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LOADS ACTING ON THE MINE CONVEYANCE ATTACHMENTS AND TAIL ROPES DURING THE EMERGENCY BRAKING IN THE EVENT OF AN OVERTRAVEL

OBCIĄŻENIE ZAWIESZEŃ NACZYŃ WYDOBYWCZYCH I LIN WYRÓWNAWCZYCH W WARUNKACH HAMOWANIA KRAŃCOWEGO GÓRNICZEGO URZĄDZENIA WYCIĄGOWEGO

It has now become the common practice among the design engineers that in dimensioning of structural components of conveyances, particularly the load bearing elements, they mostly use methods that do not enable the predictions of their service life, instead they rely on determining the safety factor related to the static loads exclusively.

In order to solve the problem, i.e. to derive and verify the key relationships needed to determine the fatigue endurance of structural elements of conveyances expressed in the function of time and taking into account the type of hoisting gear, it is required that the values of all loads acting upon the conveyance should be determined, including those experienced under the emergency conditions, for instance during the braking phase in the event of overtravel.

This study relies on the results of dynamic analysis of a hoisting installation during the braking phase when the conveyance approaches the topmost or lowermost levels.

For the assumed model of the system, the equations of motion are derived for the hoisting and tail rope elements and for the elastic strings. The section of the hoisting rope between the full conveyance approaching the top station and the Keope pulley is substituted by a spring with the constant elasticity coefficient, equal to that of the rope section at the instant the conveyance begins the underwind travel.

Recalling the solution to the wave equation, analytical formulas are provided expressing the displacements of any cross-profiles of hoisting and tail ropes, including the conveyance attachments and tail ropes, in the function of braking forces applied to conveyances in the overtravel path and operational parameters of the hoisting gear. Besides, approximate formulas are provided yielding:

- loading of the hoisting rope segment between the conveyance braking in the headgear tower and the Keope pulley
- deceleration of the conveyance during the braking phase.

The results will be utilised to derive the function governing the conveyance load variations during the emergency braking, depending on the parameters of the hoisting installations and the braking systems. These relationships are required for adequate design of the frictional contact between the ropes and the pulley and will become the basic criteria for dimensioning and design of load-bearing components of conveyances in the context of improving their reliability and safety features.

Keywords: mine hoist, dynamics, emergency braking

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Stosowane obecnie w praktyce projektowej naczyń wydobywczych, metody wymiarowania ich elementów konstrukcyjnych – głównie nośnych nie pozwalają na prognozowanie bezpiecznego okresu ich eksploatacji, a jedynie na określenie współczynnika bezpieczeństwa odniesionego do obciążeń statycznych.

Rozwiązanie problemu polegającego na opracowaniu zweryfikowanych zależności, niezbędnych do określenie trwałości zmęczeniowej elementów konstrukcyjnych naczynia wydobywczego jako funkcji czasu ich eksploatacji oraz rodzaju urządzenia wyciągowego, wymaga określenie wartości wszystkich obciążeń działających na konstrukcję naczynia, w tym w stanach awaryjnych jakim jest hamowanie krańcowe.

Rozważania zawarte w tym opracowaniu koncentrują się na wynikach analizy dynamicznej pracy górniczego urządzenia wyciągowego w warunkach hamowania krańcowego.

Dla przyjętego modelu układu zapisano równania ruchu elementów lin (nośnych i wyrównawczych) jak dla cięgna sprężystego. Odcinek lin nośnych między naczyniem (pełnym) dojeżdżającym do górnego poziomu załadowczego a kołem pędnym zastąpiono sprężyną o stałym współczynniku sprężystości równym sprężystości tego odcinka lin w momencie wjazdu naczynia w strefę „wolnych dróg przejazdu".

Wykorzystując rozwiązanie równania falowego podano wzory analityczne określające przemieszczenia dowolnych przekrojów poprzecznych lin nośnych i wyrównawczych w tym zawieszeń naczyń i lin wyrównawczych, jako funkcji sił hamowania przyłożonych do naczyń w strefie wolnych dróg przejazdu oraz parametrów ruchowych wyciągu. Ponadto podano w postaci zamkniętej uroszczone wzory z pomocą których wyznaczyć można między innymi:

- obciążenie odcinka lin nośnych między naczyniem hamowanym w wieży a kołem pędnym,
- opóźnienie hamowania naczyń.

Uzyskane rezultaty pozwolą opisać funkcję obrazującą zmianę obciążenie naczynia wydobywczego podczas hamowania krańcowego (awaryjnego) w zależności od parametrów wyciągu jak i urządzeń hamujących. Zależności te są niezbędne do właściwego zaprojektowania między innymi sprzężenia ciernego lin z kołem pędnym a ponadto stanowią jeden z podstawowych czynników koniecznych do opracowania kryteriów wymiarowania i projektowania elementów nośnych naczynia wydobywczego w aspekcie podwyższenia bezpieczeństwa i niezawodności ich pracy.

Słowa kluczowe: górnicze urządzenie wyciągowe, dynamika, hamowanie awaryjne

1. Introduction

Emergency braking of conveyances during an overtravel still remains a major problem for operators of mine hoists installations (Wolny, 2001, 2003; Kay, 2010; Stepanov, 2013).

In the article (Stepanov, 2013) discusses the methods of damping during emergency braking shaft hoisting systems. Mathematical modelling of dynamic processes has shown that the proposed system provides vibration damping during emergency braking. The developed systems will eliminate the harmful effects of vibration on the human body, reduce the dynamic forces in a mechanical system, will prevent potential slip ropes on multirope hoisting and increase the reliability and safety of operation of the shaft hoisting installation.

Theoretical considerations presented in the works (Wolny, 2003, 2011) focus on determining the displacements and deformations of cross-profiles of hoisting ropes and tail ropes from the instant the emergency braking phase begins, i.e the instant the braking force is applied to the conveyance. Issues addressed in this study are similar, in consideration of the fact that the solutions provided in previous works are of little use in engineering practice because they are mostly in the form of complex mathematical formulas.

This study provides a thorough theoretical analysis of the emergency braking process, using simplifications as to the system structure and parameters of the model, in order to determine the extreme loads acting upon the conveyance attachments and tail ropes.

Besides, the mathematical formulas used to determine the conveyance and tail rope loads during the emergency braking phase are rewritten in the form more convenient for engineering practice.

2. Mechanical model of the hoisting installation used in the dynamic analysis of the braking of the conveyance during an overtravel

Regular operation of the hoisting installation is disturbed by abnormal hoisting cycles in the event of an overtravel. Those responsible for engineering design of the mechanical parts of the hoist need to know the conditions when the conveyance hits the fender beams following an overtravel over the distance where arresting devices are provided.

The process involves the following phases:

- braking of the conveyance in the overtravel path zone
- hitting the fender beams

Theoretical considerations of the emergency braking processes supported by model tests cannot be fully verified by experiments on a real object because such experiment would pose a risk of a major failure. Of particular importance, therefore, is the selection of an adequate model of the hoisting gear, best approximating the real life conditions. The model of the hoisting gear used by the Author is that provided in the works by (Knop, 1975; Wolny, 2011), with certain modifications to adapt it to the specificity of the analysed process.

As explained in previous sections, during the emergency braking the conveyance is subjected to the action of forces $P_{1h(t)}$ and $P_{2h(t)}$ from the braking systems provided over the overtravel path, as shown in model diagram (Fig. 1) (Wolny, 2013).

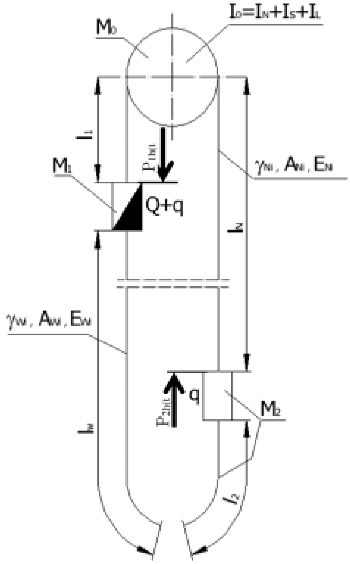

Fig. 1. Model of the hoisting gear during the emergency braking

The overtravel distance after which the conveyance ought to be “captured’ must not be longer than slightly over ten meters and the instant the process begins, the length of hosting ropes between the conveyance being arrested in the head tower and the Koepe pulley falls in the range l_1 = 30-50 m.

That means that the hoisting rope section between the conveyance being arrested in the tower and the Koepe pulley can be treated as an elastic element whose elasticity coefficient is governed by the formula (Wolny, 2003):

$$C_0 = \frac{A_N \sum_{i=1}^{n} E_{Ni}}{l_1 - V_0 t - v(y = 0, t)} \tag{1}$$

where:

l_1 — length of the hoisting rope section between the conveyance arrested in the tower and the Koepe pulley at the instant where emergency braking begins (Fig. 1),

V_0 — velocity at which the conveyance began the overtravel,

A_N — total cross-section of hoisting ropes,

E_{Ni} — elasticity modulus (Young modulus) of the hoisting rope,

$v(y = 0, t)$ — displacement of the hoisting ropes’ cross-section at the point they pass onto the pulley.

The model shown in Fig. 1 is based on the simplifying assumptions:

- both conveyances are treated as rigid (Knop, 1975; Wolny, 2011),
- internal damping in ropes is neglected as the process is very short,
- vibrations are not transmitted through the tail rope loop to the other side, which enables us to separate the closed systems of modelled masses at this point (Fig. 1).

After simplifications, the system shown in Fig. 1 becomes a 1D inertial system (Fig. 2) having a finite number of rigid and elastic lump masses continuously distributed along a straight line.

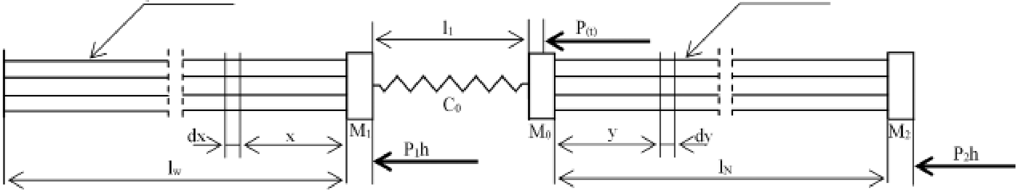

Fig. 2. Simplified model of the hoisting installation: P_{1h} – braking force in the head tower, P_{2h} – braking force in the pit bottom, M_1 – mass of the conveyance and payload, M_0 – reduced revolving masses in the head tower, M_2 – reduced mass of the hoisting gear in the pit bottom, $P_{(t)}$ – force from the emergency brake, l_1 – length of the hoisting rope section between the conveyance arrested in the tower and the Koepe pulley

Thus constructed model will be adequate as long as the total longitudinal force acting in any cross-section is more than zero.

3. Emergency braking of a mine conveyance

In order to find the displacements and deformations of hoisting ropes and tail ropes' cross-sections from the instant the emergency braking begins, i.e. after the forces P_{1h} and P_{2h} are applied, it is required that relevant equations should be solved (Gutowski & Świetlicki, 1986; Wolny, 2011) :

$$\begin{aligned} &\frac{\partial^2 u(x,t)}{\partial t^2} - a_w^2 \frac{\partial^2 u(x,t)}{\partial x^2} = 0, \\ &\frac{\partial^2 v(y,t)}{\partial t^2} - a_N^2 \frac{\partial^2 v(y,t)}{\partial y^2} = 0 \end{aligned} \tag{2}$$

for the boundary conditions:

$$\frac{\partial u(x,t)}{\partial t^2} = 0 : \quad x = l_w \tag{3a}$$

$$\begin{aligned} M_1 \frac{\partial^2 u(x,t)}{\partial t^2} = {} & A_w \sum_{i=1}^{n} E_{Wi} \frac{\partial u(x,t)}{\partial x} - k\left[u(x,t) - V_0 t\right] + \\ & + k\left[u(x,t-t_0) - V_0(t-t_0)\right]\sigma_0(t-t_0) + \\ & - \frac{A_N \sum_{i=1}^{n} E_{Ni}}{l_1 - V_o t - v(y=0,t)} \left[u(x,t) + v(y,t)\right] : \quad x = 0 \end{aligned} \tag{3b}$$

$$\begin{aligned} M_0 \frac{\partial^2 v(y,t)}{\partial t^2} = {} & A_N \sum_{i=1}^{n} E_{Ni} \frac{\partial v(y,t)}{\partial y} \\ & - \frac{A_N \sum_{i=1}^{n} E_{Ni}}{l_1 - V_0 t - v(y=0,t)} \left[u(x,t) + v(y,t)\right] : \quad y = 0 \end{aligned} \tag{3c}$$

$$\begin{aligned} M_2 \frac{\partial^2 v(y,t)}{\partial t^2} = {} & -A_N \sum_{i=1}^{n} E_{Ni} \frac{\partial v(y,t)}{\partial y} - k_0\left[v(y,t) + V_0 t\right] + \\ & + k_0\left[v[y,t] + V_0(t-T_0)\right]\sigma_0(t-T_0) : \quad y = l_N \end{aligned} \tag{3d}$$

and for the initial conditions:

$$u(x,t) = 0, \quad (t=0) \tag{4a}$$

$$\frac{\partial u(x,t)}{\partial t} = 0, \quad (t=0) \tag{4b}$$

$$v(y,t) = 0, \quad (t=0) \tag{4c}$$

$$\frac{\partial v(y,t)}{\partial t} = 0, \quad (t = 0) \tag{4d}$$

where: $u(x,t)$ – displacement of an arbitrary rope cross-section) at the distance of x, y (for $t = 0$) from the movable coordinate system associated with the masses M_0 and M_1. Those displacements are computed in coordinate systems whose origins at the instant $t = 0$ coincide with the masses M_0 and M_1 and which move at the velocity V_0 = const, the speed with which all hoists elements move at the initial moment, $P_{(t)}$ – force from the emergency brake, M_1 – mass of the conveyance and payload, M_0 – reduced vibrating masses in the head tower, M_2 – reduced mass of the hoisting gear in the pit bottom.

Furthermore, it is assumed that the force acting upon the conveyance due to the action of the braking system has the dynamic characteristic as shown in Fig. 3.

This dynamic characteristic of the braking system is based on results of dynamic testing of braking systems widely applied in Poland and world-wide (Wolny, 2003).

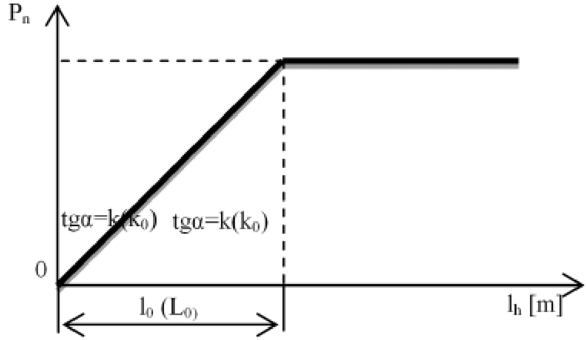

Fig. 3. Dynamic characteristic of braking systems: l_0 (L_0) – distance of braking force increase: $K_{(k0)}$ – coefficient expressing the braking force increase, $t_0(T_0)$ – time of braking force increase over the distance $l_0(L_0)$, P_h – braking force, l_h – braking distance

The solution to equations (2) with the boundary conditions (3) and initial conditions (4) is sought in the form (Gutowski & Świetlicki, 1986; Wolny, 2011):

$$u(x,t) = \varphi\left(t - \frac{x}{a_W}\right) + \psi\left(t + \frac{x}{a_W}\right) \tag{5a}$$

$$v(y,t) = f\left(t - \frac{y}{a_N}\right) + g\left(t + \frac{y}{a_N}\right) \tag{5b}$$

Substituting (5a) and (5b) into equations (3) and recalling the boundary conditions (4) we get the functions φ, ψ, f and g. Actually, general analytical formulas expressing the displacements and dynamic stress in the tail ropes' cross-sections in the intervals of plane of variables x, t and for the hoisting ropes in the intervals of the plane of variables y, t are not given here due to their intrinsic complexity.

These relationships are given for the case when the masses M_0 and M_1 are connected via an elastic element with the constant elasticity factor. As very short time passes from the instant the emergency braking begins to the moment the relevant rope section experiences the greatest load, the change in the value of the elasticity factor should not exceed 5%. This restriction simplifies the mathematical procedures, improving the clarity of the results, which is of key importance in practical applications.

Displacements are governed by the formulas:

- for tail ropes:

$$u(x,t)=\frac{kV_0}{M_1}\left\{\begin{array}{l}\dfrac{1}{\omega_1^{\ 2}}\left(t-\dfrac{x}{a_w}\right)-2\dfrac{\left(h_0\omega_{11}^2+h_1\omega_{10}^2\right)}{\omega^4\cdot\omega_0^2}\\ u\left(t-\dfrac{x}{a_w}\right)+\sum\limits_{i=1}^{4}w_i\cdot e^{a_i\left(y-\frac{x}{a_w}\right)}\end{array}\right\}+$$

$$+\frac{kV_0}{M_1}\left\{\frac{1}{\omega_1^{\ 2}}\left(t+\frac{x-2l_w}{a_w}\right)-2\frac{\left(h_0\omega_{11}^2+h_1\omega_{10}^2\right)}{\omega_1^{\ 4}\cdot\omega_{10}^2}u\left(t+\frac{x-2l_w}{a_w}\right)\right\} \tag{6}$$

- for hoisting ropes:

$$v(y,t)=-\frac{k\cdot V_0}{M_1}\left\{\begin{array}{l}\dfrac{1}{\omega_1^{\ 2}}\left(t-\dfrac{y}{a_N}\right)-2\dfrac{h_0\left(\omega_1^{\ 2}+\omega_{11}^2\right)+h_1\omega_{10}^2}{\omega^4\cdot\omega_0^2}\\ u\left(t-\dfrac{y}{a_N}\right)+\sum\limits_{i=1}^{4}S_i e^{a_i\left(t-\frac{y}{a^N}\right)}\end{array}\right\}+$$

$$-\frac{k_0V_0}{M_2\omega_2^4}\left\{\begin{array}{l}\omega_2^2\left(t+\dfrac{y-l_N}{a_N}\right)-2h_2\cdot u\left(t+\dfrac{y-L_N}{a_N}\right)+\\ +\dfrac{\omega_2^2}{\sqrt{\omega^2-h_2^2}}e^{-h_2\left(t+\frac{y-L_N}{a_N}\right)}\sin\left[\sqrt{\omega_2^2-h_2^2}\left(t+\dfrac{y-L_N}{a_N}\right)+\Phi_1\right]\end{array}\right\} \tag{7}$$

where:

$$\Phi_1=\frac{\pi}{2}+\operatorname{arctg}\frac{\left(\omega_2^2-2h_2^2\right)}{2h_2\sqrt{\omega_2^2-h_2^2}},$$

$$\omega_{10}^2=\frac{A_NE_N}{M_0L_1};\quad \omega_{11}^2=\frac{A_NE_N}{M_1L_1};\quad \omega_2^2=\frac{k_0}{M_2};\quad \omega_1^{\ 2}=\frac{k}{M_1};$$

$$2h_0=\frac{A_NE_N}{M_0a_N};\quad 2h_1=\frac{A_wE_w}{M_1a_w};\quad 2h_2=\frac{A_NE_N}{M_2a_N}$$

$$W_i = \frac{\left(a_i^2 + 2h_0 a_i + \omega_{10}^2\right)\left(a_i - a_i\right)}{a_i^2\left(a_i - a_1\right)\left(a_i - a_2\right)\left(a_i - a_3\right)\left(a_i - a_4\right)} \ \left(i = 1,2,3,4\right)$$

$$S_i = \frac{\omega_{10}^2\left(a_i - a_i\right)}{a_i^2\left(a_i - a_1\right)\left(a_i - a_2\right)\left(a_i - a_3\right)\left(a_i - a_4\right)} \ \left(i = 1,2,3,4\right)$$

$a_{i\,(i\,=\,1,2,3,4)}$ – are roots of the equation:

$$a^4 + 2\left(h_0 + h_1\right)\cdot a^3 + \left[\left(\omega_1{}^2 + \omega_{10}^2 + \omega_{11}^2\right) + 4h_0 h_1\right]a^2 +$$
$$+\left[2h_0\left(\omega_1{}^2 + \omega_{11}^2\right) + 2h_1\omega_{10}\right]a + \omega_1^2\cdot\omega_{10}^2 = 0$$

Basing on analytical formulas expressing the displacements of arbitrary cross-sections of hoisting and tail ropes, we get the relationships expressing the conveyance and tail rope loads during the braking phase:

(a) – attachment of the upper conveyance

$$S_{L_N} = \frac{A_N E_N}{L_1}\left[u\left(x = 0,t\right) + v\left(y = 0,t\right)\right] \tag{8}$$

(b) – tail rope attachment

$$S_{L_W} = A_W E_W \frac{\partial u\left(x = 0,t\right)}{\partial x} \tag{9}$$

(c) – attachment of the bottom conveyance

$$S_{L_{ND}} = A_N E_N \frac{\partial v\left(y = l_N,t\right)}{\partial y} \tag{10}$$

The following simplifications were made for the tower-type hoisting gear:

$\frac{A_W E_W}{a_W} \cong \frac{A_N E_N}{a_N} = \frac{AE}{a}$; $M_0 = M_1 = M$, which implicates further simplifications.

As regards the equality: $h_1 = h_0 = h$, $\omega_{10} = \omega_{11} = \omega_0$.

And the solution is obtained accordingly:

a) displacements of tail ropes’ cross-sections

$$u^*\left(x,t\right) = \frac{k\cdot V_0}{8M_1}\left\{\begin{aligned}&\frac{1}{h}\left(t - \frac{x}{a_w}\right)^2 + \frac{2h^2 - \omega_0^2}{h^2\omega_0^2}\left(t - \frac{x}{a_w}\right) + \\ &+\frac{\omega_0^4 - 4h^4}{2\omega_0^4 h^3}u\left(t - \frac{x}{a_w}\right) - \frac{1}{2h^3}\cdot e^{-2h\left(t - \frac{x}{a_w}\right)} + \\ &+\frac{2}{\omega_0^2\sqrt{2\omega_0^2 - h^2}}\cdot e^{-h\left(t - \frac{x}{a_w}\right)}\sin\left[\sqrt{2\omega_0^2 - h^2}\left(t - \frac{x}{a_w}\right) + \Phi_2\right]\end{aligned}\right\} +$$

$$+\frac{k\cdot V_0}{8M_1}\left\{\begin{array}{l}\frac{1}{h}\left(t+\frac{x-2l_w}{a_w}\right)^2+\frac{2h^2-\omega_0^2}{h^2\omega_0^2}\left(t+\frac{x-2l_w}{a_w}\right)+\\ +\frac{\omega_0^4-4h^4}{2\omega_0^4h^3}u\left(t+\frac{x-2l_w}{a_w}\right)-\frac{1}{2h^3}\cdot e^{-2h\left(t+\frac{x-2l_w}{a_w}\right)}+\\ +\frac{2}{\omega_0^2\sqrt{2\omega_0^2-h^2}}\cdot e^{-h\left(t+\frac{x-2l_w}{a_w}\right)}\sin\left[\sqrt{2\omega_0^2-h^2}\left(t+\frac{x-2l_w}{a_w}\right)+\Phi_2\right]\end{array}\right\} \tag{11}$$

b) displacements of hoisting ropes' cross-sections

$$v^*(y,t)=-\frac{k\cdot V_0}{8M_1}\left\{\begin{array}{l}\frac{1}{h}\left(t-\frac{y}{a_N}\right)^2-\frac{2h^2+\omega_0^2}{h^2\omega_0^2}\left(t-\frac{y}{a_N}\right)+\\ +\frac{\omega_0^4+4h^4}{2\omega_0^4h^3}u\left(t-\frac{y}{a_N}\right)-\frac{1}{2h^3}\cdot e^{-2h\left(t-\frac{y}{a_N}\right)}+\\ -\frac{2}{\omega_0^2\sqrt{2\omega_0^2-h^2}}\cdot e^{-h\left(t-\frac{y}{a_N}\right)}\sin\left[\sqrt{2\omega_0^2-h^2}\left(t-\frac{y}{a_N}\right)+\Phi_2\right]\end{array}\right\}+$$

$$-\frac{k_0\cdot V_0}{M_2\omega_2^4}\left\{\begin{array}{l}\omega_2^2\left(t+\frac{y-l_N}{a_N}\right)-2h\cdot u\left(t+\frac{y-l_N}{a_N}\right)+\\ +\frac{\omega_2^2}{\sqrt{\omega_2^2-h^2}}\cdot e^{-h_2\left(t+\frac{y-l_N}{a_N}\right)}\sin\left[\sqrt{\omega_2^2-h_2^2}\left(t+\frac{y-l_N}{a_N}\right)+\Phi_1\right]\end{array}\right\} \tag{12}$$

where: $\phi_2=\frac{\pi}{2}+\mathrm{arctg}\frac{h^2-\omega_0^2}{h\sqrt{2\omega_0^2-h^2}}$.

Relationships (11) and (12) govern the displacements of hoisting and tail ropes' cross-sections in the event of an overtravel, assuming that $\omega_1 << \omega_0$. This assumption results from limitation of the conveyance deceleration during the emergency braking and it is satisfied in most tower-type hoisting installations.

Loading of the conveyance attachments and of the tail ropes is obtained from the formulas:

a) upper conveyance attachments

$$S_{l_N}^*=\frac{AE}{l_1}\left[u^*(x=0,t)+v^*(y=0,t)\right] \tag{13}$$

b) tail rope attachment

$$S_{l_w}^*=AE\frac{\partial u^*(x=0,t)}{\partial x} \tag{14}$$

c) bottom conveyance attachment

$$S^*_{l_{ND}} = AE\frac{\partial v^*(y = l_N, t)}{\partial y} \tag{15}$$

In considerations of the effects of emergency braking, of particular importance is the load acting on the hoisting rope section between the conveyance being captured in the tower and the Koepe pulley, mainly because the friction contact between the hoisting rope and the pulley can get disrupted or the rope can get broken.

Recalling (11) and (12), the equation (13) becomes:

$$S^*_{l_N} = \frac{A_N E_N}{l_1}\frac{k \cdot V_0}{M_1}\left\{\frac{1}{2\omega_0^2}t - \frac{1}{2}\frac{h}{\omega_0^4} + \frac{1}{2}\frac{e^{-ht}}{\omega_0^2\sqrt{2\omega_0^2 - h^2}} \cdot \sin\left[\sqrt{2\omega_0^2 - h^2}\,t + \Phi_2\right]\right\} \tag{16}$$

Restricting the loads acting on this rope section to the value of the rope breaking force is one of the requirements in the selection of parameters of the braking system that would guarantee safe performance. This condition can be written as:

$$S^*_{l_N} \le S_{z_l} \tag{16a}$$

where: S_{z_l} — breaking force

The other requirement to be considered when selecting the parameters of the braking system is limitation of the conveyance deceleration during the emergency braking. For conveyances captured in the tower, this condition can be written as:

$$a_g = \frac{\partial^2 u^*\left(x = 0, t\right)}{\partial t^2} \le a_{dop} \tag{17}$$

where:

a_{dop} — admissible deceleration of the conveyances being captured in the event of an overtravel,

$u(x = 0, t)$ — displacement of the upper conveyance – Eq (11).

When the conveyance is being captured at the bottom, the condition (17) becomes:

$$a_d = \frac{\partial^2 v^*\left(y = 0, t\right)}{\partial t^2} \le a_{dop} \tag{17a}$$

where: $v^*(\mathrm{y} = 0, t)$ — displacement of the conveyance at the bottom – Eq (12), assuming that $y = 0$.

4. Summing-up

Basing on the results of dynamic analysis of the mine conveyance cycle in the event of an overtravel, the maximal loads acting upon the conveyance attachments and tail ropes can be established and variations of this loading in time can be found. These results are particularly useful in design of the attachment elements using the fatigue endurance methods, provided the parameters of the system are known beforehand. In the method presented here the solution is obtained analytically and the entire procedure uses the relative values, which enables a more comprehensive approach to the problem being addressed.

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