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EXPERIMENTAL METHOD REVIEWING FOR DYNAMIC PARAMETERS DETERMINING OF VERTICAL TRANSPORT

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Abstract

The paper presents the issues with the dynamic parameters determining (stiffness, damping, elasticity modulus) of mine elevators used with underground exploitation of raw materials. Basic parameters, such as stiffness and damping, are of variable magnitude during the lifting and this paper presents the procedure for their values determining through performed experiments at the concrete mine elevator.

Dynamic occurrences are particularly emphasized with vertical transport machines due to the fact that they are facilities with extreme heights (up to 2000 m) and lifting speeds (up to 20 m/s) using the steel ropes. A specific case of non-linearity happens at the lifting machines with steel ropes and it refers to the fact that the stiffness changes together with the change in the ropes' free lengths.

The stiffness and damping parameters can be derived from the measuring diagrams by defining the oscillation period, i.e. the frequency and logarithm decrement of the damping. Apart from the variable stiffness and damping, attention should be paid to the elasticity modulus, which is much more difficult to define in comparison with the homogenous bodies since the steel rope is a complex structure, consisting of a large number of wires layered into strands, while the strands are stranded into a rope with the core made of steel or fibre. Adequate elasticity modulus values for the ropes in exploitation can be gained through direct measuring in the real working conditions of the elevator facilities.

Key words*: vertical transport machines, dynamic parameters, steel wire ropes*

1 INTRODUCTION

Some of hoisting devices are the mine elevators, which are used to interconnect different mine horizons by using a mine cage (which is moved between at least two firmly set guide rails), whose dimensions and construction enable ore loading and are approachable to people. The mines use two systems, one with a drum and the other with a driving pulley (Koepe system).

At systems, which have a drum for lifting, the driving ropes are winding and stored into the drum. The systems of hoisting by friction (Koepe) are most common in European mines.

Modeling of the wire rope is usually done through the so-called Calvin's model which represents a parallel connection between an ideally elastic body and an ideally viscous body. Stiffness and damping, as the parameters for the model, are mostly defined through the elasticity modulus and a damping coefficient for homogenous bodies (steel, aluminium, …). Due to the specific construction of the steel wire rope, the defining of these parameters is very complex, so in practice we use approximate data obtained from "extrapolation" of the experimental results which are obtained in certain conditions (mostly static), which can lead to greater inaccuracies with the dynamic analysis of mine elevators.

2 MECHANICAL CHARACTERISTICS OF THE STEEL WIRE ROPE

2.1 Stiffness and rope elasticity modulus

Stiffness is the basic parameter of oscillatory processes and it represents a feature of a material that defines the ratio between load and deformation. It is viewed as a constant matter in most oscillatory processes with small amplitudes and elements made of steel and similar materials. On the other hand, it is a case with some materials also used in mechanical engineering that the feature is not linear, which brings to the occurrence of the so-called non-linear oscillations whose analysis is more complex on numerous levels.

A specific case of non-linearity happens at the lifting machines with steel ropes and it refers to the fact that the stiffness changes together with the change in the ropes' free lengths in the following relation:

$$c(t) = \frac{E \cdot A}{L(t)} \tag{1}$$

with:

E - elasticity modulus, Mpa

A - rope cross-section a, mm^2

$L(t) = L - \int v(t)dt$ - free rope length, m

$v(t)$ - circumferential velocity on the pulley, m/s

Apart from the variable stiffness, attention should be paid to the elasticity modulus (E), which is much more difficult to define in comparison with the homogenous bodies since the steel rope is a complex structure, consisting of a large number of wires layered into strands, while the strands are stranded into a rope with the core made of steel or fibre.

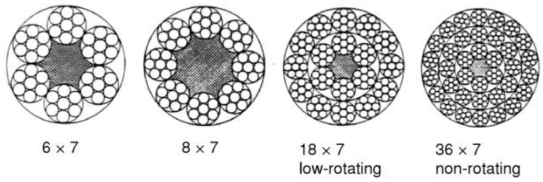

Fig. 1 *Different constructions of the wire rope*

There are different expressions mentioned in the literature [3, 8], for its calculation depending on the wire elasticity modulus and the angles at which the wires lay into a strand, and strands into a rope. These expressions only give approximate data because the real magnitudes of the elasticity modulus, apart from the above mentioned parameters, depend on the stress magnitude, core material, time spent in service (the number of load cycles), types of wire connections etc. Fig. 2 and Fig. 3 shows the experimental results [3], for the steel wire rope with a fibre core. We can show a noticeable difference in the results between the first loading of the rope (new rope), and after the tenth loadings and unloading (Fig. 2), and also the effect of the stress level with the loading (Fig. 3). The figure shows quickly the stress increasing in the wire rope because of its extension.

The change of the tensile stress in ropes with a steel core is shown in Fig. 4. The diagram also shows a sudden rise in stress when the wire ropes are lengthened. This increase is not so big with fiber core ropes, however, the remaining deformation is even bigger. More about this analysis and the results of the experiment is shown in [3].

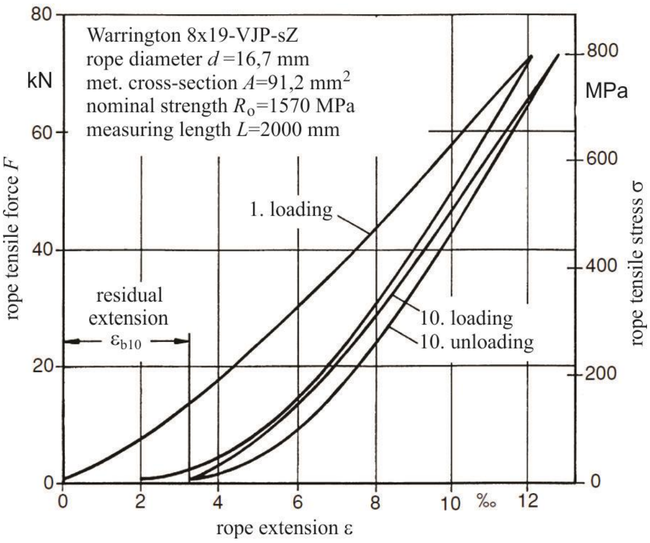

Fig. 2 *Stress-extension curves for new stranded wire ropes with fibre core, after 10 loadings, [3]*

The application of the results generated in this way is disputable when it comes to dynamic processes. Adequate elasticity modulus values for the ropes in exploitation can be gained through direct measuring in the real working conditions of the elevator facilities. By using the functional dependence between the stiffness (c), circular frequency (ω), and elasticity modulus (E), for the case of free oscillations with damping, there can be determined an elasticity modulus value by putting oscillations period (T), i.e. frequency (f),

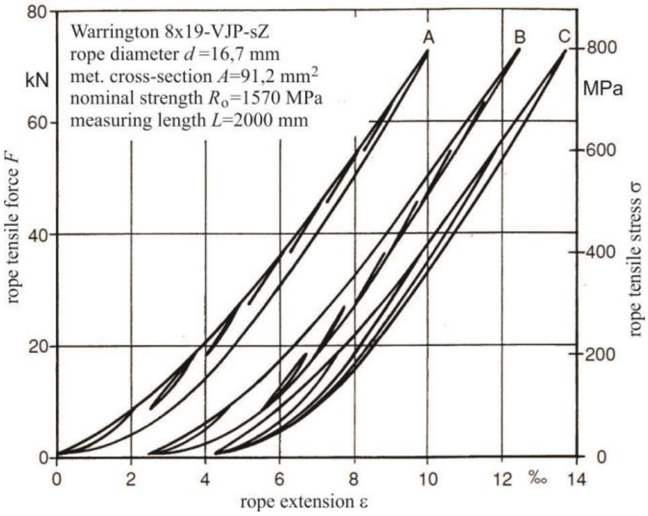

Fig. 3 *Stress-extension curves for new stranded wire ropes with fibre core, after 10 loadings for the difference stress levels, [3]*

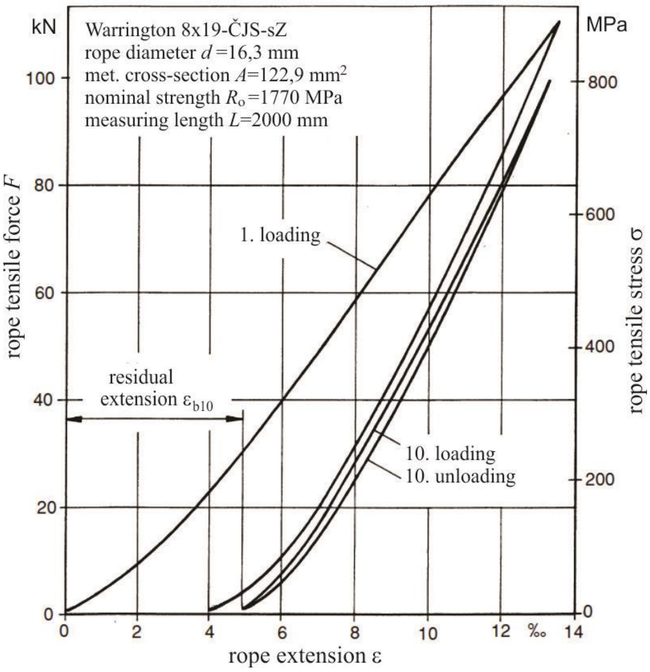

Fig. 4 *The rope tensile stress changes for wire ropes with a steel core, for a new wire rope and after 10 loadings, [3]*

from the diagrams which were experimentally obtained (Fig. 5):According to an oscillation period of the damping, circular frequency is $\tilde{\omega} = \frac{2\pi}{\tilde{T}}$, where from the basic differential equation of the motion, provides a stiffness coefficient:

$$c = M_e \cdot \omega^2 \tag{2}$$

and based on (1), there can be determined:

$$E = \frac{c \cdot L}{A} \tag{3}$$

with:

$\omega = \sqrt{\tilde{\omega}^2 + \delta^2}$ - circular frequency of free oscillations, rad/s

$\tilde{T}$ - oscillation period (measured value), Fig. 5, s

$M_e = M + q \cdot \frac{2}{3} L$ - reduced oscillatory mass, kg

M - overall mass on the wire ropes, kg

A - rope cross-section area, mm^2

During the movement, there occurs the increase or decrease in the degree of the free length of driving ropes (hoisting or lowering), which suggests that a variable length should be taken into account $L(t)$ in the expression for *Me*. Nevertheless, if the elevators have a higher hoisting velocities and mine elevators, using compensation chains and ropes practically make the reduced oscillatory mass the same in almost every moment (when considering 2/3L).

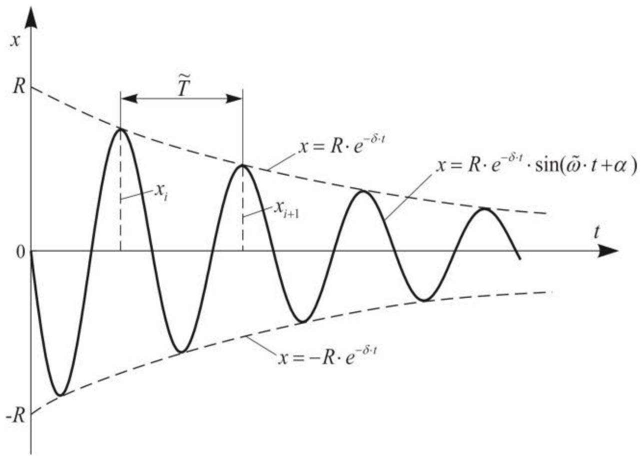

Fig. 5 *Amplitudes and the period of damped oscillations*

In the analysis of dynamic behaviour of the mine elevators, it can be concluded that the damping can be modelled as damping consisting of an inner damping of the hysteretic type and Coulomb damping occurring in the guide rails of the cage depending on eccentrical position of the load in the cage.

Similar to the elasticity modulus, the overall damping coefficient can be defined by measuring the oscillations of the mine elevators cage. Based on the theory of free harmonic oscillations with the damping, measuring oscillation amplitude, Fig. 5, a logarithm decrement can be defined, and from there on damping coefficients using the:

$$D = \ln \frac{x_i}{x_{i+1}} = \frac{1}{n} \ln \frac{x_i}{x_{i+n}} = \delta \cdot \tilde{T} \tag{4}$$

$$\delta = \frac{D}{\tilde{T}} \tag{5}$$

so the damping parameter is:

$$b = 2 \cdot \delta \cdot M_e \tag{6}$$

with:

x_i, x_{i+1} and x_{i+n} - measured amplitudes,

$\tilde{T}$ - measured oscillation period of free oscillations with the damping,

M_e - reduced oscillatory mass (mass of the cage, load and section of the ropes).

3 EXPERIMENTAL RESEARCH ON THE MINE ELEVATOR

The experiments were performed on the mine exploitation machine with the lifting capacity of 22 t (shown in Fig. 6). Its features are: mass of the empty cage – 13 t, mass of the counterweight (adjustable) 21 t, 6 ropes (27 mm diameter).

The lifting height is approximately 523 m. The driving mine shaft is of round cross section, and the diameter is 10 m. The maximum designed lifting velocity of the cage is 16 m/s. Transfer of the force to the carrying elements (the ropes) is realised through friction (Koepe system) from the pulley with grooves, Fig. 6. The mine elevator is powered by electric-motor ASEA, HSDE-2.5 with the rated/pull power (torque) of 1500/2860 kW (117,2/233,4 kNm) and the maximum rotor speed of 122,2 rpm.

Measuring system consisted of a measuring amplifier QUANTUM X MX480B, a computer with HBM catmanEasy-AP software, incremental encoder, optical indicator of the number of revolutions, triaxial acceleration sensor HBM B12, antenna for wireless measuring signal transfering (2 kom) NanoStation loco NS2L and strain gauges positioned on the connection spot of the cage and the ropes.

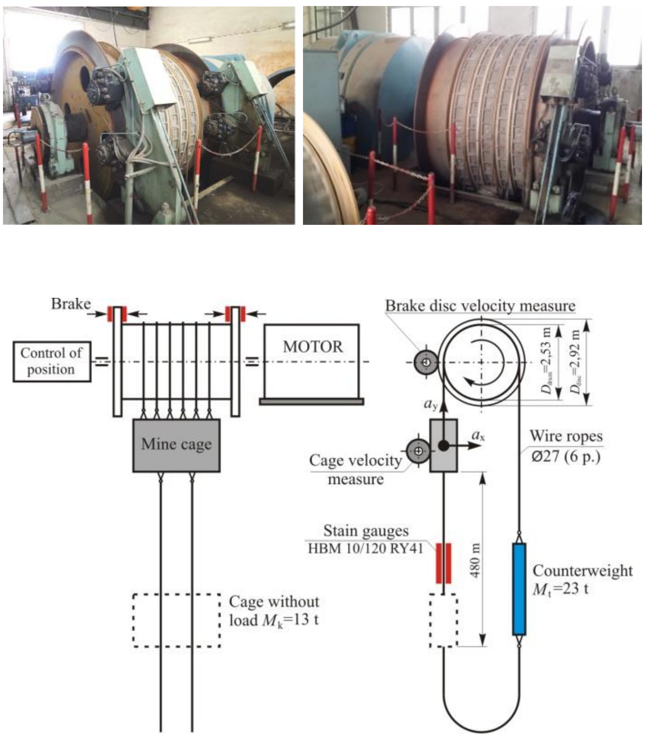

Fig. 6 *Driving mechanism and the scheme of the positions for the measuring places, [9]*

3.1 Measurement results

The determination of the parameters for a dynamic model will be shown for four movement cases (lifting and lowering of the cage), with and without a load:

I) Lowering of an empty cage from the level +406 m up to +266 m (the free end of the wire ropes on the cage sade in the start of movement is 59 m).

II) Lifting of an empty cage from the level -74 (above sea level) for 476 m.
III) Lifting of the "full cage" (with a locomotive, mass ~9350 kg) from the level -71 m up to +52 m (413 m).
IV) Lowering of the "full cage" (with a locomotive, mass ~9350 kg) from the level +52 m and return to the level -71 m (413 m).

Fig. 7 shows schemes of those four cases after the pulley has stopped.

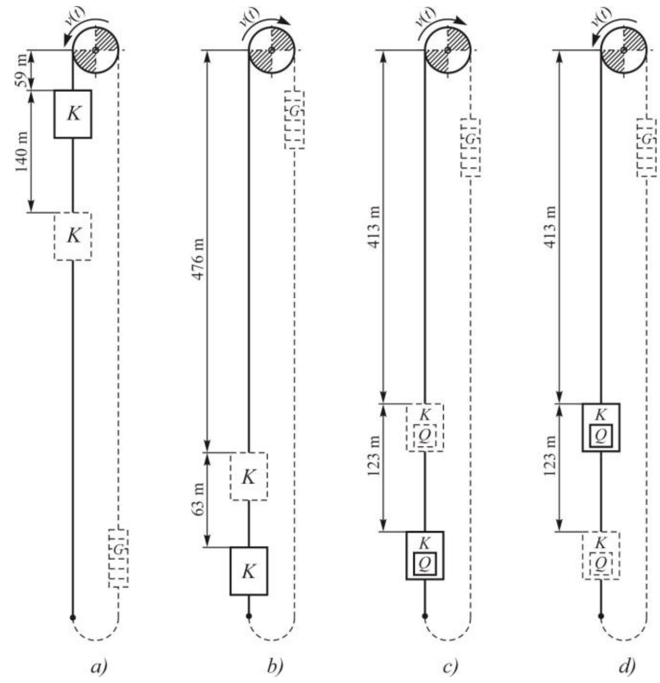

Fig. 7 *Parameters of the mine elevator suitable for the analysis*

This paper is only going to show one part of the measuring results about the definition of stiffness, damping and lifting velocity in accordance with the discussions in chapter 2.
Fig. 8 presents changes in the circumferential velocity of the drum, calculated on lifting velocity for the first movement case (I).

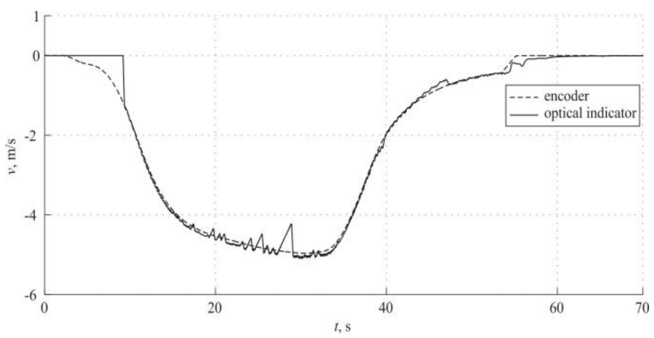

Fig. 8 *Diagram of change in the circumferential velocity of the drum (based on the measured by incremental encoder)*

Fig. 9 presents changes in the cage acceleration for the first movement case (I) with pronounced oscillation after stopping the cage, and it will be used for determining of wire ropes mechanical characteristics (free oscillations).

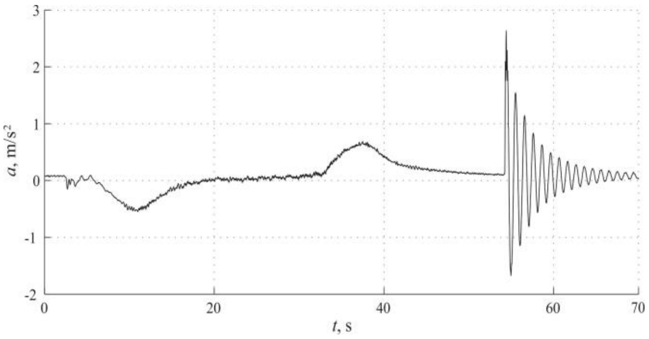

Fig. 9 *Change of the cage acceleration during the ampty cage lowering*

Forces in carrying ropes on the connection spot of the cage and the ropes (for the first movement case) are represented in Fig. 10.

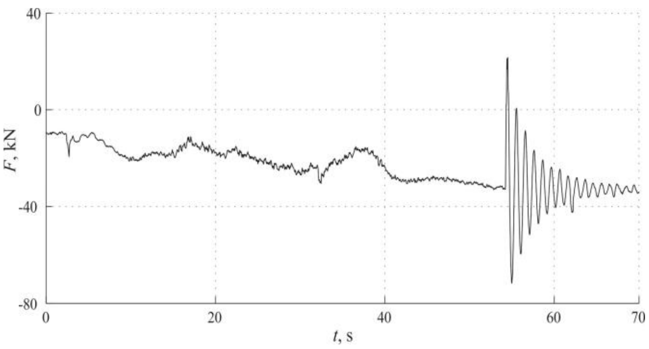

Fig. 10 *Change of the force in carrying ropes on the connection spot of the cage and the ropes*

3.2 Dynamic parameters determining according to measurement results

As it was stated in chapter 2, the stiffness and damping parameters can be derived from the measuring diagrams by defining the oscillation period, i.e. the frequency and logarithm decrement of the damping. As the Eq. (4, 6) are used in the case of free harmonic oscillations with damping, the relevant part of the diagram is the one which shows car oscillations after the pulley had been stopped. Fig. 11 shows the changes in acceleration of the cage in the above mentioned examples for periods when the cage is oscillating after the pulley had been stopped.

According to the analyses of the results shown in Tab. 1 and 2, it can be stated that the data used for the elasticity modulus is in accordance with the literature data [3]. That indicates the validity of the applied procedure which enables defining the real (drive) values with mine elevators. The values of the damping coefficient, for which there are no significant comparative data, are not of a constant magnitude. They rather differ in the analysed cases. It can be noted that the ratio (δ/ω) shows similar dependence to the elasticity modulus, depending on the stress, and it is less dependent on the frequencies which is a characteristic of hysteretic damping. Only if measurements of a larger scale were performed could the more reliable conclusions be drawn.

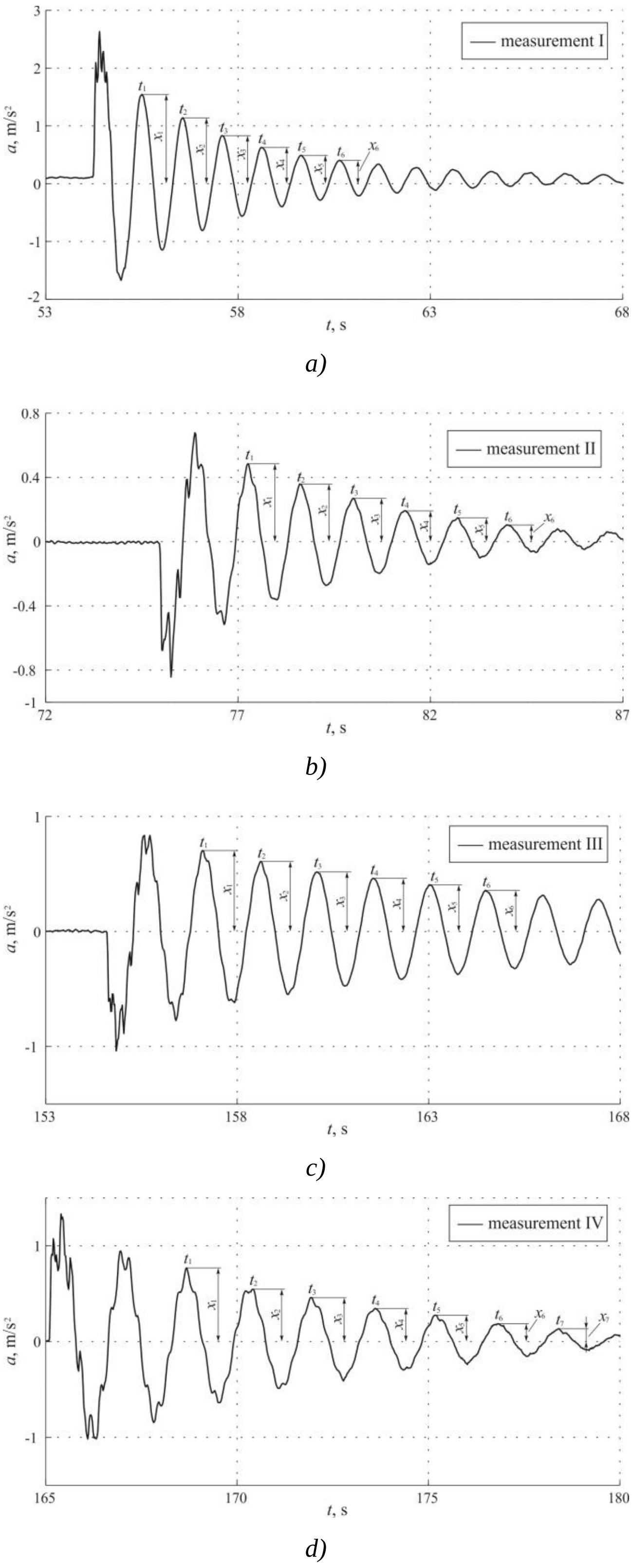

Fig. 11 *Recorded acceleration values for the cage in the stated examples*

Table 1 Values obtained through measurements

	T, s	ω, rad/s	x_i, m/s^2	x_{i+1}, m/s^2
I (Fig. 11a)	1,03	6,12	1,4439	1,0409
II (Fig. 11b)	1,36	4,63	0,4846	0,3564
III (Fig. 11c)	1,35	4,26	0,7035	0,6090
IV (Fig. 11d)	1,11	3,88	0,7688	0,5450

Table 2 Calculated values

	E, MPa	c, N/m	b, Ns/m	δ/ω
I (Fig. 11a)	100224	851906	13843	0,050
II (Fig. 11b)	123050	439466	9304	0,049
III (Fig. 11c)	134232	552528	5582	0,022
IV (Fig. 11d)	139793	443374	10652	0,047

4 CONCLUSION

Mine elevators are used in the mines with underground exploitation at the depths as deep as 2000 m with the carrying capacity of maximum 30 t and the lifting velocities up to 20 m/s. Therefore, their analysis is of special interest because they define the quality basis for optimal projecting and their maintenance in relatively heavy working conditions.

By analysing the parameters of a specific mine elevator it is possible to significantly simplify the basic model and to gain a model suitable for dynamic analysis. The system with an infinite number of DOF has come down to a system with one DOF and a forced movement which was modelled according to the velocity measured on the pulley. It is also possible to replace the rope system with the equivalent Kelvin's model with variable stiffness ($c=EA/L$) and damping.

By combining theoretical analysis with an experimental procedure it is possible to define the real values of elasticity modulus and damping, with the results of measuring the oscillation periods and amplitudes at the moment when the driving pulley is stopped. Modulus values which are defined in this way indicate an important dependence of the elasticity modulus on the load, i.e. stress. Damping coefficient is not a constant value, like with the model of viscous friction. It depends on the frequency, or the cage position, just like stiffness, and ratio (δ/ω) indicates that hysteretic damping is overwhelming and it should be examined in greater details. In order to obtain more reliable results and a more detailed analysis of stiffness and damping in such facilities, greater measuring should be conducted in both real and laboratory conditions.

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