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# Technologies for early monitoring and warning of malfunctions in transport complex facilities

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**Abstract**. The paper considers the specifics of malfunctions of transport complex facilities, which include bus stations, railway stations, sea terminals and ports, bridges, tunnels, airports, railways and waterways, highways, various structures and devices, etc. It is shown that as a result of the breakdown of these objects the schedule of work of the transport complex is broken, the safety of freight and passenger transportation is reduced, freight and passenger turnover decreases, which ultimately leads to large material losses and damage. It is noted that damage to objects of the transport complex is accompanied by the appearance of additive noises, which are superimposed on and correlated with the useful signals coming from the corresponding sensors. Therefore, algorithms have been developed for the early monitoring of malfunctions in facilities of the transport complex as a result of calculating the relay and normalized cross-correlation functions, as well as the correlation coefficient between the useful signal and the noise of the noisy signal. At the same time, it is shown that the dynamics of damage development is reflected in the noise characteristics of noisy signals, which change in time depending on the degree of malfunction and the rate of its development. In this connection, algorithms for determining the rate of malfunction development in transport complex facilities have been developed by constructing a confidence interval for the mathematical expectation of noise. It is noted that the application of the developed algorithms and technologies allows to carry out timely current and overhaul repairs, reduces the risk of destruction of objects located in the territory of the transport complex.

***Keywords*:** *transport complex; transport complex facilities; noise; useful signal; noisy signal; characteristics of the relationship between the useful signal and the noise; confidence interval; malfunction; monitoring and warning system*

## 1. INTRODUCTION

It is known that transport consists of air, rail, road, sea, river transport types. The transport complex includes transport lines and hubs, technical means of transportation and activities to transport goods and passengers. In other words, the transport complex includes sea terminals and ports, bus stations and bus stations, railway stations, bridges, tunnels, airports, railway and waterways, highways, various kinds of structures and devices [1-3].

Monitoring systems based on modern information technologies are created and implemented to improve the safety of vehicles, transportation, buildings and structures that ensure the functioning of the transport complex. Monitoring and notification systems track the state of vehicle safety systems and ensure the reliable and safe operation of engineering systems and production processes. Therefore, the monitoring system consists of subsystems of ventilation and air conditioning, lighting, heating, firefighting, power supply, water supply, geodetic monitoring, etc. For example, to automatically maintain the set temperature, timely diagnosis of malfunction of ventilation equipment is carried out; to maintain the required level of illumination in the premises the condition of lamps and other components is monitored; to reduce costs for consumption of energy resources and optimization of heat supply modes the condition of equipment and heat supply modes is monitored; to prevent and eliminate fires at an early stage the condition of fire protection and smoke exhaust system is monitored; detection of emergency and pre-emergency situations is carried out to ensure reliable operation of the power supply system equipment; diagnosis of pressure sensors is carried out to ensure uninterrupted operation of the water supply system [1-3]. Geodetic monitoring is carried out to assess the condition of soil processes, subsidence, displacement and subsidence of massifs, groundwater analysis, identification of possible seismic hazardous and landslide zones and areas. To implement this monitoring are installed appropriate sensors, such as sensors displacement, pressure, the load on the fittings and anchors, sensors crack opening, inclinometers, accelerometers, etc. [1-3].

Data on the condition of the transport complex in the form of signals are transmitted to the central monitoring station. The digital information received is recorded, processed, analyzed and conclusions are drawn about the condition of the transport complex as a whole, as well as the presence of defects and the degree of damage in each of the subsystems. In addition, conclusions are made about the causes that led to this or that malfunction [3].

However, the existing monitoring systems do not provide control of the early latent period of change in the facilities of the transport complex. In [4-9] it is shown that even smallest damage to transport complex facilities is accompanied by the appearance of additive noises, which are correlated with the useful signals of noisy signals coming from the corresponding sensors. At the same time, the dynamic of damage development is reflected in the noise characteristics, which change over time depending on the degree of malfunction and the rate of its development. One of these characteristics is the value of the confidence interval for the mathematical expectation of the noise.

Studies have shown that the use of technologies to calculate the degree of correlation of the useful signal and the noise, as well as the interval of variation of the mathematical expectation of noise, allow to identify the early latent period of defect and damage formation, determine the dynamics of its development, as well as reduce the accident risks of transport complex facilities.

## 2. PROBLEM STATEMENT

It is known that in practice, real signals are the sum of useful signals $X(t)$ and the noise $\mathrm{E}(t)$, i.e. $G(t)=X(t)+\mathrm{E}(t)$ . In this case, the total noise $\mathrm{E}(t)$ is the sum of noise $\mathrm{E}_1(t)$ from the influence of external factors and the noise $\mathrm{E}_2(t)$ correlated with the useful signal, which occurs when the normal state of facilities of the transport complex change, i.e. $\mathrm{E}(t)=\mathrm{E}_1(t)+\mathrm{E}_2(t)$. And traditionally it is assumed that the mathematical expectation of the noise $\mathrm{E}_1(t)$ is zero, $m_{\mathrm{E}_1}=0$. And for the mathematical expectation of the correlated noise $\mathrm{E}_2(t)$ the approximate equality $m_{\mathrm{E}_2}\approx 0$ is valid. When there are malfunctions in facilities of the transport complex, the value of the mathematical expectation of the total noise $\mathrm{E}(t)$ also begins to hover around zero, and the approximate equality $m_{\mathrm{E}}\approx 0$ is fulfilled. This means that the value of mathematical expectation of the total noise $\mathrm{E}(t)$ varies in some interval, depending on the degree of malfunctions and the rate of malfunction development, i.e.

$$m_{\mathrm{E}n}\le m_{\mathrm{E}}\le m_{\mathrm{E}v}\ , \qquad (1)$$

where $m_{\mathrm{E}n}$, $m_{\mathrm{E}v}$ are the lower and upper limits of the variation.

At the same time, the appearance of the noise $\mathrm{E}_2(t)$ correlated with the useful signal $X(t)$ is reflected not only in the value of the variation interval of the mathematical expectation $m_{\mathrm{E}}$ , but also in the estimates of the correlation function $R_{GG}(\mu)$ of the noisy signal $G(t)$ . It is known that the formula for calculating the estimate of the correlation function $R_{GG}(\mu)$ of the noisy signal $G(t)$ can be represented as [4-9]:

$$R_{GG}(\mu)=\frac{1}{N}\sum_{i=1}^{N}G(i\Delta t)G((i+\mu)\Delta t)= R_{XX}(\mu)+\lambda_{GG}(\mu) \tag{2}$$

where $\lambda_{GG}(\mu)$ is the total error, which, given $R_{\mathrm{EE}}(\mu)$ =0 at μ≠0, is

$$\lambda_{GG}(\mu)=\begin{cases}2R_{X\mathrm{E}}(0)+R_{\mathrm{EE}}(0) & npu \quad \mu=0\\ R_{X\mathrm{E}}(\mu)+R_{\mathrm{E}X}(\mu) & npu \quad \mu\neq 0\end{cases},$$

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

Thus, due to the contamination of the useful signals $X(t)$ with the noises $\mathrm{E}(t)$, estimates of correlation functions $R_{XX}(\mu)$ contain tangible errors $\lambda_{GG}(\mu)$ . It follows that the inequality $R_{XX}(\mu)\neq R_{GG}(\mu)$, which arises due to the presence of the noise characteristics $R_{X\mathrm{E}}(\mu)$, $R_{\mathrm{E}X}(\mu)$, $R_{\mathrm{EE}}(0)$ in the estimates $R_{GG}(\mu)$, is true in the presence of malfunctions and damage. Therefore, it is not possible to draw adequate conclusions about the technical condition of the objects of the transport complex based on the estimates $R_{GG}(\mu)$ . Since the noise $\mathrm{E}(t)$ cannot be isolated from the noisy signal $G(t)$ , the problem of extracting the information contained in the estimates of the noise characteristics $R_{X\mathrm{E}}(\mu)$, $R_{\mathrm{E}X}(\mu)$, $R_{\mathrm{EE}}(0)$ is obvious for the monitoring of the transport complex.

Given the above, it is necessary to create algorithms and technologies to determine the estimates of the noise variance $D_{\mathrm{E}}$ , cross-correlation functions $R_{X\mathrm{E}}(\mu)$, $R_{\mathrm{E}X}(\mu)$ between the useful signal and the noise, as well as the variation interval of the mathematical expectation $m_{\mathrm{E}}$ of the total noise $\mathrm{E}(t)$.

## 3. ALGORITHMS FOR EARLY MONITORING OF MALFUNCTIONS IN TRANSPORT COMPLEX FACILITIES

As noted above, when there is a malfunction of facilities on the territory of the transport complex, the noise $\mathrm{E}_2(t)$, correlated with the useful signal $G(t)$, appears. Therefore, starting from this point, the estimates of the cross-correlation functions $R_{X\mathrm{E}}(\mu)$, $R_{\mathrm{E}X}(\mu)$ and the correlation coefficient $r_{X\mathrm{E}}$ between the useful signal $X(t)$ and the total noise $\mathrm{E}(t)=\mathrm{E}_1(t)+\mathrm{E}_2(t)$ differ from zero [4-9]. This makes it possible to use the estimates $R_{X\mathrm{E}}(\mu)$, $R_{\mathrm{E}X}(\mu)$, $r_{X\mathrm{E}}$ as a carrier of diagnostic information of the early period of occurrence of malfunctions of facilities of the transport complex. To calculate the above characteristics, we will use the formula for calculating the estimates of relay cross-correlation functions between the useful signal $X(t)$ and noise `$\mathrm{E}(t)$ [4]:

$$R^r_{X\mathrm{E}}(\mu)=\frac{1}{N}\sum_{i=1}^{N} sgnX(i\Delta t)\,\mathrm{E}((i+\mu)\Delta t), \tag{3}$$

where $sgn\,X(i\Delta t)=\begin{cases}+1 & when\ \ X(i\Delta t)>0\\ 0 & when\ \ X(i\Delta t)=0\\ -1 & when\ \ X(i\Delta t)<0\end{cases}$.

Obviously, to apply this formula, it is necessary to determine the samples of the noise $\mathrm{E}(i\Delta t)$ and the useful signal $X(i\Delta t)$, which cannot be measured directly or isolated from the noisy signal $G(t)$ [4]. Let us consider one of the possible variants of the approximate calculation of the estimates of the relay cross-correlation function $R^{r*}_{X\mathrm{E}}(\mu)$ between the useful signal $X(t)$ and the noise $\mathrm{E}(t)$ as a result of calculating the relay correlation function $R^r_{GG}(\mu)$ of the noisy signal $G(t)$ [4-9]:

$$R^r_{GG}(\mu)=\frac{1}{N}\sum_{i=1}^{N} sgn\,G(i\Delta t)\,G((i+\mu)\Delta t), \tag{4}$$

where $sgnG(i\Delta t)=\begin{cases}+1 & when\ \ G(i\Delta t)>0\\ 0 & when\ \ G(i\Delta t)=0\\ -1 & when\ \ G(i\Delta t)<0\end{cases}$.

It has been shown in [4-9] that the estimate of the relay cross-correlation function $R^{r*}_{X\mathrm{E}}(\mu\Delta t)$ at different time shifts between $X(i\Delta t)$ and $\mathrm{E}(i\Delta t)$ can be determined from the formula:

$$R^{r*}_{X\mathrm{E}}(\mu)=\frac{1}{N}\sum_{i=1}^{N} sgnG(i\Delta t)\big[G((i+\mu)\Delta t)-2G((i+\mu+1)\Delta t)+G((i+\mu+2)\Delta t)\big] \tag{5}$$

It is clear that in the normal state of facilities of the transport complex due to the lack of correlation between $X(t)$ and $\mathrm{E}(t)$ the estimates of the relay cross-correlation function $R^r_{X\mathrm{E}}(t)$ between the useful signal and the noise will be close to zero. When various malfunctions and defects occur, the value of the estimate of the relay cross-correlation function $R^r_{X\mathrm{E}}(t)$ will vary depending on the degree of correlation between $X(t)$ and $\mathrm{E}(t)$. And the distinctive feature of this algorithm is that in the presence of correlation between $X(t)$ and $\mathrm{E}(t)$ the values of $R^{r*}_{X\mathrm{E}}(\mu)$ at different moments of time can be used as informative attributes of the early onset of malfunctions of transport complex facilities, as well as the degree of their escalation into an emergency state.

In addition, to assess the early onset of malfunctions in facilities of the transport complex, it is advisable to use estimates of the normalized cross-correlation function, as well as the correlation coefficient between the useful signal $X(t)$ and noise $\mathrm{E}(t)$ .

In this case, based on formula (5), he normalized cross-correlation function can be calculated from the formula:

$$\rho^*_{X\mathrm{E}}(\mu)=\frac{R^{r*}_{X\mathrm{E}}(\mu)}{\sqrt{\frac{2}{\pi}}\cdot\sigma^*_{\mathrm{E}}},\qquad(6)$$

where the standard deviation $\sigma^*_{\mathrm{E}}$ of the noise is calculated from the expression [4-9]:

$$\sigma^*_{\mathrm{E}}=\sqrt{R_{GG}(\mu=0)-2R_{GG}(\mu=\Delta t)+R_{GG}(\mu=2\Delta t)}\qquad(7)$$

At the same time, it is known that the value of the normalized cross-correlation function at $\mu=0$ is the correlation coefficient. Therefore, the value of the correlation coefficient between the useful signal $X(t)$ and the noise $\mathrm{E}(t)$ can be calculated from the expression:

$$r^*_{X\mathrm{E}}=\rho^*_{X\mathrm{E}}(0)=\frac{R^{r*}_{X\mathrm{E}}(0)}{\sqrt{\frac{2}{\pi}}\cdot\sigma^*_{\mathrm{E}}}.\qquad(8)$$

Thus, algorithms have been developed for indicating the onset of malfunctions in facilities of the transport complex, which are reduced to the calculation of the mean square deviation $\sigma^*_{\mathrm{E}}$ of the noise $\mathrm{E}(t)$, the relay cross-correlation function $R^{r*}_{X\mathrm{E}}(t)$ between $X(t)$ and $\mathrm{E}(t)$, the normalized cross-correlation function $\rho^*_{X\mathrm{E}}(\mu)$ and the correlation factor $r^*_{X\mathrm{E}}$ between the useful signal $X(t)$ and noise $\mathrm{E}(t)$.

## 4. ALGORITHMS FOR DETERMINING THE RATE OF MALFUNCTION DEVELOPMENT IN TRANSPORT COMPLEX OBJECTS

Below we propose algorithms for determining the rate of the development of malfunctions in transport complex facilities using confidence interval (1) for the mathematical expectation of the noise $\mathrm{E}(t)$. It is known that the confidence interval for estimating the mathematical expectation of the noise with a known mean square deviation $\sigma_{\mathrm{E}}$ is calculated from the expression [8,9]:

$$\left(m_{\mathrm{E}}-z_p\cdot\frac{\sigma_{\mathrm{E}}}{\sqrt{N}};m_{\mathrm{E}}+z_p\cdot\frac{\sigma_{\mathrm{E}}}{\sqrt{N}}\right),\qquad(9)$$

where $N$ is the sample size; $z_p$ is the critical value of the distribution, which can be found by setting a certain confidence probability $p=1-\alpha=\Phi(z)$; $\Phi(z)$ is the Laplace function. For example, to construct an interval with a 95% confidence level, we take α = 0.05; then for probability p=0.95 we have $z_{0.95}$ =1.96.

From formula (9) it is obvious that determining the confidence interval for the mathematical expectation of the noise requires determining the mean square deviation $\sigma_{\mathrm{E}}=\sqrt{D_{\mathrm{E}}}$ of the noise $\mathrm{E}(t)$. Obviously, the mean square deviation $\sigma^*_{\mathrm{E}}$ of the noise $\mathrm{E}(t)$ can be calculated from expression (7). Then, taking into account expression (9) and the condition $m_{\mathrm{E}}$ ≈0, we can calculate the confidence interval for the mathematical expectation $m^*_{\mathrm{E}}$ of the noise:

$$\left(m_{\mathrm{E}}-z_p\cdot\frac{\sigma^*_{\mathrm{E}}}{\sqrt{N}};m_{\mathrm{E}}+z_p\cdot\frac{\sigma^*_{\mathrm{E}}}{\sqrt{N}}\right)\qquad(10)$$

or

$$m_{\mathrm{E}} - z_p \cdot \frac{\sigma^*_{\mathrm{E}}}{\sqrt{N}} \le m^*_{\mathrm{E}} \le m_{\mathrm{E}} + z_p \cdot \frac{\sigma^*_{\mathrm{E}}}{\sqrt{N}} .$$

Since $m_{\mathrm{E}} \approx 0$, we get

$$-z_p \cdot \frac{\sigma^*_{\mathrm{E}}}{\sqrt{N}} \le m^*_{\mathrm{E}} \le z_p \cdot \frac{\sigma^*_{\mathrm{E}}}{\sqrt{N}} . \tag{11}$$

Given that the expectation cannot be a negative number, the lower limit of the confidence interval is limited to zero and the upper bound to the number $z_p \cdot \frac{\sigma^*_{\mathrm{E}}}{\sqrt{N}}$ . Hence,

$$0 \le m^*_{\mathrm{E}} \le z_p \cdot \frac{\sigma^*_{\mathrm{E}}}{\sqrt{N}} . \tag{12}$$

Thus, the lower bound of the confidence interval for the mathematical expectation of the noise $\mathrm{E}(t)$ is

$$m^*_{\mathrm{E}n} = 0, \tag{13}$$

and the upper bound:

$$m^*_{\mathrm{E}v} = z_p \cdot \frac{\sigma^*_{\mathrm{E}}}{\sqrt{N}} . \tag{14}$$

By constructing a confidence interval for the mathematical expectation of the noise $\mathrm{E}(t)$ at certain time instants, it is possible to determine the rate of the development of malfunctions of transport complex facilities.

## 5. TECHNOLOGIES FOR EARLY MONITORING OF MALFUNCTIONS IN TRANSPORT COMPLEX FACILITIES AND DETERMINING THE RATE OF THEIR DEVELOPMENT

To assess the technical condition of facilities of the transport complex it is necessary to periodically calculate estimates of the relay and normalized cross-correlation functions, as well as correlation coefficients between the useful signal $X(t)$ and the noise $\mathrm{E}(t)$ for each of the monitored parameters at different time instants $t_0, t_1, t_2, \ldots, t_k$ . The obtained values of the estimates should be entered into the base of informative attributes:

$$TS1 = \begin{bmatrix} R^{r*}_{X_1\mathrm{E}_1}(\mu)_{t_0} & R^{r*}_{X_1\mathrm{E}_1}(\mu)_{t_1} & \cdots & R^{r*}_{X_1\mathrm{E}_1}(\mu)_{t_k} \\ R^{r*}_{X_2\mathrm{E}_2}(\mu)_{t_0} & R^{r*}_{X_2\mathrm{E}_2}(\mu)_{t_1} & \cdots & R^{r*}_{X_2\mathrm{E}_2}(\mu)_{t_k} \\ \cdots & \cdots & \cdots & \cdots \\ R^{r*}_{X_n\mathrm{E}_n}(\mu)_{t_0} & R^{r*}_{X_n\mathrm{E}_n}(\mu)_{t_1} & \cdots & R^{r*}_{X_n\mathrm{E}_n}(\mu)_{t_k} \end{bmatrix} \tag{15}$$

$$TS2 = \begin{bmatrix} \rho^*_{X_1\mathrm{E}_1}(\mu)_{t_0} & \rho^*_{X_1\mathrm{E}_1}(\mu)_{t_1} & \cdots & \rho^*_{X_1\mathrm{E}_1}(\mu)_{t_k} \\ \rho^*_{X_2\mathrm{E}_2}(\mu)_{t_0} & \rho^*_{X_2\mathrm{E}_2}(\mu)_{t_1} & \cdots & \rho^*_{X_2\mathrm{E}_2}(\mu)_{t_k} \\ \cdots & \cdots & \cdots & \cdots \\ \rho^*_{X_n\mathrm{E}_n}(\mu)_{t_0} & \rho^*_{X_n\mathrm{E}_n}(\mu)_{t_1} & \cdots & \rho^*_{X_n\mathrm{E}_n}(\mu)_{t_k} \end{bmatrix} \tag{16}$$

$$TS3=\begin{bmatrix} r^*_{X_1\mathrm{E}_1-t_0} & r^*_{X_1\mathrm{E}_1-t_1} & \cdots & r^*_{X_1\mathrm{E}_1-t_k} \\ r^*_{X_2\mathrm{E}_2-t_0} & r^*_{X_2\mathrm{E}_2-t_1} & \cdots & r^*_{X_2\mathrm{E}_2-t_k} \\ \cdots & \cdots & \cdots & \cdots \\ r^*_{X_n\mathrm{E}_n-t_0} & r^*_{X_n\mathrm{E}_n-t_1} & \cdots & r^*_{X_n\mathrm{E}_n-t_k} \end{bmatrix}. \qquad (17)$$

If all characteristics (15)-(17) of the relationship between the useful signal and the noise at the time instant $t_0$ are zero

$$R^{r*}_{X_i\mathrm{E}_i}(\mu)_{t_0}=0, \rho^*_{X_i\mathrm{E}_i}(\mu)_{t_0}=0, =0, r^*_{X_i\mathrm{E}_i-t_0}$$

then it indicates the absence of malfunctions of facilities of the transport complex. Then for each parameter at the time instant $t_0$ using formulas (7), (12)-(14), the width of the confidence interval for the mathematical expectation of the noise $\mathrm{E}(t)$ at a constant level of significance and sample size is calculated:

$$0 \le m^*_{\mathrm{E}-t0} \le z_p \cdot \frac{\sigma^*_{\mathrm{E}-t0}}{\sqrt{N}}. \qquad (18)$$

Next, the set of possible values of the mathematical expectation of the noise at the time instant $t_0$, which fall within the constructed confidence interval, is compiled:

$$M^*_{\mathrm{E}-t0}=\left\{m^*_{\mathrm{E}-t0} \middle| m^*_{\mathrm{E}n-t0} \le m^*_{\mathrm{E}-t0} \le m^*_{\mathrm{E}v-t0}\right\}$$

or

$$M^*_{\varepsilon-t0}=\left\{m^*_{\mathrm{E}-t0} \middle| 0 \le m^*_{\mathrm{E}-t0} \le m^*_{\mathrm{E}v-t0}\right\}. \qquad (19)$$

In this case the difference of even one of the characteristics (15)-(17) of the relationship between the useful signal and the noise at the time instant $t_1$, as well as subsequent time instants $t_2$, ..., $t_k$ from zero

$$R^{r*}_{X_i\mathrm{E}_i}(\mu)_{t_1}\neq 0, \rho^*_{X_i\mathrm{E}_i}(\mu)_{t_1}\neq 0, r^*_{X_i\mathrm{E}_i-t_1}\neq 0$$

indicates the presence of correlation between the useful signal $X(t)$ and the noise $\mathrm{E}(t)$, resulting from the appearance of the noise $\mathrm{E}_2(t)$ correlated with the useful signal caused by changes in the normal state of facilities of the transport complex.

Then to control the dynamics and rate of the development of malfunctions and failures at the instant $t_1$ the confidence interval

$$0 \le m^*_{\mathrm{E}-t1} \le z_p \cdot \frac{\sigma^*_{\mathrm{E}-t1}}{\sqrt{N}} \qquad (20)$$

should be calculated, and a set of possible values of the mathematical expectation of the noise should be compiled:

$$M^*_{\mathrm{E}-t1}=\left\{m^*_{\mathrm{E}-t1} \middle| m^*_{\mathrm{E}n-t1} \le m^*_{\mathrm{E}-t1} \le m^*_{\mathrm{E}v-t1}\right\}$$

or

$$M^*_{\mathrm{E}-t1}=\left\{m^*_{\mathrm{E}-t1} \middle| 0 \le m^*_{\mathrm{E}-t1} \le m^*_{\mathrm{E}v-t1}\right\}. \qquad (21)$$

Then we find the difference between the sets of possible values of the mathematical expectation of the noise $M^*_{\mathrm{E}-t1}$ at the time instant $t_1$ and possible values of the mathematical expectation of the noise $M^*_{\mathrm{E}-t0}$ at the time instant $t_0$:

at $m^*_{\mathrm{E}v-t1} > m^*_{\mathrm{E}v-t0}$

$$M^*_{\mathrm{E}-t0-t1}=\backslash M^*_{\mathrm{E}-t1}\ M^*_{\mathrm{E}-t0} := M^*_{\mathrm{E}-t1} \cap \overline{M^*_{\mathrm{E}-t0}} =$$

$$=\left\{m^*_{E-t1}\middle|m^*_{E-t1}\in M^*_{E-t1}\ and\ m^*_{E-t1}\notin M^*_{E-t0}\right\}, \quad (22)$$

that is, those values of the mathematical expectation, which are included in the set $M^*_{E-t1}$, but not in the set $M^*_{E-t0}$, and establish a correspondence between the value of the difference $M^*_{E-t0-t1}$ and the degree of damage.

If after some time at the instant $t_2$ it is still not possible to eliminate the malfunction, and again the following inequalities are fulfilled:

$$R^{r*}_{X_iE_i}(\mu)_{t_2}\neq 0, \rho^*_{X_iE_i}(\mu)_{t_2}\neq 0, r^*_{X_iE_i-t_2}\neq 0,$$

then the confidence interval should be reconstructed:

$$0\le m^*_{E-t2}\le z_p\cdot\frac{\sigma^*_{E-t2}}{\sqrt{N}}, \quad (23)$$

and a set of possible values of the mathematical expectation of the noise at the time instant $t_2$ should be compiled:

$$M^*_{E-t2}=\left\{m^*_{E-t2}\middle|m^*_{En-t2}\le m^*_{E-t2}\le m^*_{Ev-t2}\right\}$$

or

$$M^*_{E-t2}=\left\{m^*_{E-t2}\middle|0\le m^*_{E-t2}\le m^*_{Ev-t2}\right\}. \quad (24)$$

After that we find the difference of the sets of possible values of the mathematical expectation of the noise $M^*_{E-t2}$ at the time instant $t_2$ and possible values of the mathematical expectation of the noise $M^*_{E-t1}$ at the time instant $t_1$:

at $m^*_{Ev-t2}>m^*_{Ev-t1}$

$$M^*_{E-t1-t2}=\backslash M^*_{E-t2}\ M^*_{E-t1}:=M^*_{E-t2}\cap\overline{M^*_{E-t1}}=$$

$$=\left\{m^*_{E-t2}\middle|m^*_{E-t2}\in M^*_{E-t2}\ and\ m^*_{E-t2}\notin M^*_{E-t1}\right\}, \quad (25)$$

that is, those values of the mathematical expectation of the noise, which are included in the set $M^*_{E-t2}$ but not included in the set $M^*_{E-t1}$, and compare the differences $M^*_{E-t1-t2}$ and $M^*_{E-t0-t1}$. If the difference $M^*_{E-t1-t2}=M^*_{E-t0-t1}$, then the malfunction develops with uniform rate. If the difference $M^*_{E-t1-t2}$ > $M^*_{E-t0-t1}$, the malfunction develops intensively, and if $M^*_{E-t1-t2}>>M^*_{E-t0-t1}$, the malfunction is transient. Then, depending on the degree of development of the malfunction, appropriate preventive or repair work should be carried out with or without shutting down the operation of the investigated facility of the transport complex.

Thus, comparing the values of the differences of the sets of possible values of the mathematical expectation of the noise $M^*_{E-t_m}$ at the time instant $t_m$ and possible values of the mathematical expectation of the noise $M^*_{E-t,m+1}$ at the time instant $t_{m+1}$, provided that the characteristics of the relationship between the useful signal and the noise are different from zero

$$R^{r*}_{X_iE_i}(\mu)_{t_m}\neq 0, \rho^*_{X_iE_i}(\mu)_{t_m}\neq 0, r^*_{X_iE_i-t_m}\neq 0,$$

conclusions are drawn about the dynamics of the malfunction.

## 6. DISCUSSION

Analysis shows that using the algorithms for calculating the characteristics of the relationship between the useful signal and the noise can identify the early stage of the occurrence of malfunctions in facilities of the transport complex. At the same time, the developed algorithms for constructing the confidence interval for the mathematical expectation of the noise allow us to determine the dynamics of malfunction development. In this case, the width of the confidence interval for the mathematical expectation of noise, which changes over time in accordance with the development of the defect, is taken as an informative feature.

Using the developed algorithms and technologies in the systems of monitoring and warning of malfunctions in facilities of the transport complex allows ensuring safe conditions of their operation, reliability, safety and comfort of passenger service, reliability of cargo and passenger transportation, significantly reduce the risk of transport accidents with severe consequences, entailing damage to property, the environment, life and health of citizens.

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