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LOADS EXPERIENCED BY LOAD-BEARING COMPONENTS OF MINE HOIST INSTALLATIONS DUE TO RANDOM IRREGULARITIES AND MISALIGNMENTS OF THE GUIDE STRING

Key words: hoisting installation, dynamics, maintenance.

Abstract: Report data from periodic overhauls of skips and cages operated in one underground mine in Poland indicate that the majority of registered defects of load-bearing elements include broken wires and cracks developing in load-bearing cables. Of particular interest is cable bending while the conveyance is being guided in the shaft due to interaction forces between the shaft steelwork and the conveyance.
Based on results reported in articles [5, 7] the author summarised the results of the dynamic analysis of a hoisting installation during its normal duty cycle, restricted to the investigation of conveyance and shaft steelwork interaction forces.
To determine stresses acting in load-bearing elements of the conveyance, a model to be used in the computational procedure was created based on its technical specification. For the defined 2D schematic model, the author found the values of force acting in the given section associated with the shaft steelwork–conveyance interaction force arising during the conveyance travel with fixed velocity V_0 = *const*. The values of forces acting in the given cable sections within the skip structure were used to determine the maximal stresses related to the single element (cable).
In the final sections, the author indicates the directions for further research necessary to work out a comprehensive solution to the original research problem.

Obciążenia elementów nośnych górniczego wyciągu szybowego wygenerowane przez losowe nierówności ciągów prowadniczych

Słowa kluczowe: górnicze urządzenie wyciągowe, dynamika, eksploatacja.

Streszczenie: Z informacji uzyskanych z okresowych badań skipu i klatek eksploatowanych w szybach jednej z polskich kopalń wynika, że większość zarejestrowanych uszkodzeń elementów nośnych to pęknięcia o charakterze zmęczeniowym, które powstają i rozwijają się głównie w cięgnach nośnych.
W opracowaniu szczególną uwagę zwrócono na zginanie tych elementów wywołane efektami prowadzenia naczynia w szybie, tj. siłami wzajemnego oddziaływania naczynia i zbrojenie szybu.
Bazując na wynikach zawartych w artykule [5, 6] przedstawiono wyniki analizy dynamicznej pracy urządzenia wyciągowego w warunkach normalnej eksploatacji, ograniczone do sił wzajemnego oddziaływania naczynia i zbrojenia.
Do wyznaczenia naprężeń w elementach nośnych konstrukcji naczynia wydobywczego opracował jego schemat obliczeniowy, bazując na dokumentacji technicznej tego typu konstrukcji. Dla przyjętego modelu obliczeniowego – płaskiego schematu ramowego – wyznaczył wartości sił przekrojowych wywołanych siłą wzajemnego oddziaływania naczynia i zbrojenia, wygenerowaną w czasie ruchu naczynia ze stałą prędkością V_0 = *const.* Wyznaczone wartości sił przekrojowych – w cięgnach konstrukcji skipu – pozwoliły na określenie maksymalnych naprężeń odniesionych do pojedynczego elementu (cięgna). W zakończeniu zwrócono uwagę na kierunki dalszych badań niezbędnych do całościowego rozwiązania problemu.

Introduction

Report data from periodic overhauls of skips and cages operated in an underground mine in Poland indicate that the majority of registered defects of load-bearing elements include broken wires and cracks developing in load-bearing cables. These cracks propagate mostly in load-bearing cables, welded sections, and in attachments to the conveyance's structural elements (skip head, hopper, bottom frame). In order to eliminate those defects and enhance the service life of the conveyance, it is required that the actual causes of those cracks should be first identified.

One may suppose that a correctly designed and engineered skip or cage should not suffer from defects due to fatigue wearing, particularly when recalling the safety factor (n=7) adopted when assessing their fatigue endurance. It is worthwhile to mention, however, that the adopted computational models of load-bearing elements in conveyances are simplified and may not fully capture the actual state of stress due to the applied loads. It is a common practice that conveyances being designed are dimensioned basing on their tensile strength test data [4, 6], and the calculation procedure relies chiefly on the maximal value of the static axial force carried by the given component. Furthermore, the effects of the bending of structural elements due to loads experienced during the conveyance guiding within the shaft are neglected, which can be attributed, at least partly, to the lack of reliable data.

Further theoretical studies and measurements are therefore necessary to determine the cables' loading and the state of stress they experience during the normal duty cycle of the hoist installation.

Therefore, theoretical studies and measurements were undertaken to find the load levels, thus allowing the full evaluation of fatigue endurance and service life of load-bearing elements of a conveyance, including the cables and ropes.

Loads acting on the conveyance were determined by investigating the dynamic behaviour of the conveyance, relying on the created models of a hoisting installation capturing all of its vital features.

Of particular interest is the bending of the load-bearing elements in a conveyance while it is being hoisted inside the shaft due to the conveyance-shaft steelwork interaction forces.

Recalling the data reported in articles [5, 7], the author summarised the results of the dynamic analysis of a hoisting installation during its normal duty cycle, restricted to the analysis of conveyance-shaft steelwork interaction forces.

1. Analysis of dynamic behaviour of a hoisting installation

Evaluation of the state of stress in load-bearing elements of a conveyance experienced while the conveyance is being hoisted in the shaft is a difficult task; therefore, the author chose to provide a short summary of the dynamic analysis [5, 6], restricted to the presentation of results that have relevance to the present study. The conveyance is represented by a triple mass model whose dynamic motion equations are based on an assumption that horizontal displacements of the modelled lumped masses are induced by random irregularities and misalignments of guide strings.

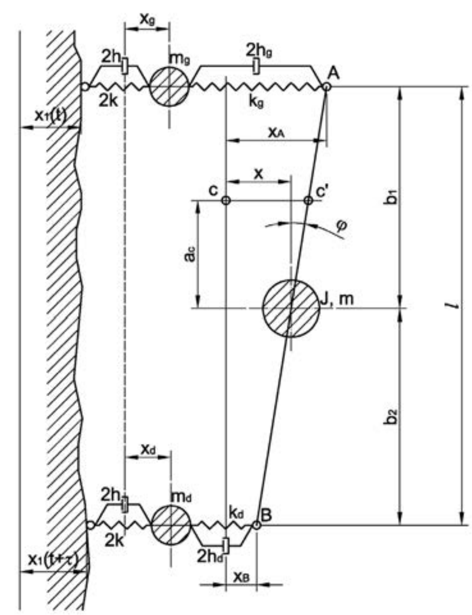

Fig. 1. Mechanical model of a hoist installation

Underlying the equations of the motion of the system are the Lagrange equations of the second type. Accordingly, we get the following [3, 4]:

$$\frac{mb_2^{\,2}+I}{I^2}\ddot{x}_A+\frac{mb_1b_2-I}{I^2}\ddot{x}+k_g\left(x_A-x_g\right)+2h_g\left(\ddot{x}_A-\ddot{x}_g\right)=0 \tag{1}$$

$$\frac{mb_1^{\,2}+I}{I^2}\ddot{x}_B+\frac{mb_1b_2-I}{I^2}\ddot{x}+k_d\left(x_B-x_d\right)=0 \tag{2}$$

$$m_g \ddot{x}_g + 2k\left(x_g - x_{I(t)}\right) - k_g\left(x_A - x_g\right) - 2h_g\left(\ddot{x}_A - \ddot{x}_g\right) + 2h\left(\ddot{x}_g - \dot{x}_{I(t)}\right) = 0 \tag{3}$$

$$m_d \ddot{x}_d + k_d\left(x_B - x_d\right) - 2k\left(x_d - x_{I(t+\tau)}\right) - 2h_d\left(\dot{x}_B - \dot{x}_d\right) + 2h\left(\dot{x}_d - \dot{x}_{I(t+\tau)}\right) = 0 \tag{4}$$

Where the following relationships and variables are used:

$$x_A = x + b_1 \cdot \varphi, \; x_B = x + b_2 \cdot \varphi$$

φ – angle of skip hopper rotation around its centre of gravity (c.o.g),
x – horizontal displacement of a hopper mass,
m – mass of a loaded skip hopper,
I – inertia moment of a loaded skip hopper,
m_g – mass of the skip head,
m_d – mass of the bottom frame,
2h, k – (linear) damping and elasticity factors of sliding and rolling shoes,
$2h_g$, k_g – damping and elasticity factors of (lateral) flexible connector between the head and hopper,
$2h_d$, k_d – damping and elasticity factors of (lateral) flexible connectors between the bottom frame and skip hopper,
x_g, x_d – horizontal displacements of the face of the skip head and bottom frame, respectively,
$x_{I(t)}$, $x_{I(t+\tau)}$ – function defining the imperfections of cage guides' front surfaces,
τ – time of conveyance ride along the path equal to the distance between the front shoes (on the head and the bottom frame),
b_1, b_2 – distance between the hopper c.o.g and front shoes on the top and at the bottom, respectively,
l – distance between top and bottom shoes.

Recalling the work by S. Kawulok [1], the misalignments and irregularities of guiding strings are treated as a stochastic random process, its spectral density given as follows:

$$S_x = \frac{2D_x\alpha}{\alpha^2 + \omega^2}\text{, m}^2\text{s} \tag{5}$$

where
ω – frequency,
D_x; α – parameters.

The relationship can be found to express the variance of the amplitude of the skip head-shaft steelwork interaction force (Fig. 2) [5], which is gin as follows:

$$D_Q = \frac{4D_x nk^2}{\pi} \cdot \frac{\pi(-1)^6 \cdot M_5}{a_0\Delta_5} = nk^2 \frac{4D_x M_5}{a_0\Delta_5}, \tag{6}$$

where

$$M_5 = b_0 \cdot a_5\{a_2(a_3 \cdot a_4 - a_2 \cdot a_5) + a_4(a_0 \cdot a_5 - a_1 \cdot a_4)\} - a_0\{a_5[b_1 (a_3 \cdot a_4 - a_2 \cdot a_5) + b_2 (a_0 \cdot a_5 - a_1 \cdot a_4)]\}$$
$$\Delta_5 = -a_5\{a_0^2 \cdot a_5^2 - 2a_0 a_1 a_4 a_5 - a_0 a_2 \cdot a_3 a_5 + a_0 a_3^2 a_4 + a + a_1^2 a_4^2 + a_1 a_2^2 + a_1^2 a_4^2 a_5 - a_1 \cdot a_2 \cdot a_3 \cdot a_4\}$$

and

$$a_0 = 1,\; a_1 = 2n_2 + n,\; a_2 = 1 + n_1 (1 + 2n_3) + 2n_2 \cdot n$$
$$a_3 = 2n_2 + n + n_1 \cdot n(1 + 2n_3),\; a_4 = 2(n_1 \cdot n_3 + n_2 n),\; a_5 = 2n_1 n_3 n$$
$$b_0 = 1,\; b_1 = 2(1 + n_1),\; b_2 = (1 + n_1)^2,\; b_3 = 0\; b_4 = 0$$

$$n_1 = \frac{m_A}{m_g};\; n_2 = \frac{h}{m_g}\sqrt{\frac{m_A}{k_g}};\; n_3 = \frac{k}{k_g};\; n = \alpha\sqrt{\frac{m_A}{k_g}}$$

The relationship (6) can be rewritten as:

$$D_Q = 4_{Dx_1} k_2 n I_5 \tag{6a}$$

where

$$I_5 = \frac{M_5}{a_0\Delta_5} \tag{6b}$$

The product $D_{x_1} n$ in (6a) is related to parameters of the random excitations, while (6b) is associated with parameters describing the investigated object.

Variations of I_5 in relation to $n_1 = \frac{m_A}{m_g}$ for two values of n_2 (for $n = \alpha\sqrt{\frac{m_A}{k_g}} = 0.1$; $n_3 = \frac{k}{k_g} = 0.01$ related to properties of the investigated object) are illustrated in Fig. 2.

The variability range of parameters n_1, n_2, n_3 and n were chosen such that they should be applicable to typical hoisting installations designed and operated in Polish collieries [6, 8].

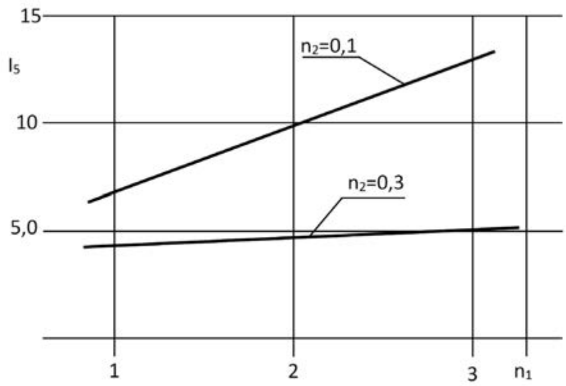

Fig. 2. I_5 **(6b) is relation to** $n_1=m_A/m_g$ **for n=0.1 and** n_3 **= 0.01**

Recalling Fig. 2, parameters of the hoisting installation can be chosen to guarantee that the ultimate stress levels should not be exceeded for a known random pattern of irregularities and misalignments of the guiding string.

As mentioned in the introductory section, most defects registered in load-bearing components of a conveyance are cracks due to fatigue wring, which typically develop and propagate in load-bearing cables at attachment points to the conveyance's structural components (skip head, skip hopper, bottom frame). It is reasonable, therefore, to determine the state of stress in the cables' transverse cross-sections, at the attachment points.

In the first place, the model (Fig. 1) is recalled to determine the loading of the skip head- skip hopper system. Accordingly, we get the following:

$$Q_k(t) = k_g(x_A - x_g) + 2h_g(\dot{x}_A - \dot{x}_g) \tag{7}$$

Substituting the Laplace transform to (7) yields:

$$Q_k(s) = k_g[x_A(s) - x_g(s)] + 2h_g[x_A(s)s - x_g(s)s] = [k_g + 2h_g \cdot s][x_A(s) - x_g(s)] \tag{8}$$

Recalling [5] [7]

$x_A(s) = W_{X_A}(s) \cdot x_1(s)$

and $x_g(s) = W_{X_g}(s) \cdot x_1(s)$,

we obtain

$$Q_k(s) = [k_g + 2h_g \cdot s][W_{X_A}(s) \cdot x_1(s) - W_{X_g}(s) \cdot x_1(s)] = (k_g + 2h_g \cdot s)[W_{X_A}(s) - W_{X_g}(s)] = W_{Q_k}(s) \cdot x_1(s) \tag{9}$$

where:

$$W_{Q_k}(s) = (k_g + 2h_g \cdot s)[W_{X_A}(s) - W_{X_g}(s)] \tag{9a}$$

Substituting for $W_{X_A}(s)$ [5]

$$W_{X_A} = \frac{2k_g(hs + k)}{m_A m_g s^4 + 2m_A h s^3 + [m_A(2k + k_g) + m_g k_g]s^2 + 2hk_g s + 2k \cdot k_g}$$

$$W_{X_g} = \frac{2[hs + k][m_A s^2 + k_g\}}{m_A m_g s^4 + 2m_A h s^3 + [m_A(2k + k_g) + m_g k_g]s^2 + 2hk_g s + 2k \cdot k_g}$$

Recalling the previous substitutions, we finally get the following:

$$W_{Q_k}(s) = (k_g + 2h_g s)\left[\frac{-2s^2(n_2 s + 2n_1 n_3)}{s^4 + 2n_2 s^3 + [1 + n_1(1 + 2n_3)]s^2 + 2n_2 s + 22n_1 n_3}\right] \tag{10}$$

To obtain the maximal loads acting in the skip head-skip hopper system, the damping has to be neglected; therefore, $h_g = 0$. Finally, we get the following:

$$W_{Q_k(s)} = \frac{-2k_g s^2 \left(n_2 s + 2n_1 n_3\right)}{s^4 + 2n_2 s^3 + \left[1 - n_1\left(1 + 2n_3\right)\right]s^2 + 2n_2 s + 2n_1 n_3} \tag{10a}$$

Thus, the spectral density of the skip head-skip hopper interaction force becomes

$$S_{Q_k}(\omega) = \left|W_{Q_k}\right|^2 S_{x_1}(\omega) \tag{11}$$

The variance of the interaction force amplitude is expressed as follows:

$$D_{Q_k} = \frac{1}{2\pi}\int_{-\infty}^{\infty}\left|W_{Q_k}\right|^2 S_{x_1}(\omega)\,d\omega \tag{12}$$

Recalling (5) and substituting for s = iω' in (10a) and bearing in mind the earlier substitution

$$d\omega = p_{10}\,d\omega'$$

We obtain

$$D_{Q_k} = \frac{{k_g}^2}{2\pi}\int_{-\infty}^{\infty}\left|\frac{-2s^2\left(n_2 s + 2n_1 n_3\right)}{s^4 + 2n_2 s^3 + \left[1 + n_1\left(1 + 2n_3\right)\right]s^2 + 2n_2 s + 2n_1 n_3}\right|^2 \frac{2D_x n}{\left[n^2 + (\omega')^2\right]}\,d\omega' =$$

$$ {k_g}^2\,\frac{8D_x n}{2\pi}\int_{-\infty}^{\infty}\frac{(i\omega')^4\left[4n_1^2 n_3^2 - n_2^2 (i\omega)^2\right]}{\left|\left[(i\omega')^4 + 2n_2 (i\omega')^3 + \left[1 + n_1\left(1 + 2n_3\right)\right](i\omega')^2 + 2n_2 (i\omega') + 2n_1 n_3\right]\left[n + \omega'\right]\right|^2}\,d\omega' \tag{13}$$

Rearranging, we get the following:

$$D_{Q_k} = {k_g}^2\,\frac{4D_x n}{\pi}$$

$$\int_{-\infty}^{\infty}\frac{\left[-n_2^2 (i\omega)^6 + 4n_1^2 n_3^2 (i\omega)^4\right]}{|(i\omega')^5 + (2n_2 + n)(i\omega')^4 + [1 + n_1(1 + 2n_3) + 2n_2 + n](i\omega')^3 + [2n_2 + n + n_1 n(1 + 2n_3)](i\omega')^2 + 2(n_1 n_3 + n_2 n(i\omega') + 2n_1 n_3 n|^2}\,d\omega' \tag{13a}$$

After further transformations, we obtain the following [2]:

$$D_{Q_k} = {k_g}^2\,\frac{4D_x n}{\pi}\int_{-\infty}^{\infty}\frac{G(i\omega')}{\left|A(i\omega')\right|^2}\,d\omega \tag{14}$$

where

$$G(i\omega') = -n_2^2 (i\omega)^6 + 4n_1^2 n_3^2 (i\omega')^4$$

$$A(i\omega') = (i\omega)^5 + \left(2n_2 + n\right)(i\omega)^4 + \left[1 + n_1\left(1 + 2n_3\right) + 2n_2 + n\right](i\omega)^3 +$$

$$+ 2n_2 + n\Big](i\omega)^3 + [2n_2 + n + n_1 n\left(1 + 2n_3\right)](i\omega)^2 + 2(n_1 n_3 + n_2 n(i\omega) + 2n_1 n_3 n$$

Computing the integral, we get the following:

$$D_{Q_k} = \frac{4D_x n}{\pi}{k_g}^2\,\frac{\pi(-1)^6 M_{50}}{a_{0_5}\cdot\Delta_{50}} \tag{15}$$

where

$$M_{50} = -a_0\left\{a_5\left[b_1^*\left(a_3 a_4 - a_2 a_5\right) + b_2^*\left(a_0 a_5 - a_1 a_4\right) + b_3^*\left(a_1 a_2 - a_0 a_3\right)\right] + b_4^*\left[a_1\left(a_1 a_4 - a_2 a_3\right) + a_0\left(a_3^2 - a_1 a_5\right)\right]\right\}$$

$$\Delta_{50} = -a_5\left\{a_0^2\cdot a_5^2 - 2a_0 a_1 a_4 a_5 - a_0 a_2 a_3 a_5 + a_0 a_3^2\cdot a_4 + a_1^2\cdot a_4^2 + a_1 a_2^2\cdot a_5 - a_1 a_2 a_3 a_4\right\}$$

and

$$b_1^* = -n_2^2\,;\; b_2^* = 4n_1^2 \cdot n_3^2\,;\; b_3^* = 0\,;\; b_4^* = 0$$

The expression (15) can be rewritten as follows:

$$D_{Q_k} = 4D_x n \cdot k_g{}^2 \cdot I_{50} \tag{16}$$

where

$$I_{50} = \frac{M_{50}}{a_0 \cdot \Delta_{50}} \tag{16a}$$

2. Stresses in load-bearing elements of a conveyance

The model used in the computational procedure to find stresses in load bearing elements of a conveyance is based on the technical specification of such devices [6], retaining the dimensions and masses of individual components.

The model used adopted when investigating the stresses in the conveyance's load-bearing elements, particularly the ropes and cables, is shown schematically in Fig. 3.

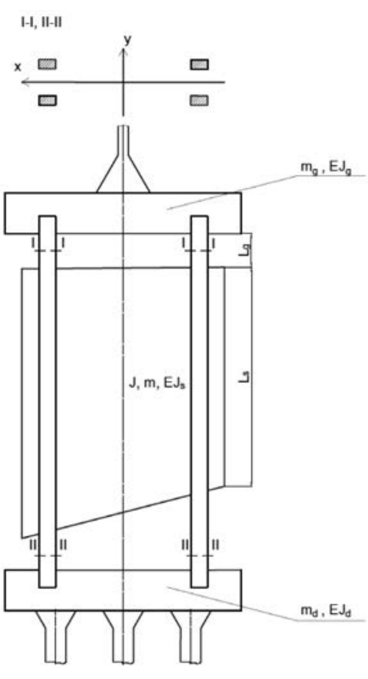

Fig. 3. Skip model used in the computational procedure

The diagram features the following components:

1. Skip head with its mass m_g and bending stiffness EJ_g,
2. Bottom frame with its mass m_d and bending stiffness EJ_d,
3. Skip hopper with its mass m and bending stiffness EJ_s,
4. Cables connecting the head to the hopper and with the bottom frame with its mass m_c and bending stiffness EJ.

Recalling that

$$EJ_g >> EJ,$$
$$EJ_d >> EJ, \text{ and}$$
$$EJ_s >> EJ,$$

the model structure can be further simplified. The skip head, bottom frame, and hopper are treated as ideally rigid and rigidly connected by ropes and cables. The inertia moment of the entire structure's cross-section is taken to be equal to the sum of inertia moments of individual cables. As the structure is symmetrical in the plane x-x and y-y and the masses of skip head, bottom frame, and hopper are taken to be rigid, further analyses use the simplified model shown in Fig. 4, whereby the skip is divided into two parts at its mid-length and in the plane x-x.

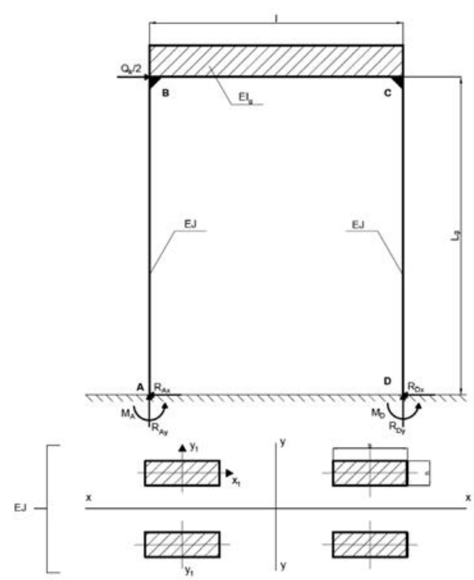

Fig. 4. Simplified model of the skip used in the computational procedure

For the adopted 2 D schematic model, the forces were determined that acted upon its cross-sections due to the force $Q_k/2$ applied as shown in Fig. 4, which was the conveyance-shaft steelwork interaction force experienced during the conveyance travel at the fixed velocity $V_0 = const.$ Plots of bending moment and the traverse and longitudinal forces acting upon the frame, as shown in Fig. 4, are given elsewhere [6].

The maximal values of bending moment registered at points A and B (as well as at points C and D because of symmetrical geometry) are equal and can be expressed as follows:

$$|M_A| = |M_B| = \frac{Q_k \cdot l_g}{16} \tag{17}$$

The maximal stress acting in a single cable is equal to

$$\sigma = \frac{M_A}{W_g} = \frac{3}{8}\frac{Q \cdot l_g}{bh^2} \tag{18}$$

where

l_g – cable length, distance between the skip hopper and head,

b, h – dimensions of the cable's cross-section (Fig. 4).

Since the parameters l_g, b I h in (18) are constant (as geometric dimensions), the only variable parameter in this equation is the force $x_g(s) = W_{X_g}(s) \cdot x_1(s)$, i.e. the internal force acting in the cable transverse sections and generated by horizontal displacements of the conveyance due to random irregularities of the guide strings.

Therefore, the relationship between the horizontal force and stresses acting in cables is found to be linear. Further, the assumption was made that the relationship between the variance of load in the head-skip hopper system (16) and the variance of amplitude of the maximal stresses in cables connecting the skip hopper and the skip head should also be linear. Accordingly, we get the following:

$$D_\sigma = \frac{6l_g}{16bh^2} D_{Q_k} \tag{19}$$

Recalling (16), we obtain

$$D_\sigma = \frac{6l_g}{16bh^2} 4D_x n \cdot k_g^{\,2} \cdot I_{50} = \frac{3}{2} D_x n \cdot k_g^{\,2} \frac{l_g}{bh^2} \cdot I_{50} \tag{20}$$

Likewise (6a), the product $D_{x1}n$ in (20) is related to parameters of the random excitations, while (16a) is associated with parameters describing the investigated object.

Variations of I_{50} in relation to $n_1 = \frac{m_A}{m_g}$ for two values of n_2 (for $n = \alpha\sqrt{\frac{m_A}{k_g}} = 0.1$, $n_3 = \frac{k}{k_g} = 0.01$ – describing the properties of the investigated object) are illustrated in Fig. 5.

The variability range of parameters n_1, n_2, n_3 and n were chosen by the same procedure as in the case of (6b).

Recalling Fig. 5 (likewise Fig. 2 in the earlier case), the parameters of the hoisting installation can be chosen to guarantee that the critical load-bearing capacity levels should not be exceeded for a known random pattern of irregularities and misalignments of the guide string (6).

The adequacy of the research method adopted to investigate the dynamic behaviour and fatigue endurance of a conveyance will be verified by testing done on a real object [6]. Measurement results and fatigue endurance data will be summarized in a separate paper.

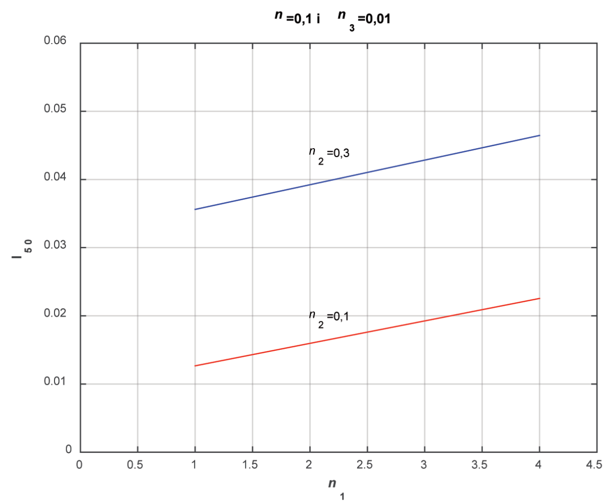

Fig. 5. **I_{50} (16a) is relation to for n = 0.1 and $n_1 = \frac{m_A}{m_g}$ $n_3 = 0.01$**

Conclusions

The analysis of dynamic behaviour of a hoisting installation during the normal duty cycle (conveyance travel with the fixed velocity V_0 = const.), based on the assumption that horizontal displacements of lumped masses in the modelled system are induced by random irregularities and misalignments of the guide strings, yields the spectral densities of interaction forces between modelled masses and of the force variance amplitudes [5, 7].

For the 2D skip model adopted for the computational procedure, the forces are obtained that act upon the load-bearing cables' cross-sections. In this study they are restricted to the applied bending moments. Determining the forces acting upon the cable cross-sections in the skip allows for finding the maximal stresses acting in a single element (cable).

Thus, the derived formula and its graphic interpretation allow the parameters to be chosen so that the stresses registered in load-bearing elements of a conveyance should not exceed the critical levels.

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