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Self-Regulating Dynamic Measurement Method

D. D. Yaparov[*,a] **and A. L. Shestakov**[*,b]

South Ural State University (NRU), Chelyabinsk, Russia

e-mail: [a]*iaparovdd@susu.ru,* [b]*president@susu.ru*

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Abstract—A dynamic measuring system is considered. A new model of the measuring system, a method for processing of measurement results and a method of restoring the input signal of the system by the noisy output signal are proposed. The estimation of the accuracy of the method and a computational experiment demonstrating the efficiency of the signal recovery method are presented.

Keywords: measurement results processing, dynamic measurements, self-regulation, signal recovery

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1. INTRODUCTION

The efficiency of technological processes is directly related to ensuring the optimal parameters of process control systems. The accuracy of compliance with and optimization of the parameters depend on the accuracy of processing of data on the system status. In case of energy-intensive and high-speed technological processes, the system status changes within a short period of time. Due to the output signal's noise pollution and the time lag in the measuring system, we need information about the input signal in order to learn the actual system status. Another factor, which has a significant influence on the accuracy of processing the system status data, is the output signal's noise pollution. The noise problem, combined with the time lag in the measuring system, becomes especially serious during processing the dynamic measuring performed within a short period of time, when even slight noise in the input data can lead to severe misrepresentation of the data processing results. Many researchers have written their works on the problem of processing noise-contaminated dynamic signals. Among the works on this research topic we should highlight an approach based on using the control theory [1]. In this work, a model of a measuring system with modal control of the dynamic characteristics is proposed; and in work [2], a number of methods for dynamic error correction, based on the application of the automatic control theory, is proposed. Another approach to processing of noise-contaminated dynamic measurements implies the creation of engineering solutions. This field of research includes works by V.A. Granovskiy [3, 4], who proposed to use test signals for the correction of noise in dynamic measurements. The work by S. Engelberg [5], which implies the introduction of additional filters to reduce the negative effects from noise, as well as the work [6], describe a new approach to data collection. A separate field of research on the processing of noise-contaminated dynamic signals is related to the use of the theory and methods of inverse problems solving. In this field, works were written by G.N. Solopchenko [7–9] (who proposed to use the A.N. Tikhonov regularization methods for dynamic measurements), the work by A.F. Verlan [10] (where the problem of processing of noise-contaminated information is reduced to solving Fredholm equations of the first kind), as well as the work by A. Forbes [11] (where the problem of processing of dynamic measurements is presented as an inverse problem being solved by using Gaussian process). In this paper, we propose a method of processing noise-contaminated dynamic measurements, which is based on the effect of self-regularization and does not require significant re-adjustment of the measuring system parameters.

2. CLOSED-LOOP MEASURING SYSTEM MODEL

At their input measuring systems have a primary measuring transducer (sensor), that is why the input signal $U(t)$ cannot be measured directly. Due to the time lag in the measuring system and in order to learn the actual system status, we need to restore the input signal $U(t)$ using the sensor's output signal. One of the methods of the input signal restoration was proposed in [12] and includes a closed-loop measuring system model. The structural model of such system is presented in Fig. 1.

In this model several groups of coefficients may be distinguished. Group one includes coefficients a_i, related to the output signal, and group two—coefficients b_j, related to the input signal. The next group includes coefficients d_j, which act as filter characteristics. The user can adjust these characteristics depending on the nature of the input signal noise. The final group includes k_i, which are feedback coefficients and are used for the correction of the dynamic error values.

The significant difficulty in using of the closed-loop model is that when the noise level of the output signal changes, arises a need to correct all the dynamic characteristics of the measuring system, and new values must be selected for coefficients k_i and d_j. Meanwhile, the changes in characteristics of one group do not automatically lead to changes in characteristics of other groups, and each characteristics within one group is corrected independently for each parameter. Thus, the process of re-adjustment of dynamic characteristics results in a more complicated algorithm of

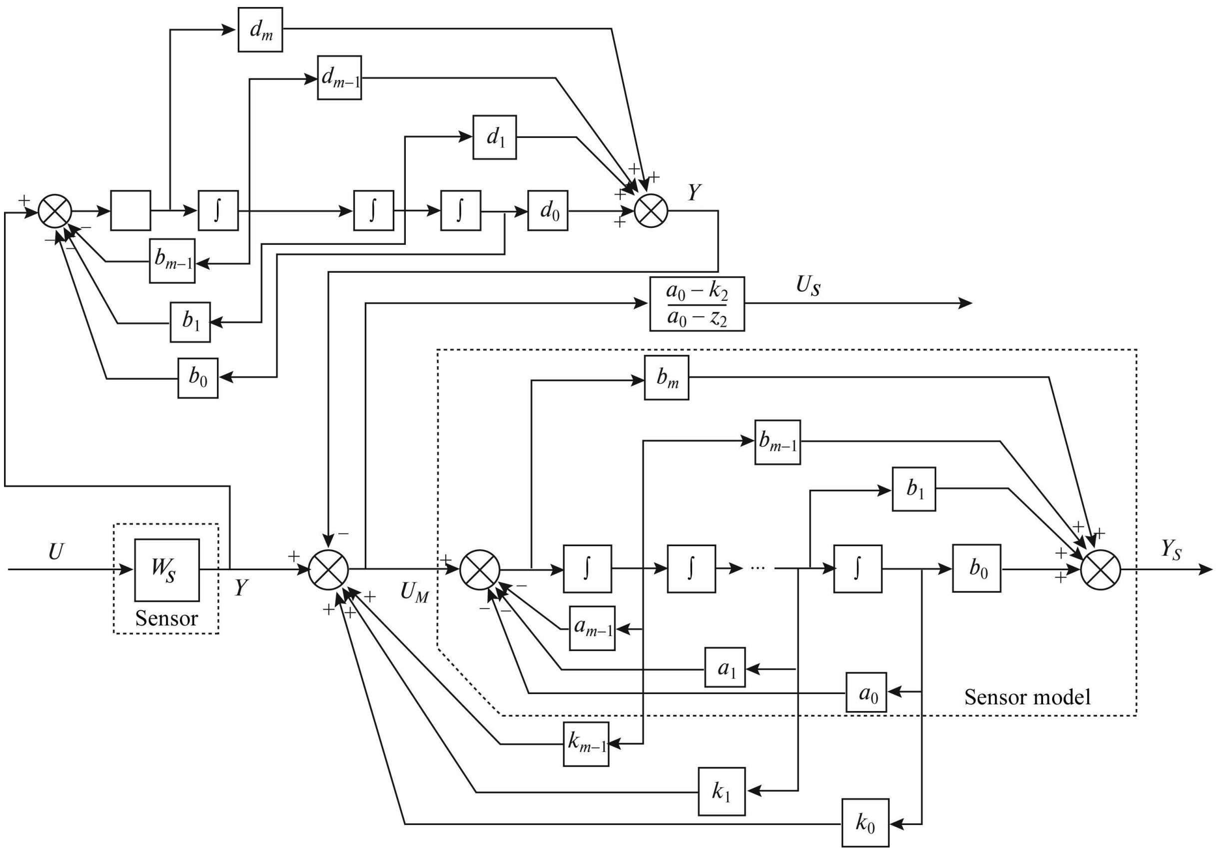

Fig. 1. Structural model of the measuring system.

signal processing. To solve the problem of making the algorithms of output signal processing less complicated, we need to develop a measuring system model, in which the number of groups of the parameters set by the user is reduced to a minimum.

3. OPEN-LOOP MEASURING SYSTEM MODEL

In this paper, we propose a discrete model of an open-loop measuring system, which allows to restore signals by using the noise-contaminated input data and avoid the use of feedback and additional filters. In other words, the model structure excludes the parameters of feedback k_i and the parameters of filters d_j, what allows to reduce the number of the parameters being set. In the proposed model, the correction block and additional filters are replaced with a block of the input signal restoration. The block model is given in Fig. 2, where $U(t)$ is the input signal, $U_\delta(t)$ is the restored signal, $Y_M(t)$ is the model's output signal, c_l, g_j are the coefficients of the measuring system model, $l = \overline{0,n}$, $j = \overline{0,m}$.

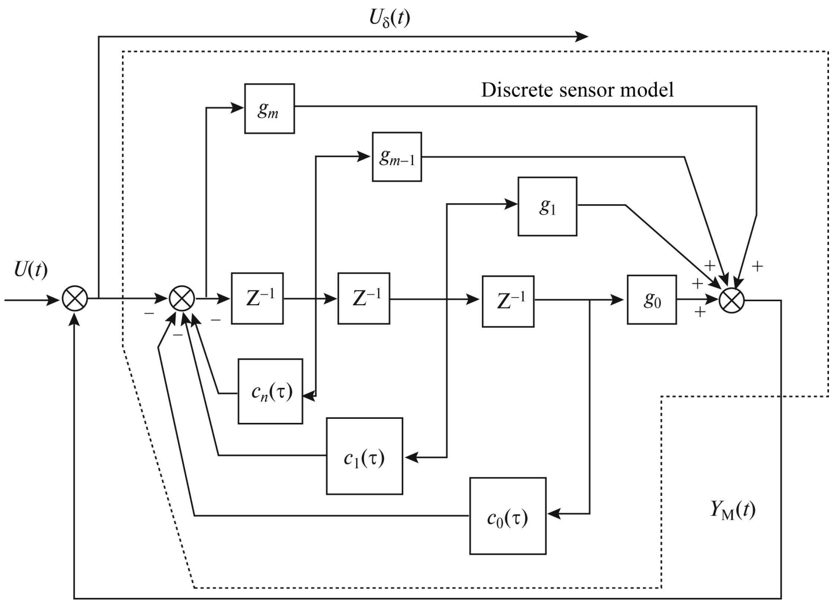

Fig. 2. Block of the input signal restoration in the open-loop discrete model. Nomenclature: $U(t)$ input signal, $U_\delta(t)$ restored signal, $Y_M(t)$ model's output signal, c_l, g_j coefficients of the measuring system model, $l = \overline{0,n}, j = \overline{0,m}$.

Let us build the mathematical model of the open-loop measuring system as follows. Based on the concept proposed in the theory of dynamic measurements [2], transfer function $W(p)$ of the open-loop measuring system is:

$$W(p) = \frac{b_m p^m + b_{m-1} p^{m-1} + \ldots + b_1 p + b_0}{a_n p^n + a_{n-1} p^{n-1} + \ldots + a_1 p + a_0} = \frac{y(p)}{u(p)}. \quad (1)$$

At stage one of building the mathematical model of the open-loop system, let us represent transfer function (1) by differential equation:

$$a_n y^{(n)} + a_{n-1} y^{(n-1)} + \ldots + a_1 y' + a_0 y = b_m u^{(m)} + b_{m-1} u^{(m-1)} + \ldots + b_1 u' + b_0 u. \quad (2)$$

Due to the output signal distortion, the following conditions correspond to the system status at the initial moment of time $t = 0$:

$$y(0) = q_0, \quad y'(0) = q_1, \ \ldots, \ y^{(n-2)}(0) = q_{n-2}.$$

Let us denote the following:

$$U = b_m u^{(m)} + b_{m-1} u^{(m-1)} + \ldots + b_1 u' + b_0 u.$$

Thus, we find that the open-loop mathematical model (2) will look as follows:

$$a_n y^{(n)} + a_{(n-1)} y^{(n-1)} + \ldots + a_1 y' + a_0 y = U, \quad (3)$$

$$y(0) = q_0,\ y'(0) = q_1,\ \ldots,\ y^{(n-2)}(0) = q_{n-2}. \quad (4)$$

The proposed mathematical model (3), (4) is multifunctional. On one hand, it serves as grounds for validation of the discrete open-loop model, when based on the known input signal $U(t)$, we need to find function $Y_M(t)$, which corresponds to the output signal of the open-loop measuring system, and compare the obtained results to the output signal $Y_S(t)$, generated by the closed-loop system. On the other hand, equation (3) is used to develop the computational scheme for restoration of the input signal $U(t)$ by the known output signal $Y(t)$. It is worth noting that when restoring the input signal, it is necessary to take into account the fact that noise will be inevitably present in the measured output signal, so the information sufficient for the restoration of the input signal by the proposed method implies that its overall level does not exceed a certain level δ. We can present this situation mathematically as follows. In the problem on restoring the input signal we need to use the noise-contaminated output signal $Y(t)$ to find the input signal $U_\delta(t)$, provided that deviation $Y(t)$ from the accurate values of the output signal does not exceed the value δ.

4. OPEN-LOOP MODEL VALIDATION

At stage one of the validation, the known input signal $U(t)$ is fed to the closed-loop system and to the open-loop system. In the closed-loop system, output signal $Y_S(t)$ is formed, and in the open-loop system—output signal $Y_M(t)$. At the next stage of the validation, deviation of $Y_M(t)$ from $Y_S(t)$ is evaluated. If the deviation value does not exceed level δ, the validation is considered to be successful.

To construct a method of forming of output signal $Y_M(t)$, the following approach is proposed. Based on the idea presented in [13], let us define functions z_k as follows:

$$\begin{gathered} y = z_1, \\ y' = z_1' = z_2, \\ y'' = z_2' = z_3, \\ \ldots \\ y^{(n-2)} = z_{n-3}' = z_{n-2}. \end{gathered}$$

Then, equation (3) can be transformed into a system of differential equations:

$$\begin{cases} y = z_1, \\ y' = z_1' = z_2, \\ y'' = z_2' = z_3, \\ \ldots \\ a_n z_{n-2}'' + a_{n-1} z_{n-2}' + a_{n-2} z_{n-2} + \ldots + a_2 z'' + a_1 z' + a_0 z = U, \end{cases}$$

and the conditions of (4) will look as follows:

$$z_1(0) = q_0,\ z_2(0) = q_1,\ \ldots,\ z_{n-2}'(0) = q_{n-2}.$$

After transforming the last equation in the system, we finally find that the following system can serve as the basis for the validation of the open-loop model:

$$\begin{cases} y = z_1, \\ y' = z_1' = z_2, \\ y'' = z_2' = z_3, \\ \ldots \\ a_n z_{n-2}'' + a_{n-1} z_{n-2}' + a_{n-2} z_{n-2} = U - a_{n-3} z_{n-3} - \ldots - a_2 z'' - a_1 z' - a_0 z \end{cases} \tag{5}$$

with the following initial conditions

$$z_1(0) = q_0,\ z_2(0) = q_1,\ \ldots,\ z_{n-2}'(0) = q_{n-2}. \tag{6}$$

From (5), (6) we need to find functions $z_k(t)$, $k = \overline{1, n-2}$. It is worth noting that problem (5), (6) pertains to the class of inverse problems, the specific feature of which is that the presence of noise or slight deviations in the input data can lead to significant misrepresentation of the final result, so regularization must be used to ensure the method stability in terms of the noise. According to the theory of inverse problems, regularization is fulfilled either by introducing additional stabilizing functional with a certain regularization parameter to the equation [14], or 'when solving some types of problems, it is possible to use only discretization, omitting the regularization step; this is called the problem self-regularization by discretization' [15]. In this paper, we propose a method, in which discretization interval acts as the regularization parameter.

The main stages of forming of $Y_M(t)$ include the following. First, we need to select some value of discretization interval τ, by dividing segment $[0; T]$ into R parts, $R = (T - 0)/\tau$. Then $t_i = (i-1)\tau$, and the value of functions $z_k(t)$ in the moment of time t_i corresponds to $z_k(t_i) = z_k^i$, $k = \overline{1, n-2}$, $i = \overline{1, R+1}$. The initial conditions will look like $z_k^1 = q_k$.

Next, based on the finite-difference representations of derivatives

$$z_{n-2}'(t_i) = \frac{z_k^i - z_k^{i-1}}{\tau},\quad z_{n-2}''(t_i) = \frac{z_{n-2}^i - 2z_{n-2}^{i-1} + z_{n-2}^{i-2}}{\tau^2},\quad i = \overline{1, K},\quad k = \overline{1, n-2},$$

we transform the last equation in system (5). We obtain:

$$z_{n-2}^i = \left(U_{i-2} - c_{n-2} z_{n-2}^{i-2} - c_{n-1} \left(\frac{z_{n-2}^{i-1}}{\tau} \right) \right) c_n, \tag{7}$$

where coefficients c_{n-2}, c_{n-1}, c_n are the coefficients of the open-loop model and are defined by the following formulas:

$$c_{n-2} = \frac{a_n}{\tau^2} - \frac{a_{n-1}}{\tau} + a_{n-2},\quad c_{n-1} = \frac{-2a_n}{\tau} + a_{n-1},\quad c_n = \frac{\tau^2}{a_n},$$

values U_i are formed from input signal $U = b_m u^{(m)} + b_{m-1} u^{(m-1)} + \ldots + b_1 u' + b_0 u$. Next, from the remaining equations of system (5) with the use of (7), we find values z_k^i, $k = \overline{n-3, 1}$ all the way to values z_1^i, which correspond to values $Y_M(t_i)$.

The validation process is considered to be successful if we meet the condition $|Y_M(t_i) - Y_S(t_i)| \leqslant \delta$ in each moment of time t_i; if otherwise, we must return to the initial stage of the computational scheme with a new parameter τ.

5. METHOD OF THE INPUT SIGNAL RESTORATION

The method of restoration of input signal $U_\delta(t)$ by using the known noise-contaminated output signal $Y(t)$ is based on the finite-difference analogue of equation (2) with fixed τ, obtained at the stage of validation of the open-loop model, and the following initial conditions:

$$u(0) = r_0, \quad u'(0) = r_1, \ \ldots, \ u^{(m-2)}(0) = r_{m-2}. \tag{8}$$

To build the computational scheme for restoration of input signal $U_\delta(t)$, let us introduce the following $Y = a_n y^{(n)} + a_{n-1} y^{(n-1)} + \ldots + a_1 y' + a_0$. By applying Y to equation (2), we obtain the following:

$$b_m u^{(m)} + b_{m-1} u^{(m-1)} + \ldots + b_1 u' + b_0 u = Y.$$

Next, like at the validation stage, we use the method of reduction of order and substitute the variables as follows:

$$\begin{aligned} u &= v_1, \\ u' &= v_1' = v_2, \\ u'' &= v_2' = v_3, \\ &\ldots \\ u^{(n-2)} &= v_{n-3}' = v_{n-2}. \end{aligned}$$

As a result, we obtain the following system:

$$\begin{cases} u = v_1, \\ u' = v_1' = v_2, \\ u'' = v_2' = v_3, \\ \ldots \\ b_m v_{m-2}'' + b_{m-1} v_{m-2}' + b_{m-2} v_{m-2} = Y - b_{m-3} v_{m-3} - \ldots - b_2 v'' - b_1 v' - b_0 v \end{cases} \tag{9}$$

with the following initial conditions: $v(0) = r_0, v'(0) = r_1, \ldots, v_{m-2}'(0) = r_{m-2}$.

The main idea of the proposed method implies that at each step of the iteration process, first, by using the finite-difference analogue of the last equation of system (9), we find value $v_{m-2}'(t_i)$ in the current moment of time t_i according to formula

$$v_{m-2}^{i} = \left(Y_{i-2} - g_{m-2} v_{m-2}^{i-2} - g_{m-1} \left(\frac{v_{m-2}^{i-1}}{\tau} \right) \right) g_m, \tag{10}$$

where coefficients g_{m-2}, g_{m-1}, g_m are the coefficients of the open-loop model and are defined by the following formulas:

$$g_{m-2} = \frac{b_m}{\tau^2} - \frac{b_{m-1}}{\tau} + b_{m-2}, \quad g_{m-1} = \frac{-2b_m}{\tau} + b_{m-1}, \quad g_m = \frac{\tau^2}{b_m}.$$

Next, using the finite-difference analogues of derivatives, we obtain the solution for system (9), and find value $v_{m-2}'(t_i)$ in the current moment of time t_i. Upon completion of the iteration process, we obtain all values v_1^i, $\overline{1, K}$. These values correspond to the restored signal $U_\delta(t_i)$.

The main advantage of the proposed method of the input signal restoration is that the dynamic error is corrected thanks to the effect of self-regularization, and the noise level in the restored input signal $U_\delta(t)$ does not exceed the noise level in the output signal.

In [16, 17], the theoretical evaluation of the error of the input signal restoration method was performed. As a result, the criterion was formulated for discretization interval τ:

$$\tau\delta^2 \leqslant \frac{\frac{c_1}{c_2} + \frac{c_0}{c_2}}{\frac{g_1}{g_2} + \frac{g_0}{g_2}}. \tag{11}$$

Condition (11) proves the dependence of the method stability on τ. According to the concept presented in [15], discretization interval τ is a regularization parameter, and the proposed method has the effect of self-regularization.

The advantage of the proposed open-loop model and the input signal restoration method is that these do not require the re-adjustment of the coefficients of dynamic characteristics k_i and d_j, and this allows to make the computational scheme significantly more simple.

6. VERIFICATION OF THE MEASURING SYSTEM MODEL AND THE INPUT SIGNAL RESTORATION METHOD

The verification of the measuring system model and the input signal restoration method was performed through experimental research, including computational experiments. In the course of the computational experiments, first, we used simulation modelling to form the test values of input signal $U(t)$. We used the test values for comparative analysis with the calculated values $U_\delta(t)$. In the course of further experimenting, we restored input signal $U_\delta(t)$ by the experimental values of output signal Y, using the discretization interval obtained at the previous stages of the research. Next, we compared the restored signal to input signal $U(t)$.

6.1. Computational Experiment Technique

The computational experiment included two stages. The goal of stage one was the numerical validation of the open-loop model. At this stage, discretization interval τ was selected. The goal of stage two was the numerical verification of the input signal restoration method. The experiment scheme is given in Fig. 3.

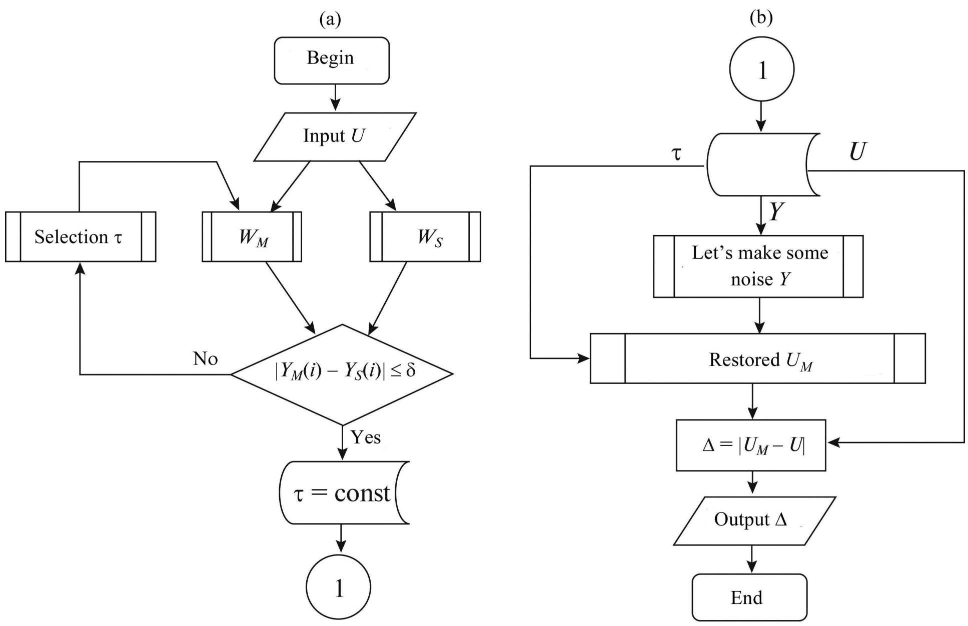

Fig. 3. Structural scheme of the computational experiment: *a* model adjustment stage; *b* signal restoration stage.

Stage I. Model validation. First, signal $U(t)$ was fed to the model with correcting feedback (W_S) and to the model without feedback (W_M) independently of each other. Next, we formed output signals Y_M and Y_S. Then, we did the calculation:

$$\Delta_Y = \max_{t\in[0,T]} |Y_M(t) - Y_S(t)|.$$

If $\Delta_Y > \delta$, then we selected a new value τ according to conditions of (11), a new output signal Y_M was formed, and we recalculated Δ. Upon the attainment of the condition $\Delta_Y \leqslant \delta$, value τ was fixed, and we moved to stage two of the experiment.

Stage II. Signal restoration. At this stage, noise-contaminated signal Y was fed to open-loop model W_M. Next, using parameter τ obtained at stage one, we found values U_δ, which corresponded to the restored input signal. Finally, we evaluated deviation of U_δ from U with the help of value

$$\Delta_U = \max_{t\in[0,T]} |U_\delta(t) - U(t)|.$$

Value Δ_U is the estimation of the accuracy of the input signal restoration method.

6.2. Computational Experiment Results

In this paper, we have presented the results of the experimental research for various orders of measuring systems regarding the restoration of the input signal by using the noise-contaminated data.

In the computational experiment, as the input signal, we took function $U(t) = 1$, and noise level $\delta = 5\%$. The experiment was conducted for measuring systems of the following orders, as given in the Table:

Computational experiment parameters

Measuring system order	Transfer function
II+I	$\dfrac{b_1p + b_0}{a_2p^2 + a_1p + a_0}$
IV+0	$\dfrac{b_0}{(a_2p^2 + a_1p + a_0)(a_5p^2 + a_4p + a_3)}$
V+III	$\dfrac{(b_1p + b_0)(b_4p^2 + b_3p + b_2)}{(a_2p^2 + a_1p + a_0)(a_5p^2 + a_4p + a_3)(a_7p + a_6)}$

Experiment results for the measuring system with the second order for the output signal and with the first order for the input signal (II+I) are presented in Fig. 4.

Deviation of the restored signal from the input one in the experiment equaled no more than 5% at $\tau = 1.2 \times 10^{-3}$.

Experiment results for the measuring system with the fourth order for the output signal and with the zeroth order for the input signal (IV+0) are presented in Fig. 5.

Deviation of the restored signal from the input one in this experiment equaled no more than 5% at $\tau = 1.75 \times 10^{-3}$.

Experiment results for the measuring system with the fifth order for the output signal and with the third order for the input signal (V+III) are presented in Fig. 6.

Deviation of the restored signal from the input one in the experiment equaled no more than 5% at $\tau = 1.75 \times 10^{-3}$.

The experiment results prove the stability of the method of the input signal restoration by using the open-loop model for systems of various orders, i.e., the noise level in the restored signal remains within the controlled limits.

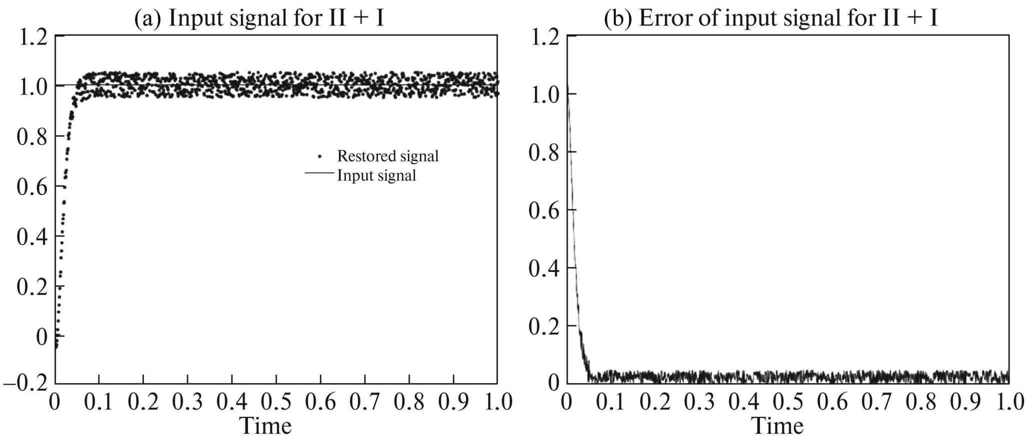

Fig. 4. (a) Charts of the source input signal $U(t)$ and the restored signal $U_\delta(t)$. (b) Deviation of the restored signal from the input one for the system with the second order for the output signal and with the first order for the input signal Δ_U.

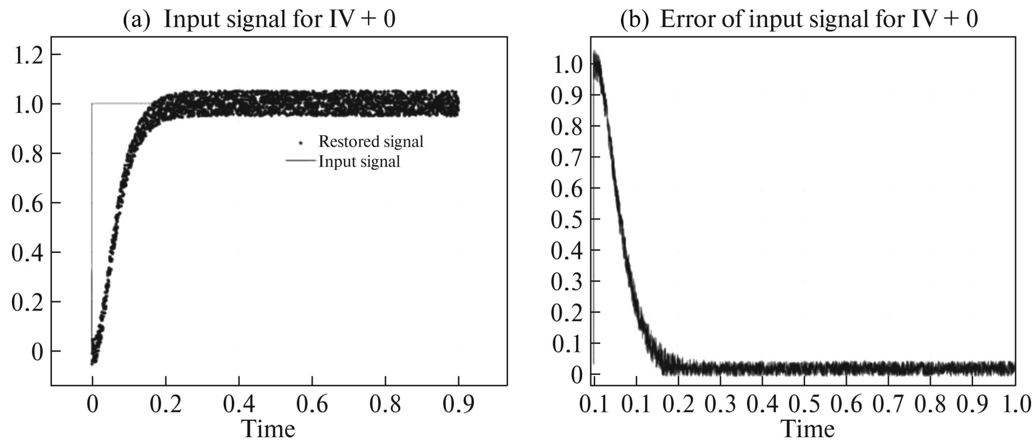

Fig. 5. (a) Charts of the source input signal $U(t)$ and the restored signal $U_\delta(t)$. (b) Deviation of the restored signal from the input one for the system with the fourth order for the output signal and with the zeroth order for the input signal Δ_U.

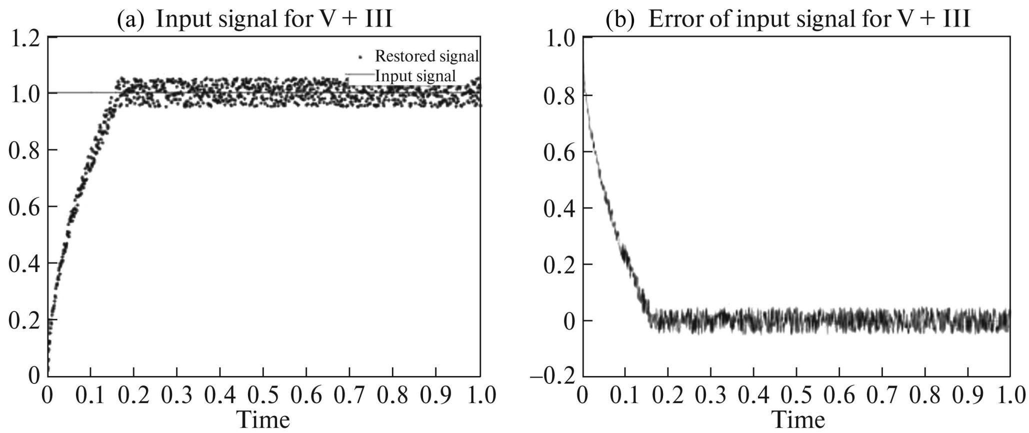

Fig. 6. (a) Charts of the source input signal $U(t)$ and the restored signal $U_\delta(t)$. (b) Deviation of the restored signal from the input one for the system with the fifth order for the output signal and with the third order for the input signal Δ_U.

7. CONCLUSION

In this paper, we have proposed the open-loop measuring system model and the method of the input signal restoration by the noise-contaminated output signal for a random order dynamic system. The input signal restoration method is based on using of regularization approaches. It has been demonstrated that this method has the effect of self-regularization. On the grounds of the built computational schemes, the computational experiment has been conducted and the comparative analysis has been performed regarding the results of restoration of the input signal with test functions. The experiment results prove that the proposed method maintains the level of error in the restored input signal at the level of error of the input data for various orders of measuring system.

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