Method of analytical modeling and simulation of technological processes subject to the influence of external factors

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Abstract. The method of analytical modeling and simulation of technological processes is presented, which makes it possible to assess the influence of external factors on the operation of information and control systems. The application of this method to study the process of detecting pipeline defects by vibroacoustic control systems is considered. A mathematical model with automatic selection of the parameters of autocorrelation functions of random disturbances is proposed, which makes it possible to take into account the influence of natural and man-made noises on the detection process. The possibility of modeling the influence of random disturbances on the working processes of technological machines is also considered. The proposed simulation models are of practical value, since they allow one to study virtual prototypes of construction and road-building machinery in various modes and reduce the cost of performing expensive field experiments.

1. Introduction

One of the important and time-consuming stages in the development of information and control systems is the process of evaluating the effectiveness of the adopted technical solutions. This problem arises when designing specialized control and diagnostic systems, for example, implementing the method of active vibroacoustic control, which is used to detect unauthorized influences and defects on pipelines [1-3]. Currently, pipeline transport is one of the most reliable and economical means of continuous transportation of the pumped product stream over long distances. However, the statistics of emergency situations at pipeline transport facilities indicate the presence of problems in the transportation of oil, oil products, etc. Along with the traditional causes of emergencies, such as corrosion (caused by natural influences) and errors of the operating personnel, unauthorized influences exert a significant influence on the state of pipelines [4].

Detection of unauthorized influences and defects on pipelines when using vibroacoustic control is based on testing the pipeline by periodic elastic vibrations caused by impact on the pipe wall. In this case, the main source of information about the test object is a harmonic signal, which tends to attenuate when propagating along the pipeline wall. As a result, systems are susceptible to vibroacoustic noise. Noise suppression in such systems can be provided by accumulating and determining the characteristics of a random signal [3, 5, and 6]. But it should be noted that the proposed solutions need to assess the efficiency of detection and identification of pipeline defects under conditions of exposure to various kinds of noise.

The problem of efficient operation of technological machines used, for example, in road construction, is also very important. It arises in connection with the increased requirements for both the productivity of machines and the accuracy of their technological operations [7]. For the design of control systems for the working processes of technological machines, it is necessary to develop simulation models. These models should take into account the fact that construction and road-building machinery is...
subject to random disturbances from the irregularities of the micro-profile of the soil surface, as well as disturbances caused by the inhomogeneity of soil properties, and also take into account the variable speed of the machine. The use of simulation models allows us to investigate the operation of machines in various modes and establish dependencies between the parameters of the working process. The paper proposes a method for analytical and simulation modeling of technological processes, according to which analytical and simulation models of workflow subsystems are included in the general simulation model. To generate random disturbance signals, we have given the expression for the transfer function of the shaping filter [8]. We have implemented automatic tuning of the parameters of the autocorrelation functions of random disturbances (for the shaping filter), which allowed us to take into account the influence of natural and man-made noise on the process of detecting pipeline defects. A software package that implements this method is presented, intended for model studies of various approaches to detecting defects in order to create an effective vibroacoustic control system. We also showed that the expression of the transfer function of the shaping filter allows us to take into account the variable speed of the machine, explore various modes of its operation and, thereby, create a theoretical basis for automating the design of workflow control systems.

2. Analytical and simulation method for assessing the influence of external factors on the detection of pipeline defects

Proposed combined analytical and simulation technique includes analytical processing of experimental data on stochastic disturbances and model studies to assess their impact on the operation of the control system or monitoring the state of the object. Let us briefly outline the essence of the method using the example of a pipeline defect detection system.

- On the basis of statistical processing of the data of a full-scale experiment on a real pipeline, we obtain estimates of the autocovariance functions (ACF) of the random processes under consideration.
- We carry out an automatic adjustment of the parameters of the approximation of autocovariance functions by analytical expressions. We carry out the synthesis of a shaping filter designed to implement a random process with the required autocovariance function.
- Next, we programmatically generate a test signal for the monitoring system under test. To do this, we superimpose an interference signal on the periodic signal of the defect (from the base of reference signals).
- We carry out a model experiment: according to the model of the monitoring system, we calculate the characteristics of the test noisy signal and compare them with the characteristics of the reference signal of the defect.
- Then we evaluate the accuracy of detecting pipeline defects by the tested vibroacoustic monitoring system.

To implement the method, a software package has been created designed to simulate the process of detecting and recognizing pipeline defects by a vibroacoustic monitoring system. In figure 1 shows the functional structure of a software package implemented in the C# programming language using Windows Forms technology. The basis of the software package is a simulation model of random disturbances, which makes it possible to assess the influence of various kinds of noise (technogenic, natural) on the operation of systems that monitor the state of an object based on the processing of random signals. For automatic adjustment of the ACF parameters of acoustic disturbances of the model, the corresponding software modules are used. Also, special software modules (performing preparation of the test signal) add noise to the defect signal. This interference signal (noise) was obtained as a result of the formation of a random process by the simulation model. The model of the tested vibroacoustic monitoring system, which detects and identifies a periodic signal in a mixture with random noise, implements a defect detection algorithm based on coherent accumulation of signal amplitudes and statistical data processing. The results of the system model operation are processed by the modules for calculating defect detection errors to assess the efficiency of the system.
Figure 1. The structure of the software package for the study of vibroacoustic monitoring systems.

In order to monitor the process of simulation and visual presentation of information, visualization software modules have been created that display the results of adjusting the ACF parameters of acoustic noise, plotting graphs and displaying numerical values of simulation results, including errors in detecting a defect signal in the form of a CSV-table (Comma-Separated Values is format for presenting tabular data).
3. Development of a simulation model of a pipeline system

Let's consider the stages of the formation of the simulation model, which is the basis of the software package. At the first stage, the collection of initial data was carried out. In order to obtain the initial data for the construction of the model, a full-scale experiment was carried out, which consisted in obtaining digital records of random fluctuations on a really operating pipeline system.

As a result of the experiment, realizations of random perturbations were obtained that characterize the most common external influences affecting the operation of pipelines. These are random processes of acoustic noises of four types: wind noise, the noise of the pumped liquid in the pipeline, rain noise, road noise (figure 2), as well as a response signal to a stimulating effect when imitating a “tie-in into the pipeline” defect.

At the second stage, on the basis of statistical processing of experimental data, estimates of the autocovariance functions of the considered random processes are obtained. When analyzing the type of ACF of the obtained realizations, a hypothesis was put forward about the sufficiency of their approximation by an analytical expression of the form:

$$ R(\tau) = \sigma^2 e^{-|\alpha|\tau} \cos(\beta\tau), \quad (1) $$

where $\alpha$ and $\beta$ are parameters characterizing the decay of the ACF and the frequency of the periodic component of the process, respectively; $\sigma$ is the standard deviation of the signal; $\tau$ - time lag. Fluctuations of a signal with an ACF of the form (1) correspond to a stationary random signal with a band-frequency spectrum, which makes it possible to form interference in the required frequency band by changing the parameters ($\alpha$ and $\beta$). When choosing an approach to modeling random processes (acoustic noise with a given ACF), various methods were considered. As a result of the performed analysis, we concluded that the spectral decomposition method for obtaining the transfer function of the shaping discrete filter [8] has sufficient flexibility and low computational complexity of the simulation algorithm. Therefore, to study the influence of external factors on the accuracy of detecting pipeline defects, this method was adopted.

![Figure 2](image)

**Figure 2.** Realizations of random processes of acoustic noise, obtained as a result of a full-scale experiment: a) wind noise; b) the noise of the pumped liquid; c) rain noise; d) road noise.

In this regard, at the third stage, a shaping filter was synthesized designed to simulate acoustic noises with the required autocovariance function. The modeling algorithm is based on a linear transformation of a stationary sequence $\xi(n)$ of uncorrelated normally distributed random numbers (discrete white noise with mathematical expectation $M_\xi = 0$ and variance $\sigma_\xi^2 = 1$) into a sequence of random numbers $\xi(n)$ correlated according to a given law.
Since the experimentally obtained ACFs of continuous signals are approximated by expression (1), the normalized autocovariance function of the corresponding discrete process has the form:

\[ R(n) = e^{-\alpha n} \cos \beta n , \]  
(2)

where \( \alpha = \bar{a}_0 \); \( \beta = \bar{\beta}_0 \); \( t_0 \) is the time sampling interval; \( n = t / t_0 \).

The discrete transfer function of the shaping filter for the implementation of a random process with an autocovariance function (2) has the form:

\[ H(z^{-1}) = \frac{a_0 + a_1 z^{-1}}{b_0 + b_1 z^{-1} + b_2 z^{-2}} , \]  
(3)

where \( a_0 = -\sigma_1 \sqrt{\rho} \); \( a_1 = \sigma \sqrt{\rho} \); \( b_1 = -2 \gamma \cos \beta \); \( b_2 = \gamma^2 \); \( \gamma = e^{-\alpha} \); \( v_1 = v_0 + \sqrt{v_0^2 - 1} \); \( v_0 = \frac{1 + \gamma}{2\gamma \cos \beta} \); \( \rho = \frac{(1 - \gamma^2) \gamma \cos \beta}{v_1} \); and \( z^{-1} \) is the inverse time shift operator.

To implement the model of a random signal, the shaping filter is represented by a recurrent dependence

\[ \tilde{\xi}(n) = a_0 \xi(n) + a_1 \xi(n-1) - b_1 \tilde{\xi}(n-1) - b_2 \tilde{\xi}(n-2) , \]  
(4)

where \( \xi \), \( \tilde{\xi} \) are the input and output signals of the shaping filter, respectively; \( a_0 \), \( a_1 \), \( b_1 \), \( b_2 \) are parameters of the filter, depending on \( \alpha \) and \( \beta \), determined by expressions in accordance with (3).

At the fourth stage, using the appropriate software modules, the parameters \( \alpha \) and \( \beta \) were automatically selected to implement the shaping filter. First, on the basis of the realizations of random noises \( \xi \) obtained in a field experiment, autocorrelation functions are constructed:

\[ R_x(n) = \frac{1}{\sigma_x^2(N-k)} \sum_{n=1}^{N-k} (\xi^n - M_\xi)(\xi^{n+k} - M_\xi) , \]  

where \( M_\xi = \frac{1}{N} \sum_{n=1}^{N} \xi^n \) is the mathematical expectation and \( N \) is the sample size. The ACFs obtained on the basis of experimental data are taken as reference ones. Further, in accordance with expression (2), autocovariance functions \( R_m(\alpha, \beta) \) were selected, which most accurately approximate the reference ACF ( \( R_x(n) \)). The automatic selection procedure was carried out by software modules that enumerate the parameters \( \alpha \) and \( \beta \) in order to minimize the adopted indicator \( L(\alpha, \beta) \). As an indicator of the approximation accuracy, the sum of the squares of the deviations between the approximating \( R_m(n) \) and empirical (reference) \( R_x(n) \) autocovariance functions was taken:

\[ L(\alpha, \beta) = \sum_{n=1}^{N} [R_m(n; \alpha, \beta) - R^n_x]_+^2 \rightarrow \min . \]

The results of automatic tuning of the parameters of the approximating autocovariance functions \( R_m(n) = R(\alpha, \beta) = e^{-\alpha n} \cos \beta n \) for acoustic noise, obtained on the basis of processing realizations of a full-scale experiment (with the best approximation accuracy), are shown in the table 1.

### Table 1. Parameters of ACFs of noise with the best approximation accuracy.

| Kind of a random process | Autocovariance function parameters | Approximation accuracy index |
|--------------------------|-----------------------------------|----------------------------|
|                          | Attenuation parameter \( \alpha \) | Periodic component frequency \( \beta \) | \( L_{\min}(\alpha, \beta) \) |
| Wind noise               | 0.015                             | 0.087                      | 10.91                       |
| Pumped liquid noise      | 0.048                             | 0.111                      | 9.54                        |
| Rain noise               | 0.251                             | 1.371                      | 11.52                       |
| Road noise               | 0.034                             | 0.205                      | 8.40                        |
For the tuned parameters of the autocovariance functions of the noise in figure 3 shows the experimentally obtained ACFs $R_e(n)$ and their approximating ACFs $R_m(n)$, as well as the corresponding realizations of the noise obtained using the shaping filter (in accordance with expression (3)).

The adequacy of the tuning parameters is visually confirmed - the graphs of the autocovariance functions practically coincide, which is due to the good accuracy of tuning the parameters of the approximating function $R_m(n)$ based on minimizing the sum of the squares of the deviations between it and the empirical ACF. In addition, it can be seen that the realizations of noise fluctuations using a shaping filter (in figures 3a-d on the right) are identical to the corresponding graphs of random processes of acoustic noise obtained as a result of a full-scale experiment (compare with figures 2a-d).

![Figure 3](image-url)

**Figure 3.** For acoustic noise: real ACF $R_e(n)$ and approximating ACF $R_m(n)$ (left); the corresponding realizations obtained using the shaping filters (right). Shown are the fluctuations of:

a) wind noise; b) the noise of the pumped liquid; c) rain noise; d) road noise.

4. **Model studies of the influence of external factors on the detection of pipeline defects**

The final stage in the study of the influence of external factors on the detection of pipeline defects is modeling in order to evaluate the effectiveness of the tested vibroacoustic monitoring system: obtaining errors in detecting defects under various types of disturbances.

As a model of the tested monitoring system, let us consider a model of a virtual device designed to detect, isolate and classify periodic signals when exposed to random noise, which makes it possible to assess the state of the monitored section of an extended object [3]. The device under test (called an identification $S$-tester) allows the recognition of the defective and defect-free state of the test object and at the same time shows noise-resistant results. The essence of the algorithm of its work is as follows: the detection and classification of a random signal is realized by accumulating the signal and determining its characteristics. In this case, the signal is measured after each iteration, and its parameters are identified: the pulse belongs to a certain class of signals (according to the identification parameter $S$) using the available conversion scale. The identification parameter $S$ is determined on the basis of measuring the average steepness of the central section of the ranged signal function, which is logically related to the type (shape) of the signal. The available scale associates the numerical parameters of the signal with the qualitative characteristic of the type of distribution of random signals (uniform, normal, bimodal, etc.). During the accumulation of iterations, the influence of the noise
component decreases, and the regular component that determines the value of the parameter $S$ increases. The obtained estimates of the identification parameter are compared with a predetermined threshold value, upon reaching which the iterations are terminated.

The results of the model experiment are shown in figure 4 and figure 5. For various noise factors, 30 experiments were carried out to detect the signal of a pipeline defect. Based on the model of the vibroacoustic monitoring system, we analyzed the test signal, which is the accumulated natural vibration of the pipe and the noise generated by the environment and the transported liquid. Figure 4 shows the results of accumulating the amplitudes of the test random process for processing by the $S$-tester. 60 coherent accumulations of the harmonic signal of imitation of the "tie-in into the pipeline" defect with the imposition of interference (rain noise) were performed in each experiment (with the signal-to-noise ratio $k_{sn}=0.5$).

Coherent accumulation of the resulting process allows us to reduce the initial noise variance $\sigma_x^2$ [3].

In this case, the general formula of the accumulation process has the form: $x_N(k) = \frac{1}{N_{im}} \sum_{n=1}^{N_{im}} x_n(k)$, where $x_N(k)$ is the averaged amplitude of the accumulated signal samples; $x_n(k)$ is the amplitude of the harmonic signal from a series of signals; $k$ is the number of the sample for averaging; $N_{im}$ is the number of accumulations. As we can see in figure 4, with the accumulation of realizations, the noise variance decreases, which depends on the number of accumulations: $\sigma_N^2 = \frac{1}{N_{im}} \sigma_x^2$.

Based on the results of a series of 30 experiments, we calculated the estimates of the average errors $\bar{e}$ in detecting the signal of the "tie-in into the pipeline" defect for various kinds of noise at the signal-to-noise ratio $k_{sn}=0.5$.

Figure 5 illustrates the influence of external factors on the accuracy of defect signal detection. As we can see, noise of any kind introduces a significant error when detecting a signal without noise reduction (number of accumulations $N_{im} = 0$).

In this case, the detection error is high and ranges from 13% to 16%. When there is an accumulation of pulses, for example, at $N_{im} = 30$, the detection error decreases (from 4% to 6%), and when $N_{im} = 1000$ is accumulated, there is practically no error (we can compare it with figures 4c, d).
Figure 5. Dependence of the average detection error on the number of accumulations of the signal to simulate the "tie-in into the pipeline" defect (using an S-tester, signal-to-noise ratio $k_{sn}=0.5$).

5. **Modeling the influence of external factors on the working processes of technological machines**

The above mathematical apparatus for modeling stochastic disturbances can also be applied to the working processes of technological machines. In particular, motor graders and bulldozers as control objects are subject to the influence of random disturbances from the environment.

The most important factors affecting the performance of working processes are the horizontal component of the resistance force arising on the working equipment when digging the soil, as well as the altitude coordinates of the micro-profile of the untreated soil surface, which affect the coordinates of the working equipment and smoothness of the leveled surface.

Figure 6 shows the process parameters values obtained experimentally for two implementations of the working process of the bulldozer [7]. Spectral density plots are approximated with high accuracy by the expression

$$S_f(\omega) = 2\sigma_f^2 \frac{\alpha^2 + \beta^2 + \omega^2}{\left(\alpha^2 + \beta^2 + \omega^2\right)^2 - 4\beta^2 \omega^2},$$

which corresponds to the continuous ACF approximation (1).

Figure 6. Resistance force on the working equipment: signals and their spectral densities.
ACF and spectral densities of the micro-profile of the soil surface depend on the longitudinal coordinate of the machine. When passing to the characteristics of disturbances in the time domain, the average speed of the machine $v$ affects the shape of the spectral density graph (figure 7).

![Figure 7](image-url)

**Figure 7.** Change in the spectral density of disturbances from the micro-profile depending on the speed of the motor grader.

The model of disturbing effects from soil conditions, taking into account the variable speed of the technological machine, is based on the transformation of expression (5) taking into account the speed of the machine $v$:

$$S_f(\omega) = \frac{2\alpha \sigma_f^2}{v} \frac{\alpha^2 + \beta^2 + \left(\frac{\omega}{v}\right)^2}{\alpha^2 + \beta^2 + \left(\frac{\omega}{v}\right)^2}$$

(6)

The corresponding expression for the continuous transfer function of the shaping filter for generating the disturbance $f$ based on white noise $Q$:

$$W_{sf}(p) = \frac{f(p)}{Q(p)} = \frac{2\alpha \sigma_f^2}{v} \left(\frac{1}{p + \sqrt{\alpha^2 + \beta^2}}\right)^2 + \beta^2 = \frac{2\alpha \sigma_f^2}{v} \left(\frac{1}{p^2 + \frac{2\alpha}{v} p + (\alpha^2 + \beta^2)}\right).$$

(7)

Thus, we have shown that the expression of the transfer function of the shaping filter allows us to take into account the variable speed of the machine, to study various modes of its operation and, thereby, showed the effectiveness of the proposed technical solutions. We have shown that the created simulation models made it possible to carry out simulation experiments, that is, to study a virtual prototype of a machine in various modes instead of carrying out field studies. The development of mathematical models of the working processes of technological machines and methods of analytical modeling and simulation allows you to create a theoretical basis for the automation of the design of control systems for work processes during road construction.

6. **Conclusion**

The method of analytical and simulation modeling of technological processes is presented, which makes it possible to assess the influence of external factors on the operation of information and control systems. The application of this technique for studying the process of detecting pipeline defects by
vibroacoustic control systems is considered. The use of vibroacoustic control systems provides an increase in the reliability and safety of pipeline transportation of the pumped products. This approach makes it possible to assess the influence of external factors on the accuracy of detection and recognition of pipeline defects. The developed software package is intended for model research, testing and release of software tools that implement various approaches to detecting defects in order to create an effective vibroacoustic control system. The advantage of the proposed mathematical model (as part of the software package) is the possibility of automatic selection of the parameters of the shaping filter of random disturbances, which makes it possible to assess the influence of various factors on the process of detecting defects of the test object. The results of evaluating the influence of changing environmental conditions on the process of monitoring the state of pipelines (and other extended structures) expand information resources in the development and improvement of monitoring and diagnostic systems.

The possibility of modeling the influence of random disturbances on the working processes of technological machines is also considered. The proposed simulation models are of practical value, since they allow one to study virtual prototypes of construction and road-building machinery in various modes and reduce the cost of conducting expensive field experiments.

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