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TECHNOLOGIES FOR MONITORING THE TECHNICAL CONDITION OF TRANSPORT INFRASTRUCTURE OBJECTS BASED ON THE COEFFICIENT OF CORRELATION BETWEEN CRITICAL VALUES OF NOISE AND USEFUL SIGNALS

Summary. Transport infrastructure objects are exposed to a large number of loads, which cause the formation of displacements, bends, wear, cracks, breakdowns, corrosion, and other defects. It is shown that at the moment of initiation of malfunctions in objects, the noise of the noisy signals coming from the corresponding sensor takes critical values that correlate with useful signals. Therefore, algorithms are developed for calculating the probability of random noise accepting critical values, a coefficient of correlation between the critical values of the noise and the useful component, and a relay cross-correlation function. Technologies for monitoring the technical condition of transport infrastructure objects are proposed based on the estimates of the developed noise characteristics. Computational experiments are conducted, and the reliability of the developed algorithms and technologies is confirmed.

1. INTRODUCTION

Today there are many transport infrastructure facilities with enormous roles in the development of cities, regions, economies, and society [1-3]. Such facilities include highways, railways, waterways, tunnels, overpasses, bridges, train stations, various stations and ports, metro, navigable hydraulic structures, airfields, and airports. All these objects are influenced by countless external loads, such as traffic loads, as well as external natural phenomena, which include the strength and direction of the wind, abrupt changes in temperature, precipitation, solar radiation, and geological features. Of all external impacts, seismic and landslide processes are the most dangerous [1-3].

Therefore, monitoring systems are created to monitor the state of transport infrastructure objects [4-14]. For instance, a landslide monitoring system makes it possible to control landslide processes; a monitoring system for karst-suffusion processes is used to control such dangerous geological phenomena as karst formation, suffusion, surface erosion of the soil, the process of soil liquefaction; the monitoring system of the subgrade of the railway track bed allows monitoring the state of the supporting soil [4]; monitoring systems of the technical condition of the object itself allows preventing the formation of serious damage [5-14]. In these systems, sensors gauging pressure, displacement, loads on reinforcement and anchors, crack opening sensors, inclinometers, accelerometers, seismometers, strain gauges, strain sensors, strainmeters, displacement sensors, temperature sensors, and hydrostatic levels, among others, are installed to measure, collect, and process initial information. Then, an estimation is made of the main parameters characterizing the development of hazardous soil and landslide processes, as well as the technical condition of the object itself—for instance, the stress-

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strain state, strength properties of structures, the temperature of elements, and the presence of defects. The values of the characteristics of these parameters are used to determine the technical condition of the vehicle, the presence or absence of defects, and the degree of danger of malfunction in its operation, after which recommendations are issued to address the malfunction [4-14].

Despite the availability of many modern accurate sensors and information processing methods, existing monitoring and control systems cannot identify the moment when the object goes from one state to another [4-14]. This is of vital importance for seismically active regions and regions exposed to hazardous geological processes since after weak but frequent earthquakes or minor but repeated landslides, invisible and undetectable microscopic cracks, deformations, and bends appear, which can seriously damage or destroy the object [4-14].

It is shown in [15, 16] that in the normal technical condition of the object, the noisy signal that comes from the corresponding sensor contains only the noise generated by external factors. At the moment when even the smallest amount of damage occurs, additional noise appears, which correlates with the useful component of the noisy signal. Therefore, the problem arises of determining the early stage of the initiation of a defect in a transport infrastructure object and the dynamics of its development by calculating the probability of the values of the noise reaching a certain critical interval, along with the correlation between the useful component and the noise.

2. PROBLEM STATEMENT

In practice, in systems designed to monitor transport infrastructure objects, a real signal coming from the corresponding sensors consists of $X(t)$ and $\mathrm{E}(t)$

$$G(t) = X(t) + \mathrm{E}(t), \tag{1}$$

where $X(t)$ is the useful component; $\mathrm{E}(t)$ is the noise with mathematical expectation $m_{\mathrm{E}} = 0$; and $X(t)$, $\mathrm{E}(t)$, and $G(t)$ are stationary random signals that obey a normal distribution law.

Because useful signals $X(t)$ are contaminated by noise $\mathrm{E}(t)$, tangible errors emerge when determining their characteristics.

The overall noise $\mathrm{E}(t)$ is made up of the noise $\mathrm{E}_1(t)$ caused by external factors and the noise $\mathrm{E}_2(t)$ caused by the initiation of a defect during the operation of objects [15, 16]. That is,

$$\mathrm{E}(t) = \mathrm{E}_1(t) + \mathrm{E}_2(t). \tag{2}$$

According to [15, 16], the formula for calculating the variance of $G(t)$ is

$$D_G = R_{GG}(0) = \frac{1}{N}\sum_{i=1}^{N} G^2(i\Delta t) = R_{XX}(0) + 2R_{X\mathrm{E}}(0) + R_{\mathrm{EE}}(0). \tag{3}$$

Therefore, the error is equal to

$$\lambda_{GG}(\mu = 0) = 2R_{X\mathrm{E}}(0) + R_{\mathrm{EE}}(0) = D_{\mathrm{E}},$$

where $R_{X\mathrm{E}}(\mu) = \frac{1}{N}\sum_{i=1}^{N} X(i\Delta t)\mathrm{E}((i+\mu)\Delta t)$ is the cross-correlation function between $X(t)$ and $\mathrm{E}(t)$, and $R_{\mathrm{EE}}(0) = \sum_{i=1}^{N} \mathrm{E}(i\Delta t)\mathrm{E}(i\Delta t)$ is the variance of the noise $\mathrm{E}(t)$.

The formula for calculating the correlation function of $G(t)$ [15, 16]:

$$R_{GG}(\mu) = \frac{1}{N}\sum_{i=1}^{N} G(i\Delta t)G((i+\mu)\Delta t) = R_{XX}(\mu) + R_{\mathrm{E}X}(\mu) + R_{X\mathrm{E}}(\mu) + R_{\mathrm{EE}}(\mu). \tag{4}$$

Since $R_{EE}(\mu)$=0 at $\mu \neq 0$, the sum noise will be equal to

$$\lambda_{GG}(\mu) \approx \begin{cases} 2R_{XE}(0) + R_{EE}(0), & \mu = 0 \\ 2R_{XE}(\mu), & \mu \neq 0 \end{cases}. \tag{5}$$

Hence, the obvious inequality is

$$R_{XX}(\mu) \neq R_{GG}(\mu). \tag{6}$$

Since part of the valuable information contained in the noise $E(t)$ of the signal $G(t)$ is unknown in practice, we cannot calculate the values of $R_{XE}(\mu)$ and $R_{EE}(0)$. Thus, the adequacy of the solution to the problem of determining the early latent stage of the initiation of a defect in a transport infrastructure object and the dynamics of their development is not ensured. In this regard, it is obviously necessary to create algorithms and technologies for estimating the noise variance $R_{EE}(0)$ and the cross-correlation function $R_{XE}(\mu)$ between the useful signal and the noise.

At the same time, [15, 16] an obvious correlation between $X(t)$ and $E(t)$ arises when the values of the noise are within a certain critical interval at the moment when $E_2(t)$ emerges. The probability $P(\alpha \leq E(t) \leq \beta)$ of the noise $E(t)$ with the density distribution function $f(\varepsilon)$ being within a certain interval $[\alpha, \beta]$ can be found using the expression:

$$P(\alpha \leq E(t) \leq \beta) = \int_{\alpha}^{\beta} f(\varepsilon) d\varepsilon. \tag{7}$$

Since the stationary ergodic noise ususally obeys the normal distribution law $N(\varepsilon, m_E, \sigma_E)$, and its mathematical expectation m_E =0,

$$N(\varepsilon) = \frac{1}{\sigma_E \sqrt{2\pi}} e^{-\frac{(\varepsilon - m_E)^2}{2\sigma_E^2}}, \tag{8}$$

then the probability $P(\alpha \leq E(t) \leq \beta)$ can be calculated as follows:

$$P(\alpha \leq E(t) \leq \beta) = \int_{\alpha}^{\beta} N(\varepsilon) d\varepsilon. \tag{9}$$

Below, we propose algorithms and techniques for determining the early stage of the initiation of a defect in a transport infrastructure object, the dynamics of its development as a result of calculating the probability (9).

3. ALGORITHMS FOR DETERMINING THE PROBABILITIES OF THE ADMISSIBLE AND CRITICAL VALUES OF NOISE

Let us calculate the distribution density function $N(\varepsilon)$. First, we need to calculate $\sigma_E = \sqrt{D_E}$. The estimate of the mean square deviation σ_E^* of the noise $E(t)$ can be calculated as [15, 16]

$$\sigma_E^* = \sqrt{R_G(0) - 2R_G(\Delta t) + R_G(2\Delta t)} \tag{10}$$

or

$$\sigma_E^* = \sqrt{\frac{1}{N}\sum_{i=1}^{N} G(i\Delta t)G(i\Delta t) - 2\frac{1}{N}\sum_{i=1}^{N} G(i\Delta t)G((i+1)\Delta t) + \frac{1}{N}\sum_{i=1}^{N} G(i\Delta t)G((i+2)\Delta t)}.$$

Then, the density distribution function of the noise $\mathrm{E}(t)$, considering that the mathematical expectation of the noise is $m_{\mathrm{E}} = 0$, will be determined from the expression

$$N^*(\varepsilon) = \frac{1}{\sigma_{\mathrm{E}}^* \sqrt{2\pi}} e^{A1}, \tag{11}$$

where $A1 = -\frac{\varepsilon^2}{2\left(\sigma_{\mathrm{E}}^*\right)^2}$.

Obviously, the probability of the noise $\mathrm{E}(t)$ being in some interval $[\alpha, \beta]$ can be calculated as follows:

$$P\left(\alpha \le \mathrm{E}(t) \le \beta\right) = \int_{\alpha}^{\beta} N^*(\varepsilon) d\varepsilon. \tag{12}$$

Thus, knowing the probability with which the noise $\mathrm{E}(t)$ takes admissible and critical values at different instants, it is possible to determine the early latent period of the initiation of defects in the structure, the dynamics of their development, and the maintainability of transport infrastructure objects, which will allow timely prevention of emergencies.

4. ALGORITHMS FOR CALCULATING THE RELAY CROSS-CORRELATION FUNCTION AND THE CORRELATION COEFFICIENT BETWEEN THE USEFUL COMPONENT OF NOISY SIGNALS AND NOISE

In the absence of damage, noise $\mathrm{E}(t) = \mathrm{E}_1(t)$ is not correlated with $X(t)$ due to external causes. However, at the initial period of damage, the noise $\mathrm{E}_2(t)$ correlated with $X(t)$ emerges. This happens at the moment when $\mathrm{E}(t)$ takes critical values. Therefore, from this moment on, the correlation between $X(t)$ and $\mathrm{E}(t)$ is non-zero. Here, the initiation and development of malfunctions of transport infrastructure objects are essentially manifested in the estimates of the cross-correlation functions $R_{X\mathrm{E}}(\mu)$ between $X(t)$ and $\mathrm{E}(t)$ [15, 16]. Therefore, to control the beginning and dynamics of changes in the technical condition of these objects, it is advisable to use the estimate $R_{X\mathrm{E}}(\mu)$.

The estimates of the relay autocorrelation function $R_{GG}^r(\mu)$ and cross-correlation function $R_{X\mathrm{E}}^r(\mu)$ can be calculated as follows [15, 16]:

$$R_{GG}^r(\mu) = \frac{1}{N} \sum_{i=1}^{N} sgn\left(G(i\Delta t)\right) G\left((i+\mu)\Delta t\right),$$

$$R_{X\mathrm{E}}^r(\mu) = \frac{1}{N} \sum_{i=1}^{N} sgn\left(X(i\Delta t)\right) \mathrm{E}\left((i+\mu)\Delta t\right), \tag{13}$$

where

$$sgnG(i\Delta t) = \begin{cases} +1, & G(i\Delta t) > 0 \\ 0, & G(i\Delta t) = 0 \\ -1, & G(i\Delta t) < 0 \end{cases}, \quad sgnX(i\Delta t) = \begin{cases} +1, & X(i\Delta t) > 0 \\ 0, & X(i\Delta t) = 0 \\ -1, & X(i\Delta t) < 0 \end{cases}.$$

We will consider options for calculating the relay cross-correlation function $R^{r*}_{X\text{E}}(\mu)$ as a result of calculating the relay correlation function $R^{r}_{GG}(\mu)$ of the noisy signal $G(t)$.

Considering that [15]

$$sgnG(i\Delta t) = sgnX(i\Delta t), \tag{14}$$

the relay correlation function $R^{r}_{GG}(\mu)$ for $\mu = 0$ of $G(t)$ can be written as

$$R^{r*}_{GG}(\mu = 0) = \frac{1}{N}\sum_{i=1}^{N} sgn\left(G(i\Delta t)\right)G(i\Delta t) =$$

$$= \frac{1}{N}\sum_{i=1}^{N} sgn\left(X(i\Delta t)\right)X(i\Delta t) + \frac{1}{N}\sum_{i=1}^{N} sgn\left(X(i\Delta t)\right)\text{E}(i\Delta t) = R^{r}_{XX}(0) + R^{r}_{X\text{E}}(0), \tag{15}$$

where $R^{r}_{XX}(\mu)$ is the relay correlation function of the useful component.

The estimates of the relay cross-correlation function $R^{r*}_{X\text{E}}(0)$ can be calculated from the expression [15, 16]

$$R^{r*}_{X\text{E}}(0) = R^{r}_{GG}(0) - 2R^{r}_{GG}(1) + R^{r}_{GG}(2) = \tag{16}$$

$$= \frac{1}{N}\sum_{i=1}^{N}\left(sgn\left(G(i\Delta t)\right)G(i\Delta t) - 2\,sgn\left(G(i\Delta t)\right)G\left((i+1)\Delta t\right) + sgn\left(G(i\Delta t)\right)G\left((i+2)\Delta t\right)\right).$$

For stationary and normal distributed noisy signals, the following equalities will hold [15, 16]:

$$\begin{cases} R^{r}_{XX}(0) + R^{*}_{XX}(2\Delta t) - 2R^{*}_{XX}(\Delta t) \approx 0 \\ R^{r}_{X\text{E}}(\mu\Delta t) \approx \dfrac{1}{N}\displaystyle\sum_{i=1}^{N} sgn\left(X(i\Delta t)\right)\text{E}\left((i+\mu)\Delta t\right) \approx 0. \\ R^{r}_{X\text{E}}(0) \approx \dfrac{1}{N}\displaystyle\sum_{i=1}^{N} sgn\left(X(i\Delta t)\right)\text{E}(i\Delta t) \neq 0 \end{cases} \tag{17}$$

Then, (16) takes the form

$$R^{r*}_{X\text{E}}(0) = R^{r}_{X\text{E}}(0). \tag{18}$$

Here, the relationship between relay and normalized cross-correlation functions for normally distributed random processes $X(t)$, $\text{E}(t)$ is expressed by the relation

$$R^{r}_{X\text{E}}(\mu) = \sqrt{\frac{2}{\pi}}\rho_{X\text{E}}(\mu)\sigma_{\text{E}}, \tag{19}$$

where $\rho_{X\text{E}}(\mu)$ is the normalized cross-correlation function between $X(t)$ and $\text{E}(t)$, σ_{E} is the mean square deviation of the noise $\text{E}(t)$.

Hence, the normalized cross-correlation function $\rho_{X\text{E}}(\mu)$ is calculated as follows [15]:

$$\rho_{X\text{E}}(\mu) = \frac{R^{r}_{X\text{E}}(\mu)}{\sqrt{\dfrac{2}{\pi}}\cdot\sigma_{\text{E}}}. \tag{20}$$

According to this formula, we need to know $R^{r}_{X\text{E}}(\mu)$ and the mean square deviation σ_{E} of the noise. Obviously, using formula (16), it is possible to calculate $R^{r*}_{X\text{E}}(\mu)$. At the same time, σ_{E} can be calculated from expression (10). Therefore, the calculation of the normalized cross-correlation function can be reduced to

$$\rho^*_{XE}(\mu) = \frac{R^{r*}_{XE}(\mu)}{\sqrt{\frac{2}{\pi}} \cdot \sigma^*_E}. \tag{21}$$

Here the value of the normalized cross-correlation function $\rho_{XE}(0)$ at $\mu = 0$ is the correlation coefficient:

$$r^*_{XE} = \rho^*_{XE}(0) = \frac{R^{r*}_{XE}(0)}{\sqrt{\frac{2}{\pi}} \cdot \sigma^*_E}. \tag{22}$$

Therefore, it is possible to estimate the correlation coefficient r_{XE} between $X(t)$ and $E(t)$:

$$r^*_{XE} = \rho^*_{XE}(0) = \frac{R^{r*}_{XE}(0)}{\sqrt{\frac{2}{\pi}} \cdot \sigma^*_E}. \tag{23}$$

Thus, using formulas (10), (16), and (19)-(23), we can calculate the correlation coefficient between $X(t)$ and $E(t)$.

5. TECHNOLOGIES FOR MONITORING THE TECHNICAL CONDITION OF TRANSPORT INFRASTRUCTURE OBJECTS

More and more large and complex bridges with unique designs have been built in recent years. These bridges are subject to countless external loads. These include traffic loads, which depend on the speed, amount, and weight of moving vehicles; the influence of external natural phenomena, which include the strength and direction of the wind, drastic changes in temperature, precipitation, solar radiation, and geological characteristics. The most dangerous among all external influences are seismic and landslide processes [7-12]. Bridges are destroyed by excessive loads. At the same time, even insignificant but frequent influences of the above factors gradually deteriorate main bridge structures. Minor and inconspicuous changes in structural elements can cause substantial deformations, leading to catastrophic damage. This is especially dangerous in seismic and landslide-prone zones, where insignificant but frequent ground shocks weaken bearing structures [7-12].

An algorithm for determining the early latent stage of a defect and calculating the probability of its development is proposed to estimate the main parameters characterizing the technical condition of a bridge structure, such as the stress-strain state, strength properties of structures, temperature of bridge elements, and the presence of defects.

In modern systems for continuous monitoring, signals received from various sensors, including accelerometers, seismometers, strain gauges, inclinometers, displacement sensors, temperature sensors, and hydrostatic level sensors, are transmitted in digital form for processing to determine the technical condition of the main structures of the bridge. These signals are random processes, each of which characterizes the technical condition of some part of the bridge structure.

Suppose the goal is to detect such defects as the presence of cracks and traces of mechanical impact on the bridge bearings and the sagging of the bearings, the presence of deviations of the bridge supporting structures vertically, or damage to the asphalt coating of the bridge in the form of transverse cracks indicating a large amplitude of vertical vibrations of the bridge superstructure. In this case, the most informative zones of the bridge are determined, and the places of installation of the mentioned sensors are selected. Then, each signal coming from the sensors is analyzed while considering which particular part of the bridge structure it controls and monitors. For instance, a digital accelerometer registers the linear acceleration, vibration acceleration, vibration velocity, and vibration displacement of the structures; a digital seismometer registers and controls the periods of natural frequencies of the bridge structure and corresponding damping logarithmic decrements; and digital strain gauges control the stress-strain state of the load-bearing structures. Each signal received from the sensors is processed using the technology proposed below. Based on the noise characteristics calculated for each of the signals, conclusions are drawn about the absence or presence of an early latent stage of a defect and the probability of its development in the part of the bridge structure in which the sensor is installed.

We will analyze the signal $G(t)$, which comes from the load cell. Using it, we need to monitor the stress-strain state of the load-bearing structures of the bridge.

1. At the initial time period t_0, when the object is in fully operational condition, the variance $D^*_{\mathrm{E},t0}$ of the noise $\mathrm{E}(t)$ of the signal $G(t)$ is calculated using the following expressions:

$$D^*_{\mathrm{E},t0} = \frac{1}{N}\sum_{i=1}^{N} G(i\Delta t)G(i\Delta t) - 2\frac{1}{N}\sum_{i=1}^{N} G(i\Delta t)G((i+1)\Delta t) + \frac{1}{N}\sum_{i=1}^{N} G(i\Delta t)G((i+2)\Delta t). \quad (24)$$

Then, we calculate the probabilities of the admissible values of the noise $\mathrm{E}(t)$ (i.e., the values of the noise within the range in which the damage is considered inexistent based on the condition $m_{\mathrm{E}} - k\sigma^*_{\mathrm{E},t0} \le \mathrm{E}(t) \le m_{\mathrm{E}} + k\sigma^*_{\mathrm{E},t0}$, where k is the selected coefficient). After that, taking into account the condition $m_{\mathrm{E}} = 0$, we calculate the variation interval of the noise $\mathrm{E}(t)$: $\varepsilon_{min} = -k\sigma^*_{\mathrm{E},t0}$; $\varepsilon_{max} = k\sigma^*_{\mathrm{E},t0}$. Then, at a certain step $\Delta\varepsilon$, we set the values of the noise $\mathrm{E}(t)$ in ascending order from ε_{min} to ε_{max}, $\varepsilon_1 = \varepsilon_{min}$, $\varepsilon_{i+1} = \varepsilon_i + \Delta\varepsilon$, $\varepsilon_{i+2} = \varepsilon_{i+1} + \Delta\varepsilon$, …, $\varepsilon_n = \varepsilon_{max}$, (25)

and form a sequence of admissible values of the noise ε_1, ε_2, …, ε_n, where $\varepsilon_{i-1} < \varepsilon_i$.

The density function of the normal distribution is then calculated:

$$N^*(\varepsilon_i)_{t_0} = \frac{1}{\sigma^*_{\mathrm{E},t_0}\sqrt{2\pi}} e^{A_{t_0}}, \text{ where } A_{t_0} = -\frac{(\varepsilon_i)^2}{2\left(\sigma^*_{\mathrm{E},t_0}\right)^2}. \quad (26)$$

After that, for the time instant t_0, we calculate the probabilities of the values of the noise $\mathrm{E}(t)$ with the mean square deviation $\sigma^*_{\mathrm{E},t_0}$ being in the admissible intervals

$$\varepsilon_1 \le \mathrm{E}(t) < \varepsilon_2,\ \varepsilon_2 \le \mathrm{E}(t) < \varepsilon_3,\ \dots,\ \varepsilon_{n-1} \le \mathrm{E}(t) \le \varepsilon_n \quad (27)$$

$$P_{1,t_0}(\varepsilon_1 \le \mathrm{E}(t) < \varepsilon_2) = \int_{\varepsilon_1}^{\varepsilon_2} N^*(\varepsilon)_{t_0} d\varepsilon,\ P_{2,t_0}(\varepsilon_2 \le \mathrm{E}(t) < \varepsilon_3) = \int_{\varepsilon_2}^{\varepsilon_3} N^*(\varepsilon)_{t_0} d\varepsilon,\ \dots,$$

$$P_{(n-1),t_0}(\varepsilon_{n-1} \le \mathrm{E}(t) < \varepsilon_n) = \int_{\varepsilon_{n-1}}^{\varepsilon_n} N^*(\varepsilon)_{t_0} d\varepsilon.$$

The values of these probabilities are entered into the database of informative attributes as reference values corresponding to the fully operational condition of the bridge.

At the instant t_1 at points (25), we re-calculate $N^*(\varepsilon_i)_{t_1}$ with the mean square deviation $\sigma^*_{\mathrm{E},t_1}$:

$$N^*(\varepsilon_i)_{t_1} = \frac{1}{\sigma^*_{\mathrm{E},t_1}\sqrt{2\pi}} e^{A_{t_1}}, \text{ where } A_{t_1} = -\frac{(\varepsilon_i)^2}{2\left(\sigma^*_{\mathrm{E},t_1}\right)^2}. \quad (28)$$

Further, for the time instant t_1, we calculate the probabilities of the values of noise $\mathrm{E}(t)$ with the mean square deviation $\sigma^*_{\mathrm{E},t_1}$ in admissible intervals (27):

$$P_{1,t_1}(\varepsilon_1 \le \mathrm{E}(t) < \varepsilon_2) = \int_{\varepsilon_1}^{\varepsilon_2} N^*(\varepsilon)_{t_1} d\varepsilon,\ P_{2,t_1}(\varepsilon_2 \le \mathrm{E}(t) < \varepsilon_3) = \int_{\varepsilon_2}^{\varepsilon_3} N^*(\varepsilon)_{t_1} d\varepsilon,\ \dots,$$

$$P_{(n-1),t_1}\left(\varepsilon_{n-1} \le \mathrm{E}(t) < \varepsilon_n\right) = \int_{\varepsilon_{n-1}}^{\varepsilon_n} N^*(\varepsilon)_{t_1} d\varepsilon . \tag{29}$$

After that, we calculate the difference of the probabilities of the noise $\mathrm{E}(t)$ in intervals (27) at the time instants t_1 and t_0:

$$\begin{gathered} P_{1,t_1-t_0}\left(\varepsilon_1 \le \mathrm{E}(t) < \varepsilon_2\right) = P_{1,t_1}\left(\varepsilon_1 \le \mathrm{E}(t) < \varepsilon_2\right) - P_{1,t_0}\left(\varepsilon_1 \le \mathrm{E}(t) < \varepsilon_2\right) \\ P_{2,t_1-t_0}\left(\varepsilon_2 \le \mathrm{E}(t) < \varepsilon_3\right) = P_{2,t_1}\left(\varepsilon_2 \le \mathrm{E}(t) < \varepsilon_3\right) - P_{2,t_0}\left(\varepsilon_2 \le \mathrm{E}(t) < \varepsilon_3\right) \\ \cdots \\ P_{(n-1),t_1-t_0}\left(\varepsilon_{n-1} \le \mathrm{E}(t) < \varepsilon_n\right) = P_{(n-1),t_1}\left(\varepsilon_{n-1} \le \mathrm{E}(t) < \varepsilon_n\right) - P_{(n-1),t_0}\left(\varepsilon_{n-1} \le \mathrm{E}(t) < \varepsilon_n\right). \end{gathered} \tag{30}$$

The differences in these probabilities exceeding admissible values $P_{1,t_1-t_0}\left(\varepsilon_1 \le \mathrm{E}(t) < \varepsilon_2\right) \ge \Delta_1$, $P_{2,t_1-t_0}\left(\varepsilon_2 \le \mathrm{E}(t) < \varepsilon_3\right) \ge \Delta_2$, …, $P_{(n-1),t_1-t_0}\left(\varepsilon_{n-1} \le \mathrm{E}(t) < \varepsilon_n\right) \ge \Delta_{n-1}$ is the informative attribute regarding the degree of damage development in bridges. Then, defects are found, and the values of probabilities (30) are saved as reference sets of defect initiation in the stress-strain state of the load-bearing structures.

After the values of the probabilities have also been obtained at the time instants t_2, t_3, …, t_k, the database of informative attributes takes the form

$$TS = \begin{bmatrix} \sigma^*_{\mathrm{E},t0} & N^*(\varepsilon_i)_{t0} & P_{1,t0} & P_{2,t0} & \cdots & P_{(n-1),t0} \\ \sigma^*_{\mathrm{E},t1} & N^*(\varepsilon_i)_{t1} & P_{1,t1} & P_{2,t1} & \cdots & P_{(n-1),t1} \\ \sigma^*_{\mathrm{E},t2} & N^*(\varepsilon_i)_{t2} & P_{1,t2} & P_{2,t2} & \cdots & P_{(n-1),t2} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \sigma^*_{\mathrm{E},tk} & N^*(\varepsilon_i)_{tk} & P_{1,tk} & P_{2,tk} & \cdots & P_{(n-1),tk} \end{bmatrix}. \tag{31}$$

After appropriate training, each row of the matrix is associated with one of the possible technical conditions of the bridge. In this case, a new column with one of the possible conditions in the stress-strain state of the load-bearing structures is added to the following matrix (32):

$$TS = \begin{bmatrix} \sigma^*_{\mathrm{E},t0} & N^*(\varepsilon_i)_{t0} & P_{1,t0} & P_{2,t0} & \cdots & P_{(n-1),t0} & 0 \\ \sigma^*_{\mathrm{E},t1} & N^*(\varepsilon_i)_{t1} & P_{1,t1} & P_{2,t1} & \cdots & P_{(n-1),t1} & 1 \\ \sigma^*_{\mathrm{E},t2} & N^*(\varepsilon_i)_{t2} & P_{1,t2} & P_{2,t2} & \cdots & P_{(n-1),t2} & 2 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \sigma^*_{\mathrm{E},tk} & N^*(\varepsilon_i)_{tk} & P_{1,tk} & P_{2,tk} & \cdots & P_{(n-1),tk} & k \end{bmatrix}. \tag{32}$$

In the above matrix, 0 is the excellent technical condition when the bridge structures meet all the requirements of regulatory documents; 1 represents good technical condition, when all the main structures of bridge structures are in operating condition, while the values of one or several parameters may not fully comply with regulatory documents; 2 reflects a satisfactory technical condition, when the main functional properties of bridge structures are partially violated but the main structures are in operating order; 3 denotes an unsatisfactory technical condition, when there are significant defects in the main structures of bridge structures, and they are capable of only partially performing the required functions (though a critical failure is unlikely); 4 represents an unsuitable (pre-emergency) technical condition, when an accident may occur if the harmful impacts continue; and 5 indicates an emergency technical condition, when there are critical defects in the main load-bearing structures and further operation of the bridge structure is impossible.

In addition to the matrix of technical conditions (32), a matrix of the dynamics of damage development of the bridge structure is also built. The degree of defect development is determined by the difference of probabilities (30) of the values of the noise $\mathrm{E}(t)$ that enter the admissible intervals (27), as well as by the difference of the estimates of correlation coefficients $r^*_{X\mathrm{E},t0}$, $r^*_{X\mathrm{E},t1}$, … $r^*_{X\mathrm{E},tk}$ between $X(t)$ and $\mathrm{E}(t)$, calculated from formula (23), at time instants t_0, t_1, t_2, t_3, …, t_k. After training, these values are associated with a certain degree of the dynamics of the failure development: 0 signifies the absence of defects; 1 denotes that a defect exists but has not developed; 2 indicates that the defect has developed slightly; 3 means the defect develops (but not rapidly); 4 reflects that the defect develops rapidly; and 5 means the defect will quickly lead to a catastrophic situation.

$$DR = \begin{bmatrix} P_{1,t1-t0} & P_{2,t1-t0} & \cdots & P_{(n-1),t1-t0} & r^*_{X\mathrm{E},t1-t0} & 1 \\ P_{1,t2-t1} & P_{2,t2-t1} & \cdots & P_{(n-1),t2-t1} & r^*_{X\mathrm{E},t2-t1} & 2 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ P_{1,tk-t(k1)} & P_{2,tk-t(k1)} & \cdots & P_{(n-1),tk-t(k1)} & r^*_{X\mathrm{E},tk-t(k1)} & k \end{bmatrix}. \tag{33}$$

Using matrices (32) and (33), we can also build a matrix of the maintainability of the bridge structure. The degree of bridge structure maintainability is determined by adding one more column to matrix (33), reflecting the type of maintenance work to be carried out to eliminate this defect:

a) no repair is required;
b) the defect can be eliminated in normal operation mode;
c) the bridge should be switched to limited operation mode to eliminate the defect;
d) traffic should be blocked for a short time to eliminate the defect;
e) traffic should be blocked for some time to eliminate the defect;
f) traffic should be blocked for a long time to eliminate the defect; e) - overhaul repairs are needed.

As a result, the following matrix of the degree of maintainability of the bridge structure is obtained:

$$SR = \begin{bmatrix} P_{1,t1-t0} & P_{2,t1-t0} & \cdots & P_{(n-1),t1-t0} & r^*_{X\mathrm{E},t1-t0} & 1 & a \\ P_{1,t2-t1} & P_{2,t2-t1} & \cdots & P_{(n-1),t2-t1} & r^*_{X\mathrm{E},t2-t1} & 2 & b \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ P_{1,tk-t(k1)} & P_{2,tk-t(k1)} & \cdots & P_{(n-1),tk-t(k1)} & r^*_{X\mathrm{E},tk-t(k1)} & k & z \end{bmatrix}. \tag{34}$$

Thus, using matrices (32)-(34), it is possible to determine the probability of defect initiation in bridge structures to determine the dynamics of development of these defects over time and the degree of maintainability of the bridge, which is a prerequisite for preventing accidents.

6. RESULTS OF COMPUTATIONAL EXPERIMENTS

Computational experiments were conducted using the MATLAB computing environment to verify the validity of the algorithm for calculating the correlation coefficient between $X(t)$ and $\mathrm{E}(t)$ of the noisy signal $G(t)$.

The stationary useful random process $X(t)$ on the interval T is presented in the form of harmonic oscillations [16]:

$$X_k(t) = \sum_{\nu=1}^{n} \left(a_{\nu k} \cos\left(\frac{2\pi\nu}{T} t + \varphi_{1\nu k} \right) + b_{\nu k} \sin\left(\frac{2\pi\nu}{T} t + \varphi_{2\nu k} \right) \right), \tag{35}$$

where $a_{\nu k}$, $b_{\nu k}$ and $\varphi_{\nu k}$, $\varphi_{1\nu k}$, and $\varphi_{2\nu k}$ are random amplitudes and phases.

The noise $\mathrm{E}(i\Delta t)$, which obeys the normal distribution laws with discrete values was formed using a random number generator. It was supposed to be the true noise. The noisy signal was formed: $G(i\Delta t)=X(i\Delta t)+\mathrm{E}(i\Delta t)$.

The relay $R_{X\mathrm{E}}^{r*}(\mu)$ and normalized cross-correlation functions and the coefficient of correlation $r_{X\mathrm{E}}^{*}$ between $X(t)$ and $\mathrm{E}(t)$ were calculated through algorithms (16), (21), and (23) using the values of the generated noisy signal $G(i\Delta t)$. The values of these characteristics were compared with the values of $R_{X\mathrm{E}}^{r}(\mu)$ and $r_{X\mathrm{E}}$ calculated by traditional algorithms, and the relative errors were calculated:

$$\Delta R_{X\mathrm{E}}^{r}(\mu)=\left|R_{X\mathrm{E}}^{r}(\mu)-R_{X\mathrm{E}}^{r*}(\mu)\right|/R_{X\mathrm{E}}^{r}(\mu)\cdot 100\%, \qquad (36)$$

$$\Delta D_{\mathrm{E}}=\left|D_{\mathrm{E}}-D_{\mathrm{E}}^{*}\right|/D_{\mathrm{E}}\cdot 100\%,\ \Delta r_{X\mathrm{E}}=\left|r_{X\mathrm{E}}-r_{X\mathrm{E}}^{*}\right|/r_{X\mathrm{E}}\cdot 100\%.$$

The random signal $X(t)=\sum_{kk} a_{kk}\cdot sin\left(2\pi\frac{(k\cdot\omega_{kk})^{n}}{T}+\varphi\right)+b$ is simulated, where φ has a uniform probability distribution in the interval (0,1); the coefficients a_{kk} and the frequencies ω_{kk} were selected as follows: $X(t)=60\cdot sin\left(\pi\frac{(k\cdot 1{,}5)^{1{,}5}}{800}+\varphi\right)+200$.

Then, we formed the noise $\mathrm{E}(t)$ with the normal distribution law, the mathematical expectation $m_{\mathrm{E}}\approx 0$ and the mean square deviation $\sigma_{\mathrm{E}}\approx 20$.

The results of the calculations are presented in Table 1.

The following conclusions can be drawn.

1) The specified $R_{X\mathrm{E}}^{r}(0)$ and calculated $R_{X\mathrm{E}}^{r*}(0)$ estimates of the relay cross-correlation function of the noise practically coincide (Table 1, line 1) (i.e., $R_{X\mathrm{E}}^{r}(0)\approx R_{X\mathrm{E}}^{r*}(0)$), and the relative error is $\Delta R_{X\mathrm{E}}^{r}(\mu)$=0. 97%.

2) The specified D_{E} and calculated D_{E}^{*} estimates of the noise variance practically coincide (Table 1, line 2) (i.e., $D_{\mathrm{E}}\approx D_{\mathrm{E}}^{*}$), and the relative error is ΔD_{E}=9.47%.

3) The specified $r_{X\mathrm{E}}$ and calculated $r_{X\mathrm{E}}^{*}$ estimates of the correlation coefficients between $X(t)$ and $\mathrm{E}(t)$ practically coincide (Table 1, line 3) (i.e., $r_{X\mathrm{E}}\approx r_{X\mathrm{E}}^{*}$), and the relative error is $\Delta r_{X\mathrm{E}}$=0.0585%.

7. CONCLUSION

The above-mentioned transport infrastructure objects and bridges enter a new technical state during long-term operation under the influence of various factors as a result of the occurrence and propagation of such defects as fatigue crack, residual stress, the influence of fatigue crack on fatigue damage, fatigue, wear, friction, and abrasion. The existing techniques of processing analog signals cannot detect the specified defects at an early latent stage of their formation. This is because the signals at the sensor outputs usually contain noise caused by external factors, which is not correlated with the useful signal. The onset of defects and faults is accompanied by the emergence of new additional noise, which has a correlation with the useful signal. Therefore, to control or increase the degree of reliability and adequacy of monitoring results, it is necessary, first of all, to analyze and calculate estimates of the characteristics of noise, as well as estimates of the relationship between the noise and the useful signal.

Table 1

Results of computational experiments

	Characteristics	Specified characteristics	Calculated characteristics	Relative errors (%)
	1	**2**	**3**	**4**
1	Relay cross-correlation function	$R^{r}_{X\mathrm{E}}(0)$=5.0364	$R^{r*}_{X\mathrm{E}}(0)$=4.9875	$\Delta R^{r}_{X\mathrm{E}}(\mu)$=0.97169
2	Noise variance	D_{E}=402.31	D^{*}_{E}=440.42	ΔD_{E}=9.47
3	Correlation coefficient	$r_{X\mathrm{E}}$=0.24366	$r^{*}_{X\mathrm{E}}$=0.24381	$\Delta r_{X\mathrm{E}}$=0.0585

This study proposes a multi-criteria control of the onset of the specified malfunctions. For this purpose, we calculated the estimates of the variance, the mean square deviation, the probability of the values of the noise getting into the critical intervals at different moments of time, the cross-correlation function, and the correlation coefficient between the useful signal and the noise. If all the specified characteristics equal zero, it can be assumed that there will be no serious malfunctions in the near future and no dangerous accidents are to be expected. If the probabilities of the values of the noise getting into the critical intervals slightly differ from the admissible probability over time, it indicates the possibility of the onset of malfunction. Then, the differences in the probabilities of getting into the critical intervals at different moments of time are calculated. If the values of these differences increase over time, it means that a malfunction may occur after some time. Then, estimates of the cross-correlation function and the correlation coefficient between the useful signal and the noise are calculated. If the value of the estimate of the correlation coefficient slightly differs from zero, it indicates that the malfunction has already occurred but is in a latent stage of incipience. An increase in the estimate of the correlation coefficient over time means that the defect is developing and signifies that urgent action should be taken.

The algorithms and technologies described in this paper allow information about the condition of the transport infrastructure object to be obtained in a timely manner while determining the hidden moment of the initiation of defects, as well as the degree and intensity of their development. The use of these technologies in monitoring systems makes it possible to reduce the probability of accidents and avoid catastrophic consequences.

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