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IDENTIFICATION MECHANICAL PARAMETERS OF STEEL ROPES FOR MINING SHAFT HOISTS UNDER DYNAMIC LOADS

Key words: mining shaft hoist, properties of steel ropes, simulation studies.

Abstract: The paper presents the results of the study of mechanical parameters of steel ropes for mining shaft hoists. Mechanical parameters understood as the modulus of elasticity of ropes and the damping coefficient are very important in the modelling of steel ropes and all numerical simulations of operating conditions of mining shaft hoists. One of the most important operating conditions of a mining shaft hoist is its braking. Knowledge of the values of the modulus of the elasticity of ropes and the damping coefficient allows one to determine the reliable braking parameters, such as the deceleration of the braking hoist conveyances, braking distance, tub oscillation after stopping, values of dynamic forces in hoist and balance ropes, etc.

Results of computer simulations of the operation of the mining shaft hoist are very important for programming the drive system of the hoist machine and of the systems that power and brake this machine.

Wyznaczanie parametrów mechanicznych lin stalowych górniczych wyciągów szybowych w warunkach obciążeń dynamicznych

Słowa kluczowe: górniczy wyciąg szybowy, własności lin stalowych, badania symulacyjne.

Streszczenie: W artykule przedstawiono wyniki badań nad parametrami mechanicznymi lin stalowych górniczych wyciągów szybowych. Parametry mechaniczne rozumiane jako moduł sprężystości lin oraz współczynnik tłumienia są bardzo ważne przy modelowaniu lin stalowych i wszelkich symulacjach numerycznych stanów pracy górniczych wyciągów szybowych. Jednym z najważniejszych stanów pracy górniczego wyciągu szybowego jest jego hamowanie. Znajomość rzeczywistych wartości modułu sprężystości lin oraz współczynnika tłumienia pozwala na wyznaczenie wiarygodnych parametrów hamowania takich jak opóźnienie hamowanych naczyń wyciągowych, drogi hamownia, drgania naczynia po zatrzymaniu, wartości sił dynamicznych w linach nośnych i wyrównawczych itp.

Wyniki symulacji komputerowych pracy górniczego wyciągu szybowego mają duże znaczenie dla zaprogramowania napędu maszyny wyciągowej oraz układu zasilająco-sterującego hamulcami tej maszyny.

Introduction

The steel rope model used in simulations of transport devices such as aerial tramways or mining shaft hoists often assumes that it is an inextensible string rod with its mass distributed uniformly along its length. This premise really simplifies all calculations. It is also a premise to the majority of operating conditions of a rope device commonly adopted during analysis. Obviously enough, the operating conditions in which mostly static loads occur are the point of interest here. Such a model, however, is unacceptable in the situations where variable dynamic load occurs in the rope [4, 7, 8, 9, 11]. Such processes are, e.g., the startup conditions of rope installations, and primarily their stopping (braking).

It is easily noticeable when travelling, e.g., in a chair lift. During normal movement (with constant speed), the seat moves very gently. When the process of braking starts, the chairs start moving abruptly in transverse directions to the axis of the rope. Especially vertical movement ("pumping") is dangerous and causes major discomfort for passengers. A similar situation is in the mining shaft hoist with the difference that the rope here hangs vertically and oscillations of the conveyance with people are far more unpleasant.

These transient states, which feature major changes in forces in the steel rope, show that the rope is not an inextensible string and knowledge of its mechanical properties (parameters) is necessary for the full assessment of its behaviour in such states. Those mechanical parameters are called rheological parameters of the rope.

These parameters understood as the modulus of elasticity of ropes and damping coefficients are very important in modelling steel ropes and all digital simulations of operating conditions of mining shaft hoists. One of the most important operating conditions of a mining shaft hoist is its braking. Knowledge of the current values of the modulus of elasticity of ropes and damping coefficient allows one to determine the reliable braking parameters, such as the deceleration of the braking hoist conveyances, braking distance, conveyance oscillation after stopping, values of dynamic forces in hoist and balance ropes, etc.

Results of computer simulation of the operation of the mine shaft hoist are very important for programming the drive and control system of the hoist machine. It is a process necessary to ensure safety of operation of the rope installation (first of all to avoid slip of the rope on the friction pulley) and the safety and comfort of passengers of the conveyance.

1. Modulus of elasticity of steel ropes

Elongation of a new steel rope consists of elastic elongation and permanent set. Permanent set of the rope depends on the value of the load force and the duration of its effect. This elongation is the result of placing and clamping of the wires in the strands and of the strands on the core of the rope. The value of this elongation depends on the structure and technology of rope making manufacturing and on the type of the core. During operation of the rope, permanent set will increase by rheological elongation. Thus, the modulus of elasticity is not a fixed value. Especially for new ropes, it assumes values from quite a large range. An additional difficulty results from the fact that modulus of elasticity of steel ropes is defined in a variety of ways. There are at least four different definitions of the modulus of elasticity of ropes in the literature [3, 5, 10]. All these definitions refer to the chart of static stretching of the rope. Therefore, the determination of static modulus of elasticity of ropes may be relatively easily done in the laboratory, with a testing machine with a range of loads that is large enough.

However, in the majority of devices, steel ropes are subject to dynamic loads. With such loads, the value of the modulus of elasticity differs from the value of the modulus of elasticity determined under static conditions.

Formula (1) is used to calculate the modulus of elasticity of ropes under dynamic loads [5]:

$$E = \frac{(2\pi)^2 \left(m + \frac{q_{ln} \cdot L}{3} \right) \cdot L}{T^2 \cdot A_{ln}} \tag{1}$$

where

m – total mass suspended at the end of the rope in kg, q_{ln} – unit mass of hoist ropes in kg/m, A_{ln} – metallic cross section of hoist ropes in m^2, L – length of the rope from the rope wheel to the conveyance suspension at the time of stopping the machine in m, T – period of the basic tone of free oscillations damped in s.

Period of the basic tone of free oscillations damped was determined from dependence (2):

$$T = \frac{t}{n_t} \tag{2}$$

where

n_t – number of oscillations during time t in s.

Tests of the dynamic modulus of the elasticity of a rope in a mine shaft hoist consists in excitation of free oscillations of the rope and of the hoist conveyance by way of an action of the brake on the rope friction pulley (safety braking: M_{ham}). Fig. 1 presents the diagram of the hoist installation during the tests.

The calculations of the modulus of longitudinal elasticity of hoist ropes and of the damping coefficient of the ropes were done based on the results of the studies conducted in the shaft with the installed hoist device with the parameters presented in Table 1.

Measurements of the decelerations of the cage consisted of the execution of a series of travels in succession with an empty cage and with the cage with the ballast of the mass of 4,500 kg and the activation of the safety brake at various depths of the shaft.

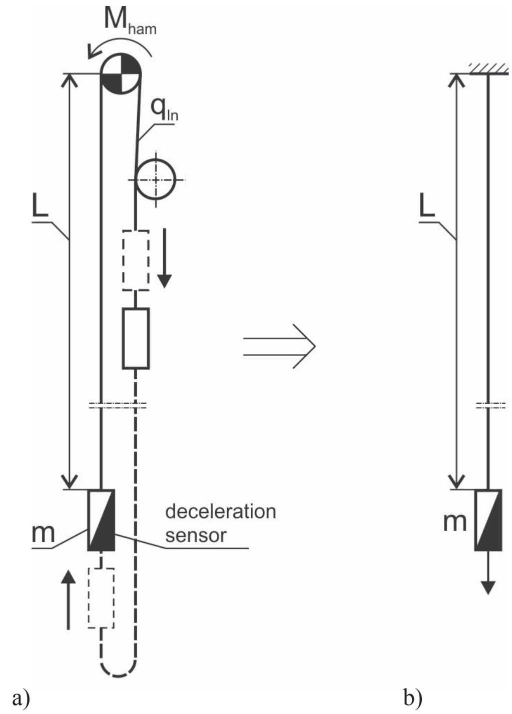

Fig. 1. The diagram of the hoist installation: a) the actual system, b) the substitute system

The charts of the course of vertical decelerations were prepared for all conveyance braking tests for the travels both upwards and downwards. The safety brake was triggered at the travel speed of about 3 m/s. Figs. 2 and 3 present sample deceleration runs registered during the measurements.

Table 1. Parameters of the hoist installation used in the study

Parameter of the shaft hoist	Symbol	Value	Unit
Empty hoist cage mass	m_{kl}	9,892	kg
Mass of the ballast in the cage	m	4,500	kg
Travelling speed of the conveyance	v	6.0	m/s
Unit mass of hoist ropes	q_{ln}	12.08	kg/m
Metallic cross section of hoist ropes	A_{ln}	0.001338	m^2

Table 2 summarises the results of the calculations of the modulus of elasticity according to the formula described in accordance with the formula (1). Figs. 4 and 5 present the results of these calculations in the form of charts.

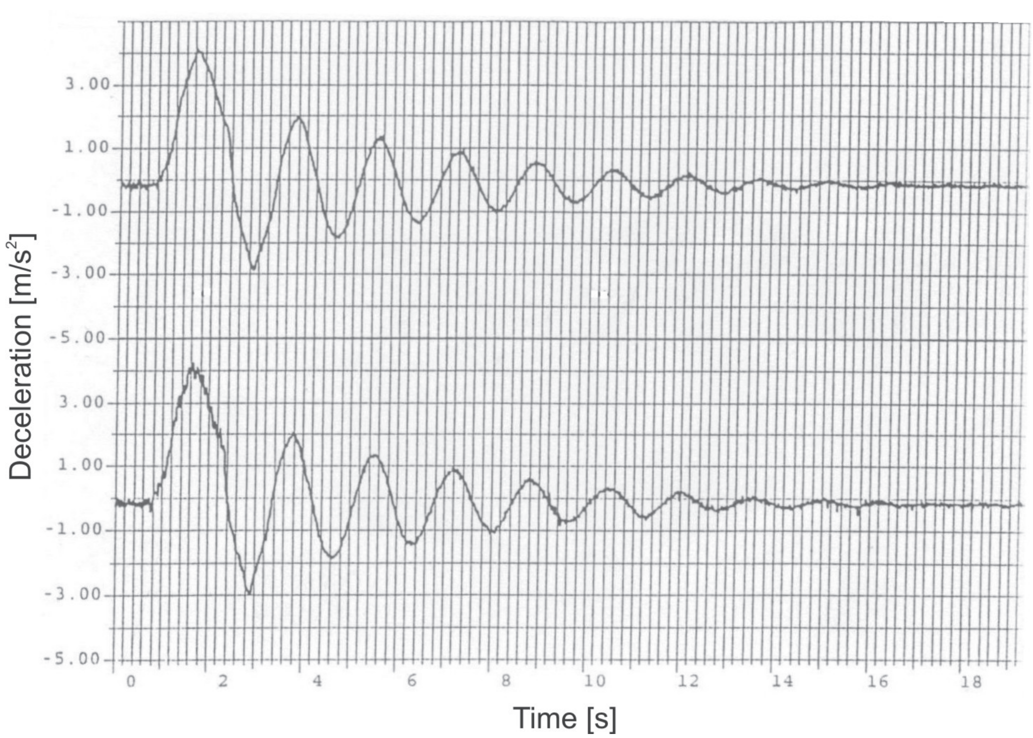

Fig. 2. The runs of vertical decelerations of the cage (the top chart) and of the balance rope (the bottom chart) for safety braking. The downward travel, the breaking depth calculated from the edge downwards: 560 m, the empty cage

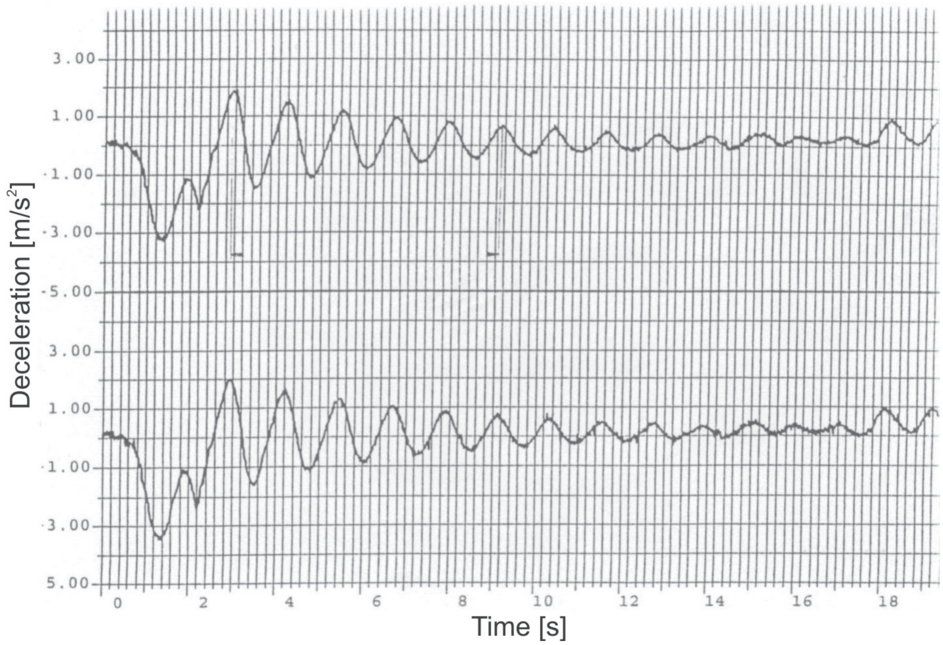

Fig. 3. **The runs of vertical decelerations of the cage (the top chart) and of the balance rope (the bottom chart) for safety braking. The upward travel, the breaking depth calculated from the edge downwards: 150 m, the cage with the ballast 4,500 kg**

Table 2. **A summary of data and results of the calculations of the modulus of elasticity**

Item	Safety brake triggering depth m	Mass suspended on the ropes kg	Rope length m	Period of oscillations s	Calculated modulus of longitudinal elasticity of ropes MPa x 10^5
cage empty					
1.	50	17,137	135	1.06	0.6268
2.	50	17,137	135	1.18	0.5058
3.	150	15,877	235	1.20	0.8101
4.	150	15,877	235	1.20	0.8101
5.	315	13,798	400	1.60	0.7104
6.	315	13,798	400	1.56	0.7473
7.	315	13,798	400	1.40	0.9278
8.	315	13,798	400	1.36	0.9832
9.	490	11,593	575	1.50	1.0490
10.	490	11,593	575	1.50	1.0490
11.	560	10,711	645	1.72	0.8561
12.	560	10,711	645	1.56	1.0410
cage with ballast of 4,500 kg mass					
13.	50	21,637	135	1.14	0.6798
14.	50	21,637	135	1.12	0.7043
15.	150	20,377	235	1.30	0.8749
16.	150	20,377	235	1.24	0.9616
17.	315	18,298	400	1.52	1.0170
18.	315	18,298	400	1.58	0.9412
19.	315	18,298	400	1.52	1.0170
20.	315	18,298	400	1.58	0.9412
21.	490	16,093	575	1.68	1.1070
22.	490	16,093	575	1.82	0.9429
23.	560	15,211	645	1.96	0.8822
24.	560	15,211	645	1.96	0.8822

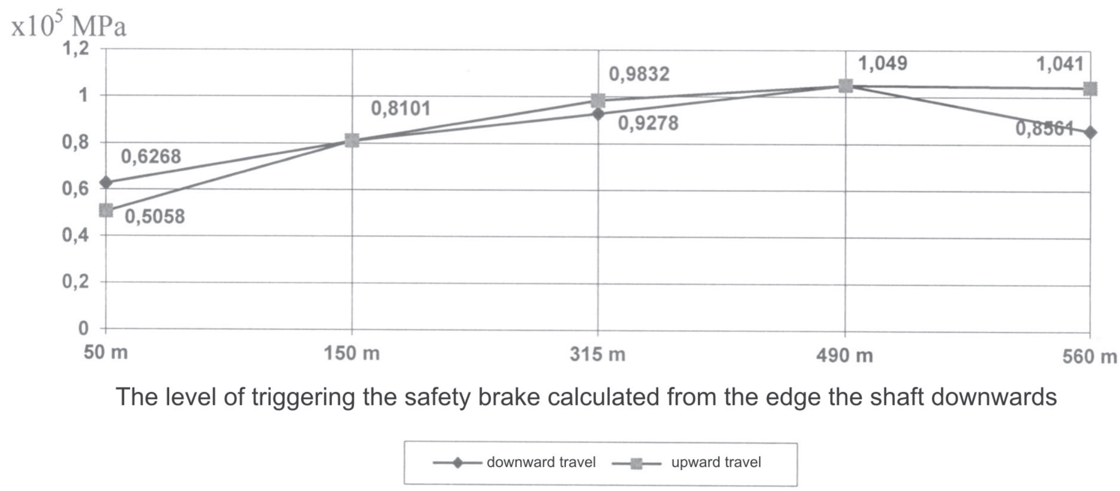

Fig. 4. The values of the modulus of elasticity calculated according to the method (1) for the empty cage

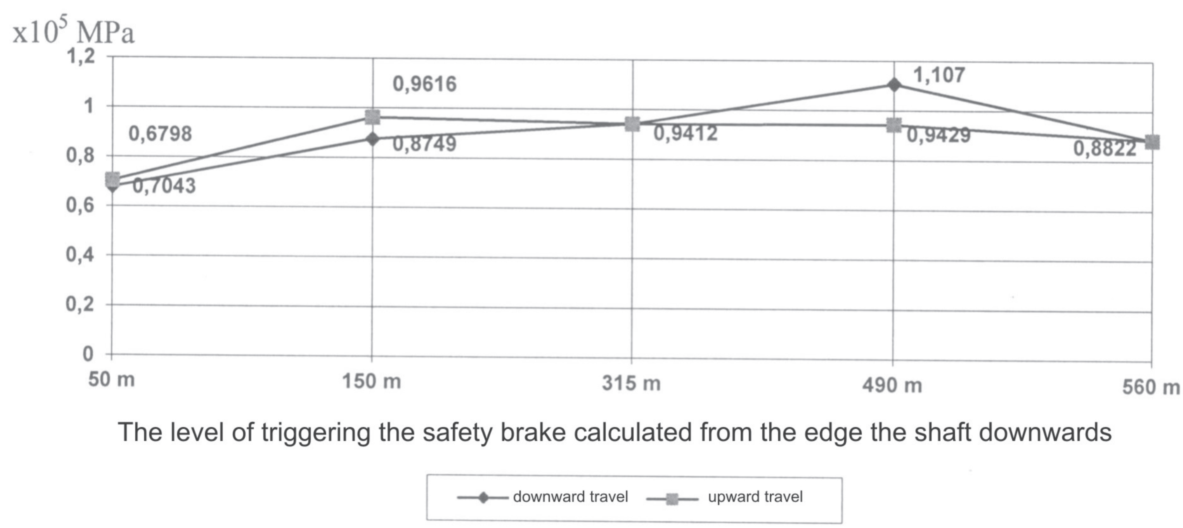

Fig. 5. The values of the modulus of elasticity calculated for the cage with the 4,500 kg ballast

The resulting charts show that the modulus of elasticity E ranges from 0.5 x 10^5 MPa to 1.1 x 10^5 MPa for the conducted measurements.

2. Determination of hoist rope damping coefficient

The tests of the modulus of elasticity for dynamic loads also allow us to assess the dampening of free longitudinal oscillations of the hoist rope. The charts presented in Figs. 2 and 3 show that free longitudinal oscillations of the rope and of the hoist conveyance are dampened and decay after some time. Assuming that external resistance related to the guide system and the resistance related to movement of air in the shaft are small and may be omitted, the cause of the decay of oscillations is internal friction (viscous) of the rope.

Damping coefficient (viscous friction) of load-bearing ropes was calculated according to the formula (3):

$$\alpha = \frac{T \cdot \log(k_t)}{8.573 \cdot n_t} \tag{3}$$

where

$T = t/n_t$ – period of the basic oscillations in s,

n_t – number of oscillations during the time t, equals 5,

k_t – multiplication of the reduction of the amplitude of oscillations during the time of n_t periods.

The method was described in a broader way in the works [1, 5, 6].

Table 3 summarises the data and the results of the calculations of the damping coefficient α.

Figure 6 presents the results of these calculations in the form of charts. The average value of the dampening coefficient was assigned to the relevant depths of triggering the safety brake.

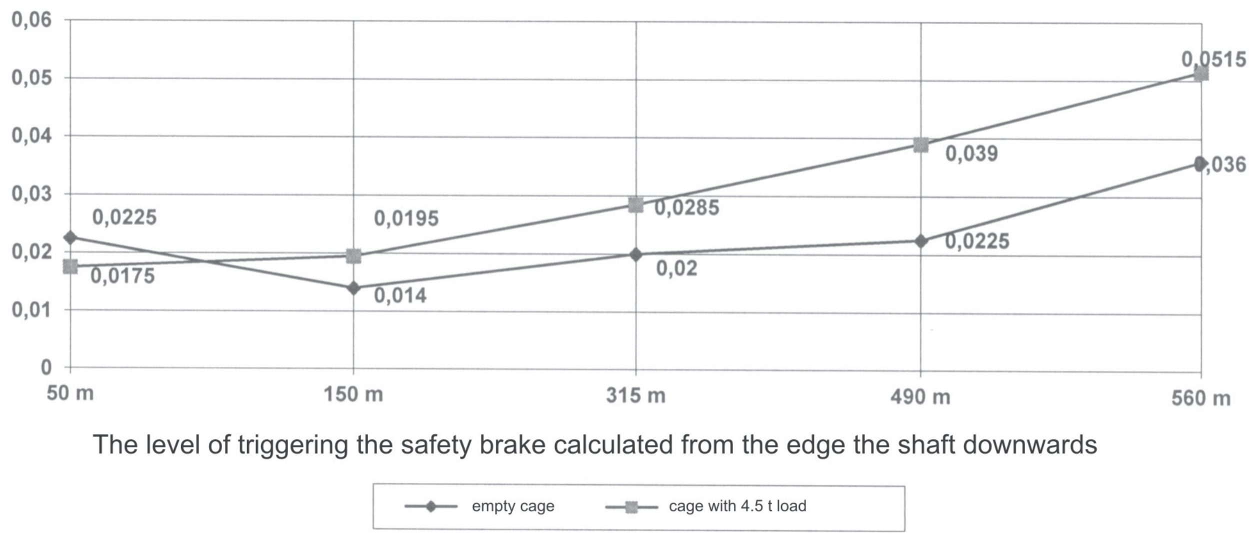

Fig. 6. The values of the damping coefficient calculated for the hoist ropes in the "Bartosz II" shaft

Table 3. A summary of the data and the results of the calculations of the damping coefficient

Item	Safety brake triggering depth m	Multiplication of amplitude reduction Times	Time of measuring 5 periods s	Period of oscillations s	Calculated damping coefficient of the ropes s
empty cage					
1.	50	6.000	5.3	1.06	0.019
2.	50	9.000	5.9	1.18	0.026
3.	150	2.889	6.0	1.20	0.013
4.	150	3.429	6.0	1.20	0.015
5.	315	3.333	8.0	1.60	0.020
6.	315	3.750	7.8	1.56	0.021
7.	315	3.500	7.0	1.40	0.018
8.	315	4.667	6.8	1.36	0.021
9.	490	5.000	7.5	1.50	0.024
10.	490	4.000	7.5	1.50	0.021
11.	560	10.250	8.6	1.72	0.041
12.	560	7.330	7.8	1.56	0.031
cage with 4,500 kg mass cart					
13.	50	2.222	6.9	1.06	0.011
14.	50	8.000	5.6	1.18	0.024
15.	150	6.600	6.5	1.20	0.025
16.	150	3.167	6.2	1.20	0.014
17.	315	3.714	7.6	1.60	0.020
18.	315	11.667	7.9	1.56	0.039
19.	315	3.571	7.6	1.40	0.020
20.	315	8.750	7.9	1.36	0.035
21.	490	12.000	7.6	1.50	0.038
22.	490	8.750	9.1	1.50	0.040
23.	560	19.00	9.8	1.72	0.058
24.	560	9.50	9.8	1.56	0.045

Conclusions

On the basis of the conducted experimental tests, the range of the values of the modulus of elasticity was determined for the steel rope of a mining shaft hoist. These values vary from 0.5×10^5 MPa to 1.1×10^5 MPa.

For calculations of dynamic processes (e.g., safety braking of the conveyances, emergency braking), the assumption should be made (due to the significant load of the hoist ropes) for the value of the modulus of elasticity of the ropes with the upper limit of the obtained value, i.e. 1.1×10^5 MPa.

For the balance ropes (less loaded), the value was assumed 0.8×10^5 MPa.

The determined values of the damping coefficient are increasing clearly with the increase of the length of the rope above the cage being braked. For the tested ropes, these values were in the range from 0.014 to 0.036 for the empty cage and from 0.020 to 0.051 for the cage with the ballast. For the cage with the load, the calculated values of the damping coefficient of the hoist ropes are higher by at least 40%.

For modelling dynamic runs with quite long durations (for example the safety braking process), taking the damping coefficient into consideration is necessary; however, for short-term processes, such as the emergency braking process (where the duration of the process does not exceed the period of oscillations), the effect of the internal dampening of the ropes seems to be negligible and is regarded as a factor of secondary importance.

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