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NOISE IMMUNITY RESEARCH FOR NONLINEAR DYNAMICAL SYSTEMS IDENTIFICATION BASED ON VOLTERRA MODEL IN FREQUENCY DOMAIN

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Abstract: The accuracy and noise immunity of the interpolation method of nonlinear dynamical systems identification based on the Volterra model in the frequency domain is studied in this paper. The polyharmonic signals are used for the testing the method. The algorithmic and software toolkit in Matlab is developed for the identification procedure. This toolkit is used to construct the informational models of test system and communication channel. The model is built as a first-, second- and third-order amplitude–frequency and phase–frequency characteristics. The comparison of obtained characteristics with previous works is given. Wavelet denoising is studied and applied to reduce measurement noise.

Keywords: identification; nonlinear dynamic systems; Volterra models; multifrequency characteristics; polyharmonic signals; wavelet denoising; communication channels.

1. INTRODUCTION

It is necessary to consider technical conditions of the communication channels (CC) operation for effective data transfer. Changes in environmental conditions cause reducing the transmission data rate: in the digital CC – up to a full stop of the transmission, in analog CC – to the noise and distortion of the transmitted signals. The new methods and supporting toolkit are developing to automate the measurement of parameters and taking into account the characteristics of the CC. This toolkit allows obtaining the informational and mathematical model of such nonlinear dynamic object, as the CC [1], i.e. to find the identification problem solution.

Modern continuous CCs are nonlinear stochastic inertial systems. The model in the form of integro–power Volterra series used to identify them [2–5].

The nonlinear and dynamic properties of such system are completely characterized by a sequence of multidimensional weighting functions – Volterra kernels.

Building a model of nonlinear dynamic system in the form of a Volterra series lies in the choice of the test actions form. Also it uses the developed algorithm that allows determining the Volterra kernels and their Fourier–images for the measured responses (multidimensional amplitude–frequency characteristics (AFC) and phase–frequency characteristics (PFC)) to simulate the CC in the time or frequency domain, respectively [6, 7].

The additional research of noise immunity to measurement noise for nonlinear dynamical systems identification method, based on the Volterra model in the frequency domain is proposed. The developed identification toolkit used to build information model of the test nonlinear dynamic object in the form of the first, second and third order model [14] where updated.

2. INTERPOLATION METHOD OF NONLINEAR DYNAMICAL SYSTEMS IDENTIFICATION

The presentation of the “input–output” type nonlinear dynamical system presented by Volterra series were given in previous work [6].

An interpolation method of identification of the nonlinear dynamical system based on Volterra series is used [7–8, 14]. It is used n–fold differentiation of a target signal on parameter–amplitude a of test actions to separate the responses of the nonlinear dynamical system on partial components $\hat{y}_n(t)$ [8].

The $ax(t)$ type test signal is sent to input of the system, where $x(t)$ – any function; $|a|\leq 1$ – scale factor for n–th order partial component allocation $\hat{y}_n(t)$ from the measured response of nonlinear dynamical system $y[ax(t)]$. In such case it is necessary to find n–th private derivative of the response on amplitude a at a=0

$$\hat{y}_n(t) = \underbrace{\int_0^t \dots \int_0^t}_{n\ times} w_n(\tau_1,\dots,\tau_n)\prod_{l=1}^{n} x(t-\tau_l)d\tau_l = \\ = \frac{1}{n!}\frac{\partial^n y\left[a\,x(t)\right]}{\partial a^n}\bigg|_{a=0}. \qquad (1)$$

Partial components of responses $\hat{y}_n(t)$ can be calculated by using the test actions and procedure (1). Diagonal and subdiagonal sections of Volterra kernel are defined on basis of calculated responses.

Formulas for numerical differentiation using central differences for equidistant knots $y_r = y[a_r x(t)] = y[rhx(t)],\ r=-r_1,-r_1+1,\dots,r_2$ with step of computational mesh on amplitude $h=\Delta a$ were received [8].

Certain limitations should be imposed on choice of frequency polyharmonic test signals while determining multidimensional AFC and PFC [6]. That's why the values of AFC and PFC in this "limited" points of multidimensional frequency space can be calculated using interpolation only. In practical realization of nonlinear dynamical systems identification it is needed to minimize quantity of such undefined points at the range of multidimensional frequency characteristics determination. This done to provide a minimum of restrictions on choice of frequency of the test signal. It is shown that existed limitation can be weakened. New limitations on choice of frequency are reducing quantity of undefined points.

It is defined: to obtain Volterra kernels for nonlinear dynamical system in frequency domain the limitations on choice of frequencies of test polyharmonic signals have to be restricted. This restrictions provide inequality of combination frequencies in the test signal harmonics. It is necessary to consider the imposed constraints on choice of the test polyharmonic signal frequencies during determination of multidimensional transfer functions of nonlinear systems. It provides an inequality of combination frequencies in output signal harmonics: $\omega_1\neq 0$, $\omega_2\neq 0$ and $\omega_1\neq\omega_2$ for the second order identification procedure, and $\omega_1\neq 0$, $\omega_2\neq 0$, $\omega_3\neq 0$, $\omega_1\neq\omega_2$, $\omega_1\neq\omega_3$, $\omega_2\neq\omega_3$, $2\omega_1\neq\omega_2+\omega_3$, $2\omega_2\neq\omega_1+\omega_3$, $2\omega_3\neq\omega_1+\omega_2$, $2\omega_1\neq\omega_2-\omega_3$, $2\omega_2\neq\omega_1-\omega_3$, $2\omega_3\neq\omega_1-\omega_2$, $2\omega_1\neq-\omega_2+\omega_3$, $2\omega_2\neq-\omega_1+\omega_3$ и $2\omega_3\neq-\omega_1+\omega_2$ for the third order identification procedure.

3. THE TECHNIQUE OF THE TEST OBJECT IDENTIFICATION

Described method was fully tested on a nonlinear test object (Fig. 1) described by Riccati equation:

$$\frac{dy(t)}{dt} + \alpha y(t) + \beta y^2(t) = u(t).\,, \qquad (2)$$

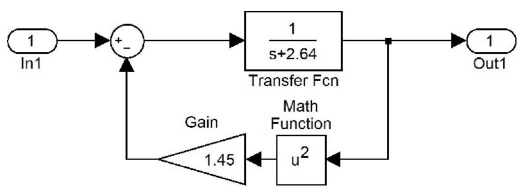

Fig. 1 – Matlab-Simulink model of the test object.

Analytical expressions of AFC and PFC for the first, second and third order model were received and presented in [8].

The main purpose was to identify the multifrequency performances characterizing nonlinear and dynamical properties of nonlinear test object. Volterra model in the form of the second order polynomial is used. Thus, test object properties are characterized by transfer functions of $W_1(j\omega_1)$, $W_2(j\omega_1,j\omega_2)$, $W_3(j\omega_1,j\omega_2,j\omega_3)$ – by Fourier–images of weight functions $w_1(t)$, $w_2(t_1, t_2)$, $w_3(t_1, t_2, t_3)$.

Structure chart of identification procedure – determination of the 1st, 2nd or 3rd order AFC of CC is presented on Fig. 2.

The weighted sum is formed from received signals – responses of each group (Fig. 2). As a result the partial components of CC responses $y_1(t)$, $y_2(t)$ and $y_3(t)$ are got. For each partial component of response the Fourier transform (the FFT is used) is calculated, and from received spectrum only an informative harmonics (which amplitudes represent values of required characteristics of the first, second and third orders AFC) are taken.

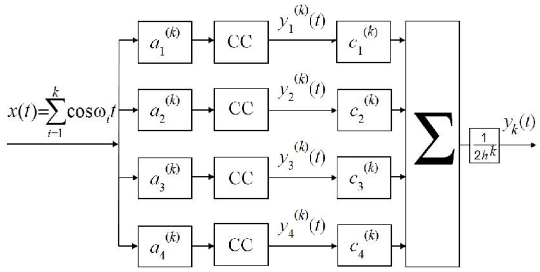

Fig. 2 – The structure chart of identification procedure using the k- order Volterra model in frequency domain, number of experiments N=4, *k* – order of the estimated Volterra kernel.

The first order AFC $|W_1(j\omega_1)|$ and PFC $\arg W_1(j\omega_1)$, where $\omega_1=\omega$ are received by extracting the harmonics with frequency f from the spectrum of the CC partial response $y_1(t)$ to the test signal $x(t)=A/2(\cos\omega t)$.

The second order AFC $|W_2(j\omega_1,j\omega_2)|$ and PFC $\arg W_2(j\omega_1,j\omega_2)$, where $\omega_1=\omega$ and $\omega_2=\omega_1+\Omega_1$, were received by extracting the harmonics with summary frequency $\omega_1+\omega_2$ from the spectrum of the CC partial response $y_2(t)$ to the test signal $x(t)=(A/2)(\cos\omega_1 t+\cos\omega_2 t)$.

The third order AFC $|W_3(j\omega_1,j\omega_2,j\omega_3)|$ and PFC $\arg W_3(j\omega_1,j\omega_2,j\omega_3)$, where $\omega_1=\omega$, $\omega_2=\omega_1+\Omega_1$, $\omega_3=\omega_2+\Omega_2$ were received by extracting the harmonics with summary frequency $\omega_1+\omega_2+\omega_3$ from the spectrum of the CC partial response $y_2(t)$ to the test signal $x(t)=(A/2)(\cos\omega_1 t+\cos\omega_2 t+\cos\omega_3 t)$.

The results (first, second and third order AFC and PFC) which had been received after procedure of identification are represented in Fig. 3–5 (number of experiments for the model N=4).

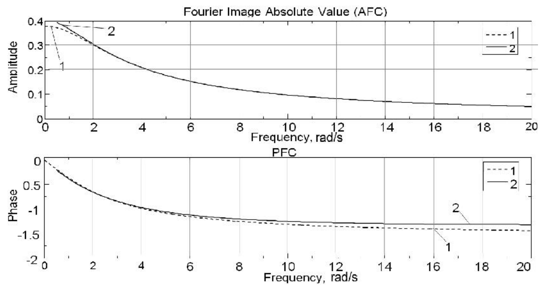

Fig. 3 – First order AFC and PFC of the test object: analytically calculated values (1), section estimation values – number of experiments for the model N=4 (2).

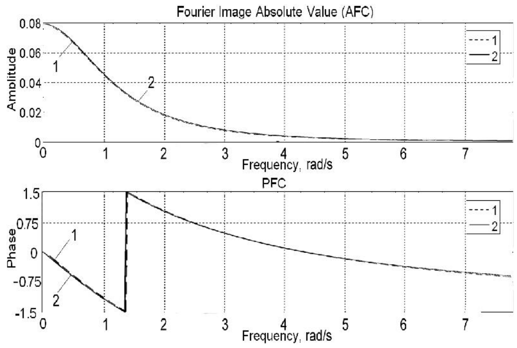

Fig. 4 – Second order AFC and PFC of the test object: analytically calculated values (1), subdiagonal cross–section values with number of experiments for the model N=4 (2), Ω_1=0,01 rad/s.

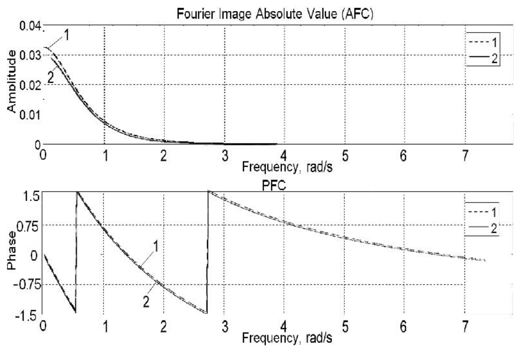

Fig. 5 – Third order AFC and PFC of the test object: analytically calculated values (1), subdiagonal cross-section values with number of experiments for the model N=6 (2), Ω_1=0,01 rad/s, Ω_2=0,1 rad/s.

The surfaces shown on Fig. 6–9 are built from subdiagonal cross–sections which were received separately. Ω_1 was used as growing parameter of identification with different value for each cross–section in second order characteristics. Fixed value of Ω_2 and growing value of Ω_1 were used as parameters of identification to obtain different value for each cross–section in third order characteristics.

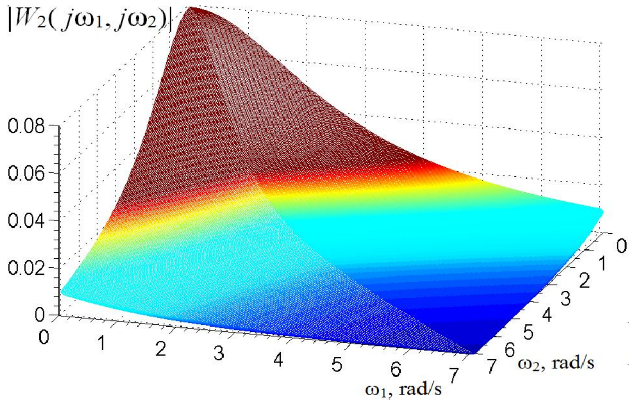

Fig. 6 – Surface of the test object AFC built of the second order subdiagonal cross–sections received for N=4, Ω_1=0,01 rad/s.

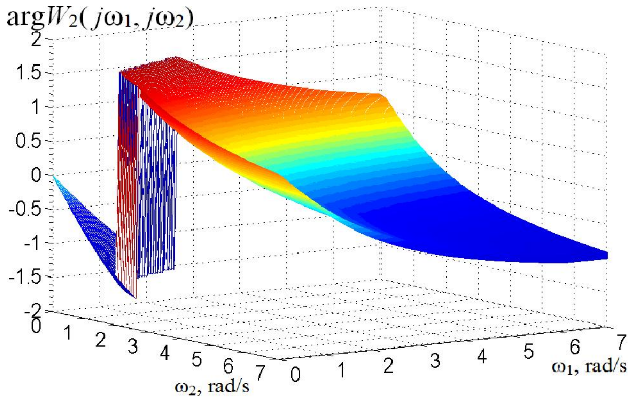

Fig. 7 – Surface of the test object PFC built of the second order subdiagonal cross–sections received for N=4, Ω_1=0,01 rad/s.

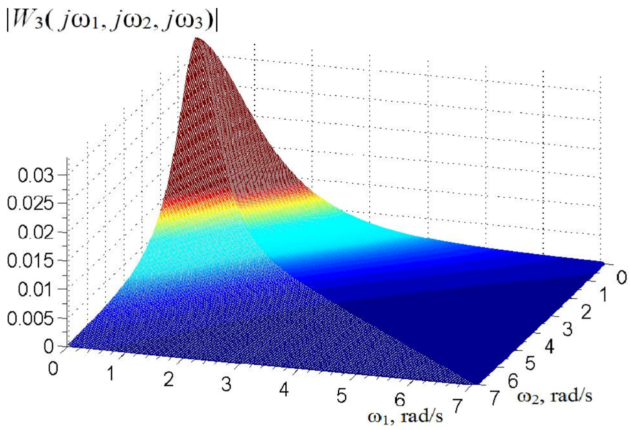

Fig. 8 – Surface of the test object AFC built of the third order subdiagonal cross–sections received for N=6, Ω_1=0,01 rad/s, Ω_2=0,1 rad/s.

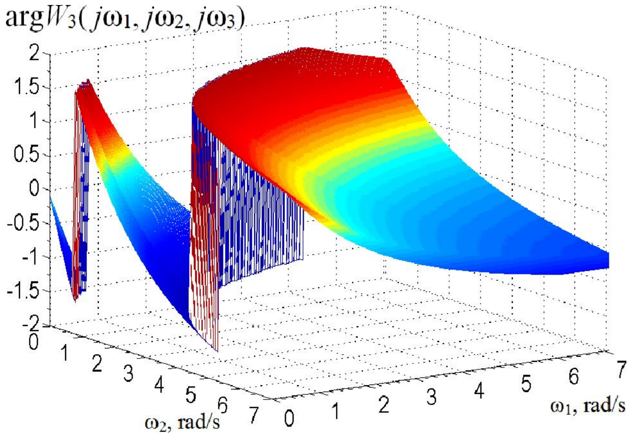

Fig. 9 – Surface of the test object PFC built of the third order subdiagonal cross-sections received for N=6, Ω_1=0,01 rad/s, Ω_2=0,1 rad/s

The second order surfaces for AFC and PFC had been received after procedure of the test object identification and are shown in Fig. 6–7 (number of experiments for the model N=4).

The third order surfaces for AFC and PFC had been received after procedure of the test object identification and are presented in Fig. 8–9 (number of experiments for the model N=6).

Numerical values of identification accuracy using interpolation method for the test object are represented in Table 1.

Table 1. Numerical values of identification accuracy using interpolation method.

Kernel order, k	Experiments quantity, N	AFC relative error, %	PFC relative error, %
1	2	2.1359	2.5420
	4	0.3468	2.0618
	6	0.2957	1.9311
2	2	30.2842	76.8221
	4	2.0452	3.7603
	6	89.2099	5.9438
3	4	10.9810	1.6280
	6	10.7642	1.5522

4. THE STUDY OF NOISE IMMUNITY OF THE IDENTIFICATION METHOD

Experimental research of the noise immunity of the identification method were made. The main purpose was the studying of the noise impact (noise means the inexactness of the measurements) to the characteristics of the test object model using interpolation method in frequency domain.

The first step was the measurement of the level of useful signal after test object (Out2 in Fig. 10). The amplitude of this signal was defined as the 100% of the signal power.

After that procedure the Random Noise signal where added to the test object output signal. This where made to simulate inexactness of the measurements in model. The sum of these two signals for the linear test model is shown in Fig. 11.

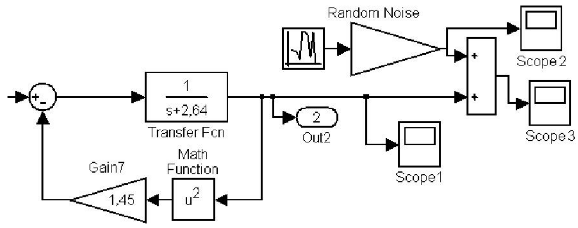

Fig. 10 – The Simulink model of the test object with noise generator and osillosopes.

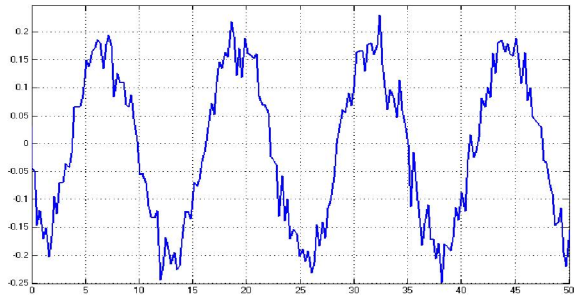

Fig. 11 – The "noised" signal of the test object, the level of noise is 50% of source signal.

The simulations with the test model were made. Different noise levels were defined for different order of the model.

The automatic wavelet denoising were used to reduce the noise impact on final characteristics of the test object. The Daubechie wavelet of the 2 and 3 level were chosen and used for the AFC and PFC denoising respectively [9, 13].

The first order (linear) model was tested with the level of noise 50% and 10% and showed excellent level of noise immunity. The second order (nonlinear) model was tested with the level of noise 10% and 1% and showed good level of noise immunity. The noised (Fig. 12) and de-noised (filtered) (Fig. 13) characteristics (AFC and PFC) with level of noise 10% are presented. The third order (nonlinear) model was tested with the level of noise 10% and 1% and showed good level of noise immunity.

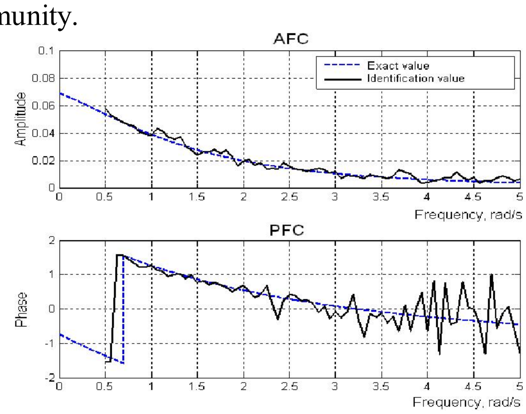

Fig. 12 – Noised characteristics (AFC – top, PFC – bottom) of the 2nd order for the test object model with noise level 10%.

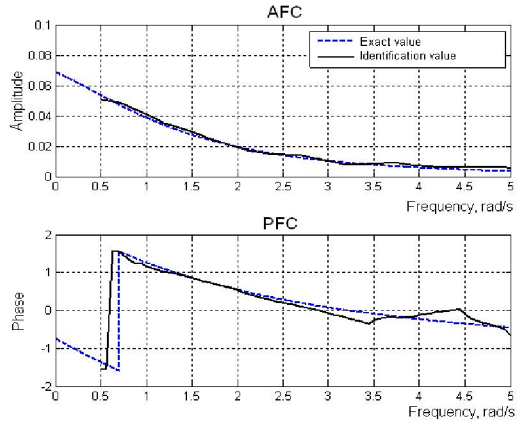

Fig. 13 – Denoised characteristics (AFC – top, PFC – bottom) of the 2nd order for the test object model with noise level 10%

The numerical values of standard deviation (SD) of the identification accuracy before and after wavelet denoising procedure are shown in Table 2.

Table 2. Standard deviation with noise impact.

k	N	Noise level = 10%		Noise level = 1%		Improvement	
		SD for AFC	SD for PFC	SD for AFC	SD for PFC	for AFC, times	for PFC, times
		(without / with denoising)					
1	2	0.000097 /0.000063	0.09031 /0.07541	–	–	**1,540**	1,198
1	4	0.000271 /0.000181	0.07804 /0.06433	–	–	1,497	1,213
1	6	0.000312 /0.000223	0.12913 /0.09889	–	–	1,399	1,306
2	2	0.000920 /0.000670	0.52063 /0.51465	–	–	1,373	1,012
2	4	0.001972 /0.001663	0.28004 /0.06877	–	–	1,186	**4,072**
2	6	0.004165 /0.003908	0.39260 /0.19237	–	–	1,066	2,041
3	4	–	–	0.000288 /0.000288	0.89857 /0.61251	1,003	1,467
3	6	–	–	0.000461 /0.000352	0.84868 /0.59319	1,310	1,431

The diagrams, showing the improvement of standard deviation for identification accuracy using the automatic wavelet denoising of the received characteristics (AFC and PFC) are shown in Fig. 14 and Fig. 15 respectively.

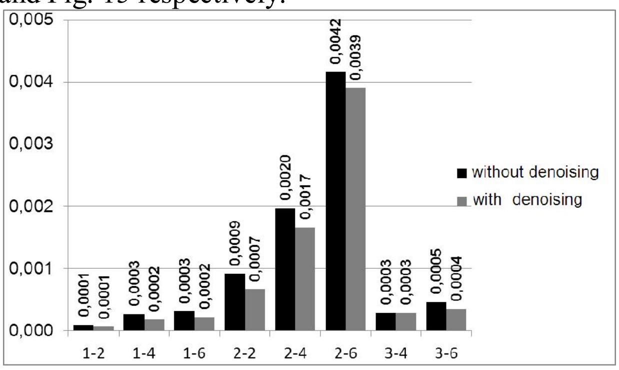

Fig. 14 – Standard deviation changing for AFC using automatic Wavelet-denoising.

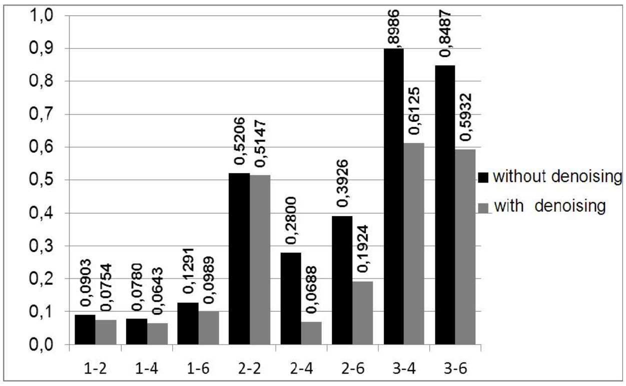

Fig. 15 – Standard deviation changing for PFC using automatic Wavelet-denoising.

5. HARDWARE-SOFTWARE TOOLKIT AND TECHNIQUE OF RADIOFREQUENCY CC IDENTIFICATION

Experimental research of the Ultra High Frequency range CC were done. The main purpose was the identification of multifrequency performances that characterize nonlinear and dynamical properties of the CC. Volterra model in the form of the second order polynomial is used. Thus physical CC properties are characterized by transfer functions of $W_1(j2\pi f)$ and $W_2(j2\pi f_1, j2\pi f_2)$ − by the Fourier–images of weighting functions $w_1(t)$ and $w_2(t_1, t_2)$.

Implementation of identification method on the IBM PC computer basis has been carried out using the developed software in Matlab software. The software allows automating the process of the test signals forming with the given parameters (amplitudes and frequencies). Also this software allows transmitting and receiving signals through an output and input section of PC soundcard, to produce segmentation of a file with the responses to the fragments, corresponding to the CC responses being researched on test polyharmonic effects with different amplitudes.

In experimental research two identical marine transceivers S.P.RADIO A/S SAILOR RT2048 VHF (the range of operational frequencies is 154,4−163,75 MHz) at 16th operational channel and IBM PC with Creative SBLive! soundcards were used. These transceivers are now used at most ships for communication with coast port stations. Sequentially AFC of the first, second and third orders were defined. The method of identification with number of experiments N=4 was applied.

General scheme of a hardware–software complex of the CC identification, based on the data of input–output type experiment was studied in [6].

The CC received responses $y[a_i x(t)]$ to the test signals $a_i x(t)$, compose a group of the signals, which amount is equal to the used number of experiments N (N=4), shown in Fig. 16.

In each following group the signals frequency increases by magnitude of chosen step. A cross–correlation was used to define the beginning of each received response. Information about the form of the test signals given in [7] were used.

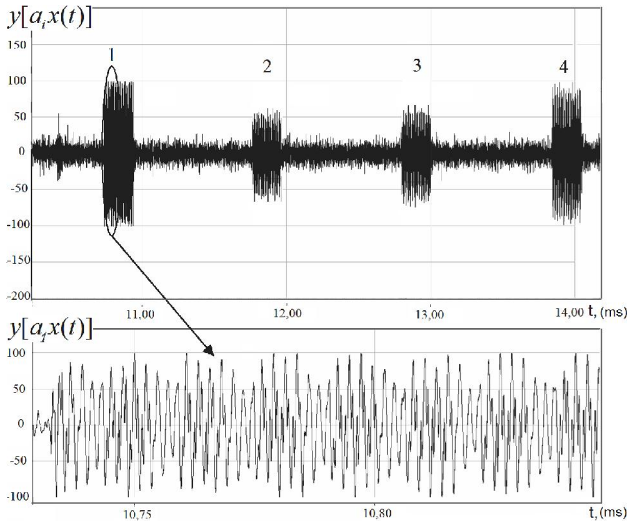

Fig. 16 – The group of signals received from CC with amplitudes: -1 (1); 1 (2); -0,644 (3); 0,644 (4); N=4.

In described experiment with use of sound card the maximum allowed amplitude 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 above. Such parameters were chosen for the experiment: start frequency f_s =125 Hz; final frequency f_e =3125 Hz; a frequency change step Δf=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 weighed sum is formed from received signals – responses of each group (Fig. 2). As a result we get partial component s of response of the CC $y_1(t)$ and $y_2(t)$. For each partial component of response a Fourier transform (the FFT is used) is calculated, and from received spectra only an informative harmonics (which amplitudes represents values of required characteristics of the first and second orders AFC) are taken.

The first order AFC $|W_1(j2\pi f)|$ is received by extracting the harmonics with frequency f from the spectrum of the partial response of the CC $y_1(t)$ to the test signal $x(t)=A/2(\cos 2\pi f t)$.

The second order AFC $|W_2(j2\pi f, j2\pi(f+F_1))|$, where $f_1=f$ and $f_2=f+F_1$, was received by extracting the harmonics with summary frequency f_1+f_2 from the spectrum of the partial response of the CC $y_2(t)$ to the test signal $x(t)=(A/2)(\cos 2\pi f_1 t+\cos 2\pi f_2 t)$.

The wavelet noise–suppression was used to smooth the output data of the experiment [9]. The results received after digital data processing of the data of experiments (wavelet "Coiflet" de–noising) for the first, second and third order AFC are presented in Fig. 17–20.

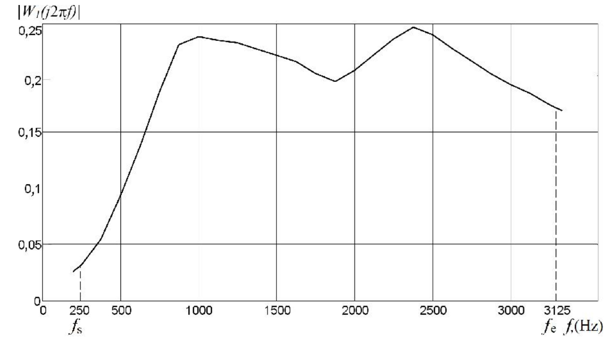

Fig. 17 – AFC of the first order after wavelet "Coiflet" second level denoisingю

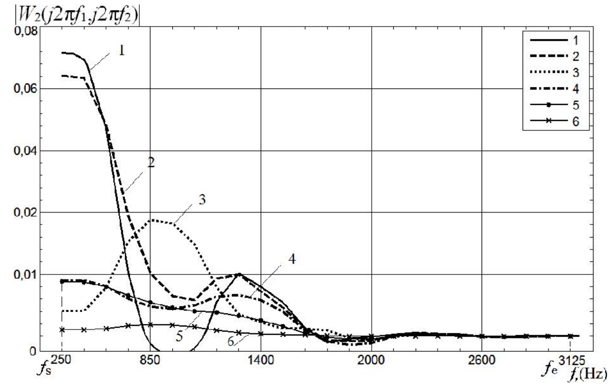

Fig. 18 – Subdiagonal cross–sections of AFCs of the second order after wavelet "Coiflet" second level denoising at different frequencies: 201 (1), 401 (2), 601 (3), 801 (4), 1001 (5), 1401 (6) Hz.

The surfaces shown in Fig. 19–20 were built from subdiagonal cross–sections that have been received separately. A growing parameter of identification Δf with different value for each section was used.

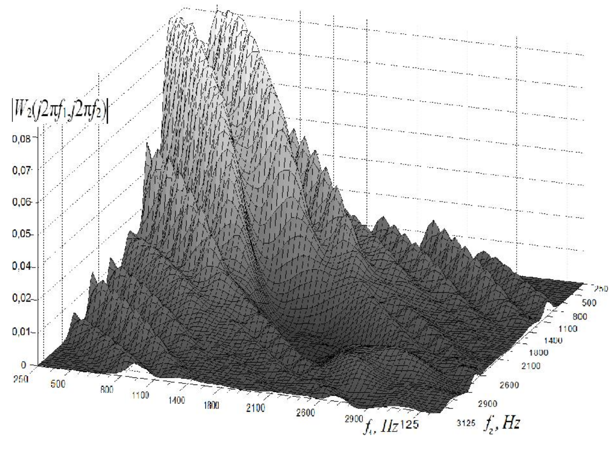

Fig. 19 – Surface built of AFC cross–sections of the second order after wavelet "Coiflet" 3rd level denoising.

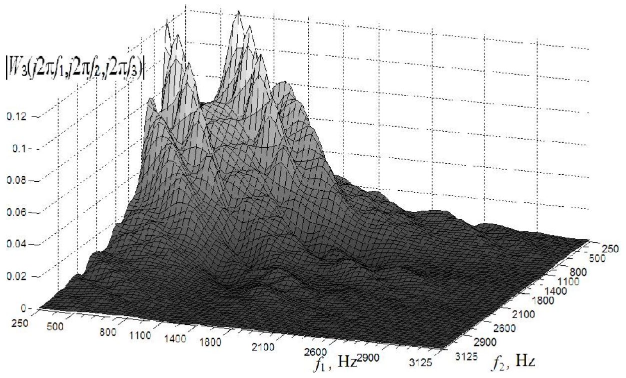

Fig. 20 – Surface built of AFC cross–sections of the third order after wavelet "Coiflet" 3rd level denoising, where $f_3 = f_1 + 100$ Hz.

6. CONCLUSION

The method based on Volterra model using polyharmonic test signals for identification nonlinear dynamical systems is analyzed. The method based on composition of linear responses combination on test signals with different amplitudes were used to differentiate the responses of object for partial components. New values of test signals amplitudes were defined and model were validated using the test object. Excellent accuracy level for received model is achieved as in linear model so in nonlinear ones. Given values are greatly raising the accuracy of identification in compare to amplitudes and coefficients studied in [10, 11]. The identification accuracy of nonlinear part for the test object has grown for 5-20% while the standard deviation in best cases is no more than 10% that means excellent adequacy of used method.

The noise immunity is very high for the linear model, high enough for the second order nonlinear model and has moderate noise immunity for the third order model. The wavelet denoising 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.

Interpolation method of identification using the hardware methodology used in [11, 12] is applied for constructing of informational Volterra model as an APC of the first and second order for UHF band radio channel. Received results had confirmed significant nonlinearity of characteristics of the tested objects that leads to distortions of signals in different type radio devices.

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