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Actuality of study of the peristaltic processes that ensure the movement of fluids in the human body is substantiated. Whereas the traditional approach to mathematical modeling of real peristaltic processes causes a number of problems associated with increasing of the computation complexity and violating of the conservation laws, the paper presents the application of mathematical modeling technology based on lattice Boltzmann equation. Theoretical Foundations of lattice Boltzmann model and especially its use in two-dimensional lattice is described. Much attention is paid to the peculiarities of formation of boundary conditions at the macroscopic level and the level of the lattice sites. Results of simulations of the peristaltic process in the digestive tract are given.

Key words: *lattice Boltzmann equation, mathematical modeling, peristaltic process, BGK-model.*

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V. D. Pavlenko, D. Sc, Professor,
V. A. Speranskyy, Ph. D.
Odessa national polytechnic university, Odessa

THE TOOLKIT FOR NONPARAMETRIC IDENTIFICATION NONLINEAR DYNAMICAL SYSTEMS BASED ON VOLTERRA MODELS IN FREQUENCY DOMAIN

The software-hardware tools used for nonlinear dynamical systems nonparametric identification based on Volterra models in frequency domain are presented. The polyharmonic test impacts are selected as the test ones. The proposed methodology and the toolkit are used for building the communication channel model.

Key words: *nonlinear dynamical systems, Volterra models, frequency domain, nonparametric identification, polyharmonic signals, multidimensional frequency characteristics, identification toolkit.*

Introduction. Increasing complexity of the technical systems and objects being studied and planned necessitates the development of mathematical models. Such models have to take into account nonlinear and dynamic properties of mentioned systems and objects. Also the development of efficient computer implementation of tools for constructing such models is needed.

One of the most important classes of such systems is the modern communication channels. In real conditions with the presence of high values of the crest factor such systems are nonlinear dynamical systems.

The quality of data transfer in communication channels depends on the media and the characteristics of the devices used for data transmission. This is very important in such areas: in sonar information channels for resource development problems, environmental monitoring of shelve waters, for remote inspection of the environment, taking into account the complicated boundary conditions and geometry of spatial inhomogeneities of the aquatic environment; to improve the accuracy of measurements in remote sensing of the Earth surface and subsurface, where the nonlinearity is introduced by atmosphere layers and weather phenomenon and prevent the passage of the test signals; in special-purpose communications systems to provide high reliability steganographic information transfer; in systems of indirect control and diagnostics of different physical nature objects.

Communication channels due to their complexity and lack of knowledge can be regarded as a «black box» system. The nonparametric dynamic models based on integral power Volterra series are usually used for mathematical modeling of such systems.

The models in form of integral Volterra series [1–4] are widely used to identify nonlinear dynamical systems [5–6]. Herewith the nonlinear and dynamical properties of the system are fully characterized by sequence of multidimensional weighting functions — Volterra kernels.

The aim of the work is the toolkit developing used for constructing the nonparametric models of nonlinear dynamical systems in a form of Volterra series in frequency domain using polyharmonic test signals. The efficiency of the developed toolkit had to be tested in practical issue for building the nonlinear dynamical model of the communication channel.

Experimental researches methodology. Identification problem for modelling nonlinear dynamical system in a form of Volterra series consists in n-dimensional weighting functions determination $w_n(\tau_1,\ldots,\tau_n)$ for time domain or it's Fourier transforms $W_n(j\omega_1,\ldots,j\omega_n)$ — n-dimensional transfer functions for frequency domain. This based on data of experimental researches of the «input-output» system. Identification of nonlinear system in frequency domain coming to determination of absolute value $|W_n(j\omega_1,\ldots j\omega_n)|$ and phase $\arg W_n(j\omega_1,\ldots,j\omega_n)$ of multidimensional transfer function at given frequencies — multidimensional amplitude–frequency characteristics (AFC) and phase-frequency characteristics (PFC) respectively. They are defined by formulas:

$$|W_n(j\omega_1,\ \ldots,j\omega_n)| = \sqrt{\left[\mathrm{Re}(W_n(j\omega_1,\ldots,j\omega_n))\right]^2 + \left[\mathrm{Im}(W_n(j\omega_1,\ \ldots,j\omega_n))\right]^2} \quad (1)$$

$$\arg W_n(j\omega_1,\ \ldots,\ j\omega_n) = \mathrm{arctg}\frac{\mathrm{Im}[W_n(j\omega_1,\ \ldots,\ j\omega_n)]}{\mathrm{Re}[W_n(j\omega_1,\ \ldots,\ j\omega_n)]}, \quad (2)$$

where Re and Im are real and imaginary parts of a complex function of *n* variables respectively.

So the nonlinear system identification procedure consists in extracting the partial components $y_n[x(t)]$ and determination of multidimensional Volterra kernels or frequency characteristics: AFC and PFC [7].

The test polyharmonic effects for identification in the frequency domain representing by signals of such type:

$$x(t) = \sum_{k=1}^{n} A_k \cos(\omega_k t + \varphi_k), \quad (3)$$

where n — the order of transfer function being estimated; A_k, ω_k and φ_k — amplitude, frequency and a phase of k-th harmonics respectively. In research, it is supposed every amplitude of A_k to be equal, and phases φ_k equal to zero.

The identification algorithm is based on nonlinear dynamical model constructing in a form of Volterra series and consists in selecting the form of the test signals. The identification methodology is implemented with approximation and interpolation methods [8–10]. The structured scheme of the computational process of the identification procedure is shown in the fig. 1.

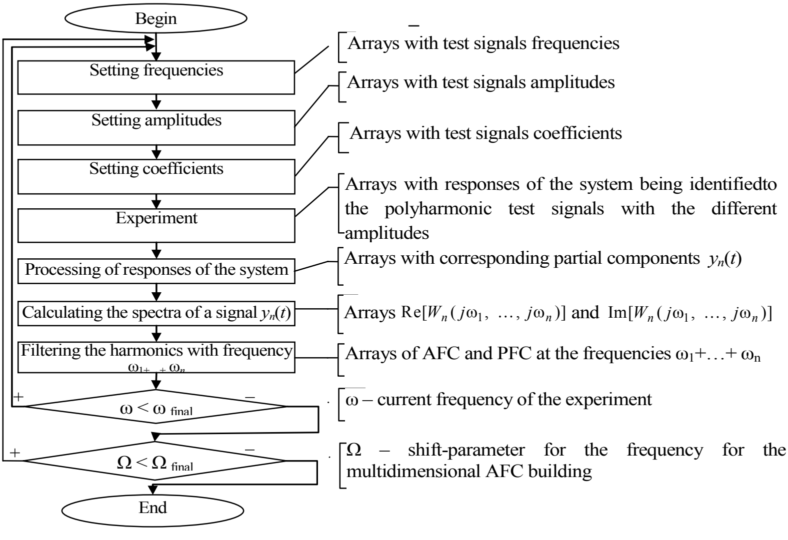


Fig. 1. *Structured scheme of the computational process of the identification procedure*

The hardware platform of the experimental researches using developed toolkit consists of IBM–PC compatible computer with two soundcards Creative Audigy 4 (signal to noise ratio less than 89 dB and distortions not higher than 0,003%). This allows characterizing the final results as reliable ones. Onboard soundcards (motherboard built-in) has much worst characteristics and higher unevenness of its AFC. Thus it cannot be used in experimental researches.

Maximum allowed amplitude in the described experiment with use of sound card was A = 0,25 V (defined experimentally). The range of frequencies was defined by the sound card pass band (20…20000 Hz), and frequencies of the test signals has been chosen from this range, taking into account restrictions specified in [5]. Such parameters were chosen for the experiment: start frequency f_s = 125 Hz; final frequency f_e = 3125 Hz; a frequency change step F = 125 Hz; to define AFC of the second order determination, an offset on frequency $F_1 = f_2 - f_1$ was increasingly growing from 201 to 3401 Hz with step 100 Hz.

The toolkit is organized from two software parts and written in C++ and Matlab languages. The first part is assigned for test signals generation with minimal impact of the operation system of used PC. The experimental results processing is implemented in the second part. The 13 modules were developed during the software part implementation. The structured scheme of the software toolkit for nonlinear dynamical systems identification is shown in fig. 2.

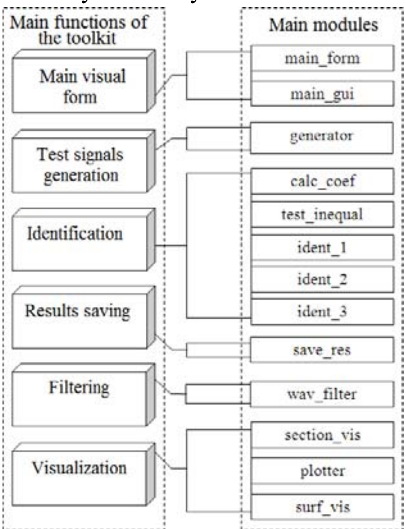


Fig. 2. *The structured scheme of the software toolkit for nonlinear dynamical systems identification*

An initialization of the identification process parameters of the nonlinear system being identified is performed in the main module (*main_form.m*). The list of those parameters:

1) start frequency f_1 of harmonic signals for the experiment;
2) quantity of the experimental steps (defines the quantity of the subdiagonal sections of the AFC and the final frequency of the experiment);
3) polyharmonic test frequency step;
4) quantity of the experiments repeats that allows to average results received for current nonlinear object;

5) quantity of the signal samples being sent to the nonlinear dynamical system input (this number have to be divisible by 2 to obtain correct work oa the Fast Fourier Transform);
6) sampling frequency of the sound signal being sent to the nonlinear dynamical system input;
7) kernel order for the Volterra model;
8) approximation order / experiments quantity for the approximation / interpolation method of the coefficients calculation and experiments providing;
9) shift between the frequencies f_2 and f_1 for the polyharmonic test signals (for nonlinear models);
10) shift between the frequencies f_3 and f_2 for the polyharmonic test signals (for nonlinear models);
11) amplitudes array for the mono- or polyharmonic test signals (depends on model order);
12) corresponding coefficients array calculated using amplitudes of the test signals;
13) time array for sound test signal forming;
14) response array (consists of the values of tested nonlinear dynamical system responses to the test harmonic signal);
15) AFC array (consists AFC points values of tested nonlinear dynamical system).

The implemented in module *main_gui.fig* visual interface contains all visual components of the windows application used to control the parameters of the experiment (fig. 3 и fig. 4).

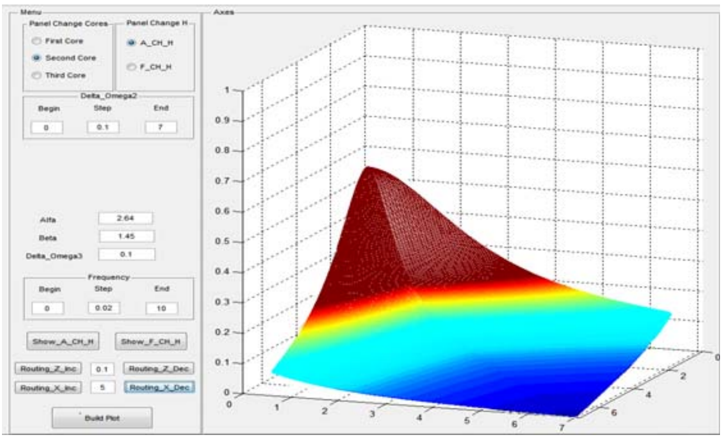


Fig. 3. *Part of the main window of the software toolkit used for standard characteristics constructing (subdiagonal sections and 3D surfaces)*

Visual elements located at the main form allow controlling the identification process by changing the values of variable parameters. Also you can manage the visualization of received results in a form of two-dimensional and three-dimensional plots of the identified system AFC.

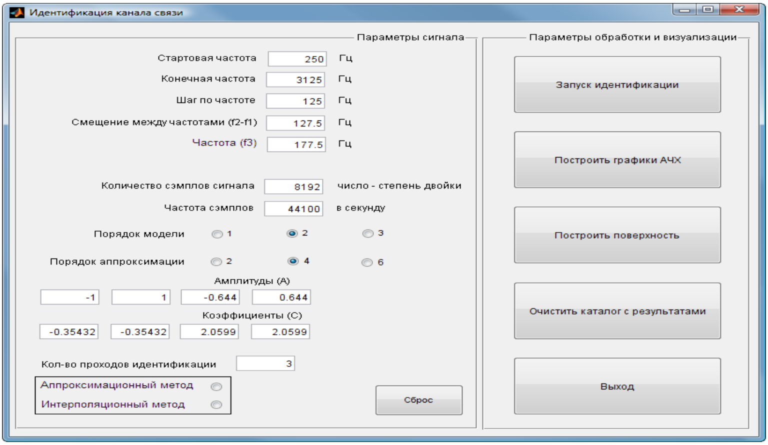


Fig. 4. *The main form of the software toolkit used for identification of nonlinear dynamical systems*

The coefficients for identification during the forming the test signals are depending on its amplitudes. The calculation of such coefficients is performed by the matrix method of SLAE decision and it's performed in *calc_coef* module. One of the identification modules of the chosen order (*ident_1*, *ident_2*, *ident_3*) begins working after starting the identification process. In common way:

- the test harmonic signals with selected amplitudes (depending on method) are generated;
- generated signals data arrays are sent to the input of the nonlinear system;
- the signals received after nonlinear system has the visual form shown in fig. 5 and they have to be preprocessed (multiplication the signals and output coefficients);
- the total (sum) response of all test signals is calculated;
- the points of AFC array for the responses of the system being identified are calculated;
- the data received during identification at the current frequency step is saved to the file.

The identification method is organized using the approximation [8] and interpolation method [10]. The identification of the nonlinear system of the 1st order is presented as textual algorithm:

Step 1. The main module (*main_form.m*) sending the parameters of the identification to the module *ident_1.m*;

Step 2. All supporting local variables and arrays are initialized;

Step 3. The loop for experiment repetitions with selected iterations

Step 3.1. The loop for changing the test frequency from start value with selected step for the selected quantity of steps (specified in parameters of the identification).

Step 3.1.1. The f_1 frequency increment at current experiment step.

Step 3.1.2. The test harmonic signal generating.

Step 3.1.3. Searching for the f_1 frequency position in signal spectra.

Step 3.1.4. The loop for each test signal amplitude in the experiment.

Step 3.1.5. The signal with specified amplitude is forming.

Step 3.1.6. The formed signal is sending to the output of the soundcard.

Step 3.1.7. The signal is receiving from the input of the soundcard.

Step 3.1.8. The multiplication of the received signal data (response) with specified amplitudes by corresponding coefficients.

Step 3.1.9. The total response calculation by summation of received signals groups.

Step 3.1.10. If the selected method is interpolation then performing division of the total response by additional method coefficient.

Step 3.1.11. Calculating the signal spectra using Fast Fourier Transform.

Step 3.1.12. Calculating the value of informational harmonics with position detected at the *Step 3.1.3.*

Step 3.1.13. Calculating the AFC and amplitude correction.

Step 3.1.14. Saving the experimental data in files as arrays with identification results for the frequency f_1.

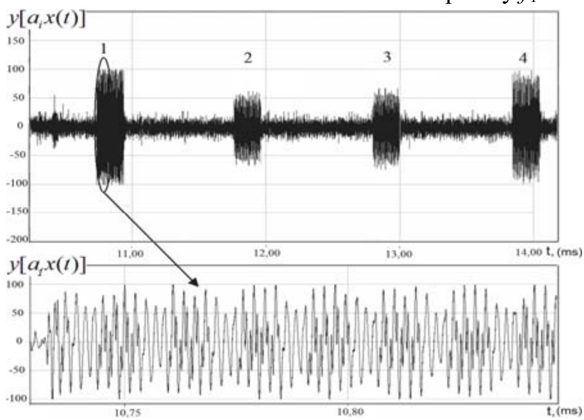


Fig. 5. *The responses (4 signals) received from channel with noises for the 2nd order model: a=–1 (1); a=1 (2); a=–0,644 (3); a=0,644 (4)*

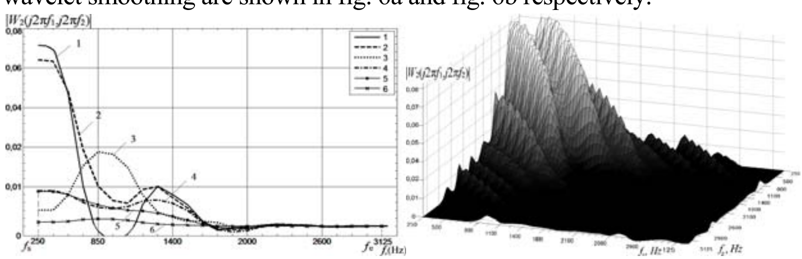
To save the data of the identification results for subsequent system model in frequency domain building the m-files are used. The names of those files are fully showing the parameters of the experiment. The files are saved at the Results subfolder of the program folder.

The format of file name with identification data of the test model allowing cataloging results looks as Vn(N)_Na_metb_nc_mad_mke__w1_f-g-h_dw1_i_w2_j.mat and consists of such fields: n — model (Volterra kernel) order, *N* — approximation order, *a* — discretization order, *b* — method (1 — interpolation, 0 — approximation), *c* — noise level (in % relatively to test signal level), *d* — scaling the test signals amplitudes relatively to initial (in %), *e* — scaling the test signals coefficients relatively to initial (in %), *f* — start frequency f_1 value, *g* — step of the frequency f_1 changing, *h* — final value of the frequency f_1, *i* — shifting between the frequencies f_2 and f_1, *j* — the value of the frequency f_3.

The format of file name with identification data of the real communication channel allowing cataloging results looks as Final_xxxx_yyyy_zzzz_Vk-N_mm-dd-yy_HH-MM-SS.mat and consists of such fields: xxxx — start frequency of the current experiment (section), *yyy* — shift between the frequencies f_2 and f_1, *zzz* — the value of the frequency f_3, *n* — model (Volterra kernel) order, *N* — approximation order, mm-dd-yy_HH-MM-SS — current date and time in selected format.

On the results of the identification data contained in the files, it is possible to draw two-dimensional plots (module *sections_vis.m*) — subdiagonal AFC sections of the nonlinear dynamical system. A 3-dimensional plots (modules *surf_vis.m*, *plotter.m*) — surfaces are built of the subdiagonal AFC sections of the nonlinear dynamical system by changing shifting between the frequencies f_2 and f_1 and changing frequency f_3 for the 2nd and 3rd order models respectively.

The automatic wavelet filtration of the graphic data is performed during the plots building. The chosen wavelet is 2nd level Coiflet. It allows to smooth output data of the real communication channel characteristics while minimal ERMSE growing. The examples of the received models for the 1st (subdiagonal sections) and 2nd (surface built of set of subdiagonal sections) orders with wavelet smoothing are shown in fig. 6a and fig. 6b respectively.



а) *б)*

Fig. 6. *a) Subdiagonal sections of AFCs of the second order after wavelet «Coiflet» 2nd level noise-suppression at different frequencies f_1:201(1), 401(2), 601(3), 801(4), 1001(5), 1401(6) Hz; b) Surface built of AFCs of the second order after wavelet «Coiflet» 3rd level noise-suppression*

Conclusions. The hardware-software toolkit was made as a result of the development and performed researches. This toolkit allows identifying and constructing the models of the system with unknown structure using the Volterra series models and polyharmonic signals in frequency domain. Using the developed toolkit for obtaining characteristics of the nonlinear systems in future will allow correcting its characteristics. Current toolkit was applied for constructing the nonparametric models of the communication channel. Results of identification of the linear and nonlinear communication channels models were presented in [8–10]. There showed significant nonlinearities of the identified systems. Thus it is necessary to take into consideration the characteristics of the system to obtain its high efficient and reliable operating modes.

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Представлено програмно-апаратні засоби, що використовуються для непараметричної ідентифікації нелінійних динамічних систем на основі моделей Вольтерра в частотній області. В якості тестових впливів обрано полігармонічні сигнали. Запропонована методологія та інструментарій використовуються для побудови моделі каналу зв'язку.

Ключові слова: *нелінійні динамічні системи, моделі Вольтерра, частотна область, непараметрична ідентифікація, полігармонічні сигнали, багатовимірні частотні характеристики, інструментальні засоби ідентифікації.*

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В. В. Палагін, д-р техн. наук, професор,
О. В. Івченко, аспірант

Черкаський державний технологічний університет, м. Черкаси

ПРОГРАМНІ ЗАСОБИ КОМП'ЮТЕРНОГО МОДЕЛЮВАННЯ ОЦІНЮВАННЯ ПАРАМЕТРІВ НЕГАУСОВИХ КОРЕЛЬОВАНИХ ВИПАДКОВИХ ПРОЦЕСІВ

У роботі наведені результати оцінювання параметрів негаусових випадкових процесів на основі застосування адаптованого методу максимізації полінома та моментно-кумулянтного опису випадкових величин. Отримані результати моделювання і ефективності запропонованого методу в порівнянні з відомими підходами.

Ключові слова: *негаусові корельовані випадкові процеси, оцінювання параметрів, метод максимізації полінома, дисперсія оцінки.*

Вступ. Проблемі статистичного аналізу багатомірних випадкових величин присвячено багато робіт [1–3], де в основному робиться припущення про їх нормальний розподіл. На практиці не завжди виконується умова нормалізації багатомірних випадкових величин [4], тому виникає необхідність розширення математичного апарату з обробки даних при негаусових завадах. Одним з підходів для вирішення даної проблеми є застосування методу максимізації поліному [5–6],

