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TECHNOLOGIES AND INTELLIGENT SYSTEMS FOR ADAPTIVE VIBRATION CONTROL IN RAIL TRANSPORT

Summary. Vibration diagnostics is of particular importance in rail transport safety systems because the signals received from vibration sensors installed on rolling stock, bridges, tunnels, and other infrastructure objects have great diagnostic information potential. Despite this, in practice, there are cases when the adequacy of the results of the vibration control and diagnostics task is not ensured. The reason is that the sampling step of the vibration signal does not change when the train speed changes. Given the need to change the sampling interval depending on the train speed, this article proposes an adaptive technology for vibration signal sampling that allows the building of intelligent systems of adaptive vibration control of malfunctions in rail transport.

1. INTRODUCTION

Vibration signals $g(i\Delta t)$ received from rail transport objects are known to normally contain significant noise $\varepsilon(i\Delta t)$. It is also known that any vibration received at the output of vibration sensors contains harmonics of different frequencies. Analyzing the amplitude of these harmonics yields information about the state of the equipment. Unfortunately, however, in this case, diagnostic information in the noise is neglected. It should be noted that the parameters of vibration displacement, vibration velocity, and vibration acceleration are usually measured in the low-frequency, middle-frequency, and high-frequency range. The advantages of vibration control by analyzing vibration signals include the versatility and availability of measuring instruments and the developed methodology, which are discussed in detail in [2-6].

Spectral methods and algorithms are currently used in control systems to analyze vibration signals. However, for a number of reasons, the adequacy of the results of the solution to the control and diagnostics problem is not ensured in practice in some cases [1]. This is because the analysis and identification of stepwise and abruptly changing vibration signals by spectral technologies in many cases require determining many spectral estimates with corresponding frequencies and amplitudes. Moreover, because of the specifics of railroad objects, the spectrum of vibration signals from the same sensors changes over time. This results in an additional error, which consequently significantly complicates the

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solution to the problem [1, 4-8] of the control of the start of the latent period of faults, both in rolling stock and the railroad bed. For this drawback to be resolved, it is necessary to develop algorithms and technologies that make it possible to determine the sampling interval adaptively.

2. PROBLEM STATEMENT

When using traditional algorithms for the analysis of noisy signals $g(i\Delta t)$, the error from the influence of the noise is equated to zero. However, in signals from rail transport objects, the influence of noise produces significant errors in the obtained results, and the influence of noise changes over time. In this case, the influence of interference changes with the lapse of time. For this reason, there is a need to develop more effective vibration signal analysis technologies and tools that use noise as a carrier of diagnostic information.

3. ADAPTIVE TECHNOLOGY FOR DETERMINING THE SAMPLING INTERVAL OF VIBRATION SIGNALS

The number of discrete values of the vibration signal is known to be finite:

$$n = X/\Delta X + 1. \tag{1}$$

In the process of measurement, its amplitude quantization occurs. Because of the properties of analog-to-digital conversion, the signal $X(t)$ appears as follows:

$$X(t) = q_0(t) + q_1(t) + q_2(t) + q_3(t) + \cdots = \sum_{k=1}^{n} q_k(t). \tag{2}$$

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 $X(t)$ in analog-to-digital conversion is represented as the sum of 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 to carry out than an analysis of the vibration signals themselves. Thus, consider the possibility of using this specific feature of the analog-to-digital conversion process to adaptively determine the sampling interval of the vibration signal. This formulation of the problem is of great practical interest in rail transport settings, 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 using traditional methods. At the same time, during analog-to-digital conversion, the original signal $X(t)$ is naturally decomposed into position-vibration signals (PVSs) $q_k(t)$, which take only the values "1" or "0". Therefore, the hardware determination of the frequency of change in these signals is quite simple. [1] For instance, the mathematical expectations of the duration $T_{1_{q0}}$, $T_{0_{q0}}$ of rectangular pulses of the lowest-order position-vibration signal $q_0(t)$ can be determined from the expressions

$$T_{1_{q0}} \approx \frac{1}{n_0} \sum_{i=2}^{n_0} T_{1_{q0i}} \tag{3}$$

and

$$T_{0_{q0}} \approx \frac{1}{n_0} \sum_{i=1}^{n_0} T_{0_{q0i}}, \tag{4}$$

where $T_{1_{q0i}}$, $T_{0_{q0i}}$ are time intervals when the following conditions are met:

$$q_0(t)=1,\ q_0(t)=0\,. \tag{5}$$

Here, the mean period of pulses of the lowest-order position-vibration signal $T_{m_{q0}}$ and the mean frequency of their repetition are determined from the follow expressions:

$$\begin{cases} T_{m_{q0}} = T_{1_{q0}} + T_{0_{q0}} \\ f_{q_0} = \dfrac{1}{T_{m_{q0}}} \\ f_{q_0} = \dfrac{1}{\left\langle T_{q_0} \right\rangle} \end{cases} . \tag{6}$$

It is conceivable that the result obtained from formula (6) 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 $g(i\Delta t)$, the values of the binary codes of neighboring samples will recur at an excessive traditional sampling frequency f_T. That is, the following inequality will hold

$$f_t >> f_T\,. \tag{7}$$

Because of this, the following inequality will also hold

$$f_t \ge f_{q_0}\,. \tag{8}$$

Therefore, the estimate of the sampling interval Δt is

$$\Delta t \le \frac{1}{f_{q_0}}. \tag{9}$$

Obviously, to calculate f_{q_0}, the mean repetition period of lowest-order pulses has to be found:

$$\begin{cases} \left\langle T_{q_0} \right\rangle = \left\langle T_{1q_0} \right\rangle + \left\langle T_{0q_0} \right\rangle \\ f_{q_0} = \dfrac{1}{\left\langle T_{q_0} \right\rangle} \end{cases} , \tag{10}$$

where $\left\langle T_{q_0} \right\rangle$ and $\left\langle T_{0q_0} \right\rangle$ are derived from the expressions

$$\left\langle T_{1q_0} \right\rangle = \frac{1}{\gamma}\sum_{j=1}^{\gamma} T_{1q_{0j}} \text{ and } \left\langle T_{0q_0} \right\rangle = \frac{1}{\gamma}\sum_{j=1}^{\gamma} T_{0q_0}\,. \tag{11}$$

It is obvious from the above discussion that it is appropriate to use adaptive sampling technology to analyze noisy vibration signals. In this case, the frequency of high-order bits of the analog-to-digital converter. That is, the validity of the following equality can be assumed:

$$\left\langle T_{q_0} \right\rangle \approx \frac{1}{2}\left\langle T_{q_1} \right\rangle, \left\langle T_{q_1} \right\rangle = \frac{1}{2}\left\langle T_{q_2} \right\rangle, \left\langle T_{q_2} \right\rangle = \frac{1}{2}\left\langle T_{q_3} \right\rangle, \ldots \tag{12}$$

For instance, the formulas for the sampling interval Δt_t of the useful signal by means of the q_3-th PVS can be represented as follows:

$$\Delta t_t \le \frac{1}{2^3 f_3}\,. \tag{13}$$

Thus, the formula for adaptively determining the sampling interval of the noisy signal $g(i\Delta t)$ and the useful signal $X(i\Delta t)$ is

$$\begin{cases} \Delta t_g \le \dfrac{1}{q_0},\ f_g = \dfrac{1}{\Delta t_g} \\ \Delta t_{g_k} \le \dfrac{1}{2^k f_k},\ f_g = \dfrac{1}{\Delta t_{g_k}} \end{cases}, \tag{14}$$

where $k = 1,2,3$.

Obviously, to determine the sampling interval of the noisy vibration signal $g(i\Delta t)$, the frequency of variation of the corresponding bits of the samples during analog-to-digital conversion according to formulas (10)-(13) can be adaptively used.

Consider the possibility of adaptive sampling in the following example. Suppose that a train travels at the speed of 50 km/h, and the technical condition of the roller bearings of the cars is monitored by analyzing the sampled vibration signals $g(i\Delta t)$. Here, with the proposed technology, the suitable sampling rate can be determined by changing the frequency of the least significant digit of the samples of $g(i\Delta t)$ from formula (14):

$$\Delta t_g = \frac{1}{q_0} = \frac{1}{2000\ \text{Hz}} = 0.0005\ \text{s}. \tag{15}$$

Suppose that the train starts traveling at the speed of 100 km/h on the same road. It is natural that the vibration frequency and, consequently, the variation frequency of the least significant digit q_0 of samples of the vibration signal $g(i\Delta t)$ will double in proportion to the speed of the train. As a result, the formula for the sampling step will take the form

$$\Delta t_g = \frac{1}{q_0} = \frac{1}{4000\ \text{Hz}} = 0.00025\ \text{s}. \tag{16}$$

It is obvious from these examples that in the first case, the sampling rate will be 2000 Hz, and in the second case, the sampling rate will be 4000 Hz. Consequently, by changing the train speed using the proposed technology, it is possible to adaptively measure the duration of the sampling step Δt_g of the vibration signal $g(i\Delta t)$.

4. POSSIBILITY OF CONTROLLING THE BEGINNING OF THE LATENT PERIOD OF MALFUNCTIONS USING THE POSITION-VIBRATION TECHNOLOGY

Studies [1-4] have shown that it is advisable to use the position-vibration technology to analyze noisy vibration signals in intelligent control and diagnostics systems of rail transport to control the beginning of malfunctions [1].

As shown earlier, during the analog-to-digital conversion of the vibration signal $X(t)$, its amplitude sampling occurs at each sampling interval Δt. As a result, the corresponding bits q_k of vibration signals are calculated using the following formula [1]:

$$q_k(i\Delta t) = \begin{cases} 1 \ \ when \ \ x_{rem(k)}(i\Delta t) \ge \Delta x 2^k \\ 0 \ \ when \ \ x_{rem(k)}(i\Delta t) < \Delta x 2^k \end{cases}, \tag{17}$$

$$x_{rem(k)}(i\Delta t) = x_k(i\Delta t) - \left[q_{k+1}(i\Delta t) + q_{k+2}(i\Delta t) + \ldots + q_{(n-1)}(i\Delta t)\right], \tag{18}$$

where

$$X(i\Delta t) > 2^n;\ x_{rem(n-1)}(i\Delta t) = X(i\Delta t),\ n \geq \log\frac{x_{\max}}{\Delta x},\ k = n-1, n-2, \ldots, 1, 0. \quad (19)$$

In the process of sampling the original signal, only when its magnitude changes by more than the quantization interval by the equation will the binary codes of its samples change. Thus, the analog-to-digital transformation of the samples of the signal $X(i\Delta t)$ is determined by the equality

$$X(i\Delta t) \approx q_{n-1}(i\Delta t) + q_{n-2}(i\Delta t) + \ldots + q_1(i\Delta t) + q_0(i\Delta t) = g^*(i\Delta t). \quad (20)$$

Each $q_k(i\Delta t)$ can be treated 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 treated as informative attributes. Obviously, the signals $q_k(i\Delta t)$ are rectangular pulses with half-periods T_1 and T_0, and the beginning of malfunction of the object leads to corresponding changes in these signals. This, in turn, will allow the malfunction do be detected, which will allow the information related to the onset of a change in the state of the object to be registered. The frequency $\langle f_k \rangle$ and $\langle T_k \rangle$ can be determined quite simply, as the mean value of half-periods of signals $q_k(i\Delta t)$ is found from the equality

$$\langle T_{qk} \rangle = \langle T_{1qk} \rangle + \langle T_{0qk} \rangle, \quad (21)$$

where

$$\langle T_{1q_k} \rangle = \frac{1}{\gamma}\sum_{j=1}^{\gamma} T_{1q_{kj}},\ \langle T_{0q_k} \rangle = \frac{1}{\gamma}\sum_{j=1}^{\gamma} T_{0q_{kj}}. \quad (22)$$

Here, γ is the number of units and zero half-periods of PVSs over the observation time T, j is the ordinal number of the q_k-th position of the PVS.

According to the above description, the estimates of $\langle T_k \rangle$ and f_{qk} can be used as additional information attributes in the process of control of technical objects. Due to the simplicity of these algorithms, the process of vibration signal analysis when solving monitoring tasks is greatly simplified in comparison with traditional analyses. As a result, any malfunction in the monitoring of the technical condition of the controlled objects will manifest itself in the variation of the combination of mean frequencies $\bar{f}_{q_0}, \bar{f}_{q_1}, \ldots, \bar{f}_{q_m}$, which can be easily calculated by means of very simple expressions:

$$\bar{f}_{q_0} = \frac{1}{\langle T_{q_0} \rangle},\ \bar{f}_{q_1} = \frac{1}{\langle T_{q_1} \rangle},\ \bar{f}_{q_2} = \frac{1}{\langle T_{q_2} \rangle}, \ldots, \bar{f}_{q_m} = \frac{1}{\langle T_{q_m} \rangle}. \quad (23)$$

Consider now the possibility of using the relationship between the beginning of the latent period of an accident and the estimates of the characteristics of positional-vibration signals [1]. As mentioned above, for many cyclic objects in rail transport, sharply changing high-frequency spectra appear in the signal at the beginning of the initiation of defects. For instance, on the roller bearings of the axleboxes of rolling stock or on reinforced concrete structures of railroad bridges, a malfunction often manifests itself as high-frequency spectra. As indicated above, when coding these continuous signals $g(i\Delta t)$, signals $q_k(i\Delta t)$ are iteratively generated as 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 1, and the sequence of the signals $q_k(i\Delta t)$ is determined as follows:

$$g(i\Delta t) - 2^{n-1}\Delta g = g_{rem(n-2)}(i\Delta t). \quad (24)$$

Then, combinations T_{1q_k}, T_{0q_k} are determined for all bits from expressions (17)-(22). In turn, the following expressions are formed:

$$\begin{cases} \bar{f}_{q_0} = \dfrac{1}{\langle T_{q_0} \rangle}, \ \bar{f}_{q_1} = \dfrac{1}{\langle T_{q_1} \rangle}, \bar{f}_{q_2} = \dfrac{1}{\langle T_{q_2} \rangle}, \dots, \bar{f}_{q_m} = \dfrac{1}{\langle T_{q_m} \rangle} \\ k_{fq_0} = \dfrac{f_{q_1}}{f_{q_0}}, \ k_{fq_1} = \dfrac{f_{q_2}}{f_{q_1}}, k_{fq_2} = \dfrac{f_{q_3}}{f_{q_2}}, \dots, k_{fq_m} = \dfrac{f_{q_m}}{f_{q_{m-1}}} \\ k_{q_0} = \dfrac{\langle T_{q_1} \rangle}{\langle T_{q_2} \rangle}, k_{q_1} = \dfrac{\langle T_{q_2} \rangle}{\langle T_{q_3} \rangle}, k_{q_2} = \dfrac{\langle T_{q_3} \rangle}{\langle T_{q_4} \rangle} \dots, k_{q_m} = \dfrac{\langle T_{q_m} \rangle}{\langle T_{q_{m-1}} \rangle} \end{cases} . \quad (25)$$

The combinations of mean frequencies of PVS $\bar{f}_{q_0}, \bar{f}_{q_1}, \bar{f}_{q_2}, \dots, \bar{f}_{q_m}$ and the combinations of the relations $k_{fq_0}, k_{fq_1}, k_{fq_2}, \dots, k_{f_m}$ and $k_{q_0}, k_{q_1}, k_{q_2}, \dots, k_{q_m}$ are determined, which can be used to form a set of informative attributes that reflect changes in the technical condition of controlled objects.

5. INTELLIGENT SYSTEM FOR THE ADAPTIVE VIBRATION CONTROL OF THE BEGINNING OF MALFUNCTIONS

Our studies have shown that using the technology of positional vibration analysis of noisy vibration signals makes it possible to build an intelligent system to control the onset of malfunctions in technical objects.

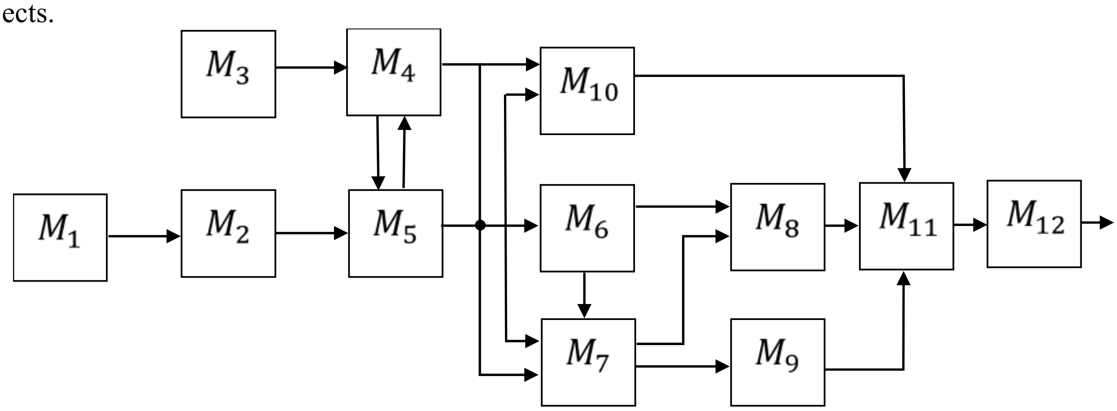

Fig. 1. A simplified block diagram of an intelligent system for the adaptive vibration control of malfunctions

Fig. 1 shows a simplified block diagram for a possible version of an intelligent system for the adaptive vibration control of the onset of malfunctions in rail transport facilities. The system comprises the following main modules: M_1 – control object; M_2 – vibration sensor; M_3 – excessive frequency generator; M_4 – sampling rate adaptation module; M_5 – module for determining the variation frequency of the least significant bit q_0 and other bits $q_1, q_2 \dots$ of samples of the vibration signals $q(1\Delta t), q(2\Delta t), \dots, q(i\Delta t), \dots, q(n\Delta t)$; M_6 – module of decomposition of the vibration signal $g(i\Delta t)$ into position vibration signals $q_0(i\Delta t), q_1(i\Delta t), \dots$; M_7 – module for determining current estimates of the frequency characteristics of position-vibration signals; M_8 – module for comparing and recording current and reference estimates of frequency characteristics of PVS; M_9 – module for generating the set of reference estimates of the frequency characteristics of position-vibration signals; M_{10} – module for estimating the noise variance D_ε and the cross-correlation function $R_{X\varepsilon}(\mu)$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ of the noisy vibration signal; M_{11} – module o37f the monitoring of the beginning of malfunctions; and M_{12}– module for generating and providing information.

The system operates as follows. When the system operates in control mode during the beginning of malfunctions, the noisy vibration signal $g(i\Delta t)$ comes from a vibration sensor M_2 installed in the unit M_1 of the rolling stock to the input of module M_5. At the same time, pulses from the output of the excessive frequency generator module M_3 are fed to the input of the sampling rate adaptation module M_4 to the other input of which a signal is received from the output of module M_5 for determining the variation frequency of the least significant bit $g_0(i\Delta t)$ of position signals. Resultantly, by synchronizing these signals at the output of module M_4, a signal is obtained with a frequency of $q_0(i\Delta t)$, which corresponds to the frequency the analysis of the current vibration signal requires. Thus, the frequency of change in the least significant digits of the PVSs in module M_4, together with the excessive frequency, is used to adaptively determine the sampling interval of the vibration signal $g(i\Delta t)$. In module M_6, the initial vibration signal $g(i\Delta t)$ is decomposed by formulas (21) and (22) into position-vibration signals $q_0(i\Delta t), q_1(i\Delta t), q_2(i\Delta t), \ldots$, and their current estimates are determined in module M_7 from formulas (14) and (17). Based on these results, a set of reference informative attributes is generated in module M_9 from the frequency characteristics of the PVS. After the learning period in the process of the control of the beginning of malfunctions is over, the current and reference informative attributes are compared in module 8. If it matches one or more reference, then it is assumed that the object is in a normal technical condition. If the current combination of informative attributes does not match the reference, then it is assumed with a high probability that there is an onset of a malfunction that usually precedes an accident. Estimates of the variance of the noise $\varepsilon(i\Delta t)$ are additionally determined in module M_{10} to increase the degree of adequacy of the control result. This is done using the expression

$$D_\varepsilon \approx \frac{1}{N}\sum_{i=1}^{N}\left[g^2(i\Delta t) - 2g(i\Delta t)g((i+1)\Delta t) + g(i\Delta t)g((i+2)\Delta t)\right]. \tag{26}$$

As a result, if the estimates of D_ε also exceed the threshold value $D_{\varepsilon\mathrm{T}}$, which is established experimentally (e.g., $D_{\varepsilon\varepsilon\mathrm{T}} = 0{,}1 - 0{,}15$), then the object is considered as being in a pre-emergency state. In this case, the corresponding information about the beginning of a malfunction is generated in module M_{11} and displayed on the driver's monitor. In addition, in module M_{12}, this information is also sent to the information center of the traffic safety system.

6. CONCLUSIONS

Ensuring the safety of rail transport necessitates enhancements to the adequacy of the results of vibration control and vibration diagnostics. This requires, first and foremost, the development of new effective technologies that allow the sampling interval of analog signals to be changed in real time if necessary. In this regard, this article proposed a technology and technical means of adaptively determining the sampling interval of analog signals in real time to enhance the reliability of vibration control and diagnostics of malfunctions in transport.

It should be noted that the adaptive-vibration technology is essentially a hardware and software tool that can be created using modern controllers. It was impossible to build them earlier based on traditional measuring instruments. These technologies can be used for purposes other than analyzing vibration signals. As shown by the example in Section 5, the area of their application is much wider, as the adaptive sampling technology is versatile. Therefore, the technology of adaptive sampling of analog signals proposed here opens the possibility of creating intelligent systems for monitoring the onset of malfunctions in various technical objects.

References

1. Aliev, T. *Noise control of the Beginning and Development Dynamics of Accidents.* Springer. 2019. 201 p.
2. Collacott, R.A. *Mechanical Fault Diagnosis and condition monitoring*. 1977. 504 p.
3. Thompson, D. *Railway Noise and Vibration: Mechanisms*, *Modelling and Means of Control*. 1st Edition. Kindle Edition. 2008. 845 p.
4. Muzaffer Metin and Rahmi Guclu. Rail Vehicle Vibrations Control Using Parameters Adaptive PID Controller. *Mathematical Problems in Engineering*. Hindawi, 2014. No. 728946. P. 1-10.
5. Lin, C.C. & Wang, J.F. & Chen, B.L. Train-Induced Vibration Control of High-Speed Railway Bridges Equipped with Multiple Tuned Mass Dampers. *Journal of Bridge Engineering.* 2005. Vol. 10(4). P. 398-414.
6. Sun, C. & Gao, L. Medium-to-low-speed freight rail transport induced environmental vibration and analysis of the vibration isolation effect of building slope protection piles. *Journal of Vibroengineering.* 2017. Vol. 19. No. 6. P. 4531-4549.
7. Anderson, D. & Gautier, P.E. & Iida, M. and other. Noise and Vibration Mitigation for Rail Transportation Systems. In: *Proceedings of the 12th International Workshop on Railway Noise*. 12-16 September 2016. Terrigal, Australia.
8. Dudkin, P.E. & Andreeva, L.A. & Sultanov, N.N. Methods of Noise and Vibration Protection on Urban Rail Transport. *Procedia Engineering*. 2017. Vol. 189. P. 829-835.

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