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# The Methodology of Experimental Researches and the Software Tools for Volterra Model Construction of Infocommunication System

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**Abstract**— This paper presents the methodology and the software tools used for nonparametric nonlinear dynamical Volterra models constructing in frequency domain. The wavelets application allowed to improve the computational stability of the identification method for measurement noises filtering of received responses and characteristics of the system being identified. The proposed methodology and developed software tools were applied for different orders infocommunication system models construction.

**Keywords**—software tools, nonlinear dynamical systems, Volterra models, nonparametric identification, multidimensional frequency characteristics, wavelet filtering

## I. 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. In addition, 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 infocommunication systems. 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 infocommunication systems depends on the media and the characteristics of the devices used for data transmission. It is very important in sonar channels for resource finding problems, environmental monitoring of shelf 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, weather phenomenon and prevent the passage of the test signals; in special-purpose infocommunication systems to provide high reliability steganography data transfer; in systems of indirect control and diagnostics of different nature objects.

Infocommunication systems due to their complexity and lack of knowledge can be interpreted 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 a form of integral Volterra series [1–3] are widely used to identify nonlinear dynamical systems. Herewith the nonlinear and dynamical properties of the system are fully characterized by sequence of multidimensional weighting functions – Volterra kernels.

The known existing software (such as NI LabVIEW Signal or COMSOL Multiphysics) are very complex and doesn't allow constructing infocommunication system models, so the development of such engineering tools is an actual problem. The engineering software tools with friendly user interface used for constructing nonparametric models of nonlinear dynamical systems in a form of Volterra series in frequency domain using polyharmonic test signals were developed.

## II. EXPERIMENTAL RESEARCHES METHODOLOGY

Identification problem for nonlinear dynamical system modelling in a form of Volterra series consists in  $n$ -dimensional weighting functions determination  $w_n(\tau_1, \dots, \tau_n)$  for time domain or it's Fourier transforms  $W_n(j\omega_1, \dots, j\omega_n)$  –  $n$ -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  $|W_n(j\omega_1, \dots, j\omega_n)|$  and phase  $\arg W_n(j\omega_1, \dots, j\omega_n)$  of multidimensional transfer function at given frequencies – multidimensional amplitude–frequency characteristics (AFC) and phase–frequency characteristics (PFC) respectively. They are defined by known formulas:

$$|W_n(j\omega_1, \dots, j\omega_n)| = \sqrt{[\operatorname{Re}(W_n(j\omega_1, \dots, j\omega_n))]^2 + [\operatorname{Im}(W_n(j\omega_1, \dots, j\omega_n))]^2} \quad (1)$$

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

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.

The test polyharmonic impacts for identification in frequency domain are presented by signals of 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;  $A_k$ ,  $\omega_k$  and  $\varphi_k$  – 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  $\varphi_k$  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 [5–7]. The

structured scheme of the computational process of the identification procedure is shown in the fig. 1.

The hardware platform of the experimental researches using developed software 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.

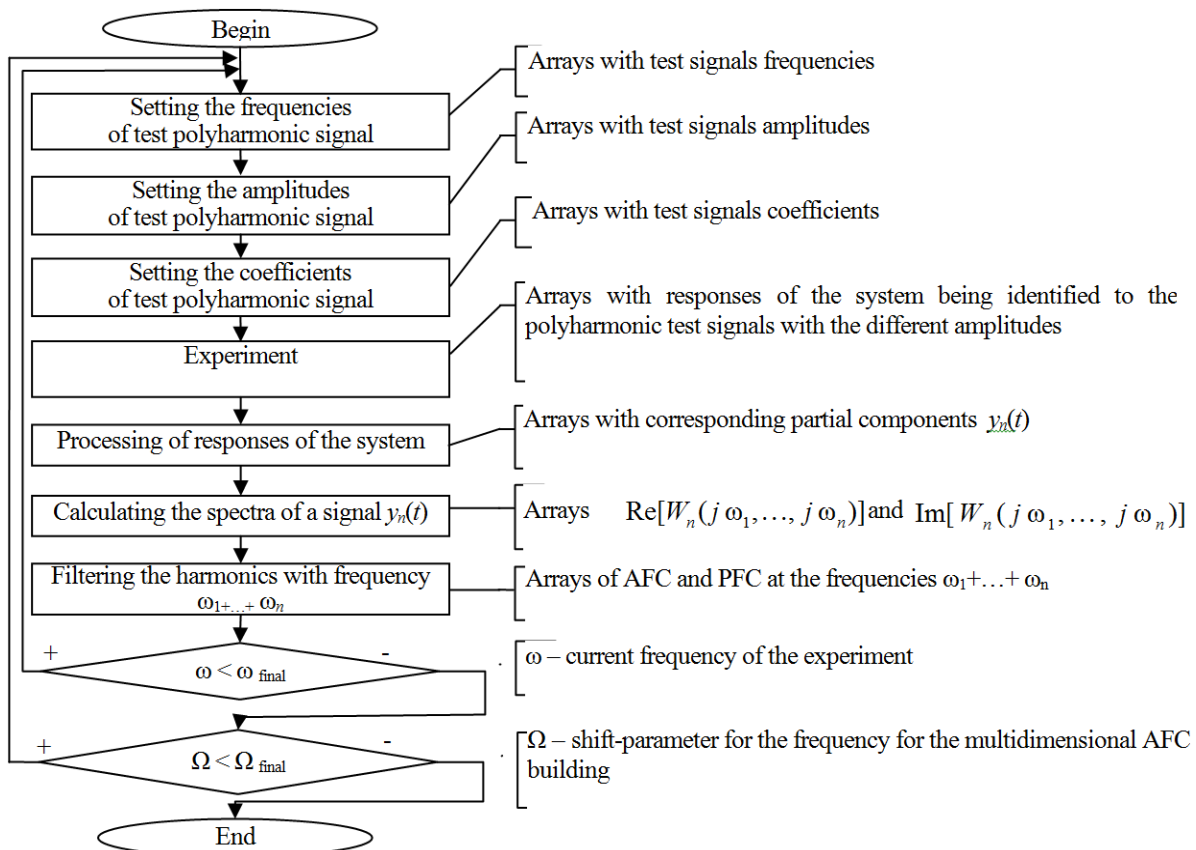


Fig. 1. Structured scheme of the computational process of the identification procedure

Maximum allowed amplitude in the described experiment with use of sound card was  $A=0,25V$  (defined experimentally). The range of frequencies was defined by the sound card pass band (20...20000 Hz). The test signals frequencies have been chosen of 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 growing from 201 to 3401 Hz with step 100 Hz.

### III. DEVELOPED SOFTWARE TOOLS

The engineering software consists of two main 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 for nonlinear dynamical systems identification is in fig. 2.

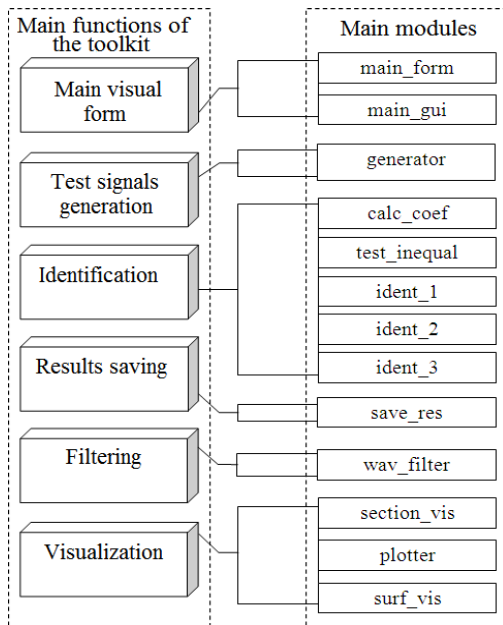


Fig. 2. The structured scheme of the software for nonlinear dynamical systems identification

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 parameters of the module:

- 1) start frequency  $f_1$  of harmonic signals;
- 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;
- 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 (the values of tested nonlinear dynamical system responses to the test signal);
- 15) AFC array (consists AFC points values of tested nonlinear dynamical system);

The visual interface contains all visual components of the windows application used to control the parameters of the experiment (implemented in module *main\_gui.fig*).

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.

The identification coefficients of the formed test signals are depending on its amplitudes. The calculation of coefficients is performed by the matrix method of SLAE solving and it's performed in *calc\_coef* module. One of the identification modules of the chosen order (*ident\_1*, *ident\_2*, *ident\_3*) starts working after beginning of 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 to be preprocessed (multiplication the signals and output coefficients);
- the total 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 procedure is organized using the approximation [5] and interpolation method [6].

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\_meth\_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 of the test signals amplitudes (in %),
- $e$  – scaling of the test signals coefficients (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  $f_3$ .

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. The 3D 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 2<sup>nd</sup> and 3<sup>rd</sup> order models respectively.

The automatic wavelet filtration of the received data is performed during the plots building. The chosen wavelet is 2<sup>nd</sup> level Coiflet. It allows to smooth output data of the real communication channel (infocommunication system) characteristics with minimal ERMSE growing.

Experimental researches of the computational

stability of the identification method were performed. The main purpose was the studying of the noise impact (noise means the inexactness of the measurements) to the characteristics of the test system model using identification method in frequency domain.

The first step is the measurement of the useful signal level after test system. The amplitude of this signal was defined as the 100% of the signal power. After that the Gaussian Random Noise signal added to the output signal of the test system. This made to simulate inexactness of the measurements in the model.

The simulations with the model were made. Different noise levels were defined for different orders of the model. The adaptive wavelet filtering used to reduce the noise impact on final characteristics of the test system. The Daubechie wavelets of the 2 and 3 level were chosen and used for the AFC and PFC filtering respectively [4].

The first order (linear) model was tested with the noise level of 50% and 10% and showed excellent level of computational stability.

The second order (nonlinear) model was tested with the level of noise 10% and 1% and showed good level of computational stability.

The third order (nonlinear) model was tested with the level of noise 1% and showed good level of computational stability. The noised and de-noised (filtered) characteristics (AFC and PFC) are presented in fig. 3-4.

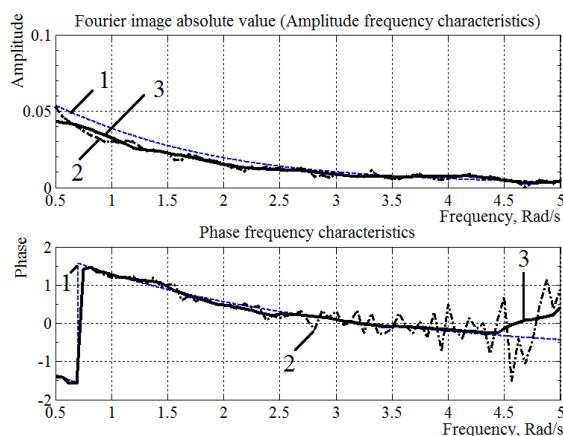


Fig. 3. Exact value (1), noised (2) and filtered (3) characteristics (AFC – top, PFC – bottom) of the second order for the test system model with noise level 10%.

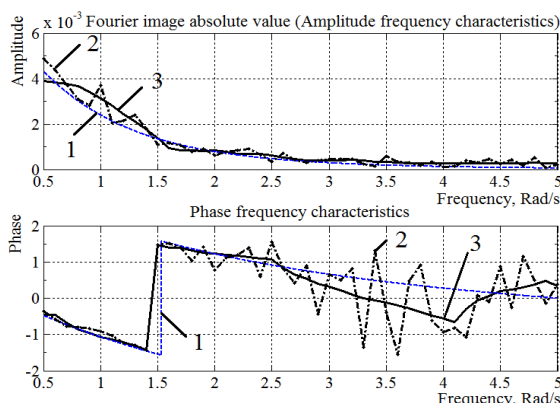


Fig. 4. Exact value (1), noised (2) and filtered (3) characteristics (AFC – top, PFC – bottom) of the third order for the test system model with level of noise 1%.

The practical researches of infocommunication system in form of UHF radiofrequency channel were made. The linear 2-D characteristics for 1<sup>st</sup> order and nonlinear 3-D characteristics for the 2<sup>nd</sup> and 3<sup>rd</sup> order model were constructed. The 3<sup>rd</sup> order is built using shifting the  $f_2$  and constant  $f_3$  value for each section of surface characteristics. Additional automatic wavelet smoothing was applied to remove practical experiment noises and helped to reduce it in 1,5–2 times.

## CONCLUSION

The software tools with user-friendly interface were developed. This software allows constructing models of nonlinear dynamical systems with unknown structure using Volterra models and polyharmonic signals in frequency domain. Errors of measurements have essential impact on results of the determined identification. Noise filtering procedures using wavelets are applied to increase of computational stability of the identification process. The filtering of the received estimates of multidimensional Volterra kernels is based on wavelet-transformation. It's allowing to receive smoothed solutions and reduce identification error in 1,5–2 times. The computational stability is very high for the linear model, high enough for the second order nonlinear model and has moderate computational stability for the third order model. The wavelet filtering is very effective and gives the possibility to improve the quality of identification for noisy measurements up to 1,54 and 4,07 times for the AFC and PFC respectively. Results of identification of the linear and nonlinear infocommunication system models were presented in [5–7]. The significant nonlinearities of the identified systems have been showed and proven. Therefore, it is necessary to obtain the models with high level of adequateness to achieve maximum effect of infocommunication systems.

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