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Technology of Adaptive Vibration Control of the Beginning of the Latent Period of Railroad Accidents

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Abstract**—At present, control and diagnostics systems are widely used in rail transport. In this case, vibration parameters, pressure, efforts, current, voltage, resistance, impulses, time intervals are used as informative attributes. The control results are displayed on the driver's monitor. Among these parameters, vibration signals are of particular importance when solving diagnostic problems. They are obtained from vibration sensors installed on rolling stock, on bridges, on tunnels and have an immense information potential. As a rule, they have a complex cyclic stepwise abruptly changing shape and are accompanied by significant noise $\varepsilon(i\Delta t)$. Control systems currently use spectral methods and algorithms to analyze these signals. However, for a number of reasons, there are cases in practice when the adequacy of the results of the solution of the control and diagnostics problem is not ensured. This is due to the fact that the analysis and identification of stepwise and abruptly changing vibration signals with the use of spectral technologies in many cases requires determining a large number of spectral estimates with the corresponding amplitudes and frequencies. In addition, the vibration signal received from these vibration sensors is characterized by a change in the spectrum depending on the speed of the train. For instance, the spectra of vibration signals at a speed of 100 km/h will differ significantly from that of the same vibration signals at a speed of 200 km/h. Therefore, the sampling interval in the first case will be unacceptable for the second case. For these reasons, solving the problems of control of both rolling stock and railroad tracks becomes significantly more complicated. In view of the above, the authors propose an adaptive technology for the forming informative attributes from the estimates of position-binary vibration signals, which makes it possible to improve the adequacy of the control results.**

Keywords— vibration control of the beginning of accidents, rolling stock, information attributes, intelligent systems, sensors, vibration, vibration and Noise technologies

I. Introduction

It is known that spectral methods are used in most cases of control and diagnostics of the technical condition of cyclic (periodic) processes [1-4]. For instance, objects with equipment of reciprocating motion, objects with rotating nodes, etc. are cyclic. The importance of this problem is due to the fact that the vibration signals received from vibration sensors on rolling stock, on railway tracks, on bridges and tunnels have the main properties of cyclic objects, which have a great information potential. The signals $g(i\Delta t)$ received from the sensors installed on all these objects, as a rule, have a complex stepwise abruptly changing form and are accompanied by significant noises $\varepsilon(i\Delta t)$. Spectral methods and algorithms are currently used in control systems to analyze these signals [1, 4-6]. However, for a number of reasons, the adequacy of the results of the solution of the control and diagnostics problem is not ensured in practice [1]. This is due to the fact that the analysis and identification of stepwise and abruptly changing vibration signals with the use of spectral technologies in many cases requires determining a large number of spectral estimates with corresponding amplitudes and frequencies. This significantly complicates the solution of problems [1, 4-6] of controlling the beginning of the latent period of malfunctions of both rolling stock and railroad tracks. Therefore, to ensure the adequacy of the results of control and diagnostics, more effective methods and algorithms are needed, which would allow not only reducing the number of terms of the "spectrum", but also improving the reliability of the obtained results in comparison with the spectral method.

II. Problem Statement

It is known that when spectral method algorithms are used for the analysis of the vibration signals $X(t)$ with bounded spectrum, they are resolved into harmonic components, using the expression

$$X(t) = \frac{a_n}{2} + \sum_{n=1}^{\infty}(a_n \cos n\omega t + b_n \sin n\omega t) \quad (1)$$

In expression (1), a_n and b_n are the amplitudes of the cosine curve and the sine curve with the frequency $n\omega$, which are taken as informative attributes in controlling the beginning of accident initiation. It is known that the following inequality should hold true to provide accuracy of reconstruction of signal $X(t)$.

$$\sum_{i=1}^{n} \lambda_i^2 \leq S, \quad (2)$$

where λ_i^2 is the squared deviations between the sum of the right-hand side of equality (1) and the samples of the signal $X(t)$ at the sampling moments $t_0, t_1, \ldots, t_i, \ldots, t_n$ with the interval Δt; S is the allowable value of the mean square deviation.

For intermittent and abruptly changing vibration signals, ensuring inequality (2) leads to increase of the number of harmonic components, which therefore complicates the analysis and identification of experimental data. In addition, for the case where the measurement information is the mixture of the useful signal $X(t)$ and the noise $\varepsilon(t)$, condition (2) holding true depends to a certain extent on the value of the spectrum of the noise $\varepsilon(t)$. In the existing methods of spectral analysis in equality (1) the influence of noise is neglected and the error of the noise $\varepsilon(t)$ is equated to zero. However, for many objects of rail transport, the influence of the noise on the accuracy of reconstruction of the source signal $X(t)$ turns out to be significant and should be taken into.

If we take into account that in the latent period of the initiation and development of a malfunction, the spectrum of the noise $\varepsilon(t)$ changes continuously, then the difficulty of solving problems of identifying cyclic noisy signals with the use of traditional spectral analysis becomes obvious. Therefore, it is necessary to create new technologies for analyzing vibration signals, taking into account the peculiarities and specifics of the operation of rail transport.

In addition, to ensure the adequacy of the solution of control problems, it is necessary to use the entire information potential of noisy vibration signals $g(i\Delta t) = X(i\Delta t) + \varepsilon(i\Delta t)$. This, first of all, requires determining the sampling interval of these signals in real time. This is due to the fact that the spectrum of vibration signals $g(i\Delta t)$ received from the vibration sensors of these objects changes depending on the speed of the rolling stock. Therefore, to ensure the required accuracy of the results, the sampling interval has to be determined based on the signal spectrum at the current time instant. In other words, to ensure the adequacy of the results of control and diagnostics, an adaptive technology for sampling vibration signals is needed.

III. Possibility of Control of the Beginning of the Latent Period of Malfunctions Using the Position-Binary Technology

Studies [1, 7-9] have shown that for the analysis of vibration signals, it is advisable to use the position-binary technology (PBT) analysis of vibration noisy signals in control and diagnostics systems of rail transport [1].

It is known that in practice, in measuring of the signals $g(t)$, there is a minimum value of increment that depends on the resolving capacity of the device in use. Denote that minimum value of increment by Δx. Therefore, during measuring of the signal, the number of its discrete values will be equal to

$$m = \frac{x}{\Delta x} + 1.$$

In the process of analog-to-digital conversion of the vibration signal $X(t)$, its amplitude sampling occurs at each sampling interval Δt, i.e., the range of its possible variations is divided into m_{max} of quantization steps, and the value of the signal that gets into the m-th interval, with

$$m\Delta X - \frac{\Delta X}{2} \leq X(t) \leq m\Delta x + \frac{\Delta x}{2} \quad (3)$$

belongs to the center of the interval $m\Delta X$. In this case, values of binary codes of corresponding bits q_k of the samples of the sampled signal $X(i\Delta t)$ with the sampling interval Δt are calculated based on the following algorithm [1, 7-9]:

$$q_k(i\Delta t) = \begin{cases} 1 & \text{when } x_{rem(k)}(i\Delta t) \geq \Delta x 2^k; \\ 0 & \text{when } x_{rem(k)}(i\Delta t) < \Delta x 2^k; \end{cases} \quad (4)$$

$$x_{rem(k)}(i\Delta t) = x_k(i\Delta t) - [q_{k+1}(i\Delta t) + q_{k+2}(i\Delta t) + \cdots + q_{(n-1)}(i\Delta t)],$$

where

$$X(i\Delta t) > 2^n;\ x_{rem(n-1)}(i\Delta t) = X(i\Delta t), n \geq \log\frac{x_{max}}{\Delta x},$$

$$k = n-1, n-2, \ldots, 1, 0.$$

In accordance with this algorithm, the equality $x_{rem(n-1)}(i\Delta t) = X(i\Delta t)$ is assumed at each sampling interval Δt, and according to condition (4), the signals $q_k(i\Delta t)$ form in the form of code 1 or 0 iteratively. At the first step, $X(i\Delta t)$ is compared with the value $2^{n-1}\Delta x$. According to (4), if $X(i\Delta t) \geq 2^{n-1}\Delta x$, then the bit $q_{n-1}(i\Delta t)$ is equated to unit and the value of the remainder $x_{rem(n-2)}$ is calculated from the difference

$$X(i\Delta t) - 2^{n-1}\Delta x = x_{rem(n-2)}$$

In the case when $X(i\Delta t) < 2^{n-1}\Delta x$, the bit $q_{n-1}(i\Delta t)$ is equated to zero, and the difference remains unchanged. The same thing occurs in the next iteration. As a result, in every conversion cycle with the sampling interval Δt, the signal $X(i\Delta t)$ is as if decomposed into the signals $q_k(i\Delta t)$,, which assume values 1 or 0 and have weights corresponding to their positions. The codes remain unchanged as long as the value of the source signal $X(i\Delta t)$ does not change in the sampling process. Let us from now onwards call these signals position-binary signals (PBS). Therefore, position-binary technology (PBT) of analysis of the vibration signal is the aggregate of successive processing procedures based on decomposition of the vibration signal into PBS.

According to algorithm (4), in the process of analog-to-digital conversion, the width of PBS will be proportional to the number of Δt, when $q_k(i\Delta t)$ remains unchanged. Depending on the shape of $X(i\Delta t)$, the same signal $q_k(i\Delta t)$ can change its value several times at corresponding time spans. Note that $T_{k1_1}, T_{k1_2}, \ldots$ here correspond to the time spans when the condition $q_k(i\Delta t) = 2^k(\Delta x = 1)$ is fulfilled; $T_{k0_1}, T_{k0_2}, \ldots$ correspond to the time spans when the condition $q_k(i\Delta t) = 2^k(\Delta x = 0)$ is fulfilled. Naturally, if object's technical condition operating in the cyclic mode remains unchanged, then combinations of the time spans $T_{k1_1}, T_{k0_1}, T_{k1_2}, T_{k0_2}, \ldots$ of PBPS in each cycle will be constant values and reiterate. Otherwise, they change as well. According to expression (4), the sum of all PBS in each cycle will be equal to the source signal, i.e.,

$$X(i\Delta t) \approx q_{n-1}(i\Delta t) + q_{n-2}(i\Delta t) + \cdots + q_1(i\Delta t) + q_0(i\Delta t) = g^*(i\Delta t).$$

Each $q_k(i\Delta t)$ can be regarded as a separate signal, and the combinations of sequences of the time spans when $q_k(i\Delta t)$ are in the state of unit or zero, can be regarded as informative attributes. Due to this, for vibration signals, those PBS $q_k(i\Delta t)$ will be periodic rectangular pulses with the corresponding unit T_1 and zero T_0 half-periods. Here, at the moments t_i, the difference between the true value of the source signal $X(i\Delta t)$ and the sum of PBS will be equal to

$$X(i\Delta t) - X^*(i\Delta t) = \lambda(i\Delta t).$$

Taking into account expression (3), the following inequality can be written:

$$\lambda(i\Delta t) \leq \pm\frac{\Delta x}{2}.$$

Due to this, the beginning of changes in object's technical condition leads to a change in the corresponding samples of the vibration signal $X(i\Delta t)$ by a value exceeding Δx, and it will reflect on its corresponding bits $q_k(i\Delta t)$. Therefore, already at the initial stage of the malfunction in the process of PBS formation in the form of the combination of the corresponding time spans $q_{n-1}(i\Delta t)$, $q_{n-2}(i\Delta t)$, …, $q_0(i\Delta t)$ of the current time instant, the difference from their analogous parameters in previous time instants will be revealed, which will allow one to form and present the information on the beginning of the latent period of changes in control object's technical condition. This only requires calculating the mean frequency $\langle f_k\rangle$ and the period $\langle T_k\rangle$ of position-binary signals. The algorithms for their calculation are easily implemented in practice, since each position-vibration signal assumes only two values. It is intuitively clear that for random and periodic noisy signals $g(i\Delta t)$ the estimate of the mean value of zero and unit half-periods of the position signals $q_k(i\Delta t)$, given the sufficient observation time T, can be calculated from the formula

$$\langle T_{q_k}\rangle = \langle T_{1q_k}\rangle + \langle T_{0q_k}\rangle, \quad (5)$$

where

$$\langle T_{1q_k}\rangle = \frac{1}{\gamma}\sum_{j=1}^{\gamma} T_{1q_{kj}}, \qquad \langle T_{0q_k}\rangle = \frac{1}{\gamma}\sum_{j=1}^{\gamma} T_{0q_{kj}}. \quad (6)$$

Here γ is the number of unit and zero half-periods of PBS in the observation time T, j is the is ordinal number of the q_k-the position of PBS.

It is demonstrated in [1] that for the sufficient observation time, if the condition of stationarity is satisfied, the estimate of the mean duration of the periods $\langle T_k\rangle$ and the mean frequency f_{q_k} of PBS will be nonrandom values. Therefore, they can be used as informative attributes to control the beginning of changes in object's technical condition. And due to the simplicity of their calculation, they can significantly simplify solving of control problems, which are traditionally solved by means of estimates of correlation or spectral characteristics of random processes. In the general case, in cyclic object's normal stable technical condition, sets of combinations of mean frequencies of PBS $q_k(i\Delta t)$ can be formed from the signal $g(i\Delta t)$. Obviously, a change in object's technical condition will lead to changes in the combinations of the estimates of their mean frequencies $\overline{f}_{q_0}, \overline{f}_{q_1}, \ldots, \overline{f}_{q_m}$, which are calculated from the expressions

$$\overline{f}_{q_0} = \frac{1}{\langle T_{q_0}\rangle}, \overline{f}_{q_1} = \frac{1}{\langle T_{q_1}\rangle}, \overline{f}_{q_2} = \frac{1}{\langle T_{q_2}\rangle}, \ldots, \overline{f}_{q_m} = \frac{1}{\langle T_{q_m}\rangle}.$$

and are nonrandom values.

Let us now consider the possibility of using the relationship between the beginning of the latent period of accidents and the estimates of the characteristics of positional-binary signals [1, 7, 8]. As mentioned above, for many cyclic objects, sharply changing high-frequency spectra appear in the signal at the beginning of the initiation of defects. For instance, on roller bearings of axleboxes of rolling stock, on reinforced concrete structures of railroad bridges, etc. a malfunction often manifests itself in the form of high-frequency spectra. As indicated above, when coding these continuous signals $g(i\Delta t)$, signals $q_k(i\Delta t)$ are iteratively generated in the form of code 1 or 0 from their samples at each sampling interval Δt. For this purpose, in the first step, samples of $g(i\Delta t)$ are compared with $2^{n-1}\Delta g$. For $g(i\Delta t) \geq 2^{n-1}\Delta g$, the value of $q_{n-1}(i\Delta t)$ is equal to one, and the sequence of the signals $\mathrm{q_k(i\Delta t)}$ is determined from the difference

$$g(i\Delta t) - 2^{n-1}\Delta g = g_{rem(n-2)}(i\Delta t).$$

Then combinations T_{1q_k}, T_{0q_k} are determined for all bits from expressions (5), (6). Then from expressions

$$\overline{f}_{q_0} = \frac{1}{\langle T_{q_0}\rangle}, \overline{f}_{q_1} = \frac{1}{\langle T_{q_1}\rangle}, \overline{f}_{q_2} = \frac{1}{\langle T_{q_2}\rangle}, \ldots, \overline{f}_{q_m} = \frac{1}{\langle T_{q_m}\rangle}$$

$$k_{fq_0} = \frac{f_{q_1}}{f_{q_0}}, k_{fq_1} = \frac{f_{q_2}}{f_{q_1}}, k_{fq_2} = \frac{f_{q_3}}{f_{q_2}}, \ldots, k_{fq_m} = \frac{f_{q_m}}{f_{q_{m-1}}}$$

$$k_{q_0} = \frac{\langle T_{q_1}\rangle}{\langle T_{q_2}\rangle}, k_{q_1} = \frac{\langle T_{q_2}\rangle}{\langle T_{q_3}\rangle}, k_{q_2} = \frac{\langle T_{q_3}\rangle}{\langle T_{q_4}\rangle}, \ldots, k_{q_m} = \frac{\langle T_{q_m}\rangle}{\langle T_{q_{m-1}}\rangle},$$

the combinations of frequencies of PBS $\overline{f}_{q_0}, \overline{f}_{q_1}, \overline{f}_{q_2}, \ldots, \overline{f}_{q_m}$ and the combinations of the relations $k_{fq_0}, k_{fq_1}, k_{fq_2}, \ldots, k_{fm}$ and $k_{q_0}, k_{q_1}, k_{q_2}, \ldots, k_{q_m}$ are detemined. It is easy to see that by forming a set of informative attributes from them, it is possible to create intelligent technologies for the control of the beginning of the latent period of malfunctions in the above objects.

IV. Adaptive Technology for Determining the Sampling Interval of Vibration Signals

As mentioned above, the vibration signal $X(t)$ can take any value within the range of X_{min} … X_{max}. At the same time, in measuring of the signals in practice, there is a minimum value of increment that can also be determined by of the device in use and depends on its resolving capacity. Therefore, during measuring of the signal, the number of its discrete values is finite:

$$n = X/\Delta X + 1,$$

and in the process of measuring the vibration signal, its amplitude quantization occurs, i.e., the range of its possible changes (X_{max}, X_{min}) is divided into n quantization intervals and the value of the signal falling into the S-th interval, at

$$S\Delta X - \frac{\Delta X}{2} \leq X(t) \leq S\Delta X + \frac{\Delta X}{2}$$

belongs to the center of the interval $S\Delta X$.

Due to the properties of analog-to-digital conversion, the signal $x(t)$ is represented here in the form

$$x(t) = q_0(t) + q_1(t) + q_2(t) + q_3(t) + \cdots = \sum_{k=1}^{n} q_k(t).$$

where the values of the signals $q_k(t)$ at each time instant represent the values of the corresponding bits of the digital equivalent of the signal $X(t)$.

Thus, the amplitude-quantized vibration signal in the process of analog-to-digital conversion is represented as the sum of the vibration signals $q_k(t)$. In this case, an approximate analysis of the frequency properties of position-vibration signals $q_k(t)$, which take only two values, is much simpler than that of the vibration signals themselves. In view of this, let us consider the possibility of using this specific feature of the analog-to-digital conversion process for adaptive determination of the sampling interval of the vibration signal. This formulation of the problem is of great practical interest for rail transport, where the frequency of the spectra of vibration signals changes depending on the speed of the rolling stock. This makes the time sampling interval somewhat difficult to determine by traditional methods. At the same time, in the process of analog-to-digital conversion, the original signal $X(t)$ is naturally decomposed into position-vibration signals $q_k(t)$, which take only the values "1" and "0". Due to this, the hardware determination of the frequency of change in these signals is quite simple. For instance, the mathematical expectations of the duration $\mathrm{T}_{1_{q_0}}$, $\mathrm{T}_{0_{q_0}}$ of rectangular pulses of the lowest-order position-vibration signal $q_0(t)$ can be determined from the expressions

$$\mathrm{T}_{1_{q_0}} \approx \frac{1}{n_0}\sum_{i=2}^{n_0} \mathrm{T}_{1_{q_{0i}}},$$

$$\mathrm{T}_{0_{q_0}} \approx \frac{1}{n_0}\sum_{i=1}^{n_0} \mathrm{T}_{0_{q_{0i}}},$$

where $\mathrm{T}_{1_{q_{0i}}}$, $\mathrm{T}_{0_{q_{0i}}}$ are time intervals when the following conditions are met:

$$q_0(t) = 1, q_0(t) = 0.$$

In this case, the mean period of pulses of the lowest-order position-vibration signal $\mathrm{T}_{\mathrm{m}\,q_0}$ and the mean frequency of their repetition are determined from the expressions

$$\mathrm{T}_{\mathrm{m}\,q_0} = \mathrm{T}_{1_{q_0}} + \mathrm{T}_{0_{q_0}},$$

$$f_{q_0} = \frac{1}{\mathrm{T}_{\mathrm{m}\,q_0}}.$$

$$f_{q_0} = \frac{1}{\langle T_{q_0}\rangle}. \quad (7)$$

We can assume that the result obtained by formula (7) is practically an estimate of the frequency of the period of the lowest-order position-vibration signal, which can be taken as an appropriate sampling frequency of the vibration signal.

Obviously, for noisy vibration signals, the values of the binary codes of neighboring samples of $g(i\Delta t)$ will be repeated at an excessive traditional sampling frequency f_T. Therefore, the following inequality will take place between the frequency f_T found by the traditional method and the current frequency f_t:

$$f_t \gg f_T. \quad (8)$$

It is intuitively clear that the estimate of the mean value of $\overline{f}_{q_0}$ for all implementations of the same vibration signal in the period of a stable technical condition of the object will be a stable value. Therefore, selecting the value of f_t so that conditions (8) are met, it is possible to calculate the estimate of the mean value of $\overline{f}_{q_0}$. Here, in the process of analog-to-digital conversion, the condition for determining sought-for frequency (8) can be represented as follows

$$f_t \geq f_{q_0}.$$

Following from this condition, the sampling interval Δt for the noisy signal $g(i\Delta t)$ can be selected in accordance with the inequality

$$\Delta t \leq \frac{1}{f_{q_0}}.$$

In that case, to calculate f_{q_0}, it is necessary to calculate the mean period of pulses of the lowest-order PBS $\langle T_{q_0}\rangle$ and their mean repetition frequency, using samples of the analyzed signal, from the expressions

$$\langle T_{q_0}\rangle = \langle T_{1q_0}\rangle + \langle T_{0q_0}\rangle,$$

$$f_{q_0} = \frac{1}{\langle T_{q_0}\rangle}, \quad (9)$$

where $\langle T_{1q_0}\rangle$ and $\langle T_{0q_0}\rangle$ are calculated from the expressions

$$\langle T_{1q_0}\rangle = \frac{1}{\gamma}\sum_{j=1}^{\gamma} T_{1q_{0j}} \quad \text{and} \quad \langle T_{0q_0}\rangle = \frac{1}{\gamma}\sum_{j=1}^{\gamma} T_{0q_0}. \quad (10)$$

Our experimental studies show the estimates of the mean frequency of low-order bits of PBS are correlated with the high-frequency spectra of the noisy vibration signal. Therefore, the sampling interval Δt of the useful signal $X(t)$ should be calculated from the frequency characteristics of high-order PBS. In the normal technical condition of object's operation, we can assume that he following approximate equality takes place between the mean values of durations of periods of PBS $q_0(i\Delta t), q_1(i\Delta t), q_2(i\Delta t), q_3(i\Delta t)$:

$$\langle T_{q_0}\rangle \approx \frac{1}{2}\langle T_{q_1}\rangle, \langle T_{q_1}\rangle = \frac{1}{2}\langle T_{q_2}\rangle, \langle T_{q_2}\rangle = \frac{1}{2}\langle T_{q_3}\rangle, \ldots \quad (11)$$

Therefore, the sampling interval Δt_X of the useful vibration signals can be calculated using the mean period of pulses of high-order bits of PBS. For instance, the formulas for calculating the sampling interval Δt_t of the useful signal by means of the q_3-th PBS can be written as follows:

$$\Delta t_t \leq \frac{1}{2^3 f_3}. \quad (12)$$

Thus, the formula for adaptive determination of the sampling interval of the noisy signal $g(i\Delta t)$ and the useful signal $X(i\Delta t)$ can be written as follows:

$$\Delta t_g \leq \frac{1}{q_0}$$

$$\Delta t_X \leq \frac{1}{2^k f_k}$$

where $k = 1, 2, 3$.

It is obvious that the sampling interval of the noisy vibration signal $g(i\Delta t)$ can be calculated from formulas (9)-(12) adaptively in real time in the process of analog-to-digital conversion, which will improve the adequacy of the results of analysis of noisy vibration signals g(iΔt).

V. CONCLUSION

In the control and diagnostics systems of rail transport, vibration, pressure, current, voltage, etc. are used as the main sources of measurement information. Among these parameters, the most informative are vibration signals, which are obtained at the outputs of vibration sensors installed in the most informative structures of rolling stock, bridges and tunnels. These are usually very noisy and stepwise, abruptly changing signals. At the same time, the noise in these signals also contain diagnostic information and their spectrum changes depending on the speed of the train. These specific features of vibration signals are currently neglected in the employed technologies of spectral analysis, which sometimes leads to the lack of adequacy of control results. To eliminate this shortcoming of control and diagnostics systems, the authors propose a technology for adaptive sampling of vibration signals and a positional-binary technology for controlling the beginning of the latent period of malfunctions.

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