Control systems design: the technology of stochastic perturbations simulation

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Abstract. An approach to the random perturbations simulation is considered for performing in the design of control systems for thermal power facilities. In order to take into account the stochastic nature of the technological processes, we proposed the simulation technique that allows us to superimpose random fluctuations on the deterministic model of the control system. To simulate random changes in process parameters, we synthesized the shaping filter that generates a random signal with the required autocovariance function. The developed technology allows us to adequately model the technological processes characterized by the action of random perturbations. This is especially important if the requirements for control quality are high. We have experimentally confirmed the suitability of the developed technology by performing control system simulation using MATLAB / Simulink.

1. Introduction

The simulation of automatic control systems (ACS) processes is one of the main issues that are researched at the initial stage of system design. Development of technological processes models includes two stages of research: parameterization of models and evaluation of model parameters using experimental data [1–6].

At the stage of parametrization, the model is being developed on the basis of a priori data on the technological process, and its structure and number of parameters are being determined. It is taken into consideration that dynamic models of technological processes (for example, channels for regulating temperature, pressure, liquid level in tanks, etc.) are approximately represented by first- or second-degree polynomials, which gives a satisfactory result for practice [1, 4, 6].

At the stage of the model parameters evaluation, information on the dynamic characteristics of the systems is being processed, and, in addition, statistical analysis of the experimental data obtained from the control objects is carried out [4, 5].

Because the data on the technological processes flow in the operating ACS is usually registered and archived by information and computing systems, it is possible to use it as input data for the development of mathematical models of control objects. That is, on the basis of archival information, data on the dynamic characteristics of systems was obtained as well as data used to build the models of random perturbations. In addition, the dynamic stochastic mathematical models of control objects were developed, taking into account the inherent nonlinearities [1–6].

To take into account the stochastic character of the change in the parameters of heat-and-power processes, it is necessary to envisage the possibility of imposing random input effects on the deterministic mathematical model.

The article considers the technology of stochastic disturbances simulation by the example of the automatic control system of a typical automation object: the steam pressure control channel in the deaerator of the turbine section of the nuclear power plant power unit. The dynamic stochastic model...
of pressure ACS is created by the MATLAB/Simulink tools (which are intended for performing scientific and engineering calculations) [7, 8].

2. The problem statement
The technological requirements to the steam pressure ACS in the deaerator of the Kol’skaya NPP power unit are as follows. The pressure controller prevents the reduction of pressure in the deaerator and maintains the set value of pressure with the required accuracy. The controller forms the control actions on the electric actuating mechanism (AM) of the control valve (CV). The controller perform pulse control on the proportional-integral (PI) control law together with the constant speed actuator.

ACS pressure in the deaerator should ensure stable operation and absence of oscillations in the control loop. The requirement for limiting the frequency of AM actuations (not more than six per minute) must be fulfilled as well [2, 3] by a constant load of the power unit. This requirement is a general one for controllers of turbine unit technological parameters [2–4].

ACS of the deaerator pressure should not allow sudden changes in pressure leading to ebullition on the suction side of the feed pumps and their steaming.

Based on the analysis of the initial data, it is necessary to estimate the dynamic characteristics of the technological object. In addition, on the basis of archival information, it is necessary to obtain data on the statistical characteristics of the operating random perturbations, because pressure changes in the deaerator, i.e., the pulsations of the measured pressure signal, are random processes. In order to take into account random effects, we must envisage the possibility of superimposing a perturbation with a band-pass frequency spectrum to the object model output. Thus, it is necessary to create a dynamic stochastic model of a control system suitable for simulation and optimization.

3. Theory. Development of dynamic stochastic model of ACS

3.1. The mathematical model description. Preparation of initial data
The mathematical model of the ACS of pressure in the deaerator has been developed with MATLAB/Simulink (see Figure 1). It includes the following submodels: controller, control valve (with AM) and control object. The error signal at the controller’s input is formed as the difference between the setpoint signal and the current pressure value.

The controller implements the traditional control method used in control systems of thermal energy parameters with constant-speed actuators [2, 3]. In this case, the controller outputs are the pulses that are sent to the actuator to open or close the control valve. The on-off time ratio of these output pulses depends on the error signal change (the dependence is the proportional-differential (PD)). The controller jointly with the AM approximately realizes PI-control law in the main, so-called sliding mode of operation. In this mode, the AM is being actuated several times in a same direction, until the deviation goes down to the controller’s dead zone.

In addition, the model incorporates inertial sections for input signals damping. The control valve with the AM is represented by the gain block modeling the transmission factor (opening 100%/Tam) taking into account the opening time of the valve Tam and the integration section with a limit of 0 to 100% according to the CV position indicator. The control object, i.e., the channel “AM position – pressure in the deaerator” is represented by a first-order inertial section.
The fluctuations of random disturbances (pulsations) of the pressure are realized by the shaping filter using the experimentally obtained autocovariance functions of signal fluctuations. The disturbances are further summed up with the output of the inertial section. The block Band-Limited White Noise generates the normally distributed white noise supplied to the input of the shaping filter. Besides, the mathematical model calculates the ACS performance integral criteria. During the period $T$ (adopted not smaller than the system response time), following quadratic integral criteria are calculated. The criterion for characterizing the magnitude and duration of the existence of control error $e(t)$ (the control parameter deviation from the setpoint): $F_1(X) = \int_0^T e^2(t)dt$. The integral quadratic criterion is calculated as well taking into account the cost of control ($u$ denotes the controller output): $F_2(X) = \int_0^T u^2(t)dt$. In addition, the third criterion is number of pulses formed by the regulator (regulating door actuations): $F_3(X) = n$.

These quality criteria were used to optimize the control system, that is, to determine the best values of the parameters $X=(k_p, T_i)$ (here $k_p$ is the gain and $T_i$ is the integration time of the controller). Minimization of the adopted criteria $F_i(X)$, $i=1,3$, ensures the speed of control, the absence of overshoot and reduction of the AM actuations [5].

At the stage of determining the model parameters, the data on the dynamic characteristics of the system provided by the Kol’skaya NPP were processed. In addition, in order to estimate the unknown parameters of the model, statistical processing of the experimental data was carried out. As a result of the initial data analysis, the dynamic characteristics of technological parameters are estimated. Table 1 shows the parameters of the control object, the pressure control channel in the deaerator, used for the subsequent calculation of the ACS parameters. In addition, statistical data on the characteristics of the operating random perturbations were obtained on the basis of archival information.

As we have already said, the pressure changes in the deaerator, that is, signal pulsations, are random processes. Figure 2a shows the graph of the pressure change in the deaerator, according to the archival information of Kol’skaya NPP. From the available data arrays, we have chosen almost stationary realizations in the sense of mathematical expectation constancy and have estimated the statistical characteristics of fluctuations by them. Figure 2b demonstrates the derived estimate of the normalized autocovariance function of these random process for the sample of size $n = 400$.
Table 1. The control object parameters.

| Parameter name                                      | Designation (dimension)     | Value          |
|----------------------------------------------------|----------------------------|----------------|
| Pressure setpoint                                  | $P_S$ (kgf cm$^{-2}$)       | 6              |
| Opening time of the control valve                  | $T_{am}$ (sec)              | 25             |
| Object transfer factor                             | $K_o$ (kgf cm$^{-2}$ (% AM position)$^{-1}$) | 0.1            |
| Time constant of the object                        | $T_o$ (sec)                 | 60             |
| Coefficient characterizing the attenuation of the  | $\alpha$                    | 0.03           |
| autocovariance function of pressure signal pulsations |                           |                |
| Coefficient characterizing the frequency of the    | $\beta$                     | 0.12           |
| periodic component of the signal pressure pulsations|                           |                |
| Standard deviation of pressure signal pulsations   | $\sigma$ (kgf cm$^{-2}$)    | 0.005          |

Figure 2. Realizations of random processes and their corresponding autocovariance functions: a), b) – pressure change; c), d) – changing the simulated pressure when using the shaping filter.

3.2. Synthesis of the forming filter

To model the random changes of pressure in the deaerator using the obtained initial data, the synthesized shaping filter was used to generate a random signal with the required autocovariance function. The transfer function of the forming discrete filter was obtained on the basis of the spectral decomposition method [1, 6].

The input signal of the shaping filter is the normally distributed discrete white noise $\xi(n)$, i.e., an uncorrelated sequence of random numbers with the mean $M_\xi = 0$ and the variance $\sigma_\xi^2 = 1$.

The experimentally obtained autocovariance functions of signal fluctuations for a continuous process are approximated by the expression

$$ R(\tau) = \sigma^2 e^{-\tilde{\alpha} |\tau|} \cos \tilde{\beta} \tau, $$

where the parameters $\tilde{\alpha}$ and $\tilde{\beta}$ characterize the decay of the autocovariance function and the frequency of the periodic component of the process, respectively; $\sigma$ designates the standard deviation of the signal; and finally, $\tau$ represents a time lag.
A stationary random signal with bandpass frequency spectrum realizes the signal pulsations with the above-mentioned autocovariance function. This allows forming pulsations in the required frequency range through varying the parameters $\tilde{\alpha}$ and $\tilde{\beta}$.

The normalized autocovariance function of the corresponding discrete process is $R(n) = e^{-\alpha n} \cos \beta n$, where $\alpha = \tilde{\alpha} t_0$, $\beta = \tilde{\beta} t_0$, and $t_0$ stands for time sampling interval.

The discrete transfer function of the shaping filter for realization of a random process with the autocovariance function (1) acquires the form

$$K(z^{-1}) = \frac{a_0 + a_1 z^{-1}}{b_1 z^{-1} + b_2 z^{-2}},$$

where $z^{-1}$ is the operator of the inverse shift in time; $a_0 = -\sigma v_1 \sqrt{\rho}$; $a_1 = \sigma \sqrt{\rho}$; $b_1 = -2\gamma \cos \beta$;

$$b_2 = \gamma^2; \quad \gamma = e^{-\alpha}; \quad v_1 = v_0 + \sqrt{v_0^2 - 1}; \quad v_0 = \frac{1 + \gamma}{2\gamma \cos \beta}; \quad \rho = \frac{(1-\gamma^2)^2 \cos \beta}{v_1}.$$

To implement the random signal model, define the shaping filter by the recurrent relationship

$$\xi(n) = a_0 \xi(n) + a_1 \xi(n - 1) - b_1 \xi(n - 1) - b_2 \xi(n - 2),$$

where $\xi$, $\overline{\xi}$ are the input and output signals of the shaping filter, respectively; $a_0$, $a_1$, $b_1$, $b_2$ denote the shaping filter parameters dependent on $\alpha$ and $\beta$.

Figure 2d represents a graph approximating the autocovariance function, and Figure 2c shows a corresponding realization of a random process, obtained by the modeling of pulsating pressure signal in the deaerator using the shaping filter (2).

4. Results of experimental studies

Experimental studies were carried out using m-files – MATLAB scripts multiple invoking developed ACS Simulink-model. We used the developed model to determine the optimum parameters of the automatic control system. Preliminary studies and previous experience of the ACS design [3, 5] have shown that the minimal values of the quality criteria are achieved by the different tuning parameters of the system. This suggests the need to reach a compromise between them in solving the optimization problem [9].

The ACS optimal parameters search was carried out by the procedure gamultiobj of the multi-objective genetic algorithm (GA) implemented on the basis of the well-known genetic algorithm NSGA-II (Non-Dominated Sorting Genetic Algorithm) [10, 11]. This algorithm constructs the optimal solutions set (Pareto solutions set) for the case of several criteria.

In comparison with traditional optimization methods, the GA is remarkable for the following substantial advantage. It carries out the solution search using a set of points (a population), but not a single point [10–12]. Using GA, the optimal parameters of the system were found and the corresponding transient processes were obtained. To use the genetic algorithm, the vector of parameters $X=(k_p, T_I)$ is taken as the “individual”.

Let us illustrate the use of the developed ACS dynamic stochastic model. Figure 3 shows the graphs of transient characteristics of ACS (perturbation of the control parameter) while minimizing the criteria $F_1(X) - F_2(X)$ in Figures 3a-3c, respectively. In the graphs the dashed curve corresponds to the controlled parameter (pressure), the dash-dotted one is the position of the AM CV, and the solid line represents the pulse output of the controller.

For clarity in Figure 3d the transient graphs are summarized in enlarged scale for the adjustable parameters of the three cases (curves 1, 2, 3 correspond $F_1$=min, $F_2$=min, $F_3$=min, respectively; curve 4 represents setpoint pressure).

As can be seen in Figure 3a, the transient process with the minimum value of the criterion $F_1(X)$ is characterized by the presence of self-oscillations. The transient process with the minimum value of $F_2(X)$ is not only characterized by a significant number of AM actuations (figure 3b), but also have overshooting and is lengthy (Figure 3d, curve 2).
Figure 3. Transient characteristics of the ACS while minimizing the criteria $F_i(X) - F_j(X)$

Figure 3c shows the ACS transient process when the minimum of the criterion $F_j(X)$ is found among the Pareto set of optimal solutions for the criteria $F_i(X)$ and $F_j(X)$. In addition, in this case the constraint $G(X) < 0$ is taken into account (it restricts the parameters to avoid self-oscillations in the system). It can be seen that the transition process is characterized not only by the absence of overshoot and high speed (figure 3d, curve 3), but also by small number of AM actuations (see figure 3c). It should be noted that using the developed model allowed to take into account the random pulsations of the controlled parameter and to estimate how often the controller actuates the AM under disturbances. For the study, several implementations were carried out. The performed optimization of the automatic control system allowed obtaining high quality of the control process.

The values of the ACS parameters chosen from the accepted ranges $k_p \in [0,0.1; 1]$, $T_i \in [1; 70]$.

5. The discussion of the results

Based on archival information on the technological processes flow provided by the Kol’skaya NPP, the estimation of the autocovariance function of random pressure changes in the deaerator was obtained. To simulate random pressure changes, a shaping filter was synthesized, which makes it possible to generate a random signal with the required autocovariance function.

Let's compare the realizations of random processes for changing the pressure in the deaerator (see Figure 2a) and for changing the simulated pressure when using the shaping filter (see Figure 2c). It can be seen that the curve of random changes in the pressure of a real process (in contrast to a simulated process) also contains more high-frequency components.

This indicates that the estimation of the autocovariance function accepted for modeling (see Figure 2d) in accordance with expression (1) only approximates the autocovariance function of the real process (Figure 2b). However, it seems inexpedient to complicate the expression of the autocovariance function by introducing additional harmonic components.

As shown by the performed studies of the model and existing operational experience, the type of autocovariance function we used for synthesis of the shaping filter (used in the ACS model) allows us to perform calculations with sufficient accuracy for practice.
6. Conclusion
As a result of the issue, it was concluded that the proposed technology for modeling stochastic parameter changes is effective in the design of automatic control systems. To simulate parameter fluctuations, the forming filter is synthesized that generates a random signal with the required autocovariance function.
Based on the processed archive data on the flow of technological processes and using the proposed technology, the dynamic stochastic model of the system for controlling the pressure in the deaerator was created. Using the developed model, we performed the optimization of the parameters of the automatic control system, designed to control the pressure in the deaerators at the Kol’skaya NPP power units.
The developed technology allows to adequately simulating the technological processes that are characterized by the action of random disturbances on the control object, which is especially important if high requirements are imposed on the control quality.

References
[1] Dorf R C and. Bishop R H 2011 Modern control systems (Prentice Hall)
[2] Denisova L A and Meshcheryakov V A 2015 Automatic parametric synthesis of a control system using the genetic algorithm Automation and Remote Control vol 76 no 1 pp 149–156
[3] Denisova L and Meshcheryakov V 2016 Synthesis of a control system using the genetic algorithms IFAC-PapersOnLine vol 49 issue 12 pp 156-161
[4] Denisova L A 2016 Automatic feed control of steam generator in the power unit of a nuclear power plant: modeling and optimization Automation and Remote Control vol 77 no 6 pp 1084–1092
[5] Meshcheryakov V and Denisova L 2016 Computer-aided design of the fuzzy control system using the genetic algorithm Dynamics of Systems, Mechanisms and Machines, Dynamics 2016 p. 7819000
[6] Denisova L 2013 Event-driven simulation of control systems with variable parameters Proceedings of the 7 th IFAC Conference MIM’13 IFAC-PapersOnLine vol 7 part 1 pp 2179–2184
[7] Xue D and Chen Y Q 2013 System simulation techniques with MATLAB and Simulink (John Wiley & Sons)
[8] Purohit G N, Sherry A M and Saraswat M 2013 Optimization of function by using a new MATLAB based genetic algorithm procedure International journal of computer applications vol 61(15) pp 1–5
[9] Podinovskiy V V and Noghin V D 2007 Pareto-optimalnie resheniya mnogokriterialnih zadach (Pareto-optimal solutions of multiobjective problems) (Moscow: FIZMATLIT)
[10] Deb K 2001 Multi-objective optimization using evolutionary algorithms (Chichester: UK, John Wiley & Sons)
[11] Deb K, Pratap A, Agarwal S and Meyarivan T 2002 A Fast and Elitist Multi-objective Genetic Algorithm: NSGA-II IEEE transactions on Evolutionary Computation 6 (2) pp 182–197
[12] Holland J H 1994 Adaptation in natural and artificial systems. An introductory analysis with application to biology, control and artificial intelligence (London: Bradford book edition)