Transverse horizontal vibrations of contact network wires for monitoring their tension during operation

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Abstract. The paper describes the structure of a hardware and software complex for monitoring and diagnostics of the contact network, provides information about the hardware blocks of the complex, considers its implementation in Matlab/Simulink, describes the regularities of change of vibration frequency under different values of tension and the linear mass of wires.

1 Introduction

In accordance with the Strategy for the development of railway transport in the Russian Federation until 2030, it is planned to improve the quality of service of the contact network, including by improving software and hardware diagnostic complexes, which will allow autonomously diagnosing the contact network [1, 2].

The hardware and software complex includes hardware blocks and software, and is an integral part of the contact network monitoring and diagnostics system. The main task of the contact network diagnostics system is to reduce the unit cost of maintaining the railway transport infrastructure.

To ensure reliable and high-quality operation of the current collection system, it is necessary to continuously monitor the operability of the contact network during operation, since the available data after the inspection trip does not reflect its current state.

It is necessary to improve the diagnostic system in order to improve the reliability, safety, durability and maintainability of the contact network in conditions of increased operating loads.

Analysis of the reports of the Directorate for energy supply of the West Siberian railway suggests that despite the increase in maintenance costs of the contact network, a high percentage of failures associated with damage to wires and cables of the contact network, air arrows, rebar elements and insulators remains [3, 4].

One of the defining parameters of the contact suspension that affects the parameters and performance of the current collection system is the tension of the contact wires, which can change quite quickly and go beyond the permissible values. However, existing methods and diagnostic tools for determining tension are not widely used in railway transport.

Currently, the main way to measure tension is to calculate the mass of loads of compensators [5], performed automatically or manually, as well as direct measurements

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using mortise or overhead dynamometers installed on the outgoing branches of contact suspensions. Using these methods, we can reliably determine the tension only near the interfaces. When the temperature changes, the tension along the length of the anchor sections will change uncontrollably within a fairly wide range. Since the high-altitude position of the wires, the speed of propagation of mechanical vibrations, and stiffness depend on the tension. Real-time monitoring of tension changes is an urgent task, the solution of which will improve the performance of the entire current collection system.

2 Materials and methods

2.1 The proposed research method

As part of the research work, a hypothesis was formulated that to ensure the required high reliability of the current collection system, it is necessary to use a software and hardware complex distributed along the entire length of the protected anchor section, capable of continuously measuring the tension of contact wires in an automatic mode at an arbitrary location.

It is proposed to measure the tension of contact wires by analyzing damped mechanical vibrations. Theoretical studies confirm the assumption that the frequency spectrum of vibrations carries information about a number of technical parameters related to the dynamic and static properties of the contact network.

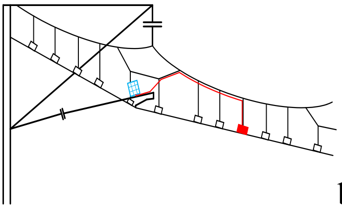
The greatest interest is the transverse vibrations of the contact network wires in the horizontal plane. Since the strings do not transmit horizontal forces from the carrier cable to the contact wire at small slopes, they do not depend on the configuration of the carrier cable and do not significantly affect the vibration process. At each passage of the current collector of the electric rolling stock, transverse vibrations in the middle of the span form a "digital imprint of the vibrating link", the parameters of which depend on the span length, the elasticity of the contact wires and their mass [6].

Vibrations in the horizontal plane depend, among other things, on the presence of abrasion, ice, and flexural rigidity. Changes in these properties lead to distortion of the "digital stamp".

2.2 Description of the hardware structure of the contact network monitoring and diagnostics system

The proposed complex is based on the use of temperature and acceleration sensors distributed over the anchor section, located in the body of string clamps (figure 1 a, b).

a



b

Fig. 1. Set of devices for diagnosing the contact network: a – acceleration sensor built into the string clip; b – layout of sensors in the span of the contact network.

The acceleration sensor is an accelerometer with a built-in data recorder that provides a maximum sampling rate of 2 kHz and allows recording accelerations when the perturbation threshold is reached [7]. When choosing an accelerometer, we must take into account the frequency range of vibrations and accelerations. The proposed acceleration range is from 0.2 to 150 m/s^2; the frequency of recorded vibrations - is from 1 to 500 Hz. The temperature sensor must be able to measure the temperature of the wires from -50 to +150°C. To maintain the dynamic characteristics of the contact suspension, the weight of the string clamp should not be more than standard.

The accelerometer and temperature sensor receive energy from a power supply unit with a solar battery installed on the main rod holder (figure 1b).

The power supply with the connecting cable associated with the analog-to-digital converter (ADC) having a radio communication module which combines up to 20 sensors with a common database in one information system (figure 2).

Data arrives at the server, where the wire tension is calculated, generated “digital stamp”, procedures for comparing the spectral composition of vibrations with the records obtained earlier are carried out.

The information server determines the spectral composition of vibrations, generates digital stamps, calculates tension, and builds retrospective data. Then the operator’s requests are processed.

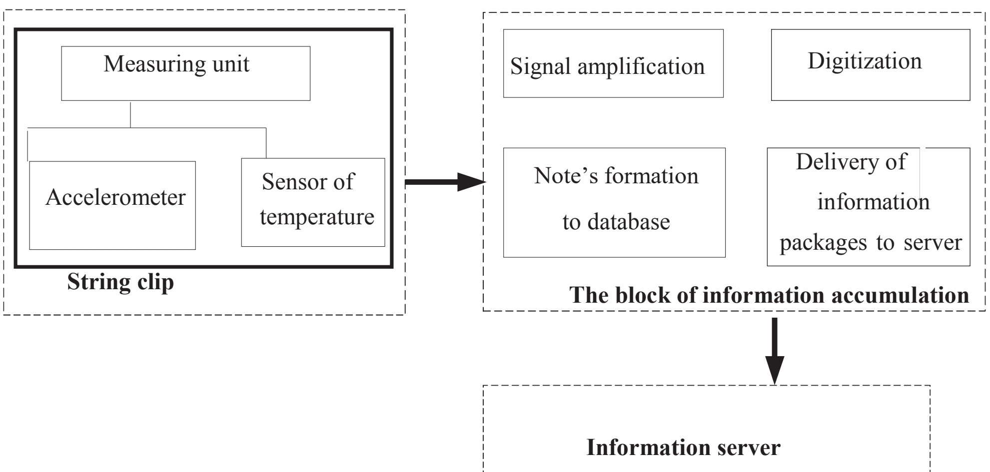


Fig. 2. Functional diagram of the hardware and software complex for monitoring and diagnostics of a contact network.

2.3 Description of the software part of the contact network monitoring and diagnostics system

Data is transmitted wirelessly to the cloud storage using a WEB interface for information exchange. The signal from the accelerometer (figure 3) after digital processing is suitable for determining the amplitude-frequency characteristics (AFC) using the methods of operational modal analysis and fast Fourier transform [8, 9]:

$$X_k = \sum_{n=0}^{n-1} x_n \cdot e^{-\frac{2\pi}{N} \cdot k \cdot n} = \sum_{n=0}^{N-1} x_n \cdot \left[\cos(\frac{2\pi \cdot k \cdot n}{N} - i \cdot \sin(\frac{2\pi \cdot k \cdot n}{N}) \right], (k = 0, \dots N\text{-}1) \quad (1)$$

where N - is the number of signal values for the registration period;

X_k, k = 0, ... N -1 – N complex amplitudes of sinusoidal signals composing the original signal; are the output data for the forward conversion and the input data for the reverse;

x_n, n =0, ..., N -1, – measured signal values;

k – is the frequency index. The frequency of the -*th* signal is k/T;

T - is the time interval during which the input data was recorded.

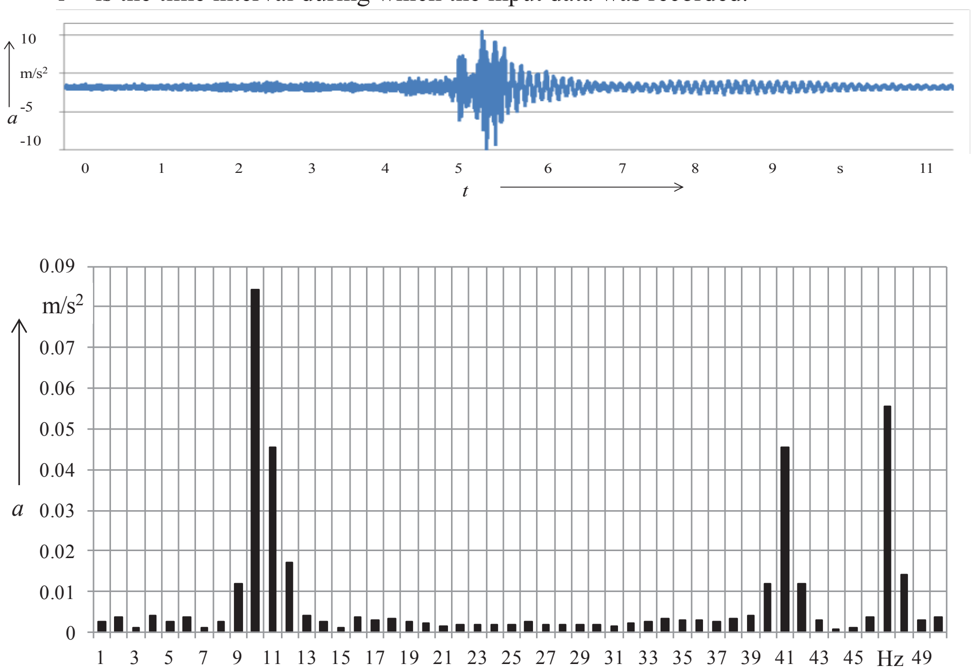


Fig. 3. Determining the frequency of vibrations using the fast Fourier transform: a – recording the vibrations of the wire; b – the spectrum of vibrations.

The model of a stretched rod was used as a mathematical tool for determining the relationship between the frequency of vibrations in the transverse plane and the tension of the contact wire. This model allows taking into account the load on the contact wire and bending rigidity:

$$\mathrm{E}_{CW} J_{CW} \frac{\partial^4 u_y}{\partial x^4} + K \frac{\partial^2 u_y}{\partial x^2} - m_{\mathrm{CW}} \frac{\partial^2 u_y}{\partial t^2} = 0, \tag{2}$$

where E_{CW} – the modulus of elasticity of the material of the contact wire of a solid section, N·m^2;

J_{CW} – moment of inertia of the cross section of the contact wire relative to the main central axis, m^4.

K – the tension of the contact wire, N;

m_{cw} –linear mass of the contact wire, kg/m.

Taking into account the assumption that the contact wire makes harmonic vibrations, the equation will have a special form of solution:

$$u_{yr}(x,t) = v_r(x)\sin(\omega_r t + \varphi_r), \tag{3}$$

in this case, relative to the function $v_r(x)$ the linear differential equation has the form:

$$\mathrm{E}_{CW} J_{CW} v_r^{IV}(x) - K v_r^{II}(x) - m_{\mathrm{CW}} \omega_r^2 v_r(x) = 0. \tag{4}$$

where ω_r – frequency of vibration of the contact wire of the corresponding harmonic r, Hz.

v_r – the amplitude of the harmonics r, defined as follows

$$v_r(x) = \frac{\vartheta(0)\cdot l}{\pi \cdot r}\cdot \sin(\frac{\pi \cdot r \cdot x}{l}),\ \text{m}; \quad (5)$$

$\vartheta(0)$ – angle of bending moments;

r – harmonic number;

l – span length, m.

The developed software calculates the tension of the contact wire based on the received vibration frequencies. The linear mass of the contact wire and its brand are also displayed. Using the contact suspension vibration equation, calculated tension dependences were obtained for various combinations of input data:

$$\mathrm{E}_{CW} \cdot J_{CW} \cdot (\frac{\pi \cdot r}{l})^4 + K \cdot (\frac{\pi \cdot r}{l})^2 - m_{\mathrm{CW}}\omega_r^2 = 0. \quad (6)$$

The parameters of the contact wire MF-100, the length of the span under the project KS-160 (l=60 m) for the first harmonic, r = 1, the modulus of elasticity is equal E_{CW} = $1.275\cdot10^{11}$ N/m^2, the tension ranged from 7000-13000 N, the linear mass was from 0.778 kg/m were adopted, which means worn-out contact wire, up to 1.202 kg/m, which means the wire is covered with ice. To calculate the moment of inertia, we assume that the contact wire has a circular cross-section:

$$J = \frac{\pi \cdot D^4}{64} = \frac{\pi \cdot (\frac{H+A}{2})^4}{64}. \quad (7)$$

where D – the diameter of the contact wire m;

H – the height of the contact wire, m;

A – the width of the contact wire, m

Based on the calculated data, diagrams of contact wire tension/linear load were obtained (figure 4).

Software allows varying the tension, selecting the linear mass of the contact wire, and getting the frequency of vibrations for different lengths of spans and brands of contact wires.

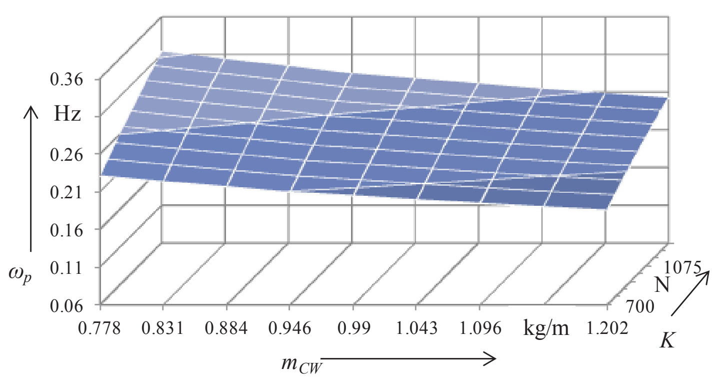


Fig. 4. The change in frequency of vibration from linear mass and tension of the contact wire**.**

The processed signals and received calculated values are sent to the database and stored there, in accordance with the rules defined by the program, on the computer's hard disk and in the cloud storage.

The database should provide access to data and the ability to quickly extract the necessary analytical information, contain the characteristics of sensors, retrospective values of their signals with reference to time and spatial coordinates, emergency and warning limits for the values of contact suspension parameters.

3 Results

Laboratory tests of the proposed device have shown that the autonomy of the software and hardware complex for power supply is not limited. The consumption of electric energy is compensated by solar battery. In terms of storage capacity, the autonomy is six months, after which digital stamps are overwritten on top of older records, while numerical data on the frequency, tension, and linear mass of the wires is stored in an area protected from erasure.

Conclusion

The developed software and hardware complex has shown its claimed effectiveness for measuring the tension of contact wires, as well as for monitoring the residual section, which makes it possible to use it in the system of monitoring and diagnostics of the contact network. The proposed scheme solution corresponds to the Strategy of digital transformation of the electric power industry of the Russian Federation, and the data obtained are suitable for use in predictive analytics systems using "big data" and artificial neural networks.

Thus, the proposed software package will reduce the cost of maintenance of the contact network and reach a new level of readiness of the infrastructure for passing high-speed traffic.

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