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Dagmara TEJSZERSKA
Politechnika Śląska, Gliwice

SENSITIVITY ANALYSIS IN MINE HOISTING SYSTEM

Summary. {PRIVATE }This paper deals with mathematical model simulating dynamic phenomena, occurring in mine hoisting systems. The performed model consists of extended model of mechanical part and model of the motor hoisting machine with control system. The sensitivity analysis and optimization of dynamic features of the system are also presented.

ANALIZA WRAŻLIWOŚCI UKŁADU WYCIĄGOWEGO

Streszczenie. W artykule przedstawiono model matematyczny opisujący zjawiska dynamiczne górniczych układów wyciągowych. Obejmuje on część mechaniczną układu, poszerzoną o elementy napędu wraz z regulacją. W ramach pracy została przeprowadzona analiza wrażliwości oraz optymalizacja cech dynamicznych układów wyciągowych.

1. Modelled hoisting system

The scheme of analysed hoisting system, consisting of longitudinally vibrating lifting and balance ropes, longitudinally, transversely and torsionally vibrating cages and torsionally vibrating winding machine and pulleys is presented on fig.1.

Electromechanical model of coupled transverse and longitudinal vibrations of hoisting system was elaborated by authors of this work [1, 2, 3, 4, 5].

Longitudinal vibrations cause fatigue wear of ropes. They are generated mainly by the processes of starting and braking, depending on electromechanical properties of winding machine and on the action of controller, changing driving moment accordingly to determined tachogram.. Great vibrations in emergency states may cause failure of all hoisting system. Transverse vibrations of cages, excited by irregularities of guides, cause great dynamic stresses in cage beams and interactions between cage and guides, resulting in erosion and fatigue wear.

Multirope system, with flexible cages, equipped with rollers and slide shoes, interacting with flexible shaft guides is analysed. Impact of dynamically varying forces in ropes - on the transverse vibrations, and of the friction forces, resulting from rollers interactions, on the longitudinal vibrations is considered. The phenomena connected with variations of load, carried by each rope, sliding of ropes and movement of suspension elements are included. The effects of variations of length of branches and stiffness of individual ropes, friction and internal damping as well as the possibility of system asymmetry were taken into account. Complex form of interaction between rollers and guides, including existence of clearances or preliminary thrust, mating of rollers and slide shoes and various stiffness of shaft guides in different points were considered.

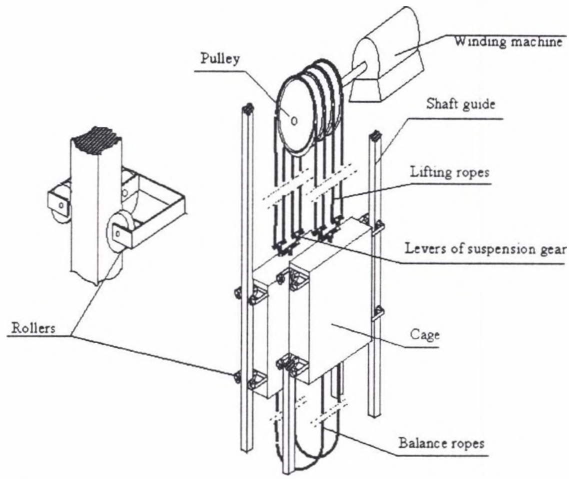

Fig.1. Scheme of analysed hoisting system
Rys.1. Schemat analizowanego układu wyciągowego

2. Method of solving model equations

The mathematical model, describing vibrations of assumed physical model of mine hoist, has the form of non-linear system of partial and ordinary differential equations. After division of continuous ropes onto discrete elements the mathematical model assumes a form of system of non-linear ordinary differential equations, binding accelerations, velocities and displacements of pulley (u), two cages, uplifting and falling (u,f - $y_{s,u}$, $z_{s,u}$,..$\Delta\varphi_f$), all discrete elements (i, j) of lifting and balance ropes (k,l - ...$x_{i,k}$,...$x_{j,l}$...), parameters of winding machine (driving moment M., voltage U), and parameters of determined tachogram (u_{det}) :

$$F(t,\ddot{u},\ldots\ddot{x}_{i,k},..\ddot{x}_{j,l}..,\ddot{y}_{s,u},\ddot{z}_{s,u},.\ddot{\Delta}_{\varphi f},\dot{u},.\dot{u}_{det},\dot{U},\dot{M},\dot{x}_{i,k},..\dot{x}_{j,l}..,\dot{y}_{s,u},\dot{z}_{s,u},.\dot{\Delta}_{\varphi f},u,u_{det},U,M,x_{i,k},..x_{j,l}..,y_{s,u},z_{s,u},.\Delta_{\varphi f})=0 \qquad (1)$$

The system is solved numerically by substitution of time derivatives by adequate finite difference expressions, based on parabolic splines of time transients of all considered dynamic displacements in every time step Δt.

Accelerations and average values of displacements and velocities in the time step Δt, introduced into equations of dynamic equilibrium, are expressed by values on the borders of time step. Method of parabolic splines was chosen as the most convenient for the purposes of the work, after analysis of the simplicity of programming, precision, time of calculation and stability of some methods of integration of ordinary differential equations.

Three sets of linear algebraic equations, with coefficients varying in time are obtained as a result of discretisation. They define dependence of all considered displacements in the end of time step on displacements and velocities in the beginning of step, for longitudinal vibrations of system and for transverse vibration of two cages :

$$\begin{aligned}
&\mathbf{A}(t)\bullet[u',U',M',\ldots\ldots x'_{i,k},\ldots x'_{j,l}\ldots]^T=\mathbf{B}\,(t,u^o,U^o,M^o\ldots\ldots x^o_{i,k},\ldots x^o_{j,l}\ldots,\dot{u}^o,\ldots\dot{x}^o_{i,k},\ldots\dot{x}^o_{j,l}\ldots),\\
&\mathbf{C}_u(t)\bullet[x'_{s,u},y'_{s,u}\ldots\Delta\varphi'_u]^T=\mathbf{D}_u\,(t,x^o_{s,u},y^o_{s,u}\ldots\Delta\varphi^o_u,\dot{x}^o_{s,u},\dot{y}^o_{s,u}\ldots\Delta\dot{\varphi}^o_u,)\\
&\mathbf{C}_l(t)\bullet[x's,u,y's,u\ldots Dj'u]^T=\mathbf{D}_l\,(t,x^o_{s,u},y^o_{s,u}\ldots\Delta\varphi^o_u,\dot{x}^o_{s,u},\dot{y}^o_{s,u}\ldots\Delta\dot{\varphi}^o_u,)
\end{aligned} \tag{2}$$

These equations are solved by triangular reduction, with selection of main element and full utilisation of properties of sparse main matrix **A** of a set, describing longitudinal vibrations. All three sets are solved parallelly, with introduction of forces in ropes, calculated by the model of longitudinal vibrations, and frictional forces, calculated by transverse vibrations model - into equations of dynamic equilibrium of cage in the model of other vibrations.

The values of forces in ropes and acting on guides, stresses in ropes and in main supporting beams of cages, accelerations and velocities of all elements, in the end of time step, are then calculated. The values of displacements x'... and velocities $\dot{x}'$... in the end of time step are treated as starting values x^o..., $\dot{x}^o$.... for the next time step.

Elements of main matrices $\mathbf{C}_{u,l}$, describing different forms of contact between rollers and guides, and elements of matrix **A** connected with variations of elasticity modulus of rope, caused by changes of stresses, with sliding of individual ropes on pulley and with motion of suspension gear - are corrected in every time step, together with calculation of elements of column matrices **B**, $\mathbf{D}_{u,l}$, containing values of displacements and velocities in the beginning of time step and actual values of excitations and other parameters.

Every change in condition of contact of one of rollers or shoes with guide - strongly changes its effective stiffness and coefficients of matrices $C,D_{u,l}$. After determination of displacements in the end of time step the conditions of contact of every roller are checked. If they are different from initial - then the first time instant of their change (inside time step Δt) is calculated, basing on above mentioned parabolic approximation of transient of every displacement. Interpolated values for this time instant are treated as initial for next time step.

The stationary positions of cages and tensions in ropes are calculated before starting the simulation of vibrations. These calculations are necessary - their lack should introduce the disturbance in the first period of motion, having the form of really non existing dynamic excitation. The equations describing stationary state are slightly simpler, but similar to general dynamic equations. Calculations of initial stationary state are performed iteratively.

3. Method of sensitivity analysis

Computer program, elaborated by authors, enables simulation of dynamic phenomena occurring in mine hoists having optional parameters. Extensive analysis of dynamic properties of mine hoists was performed with the use o: program. Separate options of program are provided for sensitivity analysis and for optimisation

Sensitivity analysis shows influence of individual features of the object on its dynamics and enabled proper selection of optimised parameters. It was performed by numeric gradient method. The gradients of criterial parameters in the space of decisive structural and process parameters were obtained by performing sequence of simulations of mine hoist motion, every with little changed value of one of decisive parameters. Gradient elements were calculated as the ratios of relative changes of criterial values to relative changes of decisive parameters.

Maximal and average values of stresses in ropes, rollers and elements of cages, amplitudes of their dynamic changes, maximal accelerations of cages in longitudinal and transverse directions, maximal driving moment, values of sliding of single ropes along the pulley and the time of whole transport process were treated as criterial dynamic factors.

Systematic sensitivity analysis was performed for group of decisive structural and process parameters, including maximal accelerations of start-up and braking and time of increasing or decreasing of acceleration in the demanded tachogram of hoist motion, gain and time constants of winding machine controller, stiffness of rollers, clearances or preliminary thrust between rollers and slide shoes and shaft guides, and factors describing irregularities of shaft guides. Independent or joint analysis of changes of parameters describing accelerations of start-up and braking, and of characteristics of side and frontal rollers are provided.

Apart from systematic sensitivity analysis extensive investigations of influence of other struc-tural and process parameters, especially describing imperfection of construction and method of operation were performed. They include properties of ropes, considering differences of individu-al ropes, asymmetry of cage structure and load and diversification of diameters of pulley grooves

Results of sensitivity analysis are presented in the form of tables, showing changed values of criterial parameters and their gradients for all analysed changes of decisive parameters. Results of simulation of mine hoist motion for individual changes of decisive parameters can be also presented in the form of time graphs, enabling comparison of transients of chosen parameters.

4. Results of sensitivity analysis

Characteristic results of performed sensitivity analysis, concerning stresses in ropes, and longitudinal vibrations generally are presented in the table below and on graphs on next sides..

Tabela1

Exemplary results of sensitivity analysis of electromechanical model of mine hoisting system (parameters characterising longitudinal vibrations).

Joined changes of parameters characterising start-up and braking accelerations in demanded tachogram.

Description of parameters

T.przysp	Time of in/decrease of start-up/ braking acceleration in demanded tachogram [s]	K reg.pr	Gain of winding machine controller
Przysprh	Start-up/ braking acceleration [m/s2]	T reg.pr	Time constant of winding machine controller [s]
A, B	Uplifted and falling branch of hoist		
Min	Minimal value of parameter	Max	Maximal value of parameter
Srm	Average absolute value of parameter	SrA	Average amplitude of parameter's changes
Wsr	Sensitivity factor for average values.	Wmx	Sensitivity factor for extreme values
Podst	Basic value of analysed parameter.	Zmian	Changed value of analysed parameter.

Analysed decisive parameter	Type of results	Long.cage acceleration X"-AB m/s^2	Stresses in rope near pulley S-A MPa	S-B MPa	Driving model Mk MNm	Transport. time T s
Basic State	Min	-1.33873	128.803	94.441	66.078	0.00
	Max	1.34112	228.661	166.947	1093.271	84.687
	Srm	0.28091	179.670	127.533	610.630	84.687
	SrA	0.03384	15.224	9.431	107.158	84.687
T.przysp	Min	-1.63875	127.792	93.967	-2.506	0.00
Podst=	Max	1.75523	230.783	170.855	1168.059	83.262
2.00	Srm	0.30380	179.771	127.471	612.549	83.262
Zmian=	SrA	0.04889	13.142	10.917	143.986	83.262
0.00	WSr	-0.04266	-0.00111	0.00093	-0.00439	0.04207
	Wmx	-0.77195	-0.02320	-0.05851	-0.17102	0.04207
T.przysp	Min	-1.13618	130.123	94.510	87.651	0.00
Podst=	Max	1.06570	228.201	164.904	1040.440	86.750
2.00	Srm	0.26816	179.565	127.583	608.816	86.750
Zmian=	SrA	0.02775	14.841	11.397	80.770	86.750
4.00	WSr	-0.02377	-0.00115	0.00075	-0.00415	0.06089
	Wmx	-0.38204	-0.00502	-0.03059	-0.12081	0.06089
K reg.pr	Min	-1.43566	128.736	93.783	11.812	0.00
Podst=	Max	1.36867	228.568	169.194	1110.105	84.587
2.0	Srm	0.28856	179.687	127.520	610.973	84.587
Zmian=	SrA	0.03441	15.986	8.588	130.464	84.587
1.0	WSr	-0.05706	-0.00074	0.00075	-0.00314	0.01181
	Wmx	-0.70489	0.00403	-0.13455	-0.15399	0.01181
K reg.pr	Min	-1.25735	128.827	94.350	83.613	0.00
Podst=	Max	1.31214	228.759	165.857	1077.704	84.700
2.0	Srm	0.27844	179.664	127.537	610.518	84.700
Zmian=	SrA	0.02987	14.722	9.225	83.534	84.700
3.0	WSr	-0.01844	-0.00024	0.00025	-0.00102	0.00148
	Wmx	-0.21611	0.00431	-0.06534	-0.14239	0.00148

Analysed decisive parameter	Type of results	Long.cage acceleration X"-AB m/s^2	Stresses in rope near pulley S-A MPa	S-B MPa	Driving model Mk MNm	Transport. time T s
K reg.pr	Min	-1.17034	128.909	94.182	85.915	0.00
Podst=	Max	1.26304	228.818	164.568	1057.373	84.700
2.0	Srm	0.27687	179.660	127.541	610.420	84.700
Zmian=	SrA	0.03284	13.705	9.800	83.126	84.700
5.0	WSr	-0.01005	-0.00014	0.00016	-0.00064	0.00049
	Wmx	-0.19407	0.00230	-0.04751	-0.10945	0.00049
K reg.pr	Min	-1.08533	129.152	93.937	85.103	0.00
Podst=	Max	1.19973	227.960	164.122	1060.839	84.725
2.0	Srm	0.27604	179.657	127.543	610.365	84.725
Zmian=	SrA	0.03063	11.071	9.228	69.600	84.725
10.0	WSr	-0.00454	-6.87E-5	7.50E-5	-0.00030	0.00055
	Wmx	-0.13178	-0.00383	-0.02116	-0.03708	0.00055
T reg.pr	Min	-1.19034	128.720	94.408	81.417	0.00
Podst=	Max	1.23026	228.700	164.916	1053.203	88.662
0.5	Srm	0.27667	179.669	127.534	610.609	88.662
Zmian=	SrA	0.02798	15.191	10.692	75.966	88.662
1.0	WSr	-0.03160	-2.70E-5	6.90E-5	-0.00019	0.46937
	Wmx	-0.82663	0.00171	-0.12167	-0.36649	0.46937
Treg.pr	Min	-1.10335	128.444	94.248	75.221	0.00
Podst=	Max	1.16431	229.169	164.350	1050.109	89.837
0.5	Srm	0.27848	179.677	127.536	610.685	89.837
Zmian=	SrA	0.02942	13.650	8.861	77.312	89.837
2.0	WSr	-0.00605	0.00011	6.17E-5	0.00017	0.20271
	Wmx	-0.43946	0.00741	-0.05186	-0.13160	0.20271
Przysprh	Min	-1.06887	132.422	96.440	162.368	0.00
Podst=	Max	1.07911	228.452	162.973	995.660	87.687
1.00	Srm	0.26959	179.466	127.627	607.142	87.687
Zmian=	SrA	0.02916	11.971	7.876	93.973	87.687
0.80	WSr	0.04220	0.00445	-0.00282	0.01595	-0.17712
	Wmx	0.97684	0.00457	0.11904	0.44642	-0.17712
Przysprh	Min	-1.61476	131.041	92.726	-47.825	0.00
Podst=	Max	1.59996	220.474	171.642	1189.418	82.687
1.00	Srm	0.28948	179.816	127.467	613.896	82.687
Zmian=	SrA	0.03767	13.722	10.954	118.646	82.687
1.20	WSr	0.03195	0.00320	-0.00198	0.01494	-0.11808
	Wmx	1.02017	-0.17902	0.14061	0.43972	-0.11808

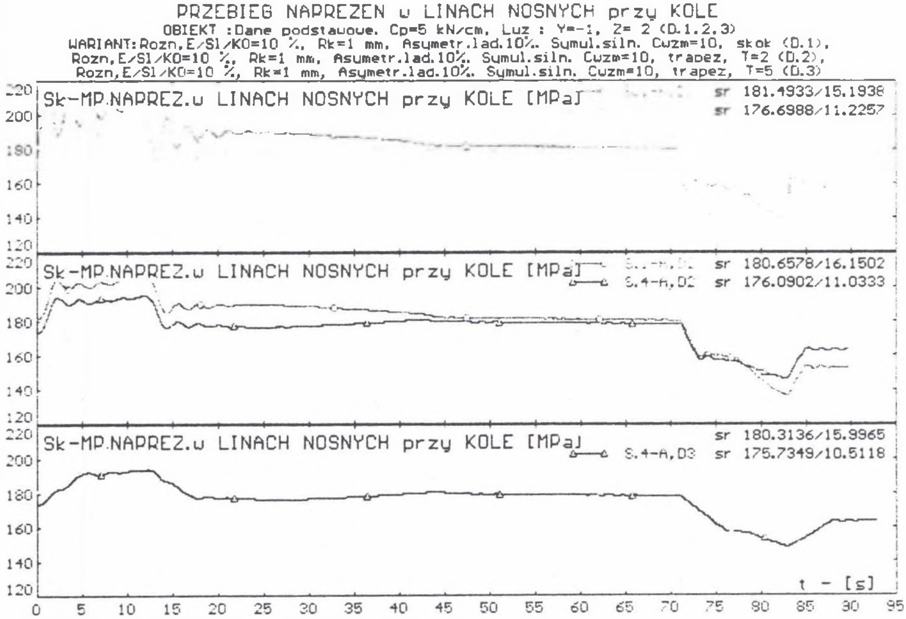

Fig.2. Effect of time T of growth and falling of acceleration in demanded tachogram of hoist motion on stresses in ropes 1 (S1) and 4 (S4) near the pulley (D1: T=0,stepwise tachogram, D2: T= 2 s, D3: T= 5 s)

Rys.2.Przebieg naprężeń w linach nośnych przy kole

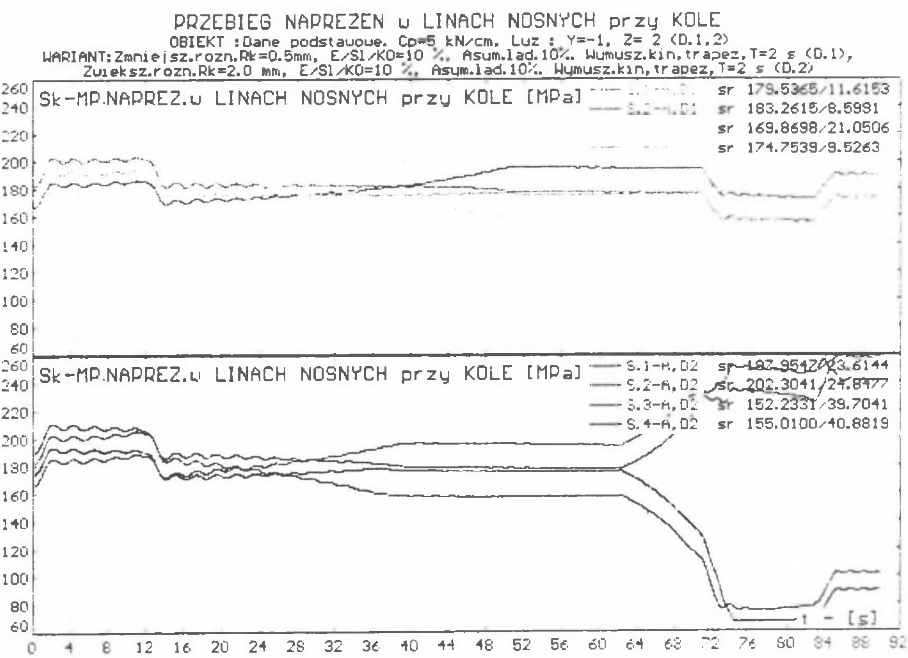

Fig.3. Effects of differentiation of diameters of rope grooves in pulleys on stresses in ropes 1..4 near the pulley (D1: relative standard deviation of diameters=0.00001, D2: s.d=0.00004)

Rys.3. Przebieg naprężeń w linach nośnych przy kole

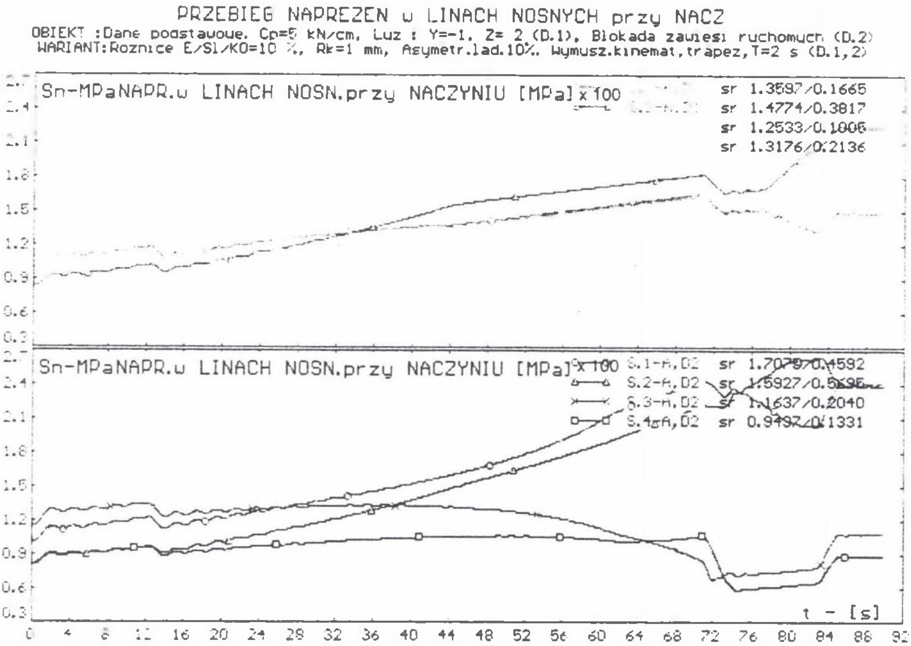

Fig.4. Effect of blockade of mobile levers of suspension gear on stresses in ropes 1..4 near the cage (D1: normal operation of levers, D2: blocked levers)

Rys.4. Przebieg naprężeń w linach nośnych przy naczyniu

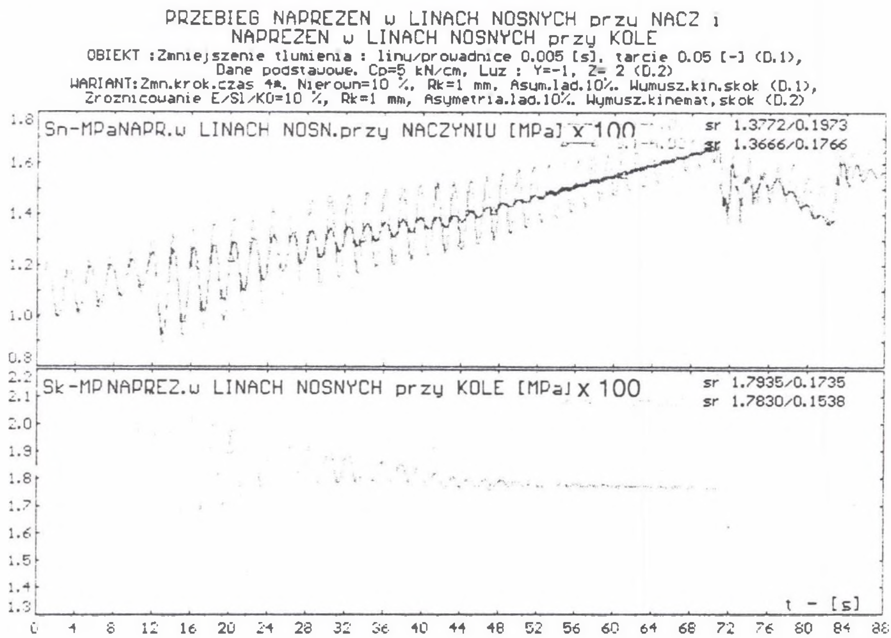

Fig.5. Effects of decrease of internal damping in ropes on stresses in ropes 1 near the cage
(D1: coefficient of internal damping 0.005 [s], D2: coefficient of internal damping 0.02 [s])

Rys.5. Przebieg naprężeń w linach przy naczyniu i naprężeń w linach nośnych przy kole

5. Conclusions

Quantitative results of sensitivity analysis strongly depend on the whole combination of structural and process parameters of mine hoist, but qualitative conclusions have more general character.

The analysis concerning parameters characterising longitudinal vibrations revealed that optimisation of gain of winding machine controller, decrease of maximal values of acceleration in demanded tachogram of hoist motion, elongation of time of growth and falling of this acceleration, and specially transition from stepwise to trapezoid form of demanded graph of acceleration causes great reduction of amplitudes of oscillations of accelerations of cages, considerable decrease of driving moment and maximal accelerations, and appreciable reduction of amplitudes of oscillations of stresses in ropes, decreasing their fatigue wear. Changes of maximal stresses in ropes are relatively small. Reduction of vibrations is bound with some elongation of global transportation time, so optimisation of dynamic properties of hoist must consider actual level of reserves of capacity of shaft.

The influence of proper operation of mobile levers of suspension gear is very important. Its blocking causes great growth of differences of stresses in individual ropes (sometime even twice), considerable growth of maximal stresses and increase of sliding of ropes, eroding pulleys. Similar is influence of differentiation of diameters of rope grooves in pulleys.

Decrease of internal damping in ropes causes very great growth of average amplitudes of oscillations and considerable increase of maximal stresses in ropes.

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Recenzent: Prof.Dr Ing. Jan Ondrouch

Abstract

The model of coupled transverse and longitudinal vibrations of hoisting system, caused by determined course of winding machine driving moment or acceleration, and by stochastic distribution of irregularities of shaft guides is presented in this work. Multirope system, with flexible cages, equipped with rollers and slide shoes, interacting with flexible shaft guides is analysed. Impact of dynamically varying forces in ropes - on the transverse vibrations, and of the friction forces, resulting from rollers interactions, on the longitudinal vibrations is considered. The phenomena connected with variations of load, carried by each rope, sliding of ropes and movement of suspension elements are included. The effects of variations of length of branches and stiffness of individual ropes, friction and internal damping as well as the possibility of system asymmetry were taken into account.

Exemplary results of simulation demonstrate the possibilities of developed model and compu-ter program. Extensive investigation of influence of parameters of the system on its vibrations is actually performed with the use of model and program. It will facilitate the selection of optimal parameters of designed hoisting systems as well as improvement of existing systems operation.