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Rzayeva N.

DEVELOPMENT OF THE ROBUST ALGORITHMS AND CONTROL SYSTEM OF TECHNICAL STATE OF CONSTRUCTION OBJECTS

Запропоновано систему контролю за змінами в технічному стані будівельних об'єктів. В основі системи лежать технології робастного noise аналізу зашумлених сигналів, які уловлюються датчиками при сейсмічних поштовхах, струсі при русі поїзда метро, коливаннях від вітру і т. д., а також спектральний аналіз перешкод. Система також дозволяє виявляти несправності в прихованому періоді зародження.

Ключові слова: *зашумлений сигнал, кореляційна функція, спектральні характеристики, будівельний об'єкт, технічний стан, система контролю.*

1. Introduction

It is known that the monitoring system of the technical state of building structures should contain:

– a subsystem of primary sensors;
– a subsystem of transfer and accumulation of primary data;
– a subsystem for received data processing and presenting results to a specialized service.

The subsystem of transfer and accumulation of primary data should ensure the digitization and transfer of data from all sensors to the local server, where all data is stored. Digitization of data from sensors should provide acceptable resolution and frequency for each type of sensor. This server must accept, process received requests and provide only authorized access from outside. The subsystem for processing and presenting results must contain a software product that provides a visualized representation of the processed primary data for the operator.

The subsystem of the operator's workplace should provide information about the status of the controlled object at the request of the operator. At the same time, only reliable processing of signals from vibrations, slope measuring sensors and their timely provision to the operator will ensure the implementation of an operational set of measures to prevent premature wear, damage, and defects. Moreover, for many construction objects, there are certain difficulties in predicting the change in the state of the object in the early stages of the origin of faults using known methods of calculating dispersion, correlation, spectral, static, and dynamic characteristics.

It is known that, for the time being, using known methods of calculating dispersion, correlation, spectral, static, and dynamic characteristics, in most cases, for many construction objects, there are certain difficulties in predicting changes in the technical state in the early stages of the origin of faults. In the best case, they make it possible to detect only pronounced defects. An analysis of the occurrence of emergency situations shows that they are always preceded by hidden micro-faults that arise in the form of micro-wear, micro-vibrations, micro-cracks, etc. in some nodes of the studied building structure. Actual is their timely detection which will make it possible to predict changes in the technical state of the building structure, and therefore, can be used to prevent and avoid serious damage. Therefore, the paper considers one of the possible options for solving the problem of monitoring the technical state of construction objects using robust noise and spectral analysis of noisy signals, as well as the spectral noise analysis [1].

2. The object of research and its technological audit

The object of research is the technical state of the construction objects.

Timely detection of the initial stage of the origin of changes in the technical state of construction objects is complicated by the imperfection of the current technical monitoring tools.

If there is a system of continuous controlling of changes in the technical state of building structures based on robust noise and spectral technologies, it will be possible to identify both the initial stage of micro-changes occurrence after the training stage of the system and the latent period of their occurrence [1].

In connection with the above, the creation of such systems is of very important practical interest. This paper is dedicated to the solution of this problem.

3. The aim and objectives of research

The aim of research is development of a technical state of construction objects of robust algorithms and control systems.

To achieve this aim, it is necessary to solve the following problems:

1. Developing technologies for identifying the origin of changes in the technical state of construction objects.
2. Investigating algorithms to determine the latent stage of the origin of changes in the technical state of controlled objects.

3. Considering the basic principles of developing a system for controlling the technical state of a construction object on the basis of sensors installed thereon.

4. Research of existing solutions of the problem

It is known that the analysed noisy signal in digital form has the following form [1–6]:

$$g(i\Delta t) = X(i\Delta t) + \varepsilon(i\Delta t). \tag{1}$$

Due to numerous reasons such as wind noise, vibrations from a passing subway train, etc., both the amplitude and the spectrum of the noise $\varepsilon(i\Delta t)$ accompanying the useful signal $X(i\Delta t)$ vary in a fairly large range. In this case, the error of the obtained estimates of the correlation functions $R_{gg}(\mu)$ of the noisy signal $g(i\Delta t)$ due to the above-mentioned reasons also changes over a very large range over time. For this reason, ensuring of a robustness condition, estimates of the correlation function in real time, that is, the dependence of the obtained results on the variation of the noise $\varepsilon(i\Delta t)$ cannot be eliminated. This, in turn, makes it difficult to analyze a noisy signal using traditional correlation methods. Therefore, in order to ensure the adequacy of identification, it is necessary to fulfill the robustness condition, that is, to eliminate the influence of these factors on the error of estimates $R_{gg}(\mu)$.

At first glance, by filtering the noise accompanying the useful signal $X(i\Delta t)$, it is possible to eliminate the effect of these errors on the result of the analysis of the noisy signal. With a stable noise spectrum, the application of filtering technology generally yields satisfactory results. However, the noise spectrum and its dispersion due to various factors vary in a wide range, and when applying the filtering technology of the noisy signal, the desired result is not achieved. Therefore, to solve the problem under consideration, it is necessary to develop technologies for calculating such estimates of correlation and spectral characteristics, which are practically not affected by changes in this noise.

To do this, first of all, it is expedient to reduce the estimates $R_{gg}(\mu)$ to a single dimensionless quantity by applying a normalization procedure [1–3]. However, our analysis shows that when applying traditional methods, an additional error is introduced into the normalized estimates of the correlation functions $r_{gg}(\mu)$. This, in turn, also makes it difficult to ensure the adequacy of the results of the analysis of the noisy signal. The solution of this problem is proposed in [1, 7–10] – an algorithm for calculating robust estimates of the normalized correlation functions $r_{gg}^R(\mu)$ of a noisy signal $g(i\Delta t)$ is developed that ensures the robustness condition, i. e.:

$$r_{gg}^R(\mu) \approx r_{XX}^R(\mu). \tag{2}$$

Experimental studies have shown that at the initial stage of the origin of changes in the technical state of an object, the effect of noise on a useful signal varies. In this case, each possible state there is corresponded by a certain range of estimates of the robust normalized correlation function of the noisy signal $r_{gg}^R(\mu)$ of the noise variance D_ε of the relay cross-correlation function $R_{X\varepsilon}^*(0)$ between the useful signal and the noise.

In addition, the analysis of possible solutions to this problem [8–10] showed that to determine the latent stage of the origin of changes in the technical state of objects, it is expedient to use robust estimates of the spectral characteristics of noisy signals a_n^R, b_n^R, the spectral characteristics of the noise a_{n_ε}, b_{n_ε}. In this regard, to ensure the adequacy of identifying changes in the technical condition of construction objects, the application of technology for calculating estimates D_ε, $R_{X\varepsilon}^*(0)$, a_n^R, b_n^R, a_{n_ε}, b_{n_ε} is provided in the given work.

5. Methods of research

It is known that the formula for calculating the estimation of the autocorrelation function $R_{gg}(\mu)$ of a noisy signal $g(i\Delta t)$ taking into account the effect of noise $\varepsilon(i\Delta t)$ can be represented in the form:

$$R_{XX}(\mu) = \frac{1}{N\sum_{i=1}^{N} g(i\Delta t)\, g((i+\mu)\Delta t)} =$$
$$= \frac{1}{N\sum_{i=1}^{N}\left[X(i\Delta t)+\varepsilon(i\Delta t)\right]\left[X((i+\mu)\Delta t)+\varepsilon((i+\mu)\Delta t)\right]} =$$
$$= \frac{1}{N\sum_{i=1}^{N}\left[X(i\Delta t)X((i+\mu)\Delta t)+X(i\Delta t)\varepsilon((i+\mu)\Delta t)\right]} +$$
$$+ \frac{1}{N\sum_{i=1}^{N}\left[\varepsilon(i\Delta t)X((i+\mu)\Delta t)+\varepsilon(i\Delta t)\varepsilon((i+\mu)\Delta t)\right]} =$$
$$= R_{XX}(\mu) + \lambda_1(\mu), \tag{3}$$

where

$$R_{XX}(\mu) = \frac{1}{N\sum_{i=1}^{N} X(i\Delta t)\, X((i+\mu)\Delta t)}. \tag{4}$$

It is also known that when the readings of the useful signal $X(i\Delta t)$ of noise $\varepsilon(i\Delta t)$, as well as the noise readings $\varepsilon(i\Delta t)$ $\varepsilon((i+\mu)\Delta t)$ do not correlate with each other, then the following equation holds:

$$\left.\begin{aligned}
R_{X\varepsilon}(\mu) &= \frac{1}{N\sum_{i=1}^{N} X(i\Delta t)\,\varepsilon(i+\mu)\Delta t} \approx 0,\\
R_{\varepsilon X}(\mu) &= \frac{1}{N\sum_{i=1}^{N} \varepsilon(i\Delta t)\, X(i+\mu)\Delta t} \approx 0,\\
R_{\varepsilon\varepsilon}(\mu) &= \frac{1}{N\sum_{i=1}^{N} \varepsilon(i\Delta t)\,\varepsilon(i+\mu)\Delta t} \approx 0.
\end{aligned}\right\} \tag{5}$$

Taking this into account, equation (3) can be written as follows:

$$R_{gg}(\mu=0)=\frac{1}{N\sum_{i=1}^{N}\begin{bmatrix}X(i\Delta t)X(i\Delta t)+\\+X(i\Delta t)\varepsilon(i\Delta t)+\\+\varepsilon(i\Delta t)X(i\Delta t)\end{bmatrix}+D_\varepsilon}\approx$$
$$\approx R_{XX}(\mu=0)+D_\varepsilon,$$
$$R_{gg}(\mu\neq 0)=\frac{1}{N\sum_{i=1}^{N}\begin{bmatrix}X(i\Delta t)X((i+\mu)\Delta t)+\\+X(i\Delta t)\varepsilon((i+\mu)\Delta t)\end{bmatrix}}+$$
$$+\frac{1}{N\sum_{i=1}^{N}\left[\varepsilon(i\Delta t)X((i+\mu)\Delta t)\right]}\approx R_{XX}(\mu\neq 0). \quad (6)$$

It is also known [1, 7–10] that if, according to expression (4), estimates $R_{XX}(\mu=0)$, $R_{XX}(\mu=1)$, $R_{XX}(\mu=2)$ of their difference are determined to be similar values:

$$\lim_{\substack{T\to\infty\\ \Delta t\to 0}} R_{XX}(\mu=0)-R_{XX}(\mu=1)\approx$$
$$\approx \lim_{\substack{T\to\infty\\ \Delta t\to 0}} R_{XX}(\mu=1)-R_{XX}(\mu=2), \quad (7)$$

therefore, we can consider equation to be valid:

$$R_{XX}(\mu=0)-R_{XX}(\mu=1)\approx$$
$$\approx R_{XX}(\mu=1)-R_{XX}(\mu=2), \quad (8)$$

consequently, it can be written as:

$$R_{XX}(\mu=0)\approx 2R_{XX}(\mu=1)-R_{XX}(\mu=2), \quad (9)$$

if we take into consideration the equations:

$$\left.\begin{matrix}R_{gg}(\mu=1)\approx R_{XX}(\mu=1),\\ R_{gg}(\mu=2)\approx R_{XX}(\mu=2),\end{matrix}\right\} \quad (10)$$

then taking into account (3), (6), (8)–(10), we have:

$$D_\varepsilon \approx R_{gg}(\mu=0)+R_{gg}(\mu=2)-2R_{gg}(\mu=1). \quad (11)$$

In other words, under the conditions (5), (7)–(10), the expression for estimating the total noise D_ε can be represented in the form [7, 8]:

$$D_\varepsilon \approx \frac{1}{N\sum_{i=1}^{N}\begin{bmatrix}g^2(i\Delta t)+g(i\Delta t)g((i+2)\Delta t)-\\-2g(i\Delta t)g((i+1)\Delta t)\end{bmatrix}}. \quad (12)$$

As mentioned above, the analysis of possible options for creating a technology for identifying the latent period of the origin of changes in the technical state of building objects has shown that for this purpose it is expedient to use the algorithm for calculating the evaluation of the relay cross-correlation function $R^*_{X\varepsilon}(0)$ between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ of the noisy signal $g(i\Delta t)$.

It is known from [1, 7–10] that in the presence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ the evaluation of the relay cross-correlation function $R^*_{X\varepsilon}(0)$ between the useful signal and the noise can be determined by the formula:

$$D^*_\varepsilon(0)=\frac{1}{N}\sum_{i=1}^{N} sgng(i\Delta t)g(i\Delta t)-$$
$$-2sgng(i\Delta t)g((i+1)\Delta t)+sgng(i\Delta t)g((i+2)\Delta t). \quad (13)$$

Expanding the right-hand side of this formula and taking into account that:

$$sgng(i\Delta t)=sgnX(i\Delta t), \quad (14)$$

expression (13) can be written as follows:

$$R^*_{X\varepsilon}(0)=$$
$$=\frac{1}{N}\sum_{i=1}^{N}\Big[\left[sgnX(i\Delta t)X(i\Delta t)+sgnX(i\Delta t)sgn\varepsilon(i\Delta t)\right]-$$
$$-2\left[sgnX(i\Delta t)X((i+1)\Delta t)+sgnX(i\Delta t)\varepsilon((i+1)\text{X}t)\right]+$$
$$+\left[sgnX(i\Delta t)X((i+2)\Delta t)+sgnX(i\Delta t)\varepsilon((i+2)\Delta t)\right]\Big], \quad (15)$$

this, when the stationary condition and the normality of the distribution law are satisfied, can be reduced to the form:

$$R^*_{X\varepsilon}(0)=\frac{1}{N}\sum_{i=1}^{N} sgng(i\Delta t)\begin{bmatrix}g(i\Delta t)+g((i+2)\Delta t)-\\-2g((i+1)\Delta t)\end{bmatrix}. \quad (16)$$

A distinctive feature of this algorithm is related to the fact that under the normal state of the object's operation the estimate $R^*_{X\varepsilon}(0)$ will be zero. However, when different faults arise when there is a correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$, the estimate $R^*_{X\varepsilon}(0)$ differs from zero which allows to reliably signal the beginning of changes in the technical state of the controlled object.

6. Research results

Now let's consider the issue of ensuring the robustness of calculating estimates of spectral characteristics in the latent period of the origin of changes in the technical state of the object. Let's assume that the monitoring time T of the realization of the noisy signal $g(i\Delta t)$ is chosen to be sufficiently large. In this case assuming that the functions $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ are stationary discretized centered random signals with mathematical expectations equal to zero, the formulas for determining the spectral characteristics a_n, b_n of a noisy signal $g(i\Delta t)$ can be represented as:

$$a_n=\frac{2}{N}\sum_{i=1}^{N}\left[X(i\Delta t)+\varepsilon(i\Delta t)\right]\cos n\omega(i\Delta t)=$$
$$=\frac{2}{N}\sum_{i=1}^{N}\left[X(i\Delta t)\cos n\omega(i\Delta t)-\right.$$
$$-\left[\frac{2}{N}\left[\sum_{i=1}^{N^+}\varepsilon(i\Delta t)\cos n\omega(i\Delta t)-\sum_{i=1}^{N^-}\varepsilon(i\Delta t)\cos n\omega(i\Delta t)\right]\right], \quad (17)$$

$$b_n = \frac{2}{N}\sum_{i=1}^{N}\left[X(i\Delta t)+\varepsilon(i\Delta t)\right]\sin n\omega(i\Delta t) = \\ = \frac{2}{N}\sum_{i=1}^{N}\left[X(i\Delta t)\sin n\omega(i\Delta t)\right] - \\ - \left[\frac{2}{N}\left[\sum_{i=1}^{N^+}\varepsilon(i\Delta t)\sin n\omega(i\Delta t) - \sum_{i=1}^{N^-}\varepsilon(i\Delta t)\sin n\omega(i\Delta t)\right]\right]. \quad (18)$$

It is clear that in the normal technical state of the object the sum of the errors of positive N^+ negative N^- pair products $\varepsilon(i\Delta t)\cos n\omega(i\Delta t)$, $\varepsilon(i\Delta t)\sin n\omega(i\Delta t)$ will be balanced. However, when the changes in the technical state arise with the appearance of a correlation between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$, the errors λ_{a_n}, λ_{b_n} will appear, and these can be determined by the expressions:

$$\lambda_{a_n} = \left[\frac{2}{N}\left[\begin{matrix}\sum_{i=1}^{N^+}\varepsilon(i\Delta t)\cos n\omega(i\Delta t) - \\ - \sum_{i=1}^{N^-}\varepsilon(i\Delta t)\cos n\omega(i\Delta t)\end{matrix}\right]\right], \quad (19)$$

$$\lambda_{b_n} = \left[\frac{2}{N}\left[\begin{matrix}\sum_{i=1}^{N^+}\varepsilon(i\Delta t)\sin n\omega(i\Delta t) - \\ - \sum_{i=1}^{N^-}\varepsilon(i\Delta t)\sin n\omega(i\Delta t)\end{matrix}\right]\right]. \quad (20)$$

Moreover, with an increase in the degree of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$, the error values also increase. Consequently, in some cases, estimates of the errors λ_{a_n}, λ_{b_n} arising from the influence of the noise $\varepsilon(i\Delta t)$ are commensurable with the required coefficients a_n, b_n. This can lead to errors in the monitoring results of the origin of changes in the technical state of the controlled object.

To ensure the robustness of the a_n, b_n estimates of the spectral characteristics of the noisy signal $g(i\Delta t)$, let's consider one of the possible options of balancing the positive and negative errors of the corresponding pair products.

Let's assume that the noise $\varepsilon(i\Delta t)$ readings of the total signal $g(i\Delta t)$ are known. In this case, the absolute error value $\lambda(i\Delta t)$ of each pair product $g(i\Delta t)\cos n\omega(i\Delta t)$, $g(i\Delta t)\sin n\omega(i\Delta t)$ can be determined by the formulas:

$$\lambda_a(i\Delta t) = \left|\varepsilon(i\Delta t)\right|\left|\cos n\omega(i\Delta t)\right|, \quad (21)$$

$$\lambda_b(i\Delta t) = \left|\varepsilon(i\Delta t)\right|\left|\sin n\omega(i\Delta t)\right|. \quad (22)$$

In this case, an estimate of the average absolute error $\lambda(i\Delta t)$ can be determined by the formulas:

$$\overline{\lambda_a(i\Delta t)} = \overline{\varepsilon(i\Delta t)\cos n\omega(i\Delta t)}, \quad (23)$$

$$\overline{\lambda_b(i\Delta t)} = \overline{\varepsilon(i\Delta t)\sin n\omega(i\Delta t)}. \quad (24)$$

However, according to expressions (21) and (22), to calculate the errors λ_{a_n}, λ_{b_n}, it is necessary to determine the readings of the noise $\varepsilon(i\Delta t)$, which is almost impossible. Conducted research in [10] has shown that it is possible to replace the non-measurable readings of noise with their approximate values. For this purpose, it is possible and expedient to use the technology of determining the estimate of the variance of the noise D_ε by expression (12), which can be represented as:

$$D_\varepsilon = \frac{1}{N}\sum_{i=1}^{N}g(i\Delta t)g(i\Delta t) - \sum_{i=1}^{N}2g(i\Delta t)g((i+1)\Delta t) + \\ + \sum_{i=1}^{N}g(i\Delta t)g((i+2)\Delta t) = \\ = \frac{1}{N}\sum_{i=1}^{N}\left[X(i\Delta t)+\varepsilon(i\Delta t)\right]\left[X(i\Delta t)+\varepsilon(i\Delta t)\right] - \\ - \frac{1}{N}\sum_{i=1}^{N}2\left[X(i\Delta t)+\varepsilon(i\Delta t)\right]\times \\ \times\left[X((i+1)\Delta t)\varepsilon((i+1)\Delta t)\right] + \\ + \frac{1}{N}\sum_{i=1}^{N}\left[X(i\mathrm{X}t)+\varepsilon(i\Delta t)\right]\times \\ \times\left[X((i+2)\Delta t)+\varepsilon((i+2)\Delta t)\right] = \\ = R_{XX}(0)+R_{X\varepsilon}(0)+R_{\varepsilon X}(0)+R_{\varepsilon\varepsilon}(0)-2R_{XX}(\Delta t) - \\ - 2R_{X\varepsilon}(\Delta t)-2R_{\varepsilon X}(\Delta t)-2R_{\varepsilon\varepsilon}(\Delta t)+R_{XX}(2\Delta t) + \\ + R_{X\varepsilon}(2\Delta t)+R_{\varepsilon X}(2\Delta t)+R_{\varepsilon\varepsilon}(2\Delta t). \quad (25)$$

Moreover, if for the noisy signal $g(i\Delta t)$ the stationary conditions and the normality of the distribution law are satisfied, the equations can be regarded as valid:

$$\left.\begin{aligned}
&R_{X\varepsilon}(0) = \frac{1}{N}\sum_{i=1}^{N}X(i\Delta t)\varepsilon(i\Delta t) \neq 0,\\
&R_{\varepsilon X}(0) = \frac{1}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)X(i\Delta t) \neq 0,\\
&R_{\varepsilon\varepsilon}(0) = \frac{1}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)\varepsilon(i\Delta t) \neq 0,\\
&R_{XX}(0)+R_{XX}(i\Delta t)-2R_{XX}(\Delta t) \approx 0,\\
&R_{\varepsilon\varepsilon}(\Delta t) = \frac{1}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)\varepsilon((i+1)\Delta t) \approx 0,\\
&R_{\varepsilon\varepsilon}(2\Delta t) = \frac{1}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)\varepsilon((i+2)\Delta t) \approx 0,\\
&R_{X\varepsilon}(\Delta t) = \frac{1}{N}\sum_{i=1}^{N}X(i\Delta t)\varepsilon((i+1)\Delta t) \approx 0,\\
&R_{X\varepsilon}(2\Delta t) = \frac{1}{N}\sum_{i=1}^{N}X(i\Delta t)\varepsilon((i+2)\Delta t) \approx 0,\\
&R_{\varepsilon X}(\Delta t) = \frac{1}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)X((i+1)\Delta t) \approx 0,\\
&R_{\varepsilon X}(2\Delta t) = \frac{1}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)X((i+2)\Delta t) \approx 0.
\end{aligned}\right\} \quad (26)$$

As a result, on the right-hand side of formula (12) we obtain:

$$D_\varepsilon \approx R_{X\varepsilon}(0)+R_{\varepsilon X}(0)+R_{\varepsilon\varepsilon}(0) \approx 2R_{X\varepsilon}(0)+D_{\varepsilon\varepsilon} \approx \\ \approx D_\varepsilon = \frac{1}{N}\sum_{i=1}^{N}\varepsilon^2(i\Delta t),$$

which shows that with the use of expression (12) it is possible to determine the estimate of the variance of the noise $\varepsilon(i\Delta t)$ of the noisy signal $g(i\Delta t)$. Wherein, taking the notation:

$$\varepsilon'(i\Delta t)=\left|g(i\Delta t)\left[g(i\Delta t)+g\left((i+2)\Delta t\right)-2g(i+1)\Delta t\right]\right|, \quad (27)$$

$$\varepsilon(i\Delta t)=\varepsilon^{e}(i\Delta t)=$$
$$=\sqrt{\left|g(i\Delta t)\left[g(i\Delta t)+g\left((i+2)\Delta t\right)-2g(i+1)\Delta t\right]\right|}=$$
$$=\sqrt{\varepsilon'(i\Delta t)}, \quad (28)$$

and admitting the validity of expression:

$$D_{\varepsilon}=\frac{1}{N}\sum_{i=1}^{N}\varepsilon^{2}(i\Delta t)=\frac{1}{N}\sum_{i=1}^{N}\varepsilon^{e2}(i\Delta t)=$$
$$=\frac{1}{N}\sum_{i=1}^{N}\left|g(i\Delta t)\left[g(i\Delta t)+g\left((i+2)\Delta t\right)-2g\left((i+1)\Delta t\right)\right]\right|, \quad (29)$$

the formula for determining the average value of $\varepsilon(i\Delta t)$ can be reduced to the definition of the average value of $\varepsilon^{e}(i\Delta t)$, i. e.:

$$\overline{\varepsilon(i\Delta t)}\approx\overline{\varepsilon^{e}(i\Delta t)}=\frac{1}{N}\sum_{i=1}^{N}\varepsilon^{e}(i\Delta t),$$

in this case, the expressions (23), (24) can be represented in the form:

$$\overline{\lambda_{a}(i\Delta t)}=\overline{\varepsilon^{e}(i\Delta t)\cos n\omega(i\Delta t)}, \quad (30)$$

$$\overline{\lambda_{b}(i\Delta t)}=\overline{\varepsilon^{e}(i\Delta t)\sin n\omega(i\Delta t)}, \quad (31)$$

which can be used to determine the approximate values of the required error estimates a_n, b_n by the expressions:

$$\lambda_{a_n}=\left[\left(\frac{N_{a_n}^{+}-N_{a_n}^{-}}{N}\right)\overline{\lambda_{a}(i\Delta t)}\right], \quad (32)$$

$$\lambda_{b_n}=\left[\left(\frac{N_{b_n}^{+}-N_{b_n}^{-}}{N}\right)\overline{\lambda_{b}(i\Delta t)}\right], \quad (33)$$

where N^{+} is the number of positive, and N^{-} is the number of negative micro-errors of pair products $g(i\Delta t)\cos n\omega(i\Delta t)$, $g(i\Delta t)\sin n\omega(i\Delta t)$.

Obviously, by determining the estimates λ_{a_n}, λ_{b_n}, it becomes possible by balancing the positive and negative errors to ensure the robustness of the estimates a_n^R, b_n^R by the formulas:

$$a_n^R=\frac{2}{N}\left\{\sum_{i=1}^{N}\left[g(i\Delta t)\cos n\omega(i\Delta t)-\lambda_a\right]\right\}, \quad (34)$$

$$b_n^R=\frac{2}{N}\left\{\sum_{i=1}^{N}\left[g(i\Delta t)\sin n\omega(i\Delta t)-\lambda_b\right]\right\}, \quad (35)$$

which makes it possible to increase the reliability of the monitoring results of the latent period of the origin of defects that precede the changes in the technical state of the monitored objects.

Conducted studies have shown that the initial stage of the origin of changes in the object is primarily reflected in the spectrum of the noise $\varepsilon(i\Delta t)$. To control the technical state during this period, it is advisable to use estimates of the spectral characteristics a_{n_ε}, b_{n_ε} of the noise $\varepsilon(i\Delta t)$ as informative features. Thus, expressions (17) and (18) can be transformed to the form:

$$a_{n_\varepsilon}=\frac{2}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)\cos n\omega(i\Delta t)\approx$$
$$\approx\frac{2}{N}\sum_{i=1}^{N}\varepsilon^{e}(i\Delta t)\cos n\omega(i\Delta t), \quad (36)$$

$$b_{n_\varepsilon}=\frac{2}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)\sin n\omega(i\Delta t)\approx$$
$$\approx\frac{2}{N}\sum_{i=1}^{N}\varepsilon^{e}(i\Delta t)\sin n\omega(i\Delta t), \quad (37)$$

which, taking the notation:

$$sgn\, g(i\Delta t)=sgn\, X(i\Delta t)=\begin{cases}+1 \text{ at } g(i\Delta t)>0,\\ \ \ 0 \text{ at } g(i\Delta t)=0,\\ -1 \text{ at } g(i\Delta t)<0,\end{cases} \quad (38)$$

and, taking into account formulas (27), (28), can be represented in the form:

$$a_{n_\varepsilon}\approx\frac{2}{N}\sum_{i=1}^{N}sgn\varepsilon'(i\Delta t)\times$$
$$\times\sqrt{\left|g(i\Delta t)\left[g(i\Delta t)+g\left((i+2)\Delta t\right)-2g(i+1)\Delta t\right]\right|}\times$$
$$\times\cos n\omega(i\Delta t)=\frac{2}{N}\sum_{i=1}^{N}sgn\varepsilon'(i\Delta t)\sqrt{\varepsilon'(i\Delta t)}\cos n\omega(i\Delta t), \quad (39)$$

$$b_{n_\varepsilon}\approx\frac{2}{N}\sum_{i=1}^{N}sgn\,\varepsilon'(i\Delta t)\times$$
$$\times\sqrt{\left|g(i\Delta t)\left[g(i\Delta t)+g\left((i+2)\Delta t\right)-2g(i+1)\Delta t\right]\right|}\times$$
$$\times\sin n\omega(i\Delta t)=\frac{2}{N}\sum_{i=1}^{N}sgn\varepsilon'(i\Delta t)\sqrt{\varepsilon'(i\Delta t)}\sin\omega(i\Delta t). \quad (40)$$

Thus, the estimates a_n^R, b_n^R obtained by expressions (34), (35) are robust, which increases the reliability of monitoring results in the latent period of the origin of changes in the technical state. However, the estimates a_{n_ε}, b_{n_ε}, calculated from expressions (39), (40), in comparison with the robust estimates a_n^R, b_n^R make it possible to register the beginning of the origin of the indicated changes much earlier.

An analysis of other possible options of estimating the spectral characteristics of the noise showed that taking into account the expressions (36)–(40), the algorithms for determining the estimates $a_{n\varepsilon}^{*}$, $b_{n\varepsilon}^{*}$ of the relay spectral characteristics of the noise $\varepsilon(i\Delta t)$ of the noisy signal $g(i\Delta t)$ can be represented as:

$$a_{n\varepsilon}^{*} = \frac{1}{N}\sum_{i=1}^{N} sgn\,\varepsilon(i\Delta t)\cos n\omega(i\Delta t) =$$
$$= \frac{2}{N}\sum_{i=1}^{N} sgn\sqrt{g(i\Delta t)\begin{bmatrix} g(i\Delta t)+g((i+2)\Delta t)- \\ -2g(i+1)\Delta t \end{bmatrix}} \times$$
$$\times \cos n\omega(i\Delta t) = \frac{2}{N}\sum_{i=1}^{N} sgn\sqrt{\varepsilon'(i\Delta t)}\cos n\omega(i\Delta t), \quad (41)$$

$$b_{n\varepsilon}^{*} = \frac{1}{N}\sum_{i=1}^{N} sgn\,\varepsilon(i\Delta t)\sin n\omega(i\Delta t) =$$
$$= \frac{2}{N}\sum_{i=1}^{N} sgn\sqrt{g(i\Delta t)\begin{bmatrix} g(i\Delta t)+g((i+2)\Delta t)- \\ -2g(i+1)\Delta t \end{bmatrix}} \times$$
$$\times \sin n\omega(i\Delta t) = \frac{2}{N}\sum_{i=1}^{N} sgn\sqrt{\varepsilon'(iXt)}\sin n\omega(i\Delta t). \quad (42)$$

Research has also shown that during the solving of monitoring and diagnostic tasks, estimates of the sign spectral noise analysis can also be used, which can be determined using the expressions:

$$a_{n\varepsilon}' = \frac{1}{N}\sum_{i=1}^{N} sgn\,\varepsilon(i\Delta t)\,\mathrm{sgn}\cos n\omega(i\Delta t) =$$
$$= \frac{2}{N}\sum_{i=1}^{N} sgn\sqrt{g(i\Delta t)\begin{bmatrix} g(i\Delta t)+g((i+2)\Delta t)- \\ -\,2g(i+1)\Delta t \end{bmatrix}} \times$$
$$\times\, \mathrm{sgn}\cos n\omega(i\Delta t) = \frac{2}{N}\sum_{i=1}^{N} sgn\sqrt{\varepsilon'(i\Delta t)}\,\mathrm{sgn}\cos n\omega(i\Delta t), \quad (43)$$

$$b_{n\varepsilon}' = \frac{1}{N}\sum_{i=1}^{N} sgn\,\varepsilon(i\Delta t)\sin n\omega(i\Delta t) =$$
$$= \frac{2}{N}\sum_{i=1}^{N} \sqrt{sgng(i\Delta t)\begin{bmatrix} g(i\Delta t)+g((i+2)\Delta t)- \\ -\,2g(i+1)\Delta t \end{bmatrix}} \times$$
$$\times\, \mathrm{sgn}\sin n\omega(i\Delta t) = \frac{2}{N}\sum_{i=1}^{N} sgn\sqrt{\varepsilon'(i\Delta t)}\,\mathrm{sgn}\sin n\omega(i\Delta t). \quad (44)$$

It is easy to see that expressions (41)–(44) for estimating $a_{n\varepsilon}^{*}$, $b_{n\varepsilon}^{*}$, $a_{n\varepsilon}'$, $b_{n\varepsilon}'$, differ in that they are easily implemented by hardware and can be used to signal the beginning of the origin of changes in the technical state of the controlled object.

When creating a system, equipping building objects with sensors that detect noisy signals $g_1(i\Delta t)$, $g_2(i\Delta t)$, ..., $g_m(i\Delta t)$ at minimal seismic shocks, shaking while subway train moving, vibrations from the wind, etc., and a laptop that processes received signals is conceived. From the readings of signals $g_1(i\Delta t)$, $g_2(i\Delta t)$, ..., $g_m(i\Delta t)$ of each object in each cycle files are formed. At the first stage, in the training process for each case, using the algorithms proposed in [1, 9, 10], and also using formulas (12), (16), (34), (35), (39) and (40) the estimates $r_{gg}^{R}(\mu)$, D_ε, $R_{X\varepsilon}^{*}(0)$, a_n^R, b_n^R, $a_{n\varepsilon}$, $b_{n\varepsilon}$ forming the corresponding reference sets are calculated. These sets are carriers of information about the initial technical state of the controlled building object.

During the operation in the monitoring mode, the current estimates of the elements of the sets are determined and compared with the estimates of the corresponding reference sets fixed in the training process according to the current readings of the signals $g_1(i\Delta t)$, $g_2(i\Delta t)$, ..., $g_m(i\Delta t)$. If under the given condition their difference does not exceed the permissible threshold level, then it is considered that the technical state of the corresponding object has not changed. Otherwise, this object is referred to a group that requires the use of mobile control and diagnostic systems, through which the final analysis and decision-making is carried out.

7. SWOT analysis of research results

Strengths. The proposed system of robust noise analysis of noisy signals, as well as spectral analysis of noise, is able not only to detect changes that have occurred in the technical state of the controlled object but also identifies the latent period of their origin. This feature will avoid premature wear, damage, and defects in the technical state of the controlled object. In comparison with the existing control systems, the application of the proposed option will provide an opportunity to take an operational set of measures to avoid serious destruction with much less material and time costs.

Weaknesses. The development of this system requires the purchase of additional equipment, namely sensitive sensors for a monitored building structure. These sensors should detect noisy signals at minimal seismic shocks, shaking while the subway train is moving, vibrations from the wind, etc.

Opportunities. In the future, this system can be used at the stage of construction of high-rise buildings, bridges, overpasses and other building structures and strategic objects.

Threats. Nowadays, using the known methods of calculating the dispersion, correlation and spectral characteristics, in most cases it is possible to predict changes in the technical state of building structures. However, they make it possible to detect only pronounced defects. An analysis of the origin of emergency situations shows that hidden micro-faults appear first. The proposed work developed complex algorithms, the hardware realization of which, in comparison with the traditional, is more difficult to implement. However, with their application, it becomes possible to identify the latent period of the origin of changes in the technical state of the controlled object.

8. Conclusion

1. Technologies in which robust noise characteristics of noisy signals detected by sensors installed on a controlled object are used as informative signs for identifying the origin of changes in the technical state of construction objects are developed.

2. To determine the latent stage of the origin of changes in the technical state of controlled objects, algorithms for calculating the robust spectral characteristics of noisy signals and the spectral characteristics of the noise are proposed.

3. The basic principles of developing a system for monitoring the technical state of a construction object based on sensors installed thereon are proposed. These sensors detect noisy signals at minimal seismic shocks, shaking while subway train moving, vibrations from the wind, etc. and a laptop processes the received signals using the proposed algorithms.

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After the training stage and the formation of reference sets of robust noise and the spectral characteristics of the analysed noisy signals, as well as the spectral characteristics of the noise, a comparison is made between newly received object monitoring estimates from current noisy signals. At the same time, a decision is made as to whether there is a risk of changes in the technical state of the controlled object or not. In the first case, the object goes to the rank, requiring the attraction of mobile monitoring and diagnostic systems, through which the final analysis and decision-making is carried out. In the second case, the monitoring of the object continues.

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РАЗРАБОТКА РОБАСТНЫХ АЛГОРИТМОВ И СИСТЕМЫ КОНТРОЛЯ ТЕХНИЧЕСКОГО СОСТОЯНИЯ СТРОИТЕЛЬНЫХ ОБЪЕКТОВ

Предложена система контроля за изменениями в техническом состоянии строительных объектов. В основе системы лежат технологии робастного noise анализа зашумленных сигналов, которые улавливаются датчиками при сейсмических толчках, встряске при движении поезда метро, колебаниях от ветра и т. д., а также спектральный анализ помех. Система также позволяет выявлять неисправности в скрытом периоде зарождения.

Ключевые слова: зашумленный сигнал, корреляционная функция, спектральные характеристики, строительный объект, техническое состояние, система контроля.

***Narmin Eldar Rzayeva,** Lecturer, Head of Research Division, Department of Information Technologies and Systems, Azerbaijan University of Architecture and Construction, Baku, Azerbaijan, e-mail: nikanel1@gmail.com, ORCID: http://orcid.org/0000-0003-0397-5412*

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Riznyk V., Solomko M.

APPLICATION OF SUPER-STICKING ALGEBRAIC OPERATION OF VARIABLES FOR BOOLEAN FUNCTIONS MINIMIZATION BY COMBINATORIAL METHOD

Розглянуто нову процедуру алгебри логіки – супер-склеювання змінних, яка застосовується при наявності у структурі таблиці істинності повної бінарної комбінаторної системи з повторенням або неповної бінарної комбінаторної системи з повторенням. Ефективність алгебричної операції суперсклеювання змінних суттєво спрощує алгоритм мінімізації булевих функцій, що дозволяє здійснювати ручну мінімізацію функцій з числом змінних до 10.

Ключові слова: *булева функція, метод мінімізації, мінімізація логічної функції, блок-схема з повторенням, мінтерми, супер-склеювання змінних.*

1. Introduction

Boolean functions minimization is still popular in various areas of digital technologies, such as PLA design, built-in self-test (BIST), control system design and the like.

The problem of disjunctive normal form (DNF) minimization is one of the multiextremal logical-combinatorial problems and reduces to an optimal reduction in the number of logical elements of the gate circuit without loss of its functionality. It should be noted that in the

