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Experimental Research of Ropeway Dynamics

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Abstract

Research of ropeways is carried out in several directions, one of which is the establishment of dynamic characteristics of rope systems under different operating conditions. In previous works, we proposed a mathematical model for calculating the frequency spectrum of ropeway, which is based on the representation of the ropeway traction circuit as a discrete-continuous dynamic system. The main purpose of the experimental studies is to confirm the adequacy of this model; its results are presented in this article. The considered single-span ropeway is usually used as a means of industrial transport for moving goods between production and storage facilities, in the mining industry – for transporting various materials from the place of extraction to railways and highways. Studies were carried out using experimental equipment developed by us. According to the results of the experiment, we drew the frequency diagrams, which show the change of eigenfrequencies of the ropeway traction circuit during the cars movement between stations. The total array of results includes information on the decoding of about a thousand oscillograms, which were obtained and studied according to the methodology developed by us.
KEY WORDS: *ropeway; dynamics; mathematical model; eigenfrequency; frequency spectrum; experimental research*

1. Introduction

Ropeway is a versatile transport system that has significant advantages over existing vehicles for transporting goods and people. The costs of construction and maintenance of ropeway are much lower than the corresponding values that characterize other modes of transport. At the same time, the duration of the transportation cycle is reduced due to the realization of the possibility of connecting final (and intermediate, if necessary) destinations for the shortest distance, due to the low dependence of the ropeway route on terrain. The combined consideration of these advantages confirms the technical and economic feasibility of using ropeways as a means of freight and passenger (including urban) transport.

The analysis of scientific literature showed that the researches of ropeways are carried out in several directions, one of which is the establishment of dynamic characteristics of rope systems under different operating conditions [1-4]. The similar research is being conducted for rail vehicles [5].

Any vehicle with a flexible traction body, in particular a ropeway, is a rather complex system in terms of mathematical modelling of the dynamics of its elements. It is characterized by the presence of lumped masses and elements with distributed parameters. In particular, in the problems considered in [6] the lumped masses are the motor rotor *1*, the mass of the gearbox parts brought to the output shaft *2*, the drive pulley *3*, the real or suppositive mass *5*, which characterizes the working force of the haulage rope tensioning device, and cars *6*. The concept of suppositive mass is introduced for tensioning devices of non-weight action, such as hydraulic; hereinafter, any tensioning devices will be called “tensioning load”. Sections *4* of the haulage rope are elements with distributed parameters (Fig. 1). This representation of the ropeway defines a mathematical model of its elements motion in the form of a system of differential equations in ordinary and partial derivatives, which is quite cumbersome and difficult to analyze.

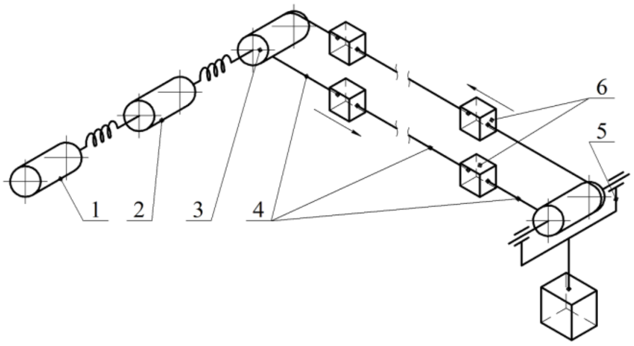


Fig. 1 Calculation scheme of ropeway as a system of lumped masses and elements with distributed parameters

To simplify the general mathematical model, you can use one of the following approaches:

1. Use the assumption that elements with distributed parameters (rope sections) are weightless [7], but this approach is acceptable only for ropeways of short length;
2. Replace the elements with distributed parameters by a system of finite number of lumped masses, which allows to make a mathematical model only from Lagrange equations of the second kind without the use of partial derivatives [8, 9];
3. Bring the masses of the subsystem “the motor rotor; the masses of the gearbox parts, reduced to the output shaft; the drive pulley” to the drive pulley, which allows you to make a mathematical model only from the equations of wave mechanics without the use of conventional derivatives [10].

The third approach was used during the theoretical studies of the ropeway frequency spectrum [6]. A mathematical model of the dynamics of the ropeway traction circuit as a discrete-continuous system consisting of lumped masses (drive pulley with the reduced masses of all rotating elements of the drive, cars, haulage rope tensioning load), interconnected by haulage rope sections as elements of distributed parameters. This model is more accurate than discrete, and allows to take into account the effect of changes in inertial and elastic characteristics of the haulage rope along its length. The developed model is compiled in general form and can be used to study ropeways of any type, purpose and field of use.

The main purpose of experimental research, the results of which are presented in this article, is to confirm the adequacy of the mathematical model for calculating the ropeway frequency spectrum, which is based on the representation of the ropeway traction circuit as a discrete-continuous dynamic system. Peculiarities of compiling and using such a model were presented and substantiated in [6].

To achieve this goal, we solved a number of problems, the main of which are the following:

1. Develop and substantiate of the experimental equipment constructive scheme;
2. Create of research methodology;
3. Manufacture, assemble and install experimental equipment and measuring system;
4. Conduct research in accordance with the created methodology;
5. Perform an analysis of the convergence of the theoretical and experimental studies results;
6. Draw a conclusion about the adequacy of the mathematical model presented in [6].

Some tasks are performed in parallel, so the presentation of the results will be combined.

2. General Characteristics of the Experimental Equipment

To confirm the adequacy of the mathematical model presented in [6], consider a single-span ropeway (Fig. 2), which consists of drive *1*, track rope anchor *2*, haulage rope *3*, track rope *4*, track rope tensioning device *5*, haulage rope tensioning device *6*, car *7*. Such ropeways are classified as pendulum, cars of which carry out reciprocating movement between the final stations. They are usually used as a means of industrial transport for the formation of dumps, for the movement of goods between production and storage facilities, in the mining industry - for transporting various materials from the place of extraction to railways and highways, ect. Pendulum ropeways can also be used to transport people, in particular as a means of passenger urban transport.

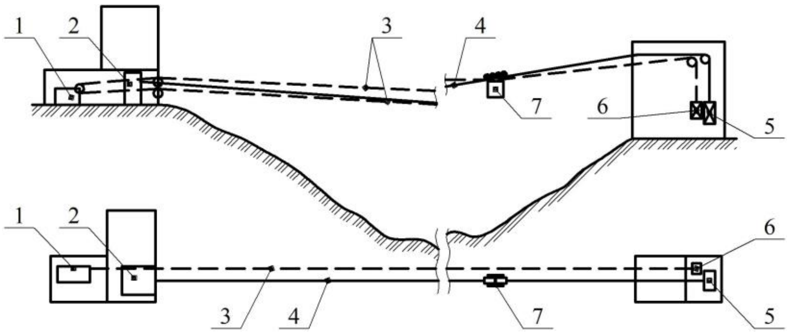


Fig. 2 Ropeway scheme

To conduct experimental studies, we will use equipment similar in design to the ropeway described above, with some changes to simplify the design and installation of its individual components and measuring equipment. This equipment (Fig. 3) has driving and tension pulleys, track and haulage ropes, cars, basic metalwork. Ensuring the force in the haulage rope required for reliable friction to the drive pulley surface is carried out by using a weight tensioning device. The tensioning device of the track rope was replaced with anchor clamps to simplify the structure of the experimental equipment, which is acceptable for ropeway of short length. Each of the pulleys are mounted on rolling bearings and rotate relative to fixed axles. Cars roll on wheels on a track rope and are rigidly connected to the haulage rope.

The experimental equipment has the following parameters:

- length of the simulated ropeway (along the car trajectory) is 2.5 m;
- drive and tension pulleys: diameter is 320 mm; weight is 15 kg;

– deflecting pulleys: diameter is 200 mm; weight is 10 kg;

– reduced weight of the tension load (taking into account the weight of the tension pulley, deflecting pulleys and the tension load) is 37 kg;

– track rope diameter is 8 mm;

– haulage rope diameter is 4,1 mm;

– car weight is variable, from 3.5 kg to 16 kg with a step of 2.5 kg (a set of loads).

To register the change in the ropeway elements acceleration we used a measuring equipment consisting of the following units:

– accelerometer (acceleration sensor) AT 1105-05; measuring range is (0… 5) g; frequency range is (0…500) Hz; measurement error is 2.5%;

– eight-channel universal amplifier QuantumX MX840A; accuracy class is 0.05;

– computer with Catman Easy software.

The results of continuous recording, which was carried out according to the following method, were stored as a tabular function by separate files of asc type.

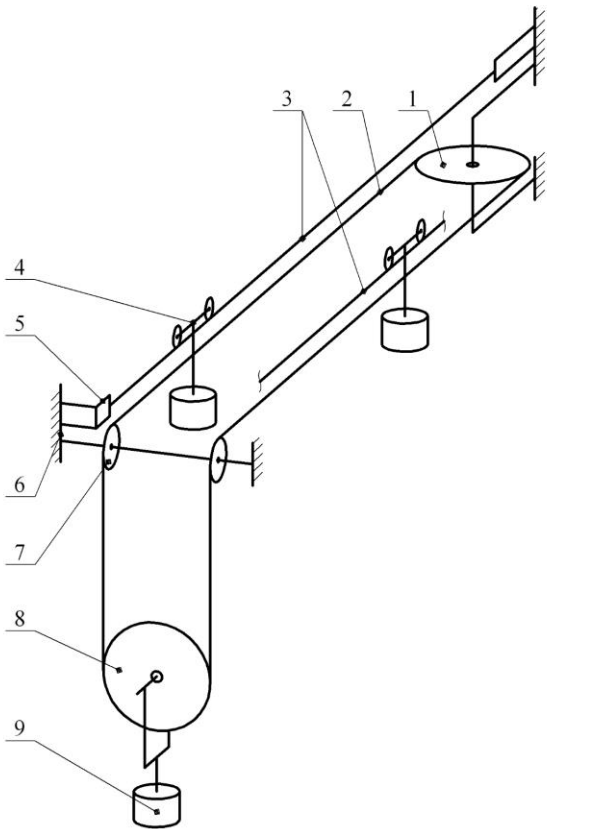


Fig. 3 Experimental equipment scheme: *1* – drive pulley; *2* – haulage rope; *3* – track rope; *4* – car; *5* – track rope anchor; *6* – supporting metal structure; *7* – deflecting pulley; *8* – tension pulley; *9* – tension load

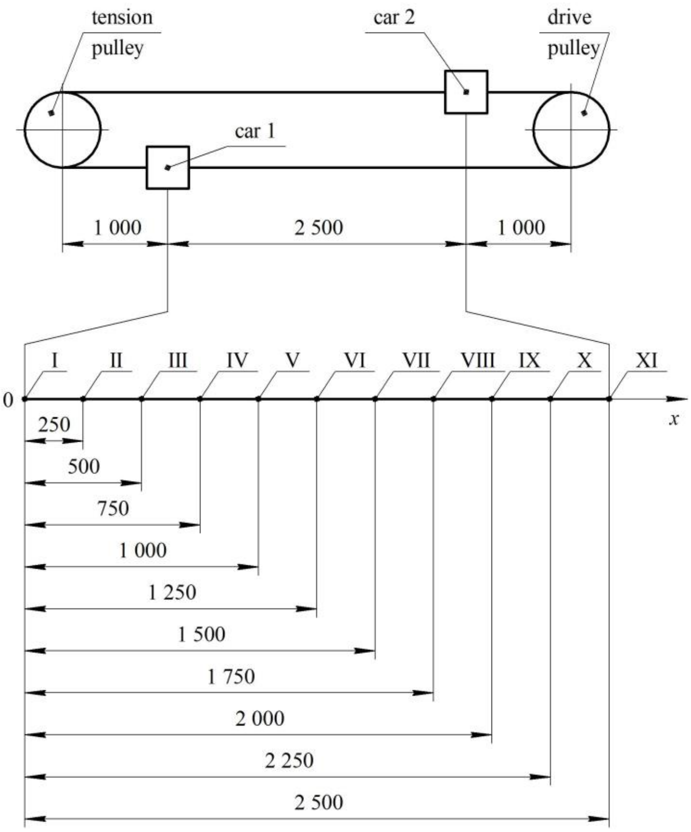


Fig. 4 Scheme of the car 1 location points during the registration of acceleration(dimensions are given in millimeters)

3. Research Methodology

Experimental studies of the ropeway frequency spectrum involve the drawing of frequency diagrams that show the change in ropeway eigenfrequencies during the movement of cars between stations. The measuring equipment used during the experiment allows to register the change in the ropeway elements acceleration as a function of time. As a result of the experiment, we obtain a number of oscillograms, by which we determine the frequency of acceleration change (the acceleration is a polyharmonic function). These values are equal to the ropeway eigenfrequencies, and therefore, by measuring in several discrete positions of the cars on the route, we built frequency diagrams.

For the experiment, we selected ten positions of the car, evenly distributed over a length of 2250 mm (Fig. 4). The eleventh position of the car is unstable under certain load conditions: if the difference in cars weight is significant (for this ropeway – more than 5 kg), there is free movement of cars in the direction of their oncoming movement under the action of its own weight. Therefore, the registration of acceleration at the point x = 2500 mm was not performed.

The experiment was performed for thirty-six combinations of car masses (m_1, m_2), which varied in the range from 3.5 kg to 16 kg with a step of 2.5 kg (m_1 = 3.5 kg, m_2 = 3.5 kg; m_1 = 3.5 kg, m_2 = 6 kg; m_1 = 3.5 kg, m_2 = 8.5 kg …

m_1 = 16 kg, m_2 = 3.5 kg; m_1 = 16 kg, m_2 = 6 kg … m_1 = 16 kg, m_2 = 16 kg).

Registration of change of car 1 movement acceleration was carried out in the following sequence:

1. place wagons with predetermined masses in the position specified by the x coordinate;
2. make a background recording of the change in acceleration until the moment of stabilization of the equipment (cessation of cars oscillations that occurred due to their forced movement);
3. give the drive pulley a single force pulse, which lead to its rotation so as to ensure a small movement of the car 1 in the direction of a positive change in the coordinate x; the free oscillations of car 1 were registered until they were completely attenuated and the oscillogram acquired the appearance of a background record.

This sequence of actions was repeated three times for each cars position and the combination of their masses. A total of 1080 oscillograms were recorded. The duration of recording one oscillogram (background – workflow – background) is up to 10 s. Next, the oscillograms were processed to remove “background noise” using the Advanced Grapher software. One of the processed oscillograms is shown in Fig. 5.

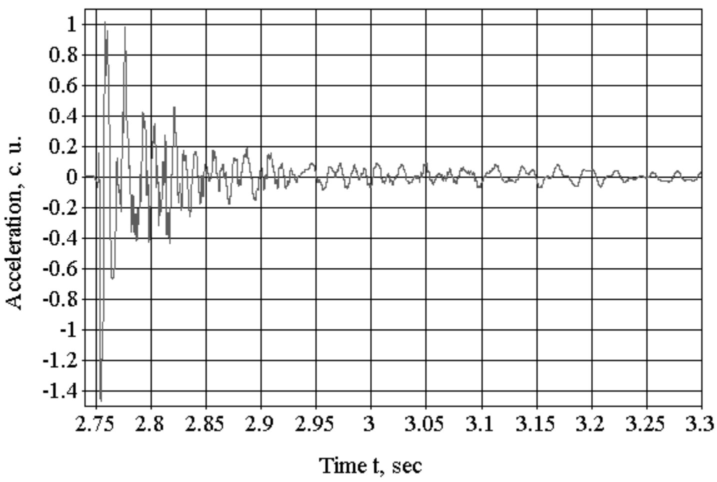


Fig. 5 Oscillogram after processing

The studied process is polyharmonic, so to establish the ropeway eigenfrequencies and compare them with the values determined analytically, we performed their preliminary calculation using the mathematical model presented in [6]. This approach made it possible to determine the approximate values of the ropeway eigenfrequencies, which must be found using oscillograms. The next step was to search on the oscillogram for the harmonics of the process under study, which are close in frequency to those determined analytically. To do this, we analyzed a fragment of the oscillogram from the moment of ropeway oscillations excitation due to the action of a single pulse. On this fragment we established the waves periods, expressed to a sufficient extent, by which we determined their frequencies:

$$\omega = \frac{2\pi}{T}, \tag{1}$$

where T – wave period.

We determined the corresponding eigenfrequencies analytically using the mathematical model presented in [6], and compare them with experimental values. The deviation is determined by the formula:

$$\Delta = \frac{|\omega_a - \omega_e|}{\omega_a} \cdot 100\%, \tag{2}$$

where ω_a and ω_e – eigenfrequency values obtained analytically and experimentally.

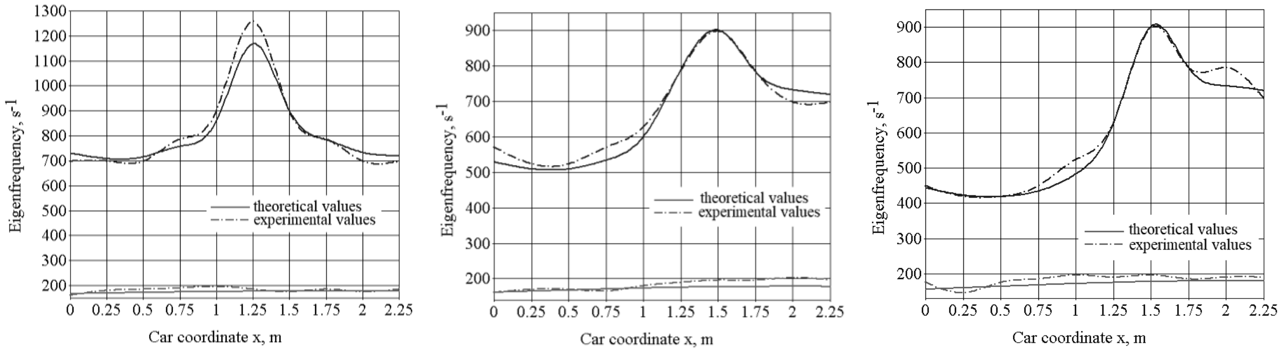
4. Analysis of Research Results

The total array of results includes information on the decoding of about a thousand oscillograms, which were obtained and studied according to the method described in the previous paragraph. To present the main results of the experiment and confirm the adequacy of the mathematical model described in [6], we consider the following combinations of initial data:

1. m_1 = 3.5 kg, m_2 = 3.5 kg;
2. m_1 = 6 kg, m_2 = 3.5 kg;
3. m_1 = 8.5 kg, m_2 = 3.5 kg.

m_1 and m_2 are cars masses, the values of which were changed by combining a certain number of loads. Other equipment parameters for all simulation cases are the same and correspond to those given in the general equipment characteristics (see above).

For each combination of masses, we performed measurements three times in each of the ten cars positions with a pitch of 250 mm (see Fig. 4). The results of the analysis of oscillograms are presented in the form of frequency diagrams (Fig. 6). On each of the graphs, two pairs of curves are shown: the first pair having a smaller amplitude characterizes the change of the first eigenfrequency, the second pair characterizes the change of the second eigenfrequency of the ropeway.



m_1 = 3.5 kg, m_2 = 3.5 kg m_1 = 6 kg, m_2 = 3.5 kg m_1 = 8.5 kg, m_2 = 3.5 kg

Fig. 6. Frequency diagrams

5. Conclusions

The difference between the results obtained analytically and experimentally is small and is characterized by deviations of experimental values of eigenfrequencies from theoretical within 14% at the points of possible influence of external dynamic processes (low frequency noise).

The results of experimental studies confirm the adequacy of the mathematical model [6] for calculating the ropeway frequency spectrum, which is based on the representation of the ropeway traction circuit as a discrete-continuous dynamic system.

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