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CONTROL OF THE BEGINNING OF ACCIDENTS IN RAILROAD OPERATION SAFETY SYSTEMS IN SEISMICALLY ACTIVE REGIONS USING THE NOISE TECHNOLOGY

Summary. On the railroads in seismically active regions, the impact of frequent weak earthquakes accelerates the initiation of defects such as wear and tear, cracks and deformation due to fatigue. An analysis of the types and stages of initiation and development of defects preceding accidents at technical facilities has shown that the registration of the beginning of the latent period of transition of objects to an emergency state based on the results of traditional technologies of analysis of measurement information in the applied control systems in the field of railway transport is delayed owing to the difficulties of noise analysis. The proposed algorithms and noise analysis technologies allow forming corresponding sets of informative attributes to control the beginning of the latent period of accidents. Their use in intelligent noise control systems will improve the safety of this mode of transportation. To this end, it is expedient to create a subsystem for noise seismic hazard warning, i.e., a subsystem for noise control of the onset of the initiation and dynamics of development of changes in the technical condition of the rolling stock, railroad tracks, bridges, tunnels, and other railroad infrastructure facilities.

1. INTRODUCTION

It is known that rail transport is the main means of cargo transportation in many countries. For this purpose, extensive railroad communications with modern bridges, tunnels and stations have been built. This complex infrastructure is managed by many different modern monitoring and diagnostic systems [1-10]. These systems ensure a high level of efficiency and safety of rail transport. However, in spite of this, at the present time, there are often wrecks of freight and passenger trains. Therefore, as our studies have shown, by solving some problems, such as ensuring control of the latent period of changes in the technical condition of railroad tracks, railroad bridges, tunnels, crossings, individual cars, and the entire rolling stock, it is possible to enhance the safety of rail transport [1]. This is particularly important for rail transport in the countries located in seismically active regions. This is owing to the fact that weak 1-3-point earthquakes often occur in these regions, affecting the technical condition of the railroad tracks, bridges, tunnels and communications. They, as a rule, do not result in great destruction, but each such weak earthquake is a potential factor contributing to the beginning of the latent period of changes of facility's technical condition. In this regard, the development and creation of technology and noise control systems to ensure the safety of rail transport in seismically active regions and countries is of undoubted practical interest [1,11].

2. APPLICABILITY OF THE NOISE TECHNOLOGY FOR CONTROLLING THE BEGINNING OF INITIATION OF ACCIDENTS AT TECHNICAL FACILITIES

It is known that the technical state of every controlled facility changes after a certain period of time during its operation. At first, in the period T_0, it is in its normal state. Then, over the period T_1, it goes into the latent emergency state, after which it goes into the period T_2. Finally, the period T_3 of a pronounced emergency state begins, when an accident takes place and facility stops functioning.

Despite the differences in the duration of the periods T_0, T_1 and T_2 for different facilities, to successfully solve control problems, we need to ensure a reliable indication of the beginning of time T_1 of the latent period of changes in the technical state of controlled facilities.

The problem is complicated by the fact that the readings of the measuring instruments in the periods T_1 and T_0 match, and so do the estimates of the informative attributes characterizing facility's technical state. For this reason, in the known control and management systems, facility's emergency state is registered at the end of the period T_1 or at the beginning of the period T_2. Because of this, the information about oil and gas-producing facilities' transition into an emergency state in some cases turns out to be belated. Therefore, to control the beginning and developmental dynamics of accidents at those facilities at the beginning of the time period T_1, it is advisable to use noise control algorithms and technologies. This is owing to the fact that in real life, control and management systems of various purpose, the noisy signals $g(t)$ obtained at facilities' sensor outputs, are the sum of the useful signal $X(t)$ and the noise $\varepsilon_1(t)$, i.e.

$$g(t) = X(t) + \varepsilon_1(t) \qquad (1)$$

The known classical conditions are fulfilled in control object's normal state for the centered noisy signals $g(t) = X(t) + \varepsilon_1(t)$ obtained at the outputs of corresponding sensors:

$$\left.\begin{array}{l} M\big[X(t)X(t)\big] \neq 0 \\ M\big[\varepsilon_1(t)X(t)\big] = 0 \\ M\big[X(t)\varepsilon_1(t)\big] = 0 \\ M\big[\varepsilon_1(t)\varepsilon_1(t)\big] \neq 0 \end{array}\right\}. \qquad (2)$$

As a result, the expression for calculating the variance of the signal $g(t)$ takes the following form:

$$D_{gg} = M\big[g(t)g(t)\big] = M\big[(X(t) + \varepsilon_1(t))(X(t) + \varepsilon_1(t))\big] =$$
$$= M\big[X(t)X(t) + X(t)\varepsilon_1(t) + \varepsilon_1(t)X(t) + \varepsilon_1(t)\varepsilon_1(t)\big] = M\big[X(t)X(t) + \varepsilon_1(t)\varepsilon_1(t)\big]. \qquad (3)$$

Therefore, we get the following:

$$D_{gg} = M\big[(X(t)X(t) + \varepsilon_1(t)\varepsilon_1(t)\big] = D_{XX}(0) + D_\varepsilon, \qquad (4)$$

where:

$$D_{\varepsilon_1} = M\big[\varepsilon_1(t)\varepsilon_1(t)\big] = M\big[\varepsilon(t)\varepsilon(t)\big] = D_\varepsilon. \qquad (5)$$

At the beginning of the latent period of initiation and development of accidents at controlled facilities, the noise $\varepsilon_2(t)$ correlated with the useful signal $X(t)$ emerges in the signals $g(t)$ received from the corresponding sensors. Thus, the period T_0 of the normal state of facility's operation ends, the period T_1 of the latent change of its technical state starts and conditions (2)-(5) are violated. This happens during the operation of any facility when there are inevitable defects from fatigue, wear, corrosion, cracks etc. The noise $\varepsilon_2(t)$ is generated, which is correlated with the useful signal $X(t)$. This, in turn, affects the estimates of the aforementioned characteristics. Therefore, starting from the moment of the latent period of initiation and development of an accident, the model of the signal $g(t)$ at the sensor output can be represented as follows:

$$g(t) = X(t) + \varepsilon_1(t) + \varepsilon_2(t) \qquad (6)$$

The presence of a correlation between the useful signal $X(t)$ and the sum noise

$$\varepsilon(t) = \varepsilon_1(t) + \varepsilon_2(t) \qquad (7)$$

results in the inequalities

$$\left.\begin{array}{l} M[X(t)X(t)] \neq 0 \\ M[X(t)\varepsilon_2(t)] \neq 0 \\ M[\varepsilon_1(t)\varepsilon_1(t)] \neq 0 \\ \varepsilon(t)\varepsilon(t) \neq 0 \\ \varepsilon(t)X(t) \neq 0 \end{array}\right\} \qquad (8)$$

and the equalities

$$\left.\begin{array}{l} M[\varepsilon_1(t)X(t)] = 0 \\ \varepsilon_1(t)\varepsilon_2(t) = 0 \end{array}\right\} \qquad (9)$$

Consequently, we have

$$\begin{aligned} D_{gg} &= M\{[X(t) + \varepsilon_1(t) + \varepsilon_2(t)][X(t) + \varepsilon_1(t) + \varepsilon_2(t)]\} = \\ &= M[X(t)X(t) + X(t)\varepsilon_1(t) + X(t)\varepsilon_2(t) + \varepsilon_1(t)X(t) + \\ &\quad + \varepsilon_1(t)\varepsilon_1(t) + \varepsilon_1(t)\varepsilon_2(t) + \varepsilon_2(t)X(t) + \varepsilon_2(t)\varepsilon_1(t) + \varepsilon_2(t)\varepsilon_2(t)] = \\ &= M[X(t)X(t) + \varepsilon_2(t)X(t) + X(t)\varepsilon_2(t) + \varepsilon_1(t)\varepsilon_1(t) + \varepsilon_2(t)\varepsilon_2(t)] = \\ &= R_{XX}(t) + 2R_{X\varepsilon_2}(t) + D_{\varepsilon_1\varepsilon_1} + D_{\varepsilon_2\varepsilon_2}, \end{aligned} \qquad (10)$$

where:

$$D_\varepsilon = M[\varepsilon_2(t)X(t) + X(t)\varepsilon_2(t) + \varepsilon_1(t)\varepsilon_1(t) + \varepsilon_2(t)\varepsilon_2(t)] = 2R_{X\varepsilon_2}(0) + D_{\varepsilon_1\varepsilon_1} + D_{\varepsilon_2\varepsilon_2} = 2R_{X\varepsilon} + D_{\varepsilon\varepsilon},$$

$$D_{\varepsilon\varepsilon} = D_{\varepsilon_1} + D_{\varepsilon_2}. \qquad (11)$$

It is obvious from expressions (10) and (11) that the estimates of $2R_{X\varepsilon_2}(0)$ and $D_{\varepsilon_1\varepsilon_2}$ reflect the effects of defect initiation on the noisy signal $g(t)$ and contain the information on the beginning and dynamics of accident development. It follows that in order to successfully solve the problem of control of the beginning of accident initiation, it is necessary to extract the information contained in the noise $\varepsilon(i\Delta t)$. Currently, control and management systems do not have a technology for extracting diagnostic information contained in the noise of the noisy signals $g(t)$. Consequently, in these systems, in order to increase the reliability and validity of control results in the latent period of initiation and development of accidents at facilities, it is necessary to maximize the extraction of information contained in the noise $\varepsilon(t)$. For this purpose, it is expedient to create algorithms and technologies for calculating the estimates of the variance of the noise $\varepsilon(t)$ and the cross-correlation function between the useful signal $X(t)$ and the noise $\varepsilon(t)$. Considering the aforementioned, various variants of calculating these estimates have been proposed.

Of these, the following algorithms have proved to be the most effective and convenient for implementation in control systems:

$$D_\varepsilon = \frac{1}{N}\sum_{i=1}^{N}[g(i\Delta t)g(i\Delta t) - 2g(i\Delta t)g((i+1)\Delta t) + g(i\Delta t)g((i+2)\Delta t)], \qquad (12)$$

$$R_{X\varepsilon}(\mu\Delta t) = \frac{1}{2N}\sum_{i=1}^{N}[g(i\Delta t)g((i+\mu)\Delta t) - 2g(i\Delta t)((i+(\mu+1))\Delta t) + g(i\Delta t)((i+(\mu+2))\Delta t)], \qquad (13)$$

where $R_{X\varepsilon}(\mu\Delta t)$ is the cross-correlation function between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$; $\mu\Delta t$ is the time shift between the samples of the useful signal $X((i+\mu)\Delta t)$ and the noise $\varepsilon(i\Delta t)$; $g((i+\mu)\Delta t)$ is the $(i+\mu)$-th sample of the noisy signal; and N is the number of samples.

In view of the aforementioned, a number of new technologies developed with the specifics of automatic control of oil and gas-producing facilities in the latent period of their emergency state taken into account have been proposed for analyzing the noise of measurement data from the outputs of sensors installed at control objects.

For instance, as our experimental studies have shown, during the control of the beginning of accidents on compressor stations, oil production facilities, drilling rigs, fixed offshore platforms, etc., a deviation of the current combinations of the aforementioned informative attributes from the estimates of the corresponding elements of the reference sets made it possible to reliably register the beginning of the transition of these facilities from the normal state into an emergency state.

3. MAIN COMPONENTS OF CREATING A RAILROAD OPERATION SAFETY SYSTEM IN SEISMICALLY ACTIVE REGIONS

It is known that a prerequisite for achieving high competitive ability in the transportation market is the compliance of rail transport with the growing demands for speed, safety and comfort. The significant advantages of this mode of transport in comparison with other types offer great prospects in increasing the volume of traffic and at the same time require the improvement of this mode of transport [2-10]. There are great achievements in this area at present. However, the seismic activity in some regions can create problems. The most important and vulnerable elements of rail transport are the moving part of cars and railroad tracks, the insufficient monitoring of the condition of which does not ensure the proper safety of the rolling stock [1-10]. As the railroad passes through seismically active regions, additional requirements for traffic safety appear. This particularly applies to the problems of controlling the onset of the emergency condition of wheels and rails, their vulnerability and derailment conditions.

Our analysis of the literature [12-19] devoted to control technologies and control systems taking into account the specific characteristics of railroads of seismically active regions has shown that the use of noise technologies [1] can indeed improve the safety of this mode of transport. To do this, it is reasonable to create a subsystem for noise seismic hazard warning [11], i.e., a subsystem for noise control of the onset of the initiation and dynamics of development of changes in the technical condition of the rolling stock and railroad tracks to incorporate in the existing railroad monitoring systems.

In view of the aforementioned, the issues of technical safety of the rolling stock and the railroad tracks, taking into account the characteristics of seismically active regions along the route, are an extremely relevant problem. Our studies have shown that in order to ensure an adequate level of safety of operation of rail transport in seismically active regions, it is necessary to create the following [1,11]:

- a subsystem of intelligent analysis of the level of seismic activity of the region in real time and prompt notification of seismic hazard along the main line;
- a subsystem of control of the beginning of the latent period of changes in the technical condition of individual cars and the entire rolling stock; and
- a subsystem for noise control of malfunction of railroad tracks, bridges, tunnels and communications throughout the entire route.

These subsystems will allow the driver and the dispatch service to receive in advance additional information and take appropriate measures to ensure traffic safety in general.

It is obvious from the aforementioned that the use of noise control technologies in the railroad operation safety system should be implemented through the following components [1].

1) Creating an intelligent seismic-acoustic seismic hazard warning network. This component includes the creation of a network of seismic-acoustic stations located along the route, as well as the

creation of software and equipment for transmitting, collecting, processing and analyzing seismic-acoustic information. Using a network of seismic-acoustic stations, the structural principle of which is given in the study by Aliev [11]; this subsystem allows calculating in real time the probability of occurrence of dangerous earthquakes on the territory of the railroad route based on noise analysis of seismic-acoustic signals. The obtained information can be used to make appropriate decisions.

2) **Creating a subsystem of noise controllers with vibration sensors, which will allow controlling the beginning and dynamics of changes in the technical condition of cars**. For this purpose, vibration sensors should be installed in the most informative parts of controlled cars and other parts of the train. Owing to this, the information received from each noise controller, reflecting the technical condition of each car and the train as a whole, can be transmitted to the interface of the rolling stock control system at a distance of at least 500-600 m.

3) **Creating a subsystem for noise monitoring of malfunctions on railroad tracks, bridges, tunnels and hub communications of the entire route.** For this purpose, vibration sensors are installed on the most informative parts of the bridge or tunnel frame. When the cars cross this part of the route, those sensors form the information reflecting their technical condition, using noise controllers.

4. POSSIBILITIES OF APPLICATION OF THE SUBSYSTEM OF NOISE CONTROL OF THE BEGINNING OF AN EMERGENCY STATE OF RAIL TRANSPORT

Fig. 1, shown later, proposes the principle of constructing one of the possible versions of the subsystem for noise control of the beginning of an emergency state of rail transport. In this version, Accutech AM20 type vibration sensors [20] are installed under the chassis wheels of each car. Vibration signals from these sensors are transmitted wirelessly to the input of the controller of that car. During the movement of the train, any change (deviation from the norm) in the state of the rails or the bed is reflected in the signals of the vibration sensors. Owing to this, the beginning of possible malfunctions at this point in time affects the estimates of the noise characteristics of the signals [1,21] obtained from vibration sensors installed in the most informative parts of the train.
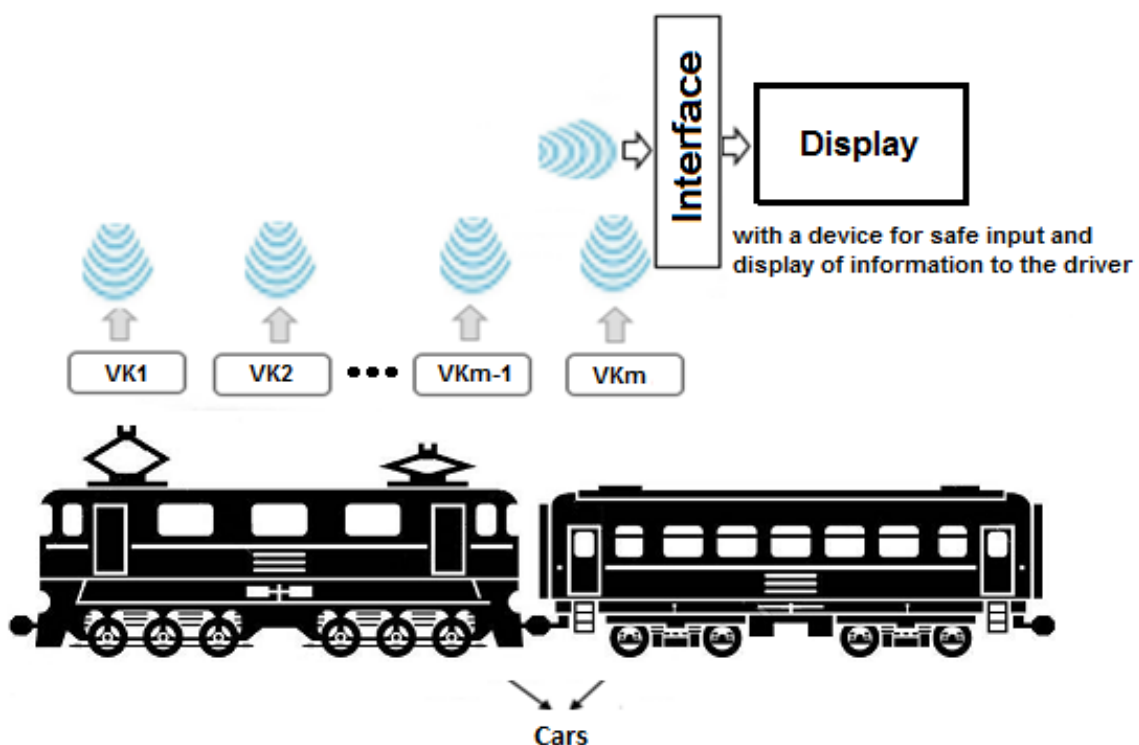

Fig. 1. The subsystem for noise control of the condition of rail transport

In the noise controllers, these signals are analyzed, e.g. on the basis of the relay correlation analysis technology, using the expression

$$R^*_{X\varepsilon}(m) = \frac{1}{N}\sum_{i=1}^{N} \operatorname{sgn} g(i\Delta t)\left[g(i+m)\Delta t + g((i+m+1)\Delta t - 2g(i+m+1)\Delta t)\right], \quad (14)$$

$$g(i\Delta t) = X(i\Delta t) + \varepsilon(i\Delta t), \quad (15)$$

where $g(i\Delta t)$ is the noisy signal, $X(i\Delta t)$ is the useful vibration signal, $\varepsilon(i\Delta t)$ is the noise caused by the initiation of various defects, and $R^*_{X\varepsilon}(m)$ is the estimate of the relay cross-correlation function between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$.

The obtained estimates allow determining the beginning of changes in the technical condition of the rails. Similarly, using the corresponding formulas given in Aliyev and Aliev et al [1,21], the estimates of the respective noise characteristics that reflect the technical condition of the cars are calculated.

When the system under consideration is intellectualized, the maximum threshold estimates of all noise characteristics at which the technical state of the controlled object is considered normal will be calculated over a certain period of time in the process of training. These estimates can be used in the training process to form a reference set in the following form:

$$W_j^{\max} = \begin{cases} D_{g_j X_\varepsilon}^{\max}, R_{g_j X_\varepsilon}^{\max}(1\Delta t), R_{g_j X_\varepsilon}^{\max}(2\Delta t), R_{g_j X_\varepsilon}^{\max}(3\Delta t),..., R_{g_j X_\varepsilon}^{\max}(m\Delta t) \\ R_{g_j X_\varepsilon}^{*\max}(1\Delta t), R_{g_j X_\varepsilon}^{*\max}(2\Delta t), R_{g_j X_\varepsilon}^{*\max}(3\Delta t),..., R_{g_j X_\varepsilon}^{*\max}(m\Delta t) \\ a_{g_j n}^{\max}, b_{g_j n}^{\max}, a_{g_j n\varepsilon}^{\max}, b_{g_j n\varepsilon}^{\max}, a_{g_j n\varepsilon_2}^{\max}, b_{g_j n\varepsilon_2}^{\max} \\ a_{g_j n}^{*\max}, b_{g_j n}^{*\max}, a_{g_j n\varepsilon}^{*\max}, b_{g_j n\varepsilon}^{*\max}, a_{g_j n\varepsilon_2}^{*\max}, b_{g_j n\varepsilon_2}^{*\max} \\ k_{g_j q_0}^{\max}, k_{g_j q_1}^{\max}, k_{g_j q_2}^{\max},..., k_{g_j q_m}^{\max}; f_{g_j q_0}^{-\max}, f_{g_j q_1}^{-\max}, f_{g_j q_2}^{-\max},..., f_{g_j q_m}^{-\max} \end{cases}, \quad (16)$$

where $D_{g_j X_\varepsilon}^{\max}$, $R_{g_j X_\varepsilon}^{\max}(1\Delta t)$, $R_{g_j X_\varepsilon}^{\max}(2\Delta t)$, $R_{g_j X_\varepsilon}^{\max}(3\Delta t)$,…, $R_{g_j X_\varepsilon}^{\max}(m\Delta t)$ и $R_{g_j X_\varepsilon}^{*\max}(1\Delta t)$, $R_{g_j X_\varepsilon}^{*\max}(2\Delta t)$, $R_{g_j X_\varepsilon}^{*\max}(3\Delta t)$,…, $R_{g_j X_\varepsilon}^{*\max}(m\Delta t)$ is the set of the correlation informative noise attributes of control; $a_{g_j n}^{\max}$, $b_{g_j n}^{\max}$, $a_{g_j n\varepsilon}^{\max}$, $b_{g_j n\varepsilon}^{\max}$, $a_{g_j n\varepsilon_2}^{\max}$, $b_{g_j n\varepsilon_2}^{\max}$ and $a_{g_j n}^{*\max}$, $b_{g_j n}^{*\max}$, $a_{g_j n\varepsilon}^{*\max}$, $b_{g_j n\varepsilon}^{*\max}$, $a_{g_j n\varepsilon_2}^{*\max}$, $b_{g_j n\varepsilon_2}^{*\max}$ is the set of the spectral informative noise attributes of control; and $k_{g_j q_0}^{\max}$, $k_{g_j q_1}^{\max}$, $k_{g_j q_2}^{\max}$,…, $k_{g_j q_m}^{\max}$; $f_{g_j q_0}^{-\max}$, $f_{g_j q_1}^{-\max}$, $f_{g_j q_2}^{-\max}$,…, $f_{g_j q_m}^{-\max}$ is the set of the position-binary informative noise attributes of control.

Owing to this, when the train moves, as a result of applying the appropriate noise analysis technology, a set of estimates are formed that reflect the current technical condition of the cars, the entire train, rails, bridges, tunnels and communications throughout its traffic route.

If there is a defect, for instance, on the rail, along which the car is currently moving, some of the current estimates of the noise characteristics will be greater than the corresponding maximum threshold reference value. If there is a malfunction, the estimates of some noise characteristics will be greater than the corresponding maximum reference ones. The information about this will be transmitted through the interface of the train control system for saving and displaying on the driver's monitor. The same will happen when the train crosses bridges and tunnels. At the same time, the information received via wireless communication from the noise controllers will reflect their technical condition. In addition, a change in the technical condition of the parts of the car itself will also be reflected in the estimates of the specified noise characteristics of the vibration signals. Naturally, all this information will be transmitted through the interface of the train control system for registration and displaying on the driver's monitor.

Thus, the subsystem will provide noise control over the technical condition of the parts of individual cars and the entire train, as well as the railroad tracks, bridges, tunnels and communications, along the entire route. It is clear that duplicating the relay-correlation analysis of vibration signals by

means of various noise analysis technologies increases the reliability of the results of the proposed system.

5. CONCLUSION

The registration of the beginning of the latent period of object's transition to the emergency state based on the results of traditional technologies for analyzing measurement information in control systems in some cases is delayed. This is owing to the inability to analyze the noise correlated with the useful signal, which prevents predicting accidents and avoiding catastrophic consequences.

The proposed algorithms and noise analysis technologies allow forming corresponding sets of informative attributes to control the beginning of the latent period and the dynamics of accident development. Their use in various intelligent systems, including for the purpose of monitoring of the state of rail transport, will significantly improve the safety of operation of technical facilities.

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