Informatics and Control Problems 39 Issue 2 (2019)
journal homepage: www.icp.az

Noise control of the beginning and development dynamics of accidents in rail transport

T.A. Aliev[a*], T.A. Babayev[a], T.A. Alizada[a], N.E. Rzayeva[b]

[a] *Institute of Control Systems of ANAS, Baku, Azerbaijan*
[b] *Azerbaijan University of Architecture and Construction, Baku, Azerbaijan*

A R T I C L E I N F O

Article history:
Received 22.11.2019
Received in revised form 09.12.2019
Accepted 23.12.2019
Available online 30.12.2019

Keywords:
Rail transport
Running gear
Rolling stock
Noise
Control
Fault
Accident
Noise control
Estimate
İntelligent systems
İnformative attributes
Reference
Sets
Correlation
Spectral analysis

A B S T R A C T

The paper is devoted to the issue of improving the reliability and validity of the results of control the technical condition of the running gear of rail transport in real time. In contrast to traditional fault monitoring systems, the authors propose enhancing the validity of the control of the onset of defects that usually precede typical faults by using noise technologies. The possibility of creating an intelligent noise technology that can solve diagnostic problems with the indication of the beginning of the latent period of the emergence of typical defects preceding faults is considered. To this end, using this technology, reference sets of informative attributes are formed in the training process. The reference sets, in turn, are used to determine the condition of the object at the beginning of the initiation of defects by comparing them with current noise estimates. This makes it possible to receive in real time all necessary information about the current condition of the most critical components of the running gear reflecting changes in their operational parameters. At the same time, it also allows controlling the dynamics of the development of defects, which makes it possible to enhance the safety of the operation of rail transport.

1. Introduction

The main condition for ensuring the safety of train movement in railway transport is the reliable and fail-safe operation of rolling stock. To ensure the required reliability of the rolling stock, it is necessary to constantly control the technical condition of its running gear. In modern conditions, obtaining reliable information about its technical condition is impossible without technical diagnostic systems. Various diagnostic systems are currently used to assess the technical condition of the running gear of rolling stock in motion (based on the principle of their use: stationary, airborne, portable, incorporated directly into the controlled object, etc.). The main goal of technical diagnostics is to determine the type and location of defects. Vibration parameters,

[*] Corresponding author.
E-mail addresses: director@cyber.az (T.A. Aliev), tbabayev@bk.ru (T.A. Babayev), tahiralizada@gmail.com (T.A. Alizada), nikanel1@gmail.com (N.E. Rzayeva)

www.icp.az/2019/2-02.pdf

pressure, force, current, voltage, resistance, pulses, time intervals, etc. are used as diagnostic indicators. Receiving the information on deviations from the nominal readings of the controlled parameters (temperature, vibration, noise, etc.) during movement, the driver of a high-speed passenger train informs the dispatcher, who, in turn, informs the relevant units.

Traditional technologies used in control systems for the analysis of noisy signals do not allow extracting diagnostic information sufficient to identify the beginning of the latent period of the initiation of defects in the core components of the running gear of the rolling stock. This affects the reliability of the control results, which sometimes leads to errors that inevitably cause accidents with undesirable consequences. Therefore, to enhance the reliability of fail-safe operation by early detection of the onset of faults and organization of timely maintenance of the rolling stock, it is essential to create new, more effective technologies for analyzing noisy signals.

2. Problem statement

It is known that the technical condition of the running gear in rail transport changes after a certain period of time during its operation. At first, in the period T_0, it is in a normal state. Then, over the period T_1, it goes into a latent form of emergency state. After that, it goes into the period T_2. Finally, the period T_3 of a pronounced emergency condition begins, when an accident occurs and the object stops functioning.

Despite the differences in the duration of the periods T_0, T_1 and T_2 for different objects, successful solution of control problems requires reliable indication of the beginning of the time T_1 of the latent period of changes in the technical condition of the control object.

The problem is compounded by the fact that the readings of the measuring instruments in the period 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, object'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 object's transition into an emergency state in some cases turns out to be belated. Therefore, to control the beginning and development dynamics of accidents at those objects at the beginning of the time period T_1, it is advisable to use noise control algorithms and technologies. This is due to the fact that in real-life control and management systems of various purpose, the noisy signals $g(t)$ obtained at control object's sensor outputs are the sum of the useful signal $X(t)$ and the noise $\varepsilon_1(t)$ i.e.

$$g(t) = X(t) + \varepsilon_1(t).$$

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:

$$\left.\begin{matrix} M[X(t)X(t)] \neq 0, M[\varepsilon_1(t)X(t)] = 0 \\ M[X(t)\varepsilon_1(t)] = 0, M[\varepsilon_1(t)\varepsilon_1(t)] \neq 0 \end{matrix}\right\}. \quad (1)$$

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

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

$$= M[X(t)X(t) + X(t)\varepsilon_1(t) + \varepsilon_1(t)X(t) + \varepsilon_1(t)\varepsilon_1(t)] = M[X(t)X(t) + \varepsilon_1(t)\varepsilon_1(t)]. \quad (2)$$

Therefore, we get

$$D_{gg} = M[X(t)X(t) + \varepsilon_1(t)\varepsilon_1(t)] = D_{XX} + D_{\varepsilon_1}, \quad (3)$$

where

$$D_{\varepsilon_1} = M[\varepsilon_1(t)\varepsilon_1(t)] = M[\varepsilon(t)\varepsilon(t)] = D_\varepsilon \quad (4)$$

At the beginning of the latent period of initiation and development of accidents at objects, 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 object's operation ends, the period T_1 of the latent change of its technical state starts and conditions (1)-(4) are violated. This happens during the operation of the running gear 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 vibration sensor output can be represented as follows

$$g(t) = X(t) + \varepsilon_1(t) + \varepsilon_2(t).$$

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

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

results in the inequalities

$$\begin{cases} M[X(t)X(t)] \neq 0, \\ M[X(t)\varepsilon_2(t)] \neq 0, \\ M[\varepsilon_1(t)\varepsilon_1(t)] \neq 0, \\ M[\varepsilon(t)\varepsilon(t)] \neq 0, \\ M[\varepsilon(t)X(t)] \neq 0. \end{cases}$$

and the equalities

$$\begin{cases} M[X(t)\varepsilon_1(t)] = 0, \\ M[\varepsilon_1(t)\varepsilon_2(t)] = 0. \end{cases}$$

Consequently, we have

$$\begin{aligned} D_{gg} &= M\{[X(t) + \varepsilon_1(t) + \varepsilon_2(t)][X(t) + \varepsilon_1(t) + \varepsilon_2(t)]\} \\ &= M[X(t)X(t) + X(t)\varepsilon_1(t) + X(t)\varepsilon_2(t) + \varepsilon_1(t)X(t) + \varepsilon_1(t)\varepsilon_1(t) + \varepsilon_1(t)\varepsilon_2(t) \\ &\quad + \varepsilon_2(t)X(t) + \varepsilon_2(t)\varepsilon_1(t) + \varepsilon_2(t)\varepsilon_2(t)] \\ &= M[X(t)X(t) + X(t)\varepsilon_2(t) + \varepsilon_1(t)\varepsilon_1(t) + \varepsilon_2(t)X(t) + \varepsilon_2(t)\varepsilon_2(t)] \\ &= D_{XX} + 2R_{X\varepsilon_2} + D_{\varepsilon_1\varepsilon_1} + D_{\varepsilon_2\varepsilon_2}, \end{aligned} \quad (5)$$

where

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

Here,

$$D_{\varepsilon\varepsilon} = D_{\varepsilon_1\varepsilon_1} + D_{\varepsilon_2\varepsilon_2}. \quad (6)$$

It is obvious from expressions (5) and (6) 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 systems in rail transport 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 objects, 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 above, various variants of calculating these estimates have been proposed.

Given the above, noise analysis of measurement data obtained at the outputs of vibration sensors installed, for instance, on the running gear of the rolling stock of trains, requires creating new, more effective technologies for the control of the beginning and dynamics of an emergency state.

3. Possibilities of using the theory of fuzzy sets for fault diagnostics

Studies have shown that to solve the problems of fault diagnostics in case of axleboxes and other units of rolling stock, fuzzy sets can be used, as they take into account such difficult-to-formalize factors as the experience and intuition of a highly qualified expert specialist. For instance, the apparatus of the theory of fuzzy sets for the diagnosis of axleboxes of the rolling stock (ARS) in a fuzzy expert system (FES) allows one to get operational conclusions about the technical diagnosis of faults by abandoning the traditional requirements for the accuracy of its functional description.

To enter knowledge into the knowledge base (KB) of a diagnostic FES, a knowledge representation language is used that takes into account the specific features of the object. A set of heuristics used by highly qualified specialists serves as the algorithm for solving the problem. The knowledge formulated by experts are entered into the system knowledge base

An analysis of the possibility of diagnosing faults of the running gear of the rolling stock with the use of this technology demonstrates that the use of these systems makes it possible to detect the initiation of a defect with sufficient reliability in its pronounced stage. Unfortunately, sometimes it can be delayed, which in some cases can cause accidents with catastrophic consequences.

In view of the above, to enhance the validity and reliability of control results, it is advisable to use in diagnostic systems a technology for monitoring the beginning of the transition of the main running gear of the rolling stock to the latent period of an emergency state using [1, 2].

4. Possibilities of noise control of the onset of defects preceding faults in rail transport

It is known that the running gear of a rolling stock breaks down due to the initiation of various defects, such as wear, crack, fatigue deformation, etc. [1-3]. In some cases, they lead to disastrous consequences. As was stated earlier, to prevent them, it is necessary to control the initiation of defects preceding such accidents. The solution to the problem of controlling the onset of the initiation of a defect that leads to a violation of the integrity and operability of the structure requires first creating appropriate technologies and software for analyzing the signals received at the outputs of the corresponding sensors. Here, it is important to obtain the necessary information to control the onset of all kinds of defects. To this end, based on the statistics of the most dangerous accidents that have occurred, it is necessary to determine the type of sensors, the location of their installation ("vulnerable spots") that ensures obtaining sufficient information from the object, making early detection of defect initiation reliable enough [4-8].

The sensors that receive signals reflecting the beginning of the initiation of the most common defects have the largest information capacity. Such technological parameters as temperature, pressure, vibration, acoustic and thermal radiation, etc. contain sufficient data to control the initiation of the corresponding defects. For instance, the types of data required for controlling the condition of most running gear of the rolling stock include: the vibration spectrum of rolling stock elements, the spectrum of acoustic vibrations, and other parameters that characterize the functioning of the system. Moreover, at the beginning of fault initiation, not only the values of these parameters are important, but also the dynamics of changes in their noises at a given time. For instance, axleboxes of wheelsets are typical systems characterized by the variation of the vibration parameters $g(i\Delta t)$ of both the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ due to changes in the technical condition during operation:

$$g(i\Delta t) = X(i\Delta t) + \varepsilon(i\Delta t).$$

In the control of the beginning of the latent period of faults, it is natural that, in addition to the vibration signals, it is also possible to analyze acoustic and other signals received at the outputs of appropriate sensors.

Studies and analysis of failures of running gear of the rolling stock demonstrate that the onset of faults and the dynamics of their development are accompanied by the appearance of the noise $\varepsilon_2(i\Delta t)$ correlated with the useful signal. The noise $\varepsilon(i\Delta t)$ forms from the noise $\varepsilon_1(i\Delta t)$ caused by the influence of external factors and by the noises $\varepsilon_2(i\Delta t)$ that emerge as a result of the initiation of the corresponding defects. As a result, the sum noise

$$\varepsilon(i\Delta t) = \varepsilon_1(i\Delta t) + \varepsilon_2(i\Delta t),$$

forms, which in the latent period of accidents correlates with the useful signal.

Therefore, when solving the problem of controlling the beginning and development dynamics of this process, it is advisable to use the estimates of the static characteristics of the sum noise $\varepsilon(i\Delta t)$ as informative attributes.

In the following paragraphs, we consider one of the possible versions of the noise control of the onset of a fault in the running gear of the rolling stock. In this version, vibration sensors are installed, for instance, on the axleboxes of the wheelsets. When the rolling stock moves, vibration signals from these sensors are transmitted wirelessly to the input of the controller of that particular car. Any change in the condition (deviation from the norm) of the controlled components is reflected in the signals $g(i\Delta t)$ of the vibration sensors, which are analyzed on the noise analysis controllers.

Of these, the following algorithms turned out to be the most efficient and convenient for implementation in rail transport control systems:

$$D_\varepsilon = \frac{1}{N}\sum_{i=1}^{N}\left[g(i\Delta t)g(i\Delta t) - 2g(i\Delta t)g\big((i+1)\Delta t\big) + g(i\Delta t)g\big((i+2)\Delta t\big)\right];$$

$$R_{X\varepsilon}(\mu\Delta t) = \frac{1}{2N}\sum_{i=1}^{N}\left[g(i\Delta t)g((i+\mu)\Delta t) - 2g(i\Delta t)g\big((i+(\mu+1))\Delta t\big) + g(i\Delta t)g((i+(\mu+2))\Delta t)\right];$$

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 nose $\varepsilon(i\Delta t)$; $g((i+\mu)\Delta t)$ is the $(i+\mu)$-th sample of the noisy signal; N is the number of samples.

Due to this, in the beginning of the initiation of faults, the estimate $R_{X\varepsilon}(\mu)$, D_ε of the noise characteristics of the vibration signal $g(i\Delta t)$ differs from the normal (reference) estimates, which makes it possible to register the beginning of the latent period of changes in the technical condition of the corresponding component. Similarly, using the appropriate formulas for other noise characteristics of the vibration signal $g(i\Delta t)$ given in the book [1], it is possible to control the technical condition of all controlled nodes of the train's running gear. To this end, during the system operation, as a result of certain amount of training, the maximum reference threshold estimates of all noise characteristics are determined, at which the technical condition of the controlled component is considered normal. A reference set of informative attributes is formed from them in the form

$$W_j^{max} = \{D_\varepsilon^{max}, R_{X\varepsilon}^{max}(1\Delta t), R_{X\varepsilon}^{max}(2\Delta t), R_{X\varepsilon}^{max}(3\Delta t), \ldots, R_{X\varepsilon}^{max}(m\Delta t). \quad (7)$$

In a similar manner, the reference set of other noise characteristics is formed. Due to this, during the train movement, as a result of application of all kinds of noise technologies for analyzing vibration signals, a set of informative attributes are formed on the noise controller, reflecting the current technical condition of all the controlled components of the train's running gear along the entire route of its movement. In case of a defect, e.g. in the axleboxes of wheelsets at the current moment of the train car's movement, some current estimates of the noise characteristics will be greater than the corresponding reference threshold value formed from expression (7) of reference informative attributes. In other words, if there is a fault in the current state of the controlled component, the current estimates of some noise characteristics will be greater than the corresponding maximum reference estimates. Due to this, the information can be compiled for wireless transmission from the noise controllers. Therefore, the information that will reflect the technical condition of the corresponding components of the running gear of the rolling stock can be registered and displayed on the driver’s monitor screen.

Thus, along the entire route, the version under discussion will provide noise control of both the technical condition of all the controlled components of individual cars and the rolling stock as a whole. It is clear that duplication of the correlation noise analysis of vibration signals using other noise analysis technologies can enhance the reliability and validity of the results of the proposed system. Some algorithms of spectral analysis of the noise of vibration signals that are also advisable to use in the noise control of the running gear of the rolling stock are given in the following paragraphs.

5. Spectral technology for the noise control of the beginning of faults in the running gear of the rolling stock

As was mentioned earlier, the initiation of faults and the dynamics of their development are accompanied by the emergence of the noise $\varepsilon_2(i\Delta t)$ correlated with the useful signal $X(i\Delta t)$. The noise $\varepsilon_2(i\Delta t)$ is added to the noise $\varepsilon_1(i\Delta t)$, forming the sum noise $\varepsilon(i\Delta t)$ that in the latent period of accidents correlates with the useful signal.

Therefore, when solving the problem of controlling the beginning and dynamics development of faults, it is advisable to also use estimates of the spectral characteristics of the sum noise $\varepsilon(i\Delta t)$ as informative attributes. An analysis of possible solutions to this problem showed [1, 4-8] that for this purpose it is advisable to replace non-measurable samples of the noise $\varepsilon(i\Delta t)$ with their approximate equivalent values $\varepsilon^e(i\Delta t)$. In this case, it is possible to use the technology for calculating the estimate of the noise variance D_ε from the expression

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

which can also be represented as

$$\frac{1}{N}\sum_{i=1}^{N}\varepsilon^2(i\Delta t) \approx \frac{1}{N}\sum_{i=1}^{N}g(i\Delta t)\left[g(i\Delta t) + g\big((i+2)\Delta t\big) - 2g((i+1)\Delta t)\right].$$

Due to this, assuming the notation,

$$\varepsilon'(i\Delta t) \approx g(i\Delta t)\left[g(i\Delta t) + g\big((i+2)\Delta t\big) - 2g((i+1)\Delta t)\right], \tag{8}$$

$$\operatorname{sgn}\varepsilon'(i\Delta t) = \begin{cases} +1 & \text{when} \quad \varepsilon'(i\Delta t) > 0 \\ 0 & \text{when} \quad \varepsilon'(i\Delta t) = 0, \\ -1 & \text{when} \quad \varepsilon'(i\Delta t) < 0 \end{cases} \tag{9}$$

the formula for calculating the equivalent values of the samples of the noise $\varepsilon^e(i\Delta t)$ can be represented as:

$$\varepsilon(i\Delta t) \approx \varepsilon^e(i\Delta t) = \operatorname{sgn}\varepsilon'(i\Delta t) \times \sqrt{\left|g(i\Delta t)\left[g(i\Delta t) + g\big((i+2)\Delta t\big) - 2g((i+1)\Delta t)\right]\right|} =$$
$$= \operatorname{sgn}\varepsilon'(i\Delta t) \times \sqrt{|\varepsilon'(i\Delta t)|}.$$

Here, assuming that the expression,

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

holds true, the formula for calculating the mean value $\bar{\varepsilon}(i\Delta t)$ of samples of the noise $\varepsilon(i\Delta t)$ can be reduced to calculating the mean value of equivalent samples of the noise $\varepsilon^e(i\Delta t)$, i.e.

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

Due to this, the expression for determining the estimates of the spectral characteristics of the noise can be represented in the following form:

$$a_{n_\varepsilon} \approx \frac{2}{N}\sum_{i=1}^{N}\varepsilon^e(i\Delta t)\cos n\omega(i\Delta t), \quad (10)$$

$$b_{n_\varepsilon} \approx \frac{2}{N}\sum_{i=1}^{N}\varepsilon^e(i\Delta t)\sin n\omega(i\Delta t). \quad (11)$$

It is easy to see that, taking into account notation (8) and (9), expressions (10) and (11), i.e. formulas for determining the estimates of the spectral characteristics of the noise can be represented in the following form:

$$a_{n_\varepsilon} \approx \frac{2}{N}\sum_{i=1}^{N}\mathrm{sgn}\varepsilon'(i\Delta t) \times \sqrt{\left|g(i\Delta t)\big[g(i\Delta t) + g\big((i+2)\Delta t\big) - 2g((i+1)\Delta t)\big]\right|}\cos n\omega(i\Delta t) =$$
$$= \frac{2}{N}\mathrm{sgn}\,\varepsilon'(i\Delta t) \times \sqrt{|\varepsilon'(i\Delta t)|}\cos n\omega(i\Delta t), \quad (12)$$

$$b_{n_\varepsilon} \approx \frac{2}{N}\sum_{i=1}^{N}\mathrm{sgn}\varepsilon'(i\Delta t) \times \sqrt{\left|g(i\Delta t)\big[g(i\Delta t) + g\big((i+2)\Delta t\big) - 2g((i+1)\Delta t)\big]\right|}\sin n\omega(i\Delta t) =$$
$$= \frac{2}{N}\sum_{i=1}^{N}\mathrm{sgn}\,\varepsilon'(i\Delta t) \times \sqrt{|\varepsilon'(i\Delta t)|}\sin \omega(i\Delta t). \quad (13)$$

Thus, the use of algorithms (12) and (13) opens the possibility for registering the beginning of the latent period of faults, since the estimates a_{n_ε} and b_{n_ε} will differ from the reference informative attributes only at the beginning of an emergency state. Because of this, the use of these expressions will make it possible to enhance the reliability of the control of the onset of the latent period of initiation of faults in the running gear of the rolling stock.

Studies have shown that the dynamics of development of running gear faults affects the degree of correlation between the samples of the noise $\varepsilon(i\Delta t)$, as well as the correlation between samples of the equivalent noise $\varepsilon^e(i\Delta t)$. In this case, the formula for forming the equivalent noise at $\mu = 1\Delta t$ can be written as:

$$\varepsilon^e((i+1)\Delta t) = g(i\Delta t)\big[g\big((i+1)\Delta t\big) + g((i+3)\Delta t) - 2g((i+2)\Delta t)\big].$$

At $\mu = 2\Delta t$, this expression will take the following form:

$$\varepsilon^e((i+2)\Delta t) = g(i\Delta t)\big[g\big((i+2)\Delta t\big) + 2g((i+4)\Delta t) - 2g((i+3)\Delta t)\big].$$

At $\mu = m\Delta t$, the expression can be written in a generalized form:

$$\varepsilon^e((i+m)\Delta t) = g(i\Delta t)\big[g\big((i+m)\Delta t\big) + 2g((i+m+2)\Delta t) - 2g((i+m+1)\Delta t)\big].$$

Due to this, based on the results of a spectral analysis of the equivalent $\varepsilon^e(i\Delta t)$ of the noise $\varepsilon(i\Delta t)$ at $\mu = 1\Delta t, 2\Delta t, 3\Delta t, \ldots, m\Delta t$, i.e. $\varepsilon^e((i+1)\Delta t)$, $\varepsilon^e((i+2)\Delta t)$, $\varepsilon^e((i+3)\Delta t)$,..., $\varepsilon^e((i+m)\Delta t)$, it is possible to control the dynamics of accident, using the following expressions:

$$\begin{cases} a_{1\varepsilon}^* \approx \frac{2}{N}\sum_{i=1}^{N} \varepsilon^e\big((i+1)\Delta t\big)\cos n\omega(i\Delta t) \\ b_{1\varepsilon}^* \approx \frac{2}{N}\sum_{i=1}^{N} \varepsilon^e\big((i+1)\Delta t\big)\sin n\omega(i\Delta t) \\ a_{2\varepsilon}^* \approx \frac{2}{N}\sum_{i=1}^{N} \varepsilon^e\big((i+2)\Delta t\big)\cos n\omega(i\Delta t) \\ b_{2\varepsilon}^* \approx \frac{2}{N}\sum_{i=1}^{N} \varepsilon^e\big((i+2)\Delta t\big)\sin n\omega(i\Delta t) \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ a_{n\varepsilon}^* \approx \frac{2}{N}\sum_{i=1}^{N} \varepsilon^e\big((i+n)\Delta t\big)\cos n\omega(i\Delta t) \\ b_{n\varepsilon}^* \approx \frac{2}{N}\sum_{i=1}^{N} \varepsilon^e\big((i+n)\Delta t\big)\sin n\omega(i\Delta t) \end{cases}.$$

If the fault is stable, then these estimates will be equal. However, in the presence of fault development dynamics, the estimates $a_{1\varepsilon}^*$, $b_{1\varepsilon}^*$; $a_{2\varepsilon}^*$, $b_{2\varepsilon}^*$;...; $a_{n\varepsilon}^*$, $b_{n\varepsilon}^*$ will differ from each other, and in the case of high dynamics of the development of the defect degree, these differences will be significant.

6. Spectral technology for noise signaling of the beginning of the latent period of faults

Our analysis of the spectral noise control technologies has demonstrated that during the operation of the rolling stock, the signaling of the beginning of the latent period of faults is also important [1]. For this purpose, in addition to the aforementioned estimates, it is also advisable to use the estimates $a_{n_\varepsilon}^{**}$ and $b_{n_\varepsilon}^{**}$ and the relay spectral characteristics of the noise $\varepsilon(i\Delta t)$ of the noisy signals $g(i\Delta t)$, which can be calculated from the expressions:

$$a_{n_\varepsilon}^{**} \approx \frac{2}{N}\sum_{i=1}^{N} \operatorname{sgn} \varepsilon^e(i\Delta t) \times \cos n\omega(i\Delta t),$$
$$b_{n_\varepsilon}^{**} \approx \frac{2}{N}\sum_{i=1}^{N} \operatorname{sgn} \varepsilon^e(i\Delta t) \times \sin n\omega(i\Delta t).$$

These studies also demonstrated that the technology of sign spectral noise analysis can also be used for the signaling of the beginning of the onset of faults by means of the following expressions:

$$a'_{n_\varepsilon} \approx \frac{2}{N}\sum_{i=1}^{N} \operatorname{sgn} \varepsilon^e(i\Delta t)\operatorname{sgn} \cos n\omega(i\Delta t),$$
$$b'_{n_\varepsilon} \approx \frac{2}{N}\sum_{i=1}^{N} \operatorname{sgn} \varepsilon^e(i\Delta t)\operatorname{sgn} \sin n\omega(i\Delta t).$$

The advisability of applying the technologies of relay and sign spectral analysis for the signaling of the beginning of the latent period of accidents is due to the fact that its hardware implementation is easy. At the same time, it is advisable to ensure the reliability of the signaling by duplicating these technologies with the technology of relay correlation analysis $R_{X\varepsilon}^*(\mu)$ calculated from the formula:

$$R_{X\varepsilon}^*(\mu) \approx \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)\big[\operatorname{sgn} g((i+1)\Delta t) + \operatorname{sgn} g((i+3)\Delta t) - 2\operatorname{sgn} g\big((i+2)\Delta t\big)\big],$$

where $R_{X\varepsilon}^*(\mu)$ is the estimate of the relay cross-correlation function between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$.

If the obtained estimates will be greater than the reference one at $\mu = 1\Delta t$ the dynamics of the development of faults can be considered slow. If the estimates are greater than the reference one at $\mu = 2\Delta t$, then the dynamics is moderate. In case of a difference from the reference informative attributes at $\mu = 3\Delta t$ and above, the development dynamics can be considered accelerated.

7. Conclusion

Traditional technologies do not allow extracting diagnostic information sufficient to identify the beginning of the latent period of the initiation of defects in the core components of the running gear of the rolling stock. This affects the time of registration of the onset of faults, which sometimes leads inevitable accidents with undesirable consequences. Therefore, to enhance the reliability of fail-safe operation and timely maintenance of the rolling stock, it is necessary to create new, more effective technologies for analyzing noisy signals that allow early detection of the onset of faults.

Our analysis of running gear of the rolling stock has demonstrated that during the initiation of corresponding defects, the noisy signals at the outputs of the sensors carry the information about it in the form of the noise of a random function. This is because during the onset of an accident due to the imposition of a large number of various dynamic effects in the controlled components, noises appear. Therefore, noise components of noisy signals, being of chaotic random nature, contain enough information about the beginning of changes in the technical condition of an object. For instance, vibration signals of axleboxes of wheelsets contain a large number of different noises. They make it difficult to detect the onset of a defect when traditional signal analysis technologies are used. At the same time, in some cases, noises are the carriers of diagnostic information about the onset of a fault. Therefore, to control the beginning of the initiation of faults, it is necessary to create technologies that allow calculating informative attributes by using not only useful signals, but also noise [1, 4-8]. Here, to ensure the control of a defect at the beginning of its initiation, the first and foremost task is to choose the type and place of installation of the appropriate sensors that ensure the object's controllability. To analyze both the sum signal $g(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$, it is advisable to employ the technologies that allow determining the appropriate informative attributes.

Due to the extreme importance of ensuring fail-safe operation of the rolling stock, it is advisable to control the beginning and development dynamics of faults by duplicating by several noise control and noise signaling technologies proposed in [1]. In this case, the reference set of the estimates of the noise characteristics of noisy signals will take the form:

$$W_j^{max} = \begin{cases} D_\varepsilon^{max}, R_{X\varepsilon}^{max}(1\Delta t), R_{X\varepsilon}^{max}(2\Delta t), R_{X\varepsilon}^{max}(3\Delta t), \dots, R_{X\varepsilon}^{max}(m\Delta t) \\ R_{X\varepsilon}^{*max}(1\Delta t), R_{X\varepsilon}^{*max}(2\Delta t), R_{X\varepsilon}^{*max}(3\Delta t), \dots, R_{X\varepsilon}^{*max}(m\Delta t) \\ a_{1\varepsilon}^{max}, b_{1\varepsilon}^{max}; a_{2\varepsilon}^{max}, b_{2\varepsilon}^{max}; a_{3\varepsilon}^{max}, b_{3\varepsilon}^{max}; \dots;\ a_{n\varepsilon}^{max}, b_{n\varepsilon}^{max} \\ a_{1\varepsilon}^{*max}, b_{1\varepsilon}^{*max}; a_{2\varepsilon}^{*max}, b_{2\varepsilon}^{*max}; a_{3\varepsilon}^{*max}, b_{3\varepsilon}^{*max}; \dots;\ a_{n\varepsilon}^{*max}, b_{n\varepsilon}^{*max} \end{cases}$$

which, combined with current informative attributes, will constitute the basis of the dataware for the solution of the control problem. As a result, the reliability and validity of the results of the control of the beginning and development dynamics of faults will improve.

In conclusion, it should be noted that, despite the influence of various factors that make it difficult to ensure fail-safe operation of the rolling stock of rail transport, currently used technologies and systems provide satisfactory control of their functioning. However, due to the extreme importance of this issue, to control current state of the core components of the rolling stock, it is advisable to duplicate traditional control algorithms with the proposed algorithms for the noise control of the onset and development dynamics of faults. This will ensure early diagnostics of such faults of the running gear of the rolling stock as bearing defects, lacking and insufficient lubrication, malfunctions of wheel-and-motor units, mounting defects, imbalance of rotating parts, gear defects, leakage in the feed and brake lines, break valve malfunctions, brake cylinder malfunctions, compressor malfunctions, etc. Thus, the use of algorithms and technology of noise control in combination with traditional algorithms and technologies can significantly enhance the effectiveness and reliability of ensuring fail-safe operation of the rolling stock of rail transport.

References

[1] T. Aliev, Noise Control of the Beginning and Development Dynamics of Accidents, Springer, 2019.
[2] S.M. Bagirov, E.K. Manafov, Fuzzy expert system for diagnosing malfunctions of axleboxes of rolling stock, Bulletin of the RSUPS. No.4 (2009) 76-79 (in Russian)
[3] A.A. Amelina, Design and repair of car axleboxes with roller bearings, Moscow, Transpor, 1971, 286 p. (in Russian)
[4] T. Aliev, Digital Noise Monitoring of Defect Origin, Springer, 2007.
[5] T. Aliev, Robust Technology with Analysis of Interference in Signal Processing, Kluwer, 2003.
[6] T.A. Aliev, T.A. Alizada, G.A. Guluyev, A.H. Rzayev, N.E. Rzayeva, Robust technology and system for management of sucker rod pumping units in oil wells, Mechanical Systems and Signal Processing. 99 (2018) 47-56.
https://doi.org/10.1016/j.ymssp.2017.06.010
[7] T.A. Aliev, T.A. Alizada, N.E. Rzayeva, Noise technologies and systems for monitoring the beginning of the latent period of accidents on fixed platforms, Mechanical Systems and Signal Processing. 87 Part A (2017) 111-123.
https://doi.org/10.1016/j.ymssp.2016.10.014
[8] T.A. Aliev, G.A. Guluyev, F.H. Pashayev, A.B. Sadygov, Noise monitoring technology for objects in transition to the emergency state, Mechanical Systems and Signal Processing. 27 (2012) 755-762.
https://doi.org/10.1016/j.ymssp.2011.09.005

Reviewer: Associate Professor G.A. Guluyev, DSc (Engineering)