The Engineering Software Tools for Nonlinear Dynamical Systems Identification Based on Volterra Models in Frequency Domain

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Abstract—**The engineering software tools used for nonlinear dynamical systems nonparametric identification based on Volterra models in frequency domain is presented. The polyharmonic test sequences with different amplitudes are used for test procedures. The wavelets application for filtering of measurement noises of received responses and characteristics of the identifiable system allowed enlarging computational stability of the identification method. The proposed methodology and the software tools applied for construction of the communication channel models.**

Keywords—*engineering software, 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 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. It 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 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 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 engineering software tools developing used for constructing the nonparametric models of nonlinear dynamical systems in a form of Volterra series in frequency domain using polyharmonic test signals were developed. The efficiency of the developed software has been tested in practical issue for building the nonlinear dynamical model of the communication channel.

II. Experimental researches methodology

Identification problem for nonlinear dynamical system modelling in a form of Volterra series consists in n-dimensional weighting functions determination $w_n(\tau_1,\ldots,\tau_n)$ 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 known formulas:

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

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

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 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 [5–8]. 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.
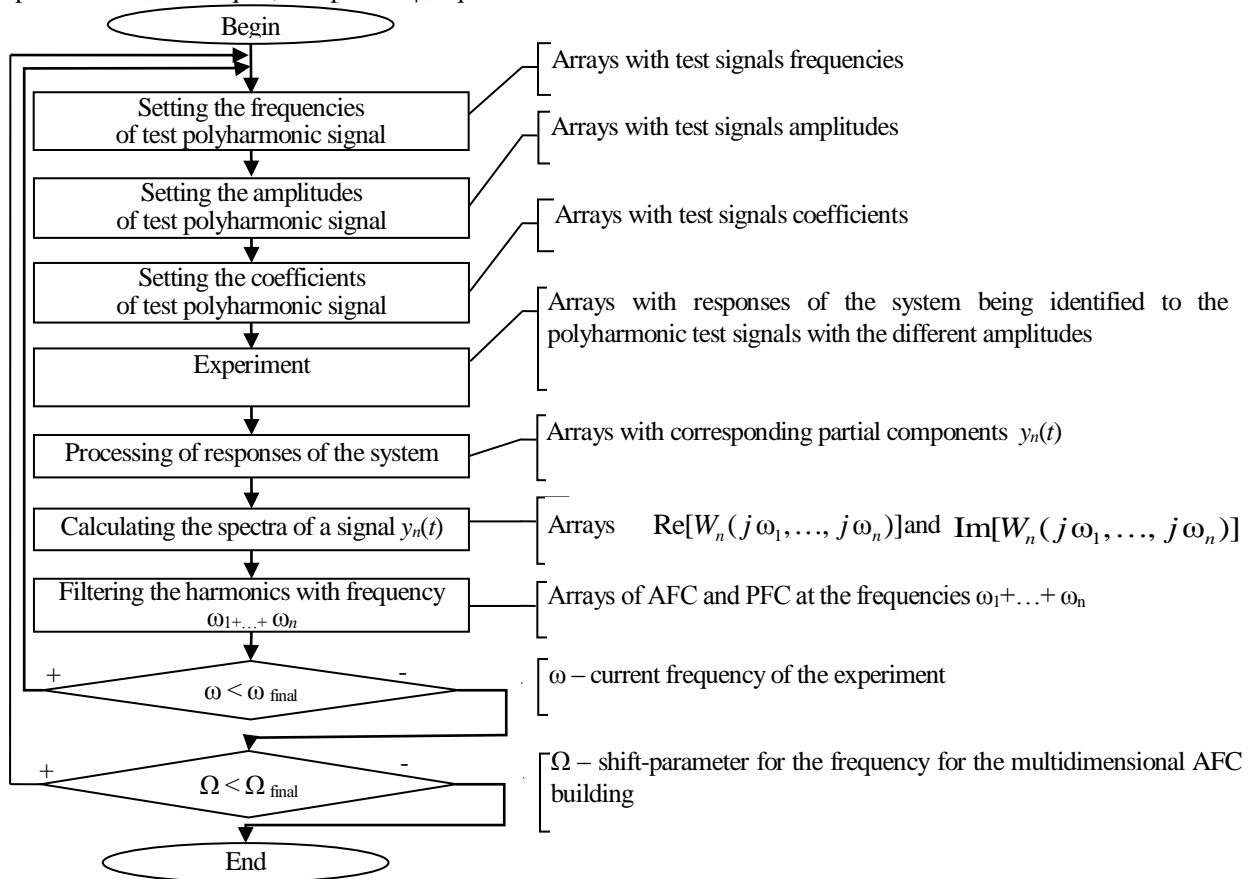

Figure 1. Structured scheme of the computational process of the identification procedure

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), 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.

III. Enginering software tools

The software 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 for nonlinear dynamical systems identification is in fig. 2.
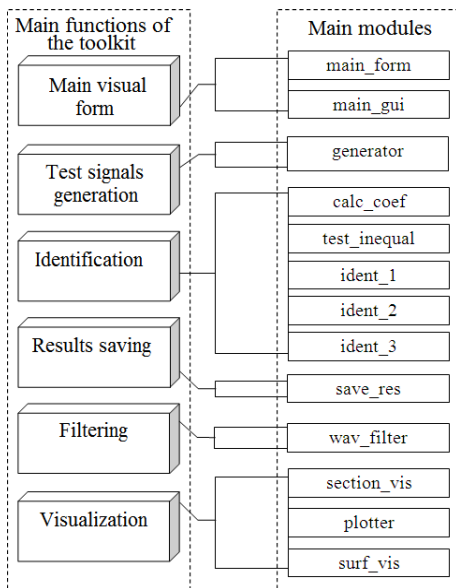

Figure 2.   The structured scheme of the software for nonlinear dynamical systems identification

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 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).
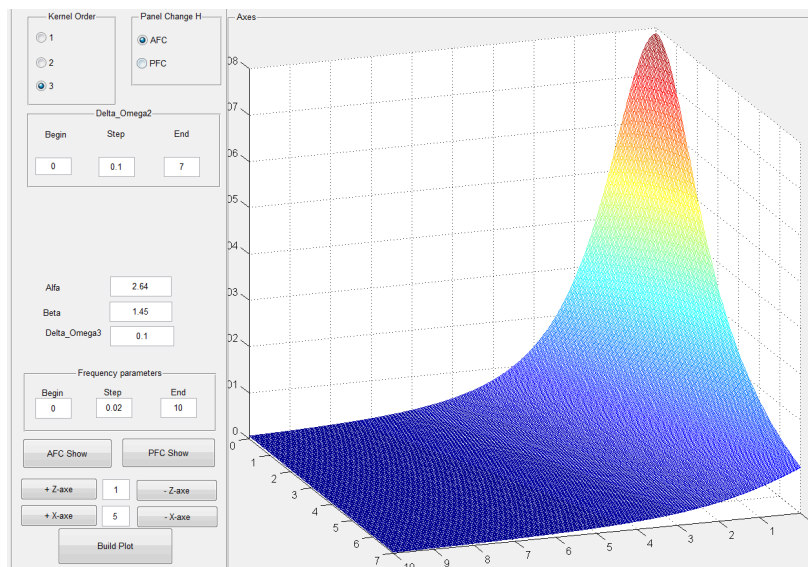

Figure 3.   Part of the main window of the software used for standard characteristics constructing (subdiagonal sections and 3D surfaces)

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.

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 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 [5] and interpolation method [7]. 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 3.1.4.1. The signal with specified amplitude is forming.

Step 3.1.4.2. The formed signal is sending to the output of the soundcard.

Step 3.1.4.3. The signal is receiving from the input of the soundcard.

Step 3.1.4.4. The multiplication of the received signal data (response) with specified amplitudes by corresponding coefficients.

Step 3.1.4.5. The total response calculation by summation of received signals groups.

Step 3.1.4.6. If the selected method is interpolation then performing division of the total response by additional method coefficient.

Step 3.1.4.7. Calculating the signal spectra using Fast Fourier Transform.

Step 3.1.4.8. Calculating the value of informational harmonics with position detected at the *Step 3.1.3*.

Step 3.1.4.9. Calculating the AFC and amplitude correction.

Step 3.1.5. Saving the experimental data in files as arrays with identification results for the frequency f_1.

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 V*n*(*N*)_N*a*_met*b*_*n*c_ma*d*_mk*e*__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*_V*k*-*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. 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.

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 was the measurement of the level of useful signal 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 test 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 level of noise 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 noised and de-noised (filtered) characteristics (AFC and PFC) with level of noise 10% are presented in fig. 4.
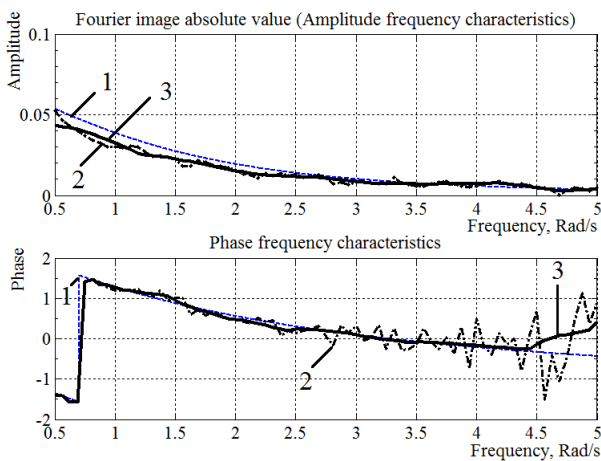

Figure 4.   Exact value (1), noised (2) and filtered (3) characteristics (AFC – top, PFC – bottom) of the second order for the test system model with noise level 10%.

The third order (nonlinear) model was tested with the level of noise 10% and 1% and showed good level of computational stability. The noised and de-noised (filtered) characteristics (AFC and PFC) with level of noise 1% are presented in fig. 6.
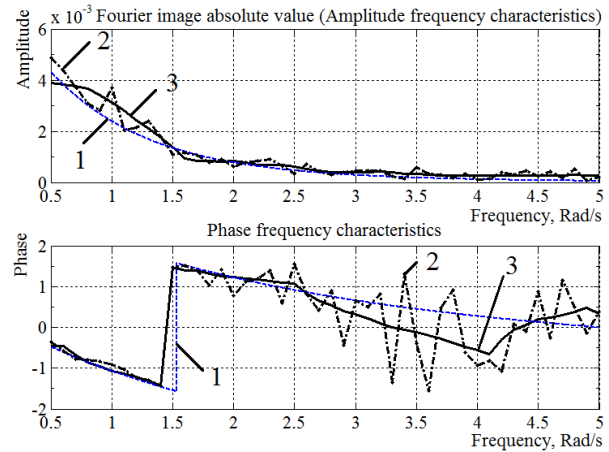

Figure 5.   Exact value (1), noised (2) and filtered (3) characteristics (AFC – top, PFC – bottom) of the third order for the test system model with level of noise 1%.

The example of the received model of 3rd order (surface built of set of subdiagonal sections) with wavelet smoothing is shown in fig. 6.
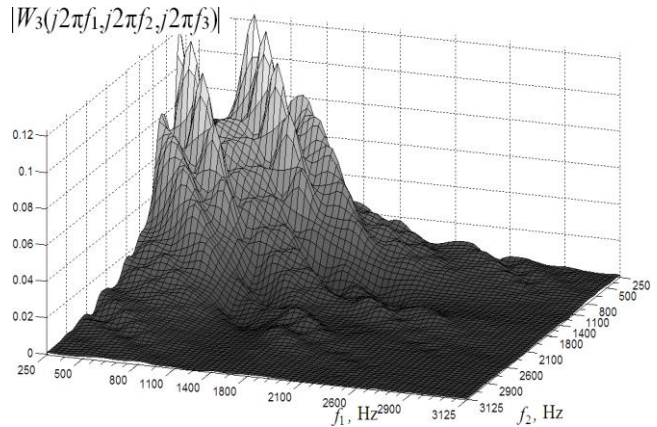

Figure 6.   Surface built of AFCs of the third order after wavelet "Coiflet" third level noise-suppression, where f_3= 127,5 Hz.

IV.   Conclusion

The engineering software tools developed and researches with its using are presented. This software allow identifying and building the models of the system with unknown structure using the 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 allows 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 of the noisy measurements up to 1,54 and 4,07 times for the AFC and PFC respectively. Results of identification of the linear and nonlinear communication channel models were presented in [5–8]. 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 such used nonlinear dynamical system as communication channels.

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