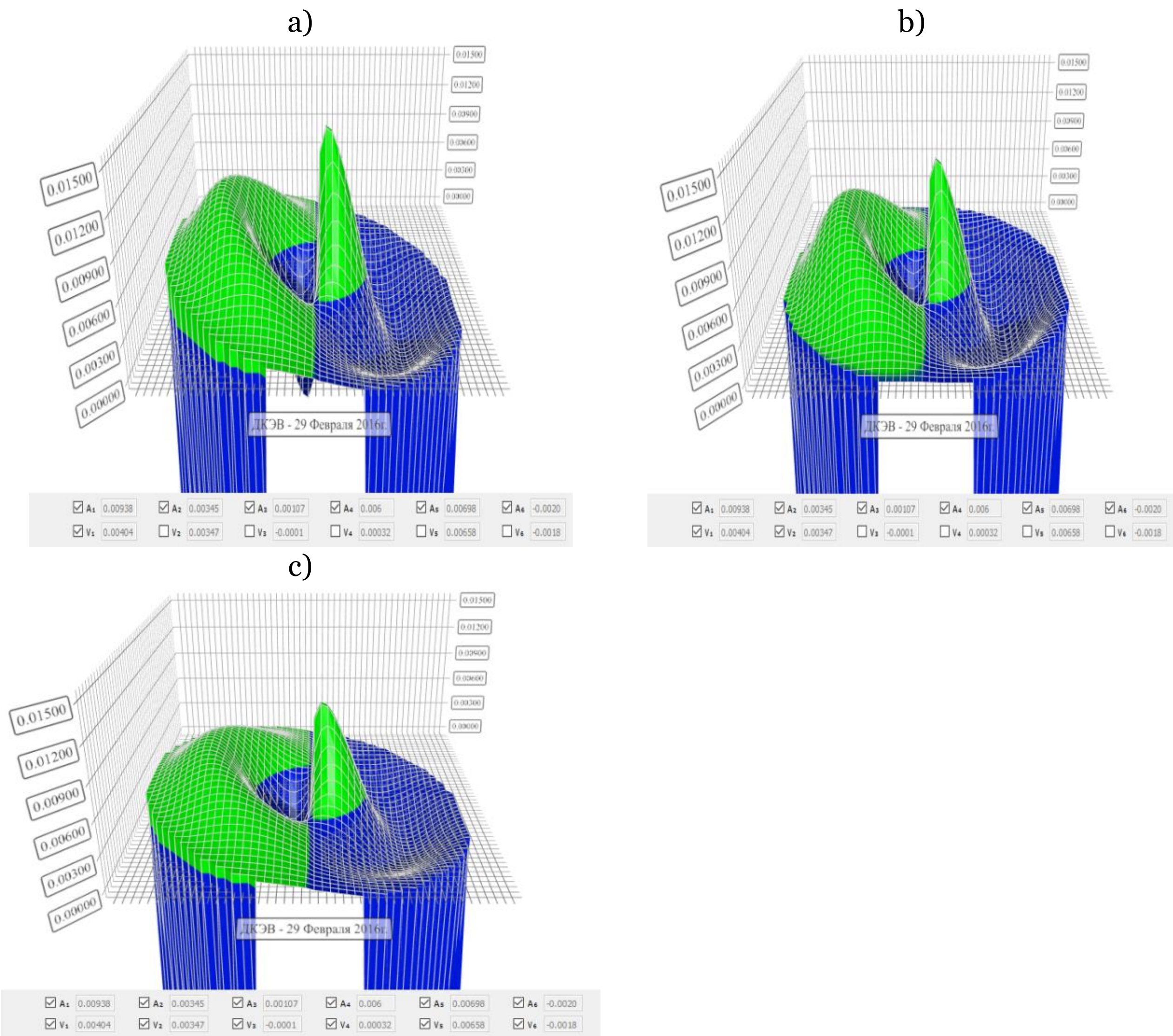

Figure 5: Approximation of the ERCS deviations values from the initial time slice by a set of "natural" functions: a) only 1st "natural" function is used; b) 1st and 2nd functions are used; c) all 6 functions are used

As can be seen from the figures above, when all functions from the sets of "natural" and harmonic functions for describing the deformation of the neutron field are taken into account, the distributions are identical, which corresponds to the algorithm. We will consider this distribution to be true. The example of the approximating harmonic functions shows that when only four functions are taken into account, the difference between the obtained distribution and the true one is noticeable, but not critical. However, if the number of functions is reduced by at least one, the difference becomes noticeable. In the case of approximation by "natural" functions, it can be seen that when only the first two functions are taken into account, the difference between the obtained distribution and the true one is hardly noticeable. This result confirms the earlier assumption that natural functions are much better suited to estimate the deformation of the neutron field $\delta\varphi(\vec{r},t)$, since a smaller number of functions may be required to describe them. This, in turn, opens up new possibilities for solving the problems of predictive diagnostics of in-reactor control sensors, since it becomes possible to monitor the process of their degradation by fictitiously inhibiting the readings of the sensors and comparing them with the value restored as a result of the approximation. Finally, Figures 6 and 7 show the dynamics of deformation of the neutron field in various sections for a fixed height of the reactor and the dynamics of deformation for a fixed section along the height of the reactor.

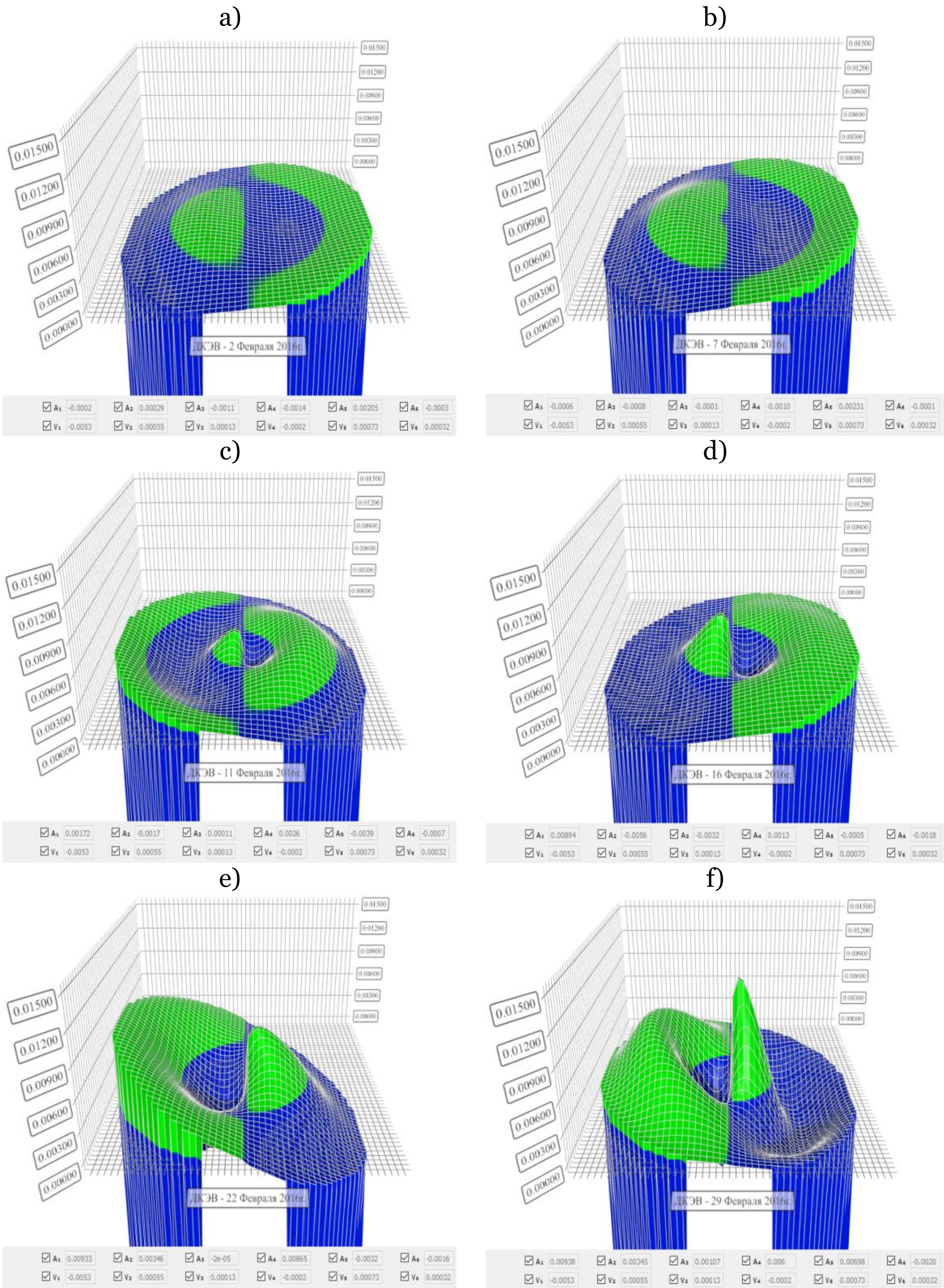

Figure 6: Deformation of the neutron field in time for a fixed height of the core – 1m: a)2.02.2016; b)7.02.2016; c)12.02.2016; d)16.02.2016; e)22.02.2016; f)29.02.2016

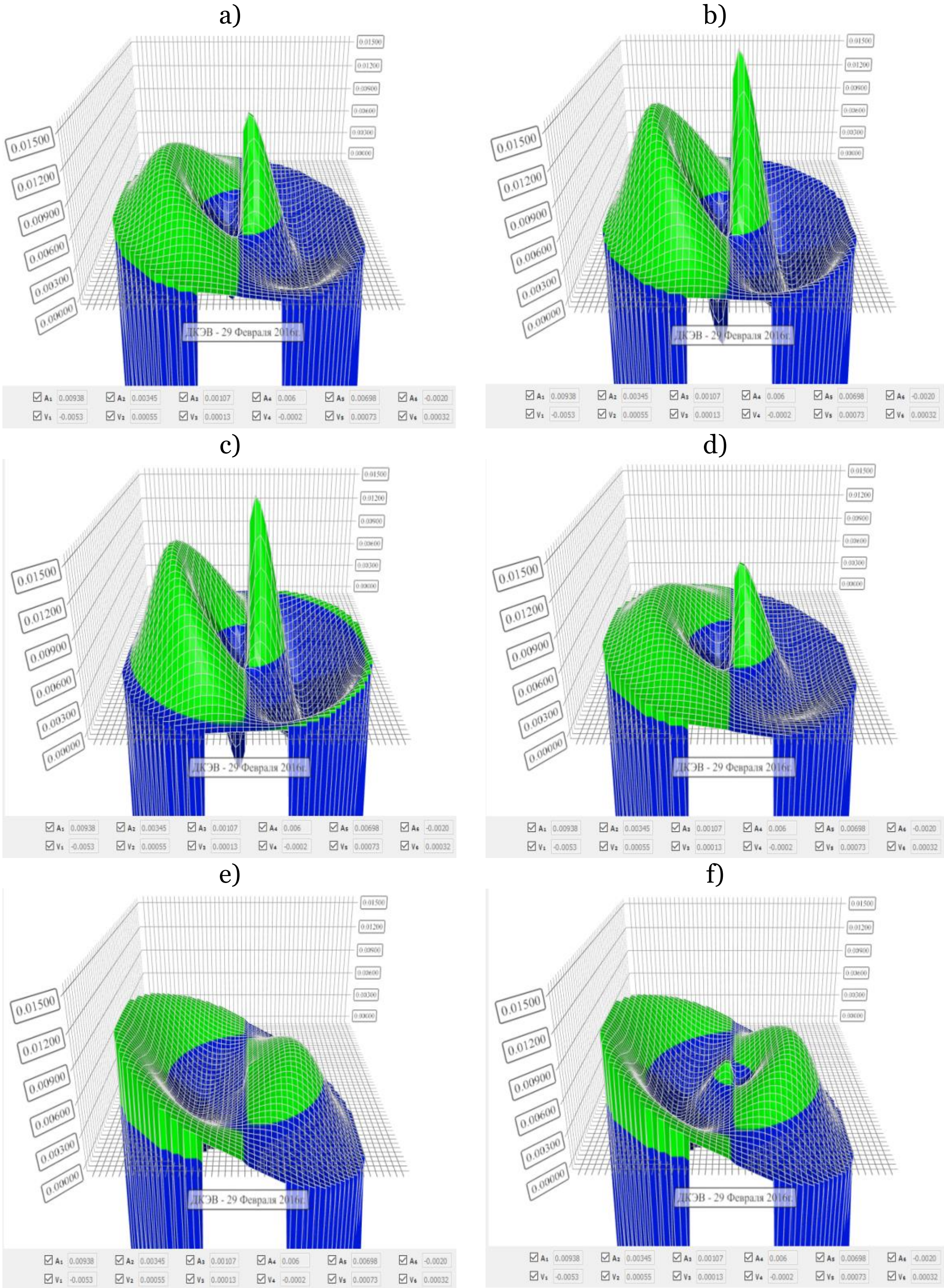

Figure 7: Deformation of the neutron field in the height of the core for a fixed time slice – 29.02.2016: a)1.0 m; b)2.0 m; c)3.0 m; d)4.0 m; e)5.0 m; f)6.0 m

4. Conclusion

This paper describes the algorithm for calculating natural three-dimensional deformation functions of the neutron field in a nuclear reactor. In the course of the work, a software package was developed for three-dimensional visualization of archived operational parameters, the dynamics of neutron fields, and the computational and experimental determination of the natural three-dimensional functions of the reactor. Using the archival data of the Smolensk NPP as an example, the dependence of the estimate of neutron field distribution on the number of approximating natural three-dimensional functions was analyzed. It was shown that to describe the distribution of the neutron field, it is sufficient to take into account only two natural functions, which opens up new possibilities for solving the problems of predictive diagnostics of in-reactor control sensors.

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