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STANISŁAW WOLNY*

BRAKING DISTANCE OF HOIST CONVEYANCES REQUIRED FOR SAFE STOPPING UNDER THE CONDITIONS OF EMERGENCY BRAKING

DROGI HAMOWANIA NACZYŃ WYDOBYWCZYCH KONIECZNE DO BEZPIECZNEGO ZREALIZOWANIA PROCESU AWARYJNEGO (KRAŃCOWEGO) HAMOWANIA SZYBOWYCH URZĄDZEŃ WYCIĄGOWYCH

This study investigates selected aspects of the dynamic behaviour of mine hoists during the emergency braking in an event of overtravel. Characteristics of the braking force that needs to be applied in the headgear and in the pit bottom to arrest the conveyance in the event of an overtravel are derived from laboratory and industrial test data and recalling the results reported in literature. The real hoist installation is replaced by a model whereby the equations of motion of rope elements are written as for elastic strings, taking into account the variable length of the hoisting rope section between the Koepe pulley and the conveyance being arrested in the head tower.

Analytical formulas are provided whereby the displacement of the top conveyance with the payload for the constant elasticity coefficient of the hoisting rope section between the conveyance being arrested in the head tower and the Koepe pulley is expressed as the function of the braking force and of the operational parameters of the hoist gear.

The hoist operation is investigated in the event of emergency braking, taking into account the two aspects of the cycle:

– the time required for the conveyance to be stopped,
– the distance travelled by the conveyance until it is stopped.

The results of the dynamic analysis of the hoist installation in the conditions of emergency braking may be utilised in selection of the effective and adequate braking system guaranteeing the safety of the system operation.

Keywords: mine hoists, dynamics, loading, emergency braking

Opracowanie poświęcono wybranym aspektom analizy dynamicznej pracy górniczego urządzenia wyciągowego, awaryjnie hamowanego w strefie wolnych dróg przejazdu. Na podstawie wyników badań laboratoryjnych i przemysłowych oraz analizy literatury, przyjęto charakterystyki sił hamowania układów mających awaryjnie wyhamować naczynia po przejeździe przez nie tzw. wolnych dróg przejazdu, odpowiednio dla wieży i rząpia. Wyciąg zastąpiono modelem, dla którego zapisano równania ruchu ele-

* AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, AL. A. MICKIEWICZA 30, 30-059 KRAKOW, POLAND
E-MAIL: Stwolny@agh.edu.pl

mentów lin jak dla cięgna sprężystego z uwzględnieniem zmiennej długości odcinka lin nośnych między naczyniem hamowanym w wieży a kołem pędnym.

Podano wzory analityczne określające przemieszczenie masy naczynia górnego wraz z urobkiem, hamowanego w wieży, dla stałej wartości współczynnika sprężystości odcinka lin nośnych między naczyniem hamowanym w wieży a kołem pędnym, jako funkcję siły hamującej oraz parametrów ruchowych wyciągu.

Przeprowadzono analizę pracy urządzenia wyciągowego w warunkach hamowania awaryjnego w aspekcie:

- koniecznego czasu, po osiągnięciu którego naczynie wydobywcze zostaje unieruchomione,
- wymaganej drogi, jaką przebędzie naczynie do momentu jego unieruchomienia.

Wyniki analizy dynamicznej pracy urządzenia wyciągowego w warunkach hamowania (krańcowego) awaryjnego, zawarte w opracowaniu mogą stanowić podstawę do poprawnego – gwarantującego bezpieczne zrealizowanie procesu – doboru układu hamującego.

Słowa kluczowe: wyciąg górniczy, dynamika, obciążenia, hamowanie awaryjne

1. Introduction

Under the current safety assessment regulations (Regulation by the Minister of Economy, 2002), the safety factor for hoisting ropes should be 7 and it should be defined as the ratio of rope breaking load to the maximal stress and taking into account the static loads.

Such high levels of safety factors for hoisting installations featuring high load capacity and hoisting depth hinder the construction and engineering of hoist members. The calculation and design procedure is based on the admissible stress method, and the safety limit for the given material is taken to be its immediate endurance R_m. The values of the safety factors are defined arbitrarily, basing on the analysis of past failures and assuming that stress levels in critical rope cross-sections should be derived by the simplest calculation procedures and the fatigue endurance formulas.

Many hoist components have intricate shapes and are over-rigid, hence the real state of stress is different than the designed one, based on the current guidelines (Regulation by the Minister of economy, 2002). Furthermore, loads acting on rope attachments and tail ropes fluctuate in time, both during the normal duty cycles and in emergency (Klich, 1980; Knop, 1975; Wolny, 1988, 2003, 2011).

Despite extensive research efforts (Wolny, 1988, 2003) aimed to solve this problem, the endurance calculations of hoist members (rope attachments and tail ropes in particular) are far from complete, leaving out certain vital aspects:

- the maximal stresses in rope attachments are computed basing on static loads only,
- calculation procedures for handling the hoist members involve major simplifications (stretched rods, freely-supported beams),
- the admissible stress method has prevalence.

As the state of stress in rope attachments and in tail ropes is unknown at the stage of hoist design and operation, reliable forecasts of the service life of the hoist installation are nearly impossible.

In order that the FEM approach and the ultimate state methods can be applied in dimensioning and safety assessment and that the fatigue endurance methods should be used to find the service life of hoist installations, it is required that:

- dynamic behaviour of the hoist installation should be analysed during the typical duty cycles and under emergency conditions;

– fatigue endurance of load-bearing members should be analysed in the function of their service period and the type of hoisting installation;
– optimal loads in structural elements of the conveyance should be determined in the function of constructional and operational parameters of the system.

Emergency braking conditions when the braking force is applied directly to the conveyances and certain aspects of typical duty cycles were investigated in separate studies (Klich,1980; Wolny, 1988, 2003).

Further research efforts are still merited to find the required time after which the conveyance is stopped and the distance the conveyance will travel until its arrest. This study is focused on finding the solutions to these problems which, as mentioned earlier, may support the selection of the braking system.

2. Mechanical model of the hoist for the dynamic analysis of the braking phase of conveyances during an overtravel

Normal duty cycles of hoisting installations get disturbed when the conveyances begin 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 testing data 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 (Knop, 1975; Wolny, 1988) 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 along the overtravel path, as shown in model diagram (Fig. 1).

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

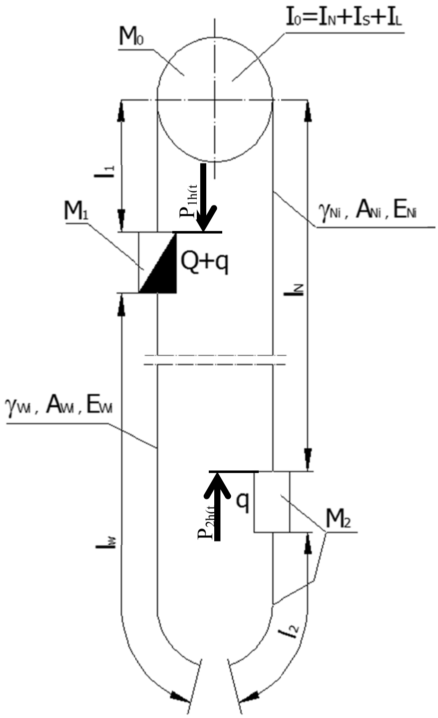

Fig. 1. Model of the hoisting gear during the emergency braking

ropes between the conveyance being arrested in the head tower and the Koepe pulley ranges from l = 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, 1988).

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

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, 2003),
- 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.

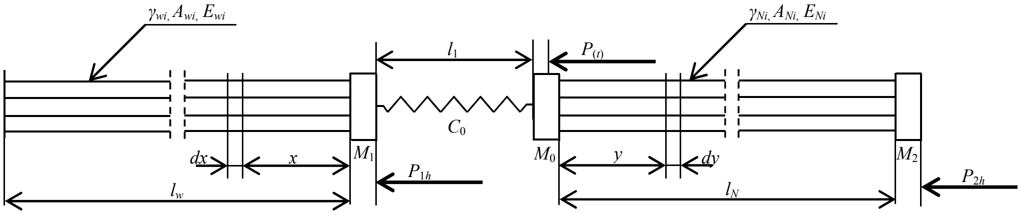

Fig. 2. Simplified model of the hoisting installation: P_{1h} – braking force in the head tower, P_{2h} – braking force at the pit bottom, M_1 – mass of the conveyance and payload, M_0 – reduced revolving masses in the head tower, M_2 – reduced mass of the hoisting gear in the pit bottom, $P_{(t)}$ – 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 the 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 (Wolny, 2003).

$$\frac{\partial^2 u(x,t)}{\partial t^2} - a_w^2 \frac{\partial^2 u(x,t)}{\partial x^2} = 0,$$

$$\frac{\partial^2 v(y,t)}{\partial t^2} - a_N^2 \frac{\partial^2 v(y,t)}{\partial y^2} = 0 \tag{2}$$

for the boundary conditions:

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

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

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

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

and for the initial conditions:

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

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

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

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

where: $u(x,t)$, $v(y,t)$ – 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 obtained by dynamic testing of braking systems widely applied in Poland and world-wide (Wolny, 1988).

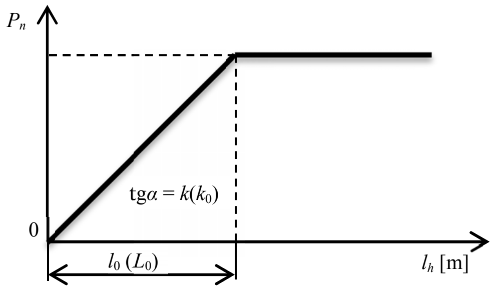

Fig. 3. Dynamic characteristic of braking systems: $l_0(L_0)$ – distance of braking force increase: $K(k_0)$ – coefficient expressing the braking force increase, $t_0(T_0)$ – time of braking force increase over the distance $l_0(L_0)$, P_h – braking force, l_h – braking distance

The solution to equations (2) with the boundary conditions (3) and initial conditions (4) is sought in the form given in (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. 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. The procedure applied to find the solution is given elsewhere (Wolny, 2003).

This study is restricted to the analysis of dynamic phenomena involved in the conveyance being arrested in the head tower.

4. Displacement of a conveyance being arrested in the head tower

Displacements of any cross-sections of tail ropes in the conditions of emergency braking can be obtained from the formula (11).

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

$$+\frac{k\cdot V_0}{8M_1}\left\{\begin{aligned}&\frac{1}{h}\left(t+\frac{x-2l_w}{a_W}\right)^2+\frac{2h^2-\omega_0^2}{h^2\omega_0^2}\left(t+\frac{x-2l_w}{a_W}\right)+\\&+\frac{\omega_0^4-4h^4}{2\omega_0^4h^3}u\left(t+\frac{x-2l_w}{a_W}\right)-\frac{1}{2h^3}\cdot e^{-2h\left(t+\frac{x-2l_w}{a_w}\right)}+\\&+\frac{2}{\omega_0^2\sqrt{2\omega_0^2-h^2}}\cdot e^{-h\left(+\frac{x-2l_w}{a_w}\right)}\sin\left[\sqrt{2\omega_0^2-h^2}\left(t+\frac{x-2l_w}{a_W}\right)+\Phi_2\right]\end{aligned}\right\} \qquad (6)$$

Displacement of the conveyance is derived from Eq. (6), substituting 0 for x. Hence, displacement of a conveyance arrested in the head tower (until the return of the elastic deformation wave) becomes:

$$u^*(x=0,t)=\frac{kV_0}{8M_1}\left\{\begin{aligned}&\frac{1}{h}t^2+\frac{2h^2-\omega_0^2}{h^2\omega_0^2}t+\frac{\omega_0^4-4h^4}{2\omega_0^4h^3}-\frac{1}{2h^3}e^{-2ht}+\\&+\frac{2}{\omega_0^2\sqrt{2\omega_0^2-h^2}}e^{-ht}\sin\left[\sqrt{2\omega_0^2-h^2}\,t+\phi_2\right]\end{aligned}\right\} \qquad (7)$$

where:

$$\varnothing_2=\frac{\pi}{2}+\operatorname{arctg}\frac{\omega_0^2-h^2}{h\sqrt{2\omega_0^2-h^2}}\;;\;\omega_0^2=\frac{AE}{Ml_1}\;;\;h=\frac{AE}{2Ma}$$

and:

- k – linear coefficient of the braking force increase in the head tower (characteristics of the braking system),
- AE – tensile rigidity of ropes,
- M – mass of the conveyance being arrested in the head tower,
- a – velocity of elastic wave propagation in ropes,

- l_1 – length of the hoisting rope section between the conveyance being arrested in the headgear tower and the Koepe pulley,
- V_0 – velocity at which the conveyance arrested in the head tower begins an overtravel.

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.

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

$$\frac{A_w E_w}{a_w} \cong \frac{A_N E_N}{a_N} = \frac{AE}{a}, \quad M_0 = M_1 = M$$

which implicates the following equalities:

$$h_1 = h_o = h, \quad \omega_{10} = \omega_{11} = \omega_0 .$$

4.1. Velocity of the conveyance being stopped in the head tower

Velocity of the conveyance being stopped in the head tower is derived from the formula:

$$V_{(t)} = \frac{\partial u^*(x=0,t)}{\partial t}$$

Rearranging, we get:

$$V_{(t)}^{\;*} = \frac{kV_0}{M}\left\{\begin{array}{l} \dfrac{1}{4h}t - \dfrac{\omega_0^2 - 2h^2}{8h^2\omega_0^2} + \dfrac{1}{8h^2}e^{-2ht} + \\ + \dfrac{\sqrt{2}}{4\omega_0}\dfrac{e^{-ht}}{\sqrt{2\omega_0^2 - h^2}}\sin\left(\sqrt{2\omega_0^2 - h^2}\,t + \phi_3\right) \end{array}\right\} \tag{8}$$

where:

$$\phi_3 = \pi + \text{arc tg}\frac{\sqrt{2\omega_0^2 - h^2}}{h}$$

The dependence (8) yields the time t after which the conveyance is stopped and its velocity becomes $V_0 = 0$. Neglecting small – valued expressions and recalling that $\omega_0 \geq 2h$ we get:

$$t_h = 2\sqrt{\left[\frac{M}{k} + \frac{\omega_0^2 - 2h^2}{8h^2\omega_0^2}\right] - \frac{1}{8h^2}} \tag{9}$$

Substituting and rearranging gives:

$$t_h = \sqrt{M\left(\frac{4}{k} - \frac{l_1}{AE}\right)} \tag{10}$$

4.2. Braking distance of a conveyance in the head tower

Recalling Eq (10), the relationship (8) gives the distance travelled by a conveyance being captured in the head tower in the event of an overtravel. The braking distance is given as:

$$L_h = V_o t_h - V^{*}_{(t)} t_h \tag{11}$$

After necessary transformations and neglecting small-valued expressions, we get:

$$L_h = V_0 \left\{ \sqrt{M\left(\frac{4}{k} - \frac{l_1}{AE}\right)} - \frac{l_1 k}{4AE}\left[\sqrt{M\left(\frac{4}{k} - \frac{l_1}{AE}\right)} - \frac{l_1}{2a}\right]\right\} \tag{12}$$

For most hoist installations (where the material is being hauled) and assuming the considerable time required for the braking force increase, the conveyance will be securely arrested after the time shorter than $t_h = 2 \, {l_N}/{a_N}$ (Eq 10), i.e. before the return of the elastic tensile deformation wave in ropes. This time period falls in the range 0.33-0.66 s, depending on the way the braking process is realised (conveyance being arrested in the head tower and at the pit bottom or the conveyance being arrested in the head tower only).

That means that the braking distance expressed by (12), given as the time limit (from-to) is an exact value. Limiting the braking distance to its necessary value (Eq. 12) is a key condition that needs to be satisfied when determining the required parameters of the braking system.

5. Conclusions

The dynamic analysis of a hoist installation during the overtravel of a conveyance was performed to determine the following parameters:

- time after which the conveyance is captured,
- distance which that conveyance travels before its capture.

Results of the dynamic analysis of the hoist behaviour during the emergency braking of a conveyance summarised in (Wolny, 2003) and (Wolny, 2011) as well as results reported in this study provide the full data necessary for correct design of the braking system guaranteeing secure arresting of the conveyance. Furthermore, they can be well utilised to design of other load-bearing members in the hoisting installation, such as rope attachments and tail ropes, to ensure the safe operations of mine hoists.

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