Arch. Min. Sci. **63** (2018), 1, 61-74

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.24425/118885

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MODEL TESTS OF LONGWALL SHEARER WITH STRING FEED SYSTEM

BADANIA MODELOWE KOMBAJNU ŚCIANOWEGO Z CIĘGNOWYM SYSTEMEM POSUWU

This article concerns model tests of longwall shearer with string feed system. The introduction outlined the problem of exploitation of thin seams, in particular hard coal seams, and briefly described the construction and operation technology of a single-unit shearer with a string feed system for their exploitation. The problem of modeling of longwall machines with such a feed system was presented, as well as the author's physical and mathematical model of a longwall unitary shearer. Then, for the assumed parameters, model tests were carried out on the dynamics of the longwall shearer together with the string feed system. Comprehensive dynamic tests were carried out for the wall height range from 1.0 m to 1.6 m, length from 180 m to 300 m and taking into account four dimensions of the applied chain. As a result, a number of information was obtained concerning the kinematics of the longwall shearer, its feed along the wall, as well as translations and rotation in relation to particular axes and loadings of particular construction nodes. The most important part are the results of model tests, which together with their interpretation enable verification and optimization of the construction as well as the selection of power of feeder drives and shearer body.

Keywords: thin seams, longwall shearer, analytical loadings tests, model tests, physical and mathematical model of the longwall shearer, load on the longwall shearer

W ostatnich latach kopalnie węgla kamiennego jak i producenci maszyn górniczych coraz więcej uwagi poświęcają możliwości skutecznej eksploatacji cienkich pokładów, czyli o miąższości od 1.0 m do 1.6 m. Sytuacja ta wynika ze znacznej ilość węgla zlokalizowanego w tych pokładach oraz braku odpowiedniego umaszynowienia pozwalającego na ich efektywną eksploatację w warunkach występujących w polskich kopalniach. W związku z tym omówiono innowacyjny kompleks ścianowy do eksploatacji pokładów cienkich. Realizacja prototypu takiego kompleksu, który nie ma odpowiednika wśród istniejących rozwiązań wymagała opracowania modelu fizycznego i matematycznego oraz realizacji badań symulacyjnych. Badania miały na celu przede wszystkim określenie obciążeń działających na poszczególne węzły konstrukcyjne kombajnu oraz napędów posuwu. Badania analityczne oraz symulacyjne są mocno rozwijaną dziedziną, ponieważ oprócz aspektu poznawczego, pozwalają na zminimalizowanie

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wystąpienia błędów w prototypie. Badania te, dzięki możliwości przetestowania wielu wariantów, również o skrajnych i krytycznych wartościach parametrów wejściowych, są źródłem cennych informacji, które nie są możliwe do uzyskania podczas badań rzeczywistego obiektu.

Podczas pracy, na kombajn działa szereg obciążeń wynikających z procesu urabiania organem frezującym, procesu ładowania ładowarką odkładniową, grawitacji, oporów ruchu kombajnu i łańcucha oraz siły z napędów posuwu. Przyjmując szereg akceptowalnych uproszeń opracowano model fizyczny a następnie matematyczny kombajnu jednoorganowego z cięgnowym systemem posuwu. Zapisany, za pomocą równań, model dynamiczny kombajnu z cięgnowym systemem posuwu umożliwił przeprowadzenie badań modelowych w środowisku Matlab. Parametry geometryczne kombajnu oraz jego masę, momenty bezwładności oraz położenie środka ciężkości wyznaczono na podstawie projektu wstępnego kombajnu w programie Autodesk Inventor. Kompleksowe badania dynamiki zrealizowano dla zakresu wysokości ściany od 1.0 m do 1.6 m, długości od 180 m do 300 m oraz przy uwzględnieniu czterech wielkości zastosowanego łańcucha. W rezultacie uzyskano szereg informacji na temat kinematyki kombajnu, jego posuwu wzdłuż ściany oraz translacji i rotacji względem poszczególnych osi oraz obciążenia poszczególnych węzłów konstrukcyjnych. Najważniejszą cześć stanowią wyniki badań modelowych, które wraz z ich interpretacją umożliwiają weryfikację i optymalizację konstrukcji oraz dobór mocy napędów posuwu i organu kombajnu. Szczególnie istotne jest obciążenie działające na płozy kombajnu, ramię ładowarki, zaczepy łańcucha napędowego oraz wał organu urabiającego. Dodatkowo wyznaczono wymaganą siłę napięcia wstępnego łańcucha gwarantującą prawidłową pracę cięgnowego systemu posuwu.

Zaproponowane rozwiązanie kombajnu jednoorganowego rozwiązuje szereg problemów związanych eksploatacją omawianych pokładów. Prezentowane rozwiązanie jest konstrukcją nową, znacznie różniącą się od obecnie produkowanych kombajnów ścianowych, stąd wyniki przeprowadzonych badań są kluczowe dla realizacji prototypu maszyny i całego kompleksu.

Słowa kluczowe: cienkie pokłady, kombajn ścianowy, badania analityczne obciążenia, badania modelowe, model fizyczny i matematyczny kombajnu, obciążenie kombajnu

1. Introduction

Recent years, hard coal mines and manufacturers of mining machinery have been paying more and more attention to the possibility of effective exploitation of thin seams, i.e. of thicknesses from 1.0 m to 1.6 m. This situation results from the large amount of coal located in these seams (Bołoz, 2015) and the lack of suitable machinery enabling their effective exploitation, in conditions specific for Polish mines. Concerning industrial field, Poland uses longwall systems, equipped with longwall shearer or plow systems (Korzeniowski, 2011; Krauze, 2016).

In recent years, several solutions of machines based on longwall systems have been developed, which are intended for exploitation of thin seams (Kotwica, 2016). In particular, the system equipped with a single-unit longwall shearer allows to eliminate to a large extent the defects of currently used plow and longwall shearer system (Bołoz, 2013, 2016). The solution of the thin seam systems is an example of innovation in mining machinery, which is important for the development of the industry and competitiveness (Midor, 2017; Zasadzień, 2015; Vanek, 2017). Implementation of this system is an opportunity for Polish companies to create effective competition for longwall and plow complexes.

Fig. 1 shows a longwall shearer longwall complex consisting of a one-unit longwall shearer 1, a scraper wall conveyor 2, a section of mechanised wall box 3 and a bottom-wall scraper conveyor 4. At the ends of the wall conveyor, there are its drives 5 and drives 6 of the longwall shearer. The level of the bottom of the pavement is lowered in relation to the bottom of the wall in such a way that the wall conveyor 4, conveyor 5 drive and longwall shearer 6 drive are built under the wall conveyor gutters. In the presented solution, the face transfer of wall conveyor 2 to wall conveyor 4 was used.

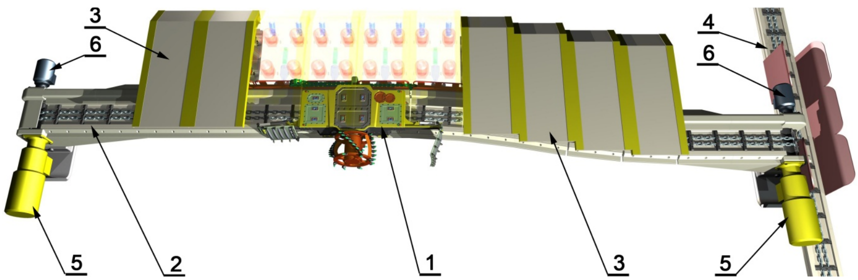

Fig. 1. Wall system for the exploitation of thin seams (Kotwica, 2016)

The hull of the longwall shearer can accommodate a power unit with a power output of approx. 2×120 kW together with a suitable planetary gearbox, safety features, lubrication and cooling system. The power output was determined on the basis of power utilisation reports from longwall shearer bodies and analysis of mining resistance for the designed knife system (Litak, 2010). In addition to the drive unit, the hull also includes hydraulic system, automation, control and diagnostics. The necessary and required sprinkler system can be installed in the body or similarly to plow system – in wall housings. The use of a water and airborne system (Prostański, 2012) is foreseen for dust reduction. This solution, together with the technology of work, parameters and analysis of daily extraction is presented in several literature papers (Bołoz, 2012, 2013, 2016).

The realisation of a prototype complex, which has no equivalent among the existing solutions, requires the development of a theoretical model and model research. Analytical and model researches are a highly developed field, because apart from the cognitive aspect, they allow to minimize the occurrence of errors in the prototype. Model tests, thanks to the possibility of testing many variants, including extreme and critical values of the input parameters, bring with them important information that is not possible to obtain when testing a real object.

2. Load on the single-unit longwall shearer

During operation, the longwall shearer is subjected to a number of loads from the milling unit, the loading process with a part loader, gravity, the resistance of the longwall shearer and chain movement, as well as forces from the feed drives.

Fig. 2 shows the model of a single-unit longwall shearer and below there is a load diagram. It shows the geometry of the combine plotted with orange lines. The *xyz* coordinate system was adopted at the centre of gravity of the longwall shearer. The forces and moments acting in the direction and in relation to the x, y, z axes are marked in blue, red and green. In addition, the hull, unit and loaders are subjected to load forces. Their components were marked succesively as G_x, G_y, G_z, G_{xo}, G_{yo}, G_{zo}, G_{xl1}, G_{yl1}, G_{zl1}, G_{xl2}, G_{yl2}, G_{zl2}. P_1 is a force in the branch of active chain, while P_2 is a force in the passive branch. A longwall shearer running through the guides generates press forces, lateral forces and resulting frictional forces. The vertical reactions in the skids are marked successively as N_1, N_2, N_3, N_4 and side reactions are B_1, B_2. These reactions additionally induce friction forces in the direction of the z axis, marked as T_1, T_2, T_3, T_4 and friction forces in the direction of the y axles are marked as T_{b1}, T_{b2}, T_{b3}, T_{b4}. The relevant linear dimensions and the position angle of the loader are also indicated in the diagram. Due to the expected low values, the load in the direction of the *y*-axis caused by the shape between the wall and the longwall shearer was omitted, as well as the force induced by the resistance of the cable stacker crane movement. The load from the mining pores can also be determined by determining the actual cutting resistance of the tool during empirical tests (Biały, 2014, 2016).

Taking a series of acceptable simplifications into consideration, a physical model was developed which is shown schematically in Fig. 3, and then a complete mathematical model of a single-unit longwall shearer with feed string system. The physical model diagram is marked with important symbols describing the drive of longwall shearer. Coordinates (x, y, z, φ), masses (m), mass moments of inertia (I), driving moments (M) of resistance moments (M_o), elasticity coefficients (k), chain tension force (F) and chain resistance (O) were applied. The longwall shearer has six degrees of free, whereas only the sprocket wheels rotate.

The adopted model is different from the known models, designed for analysis of longwall shearer, plows with drawbar feed systems or scraper conveyors. When considering significant

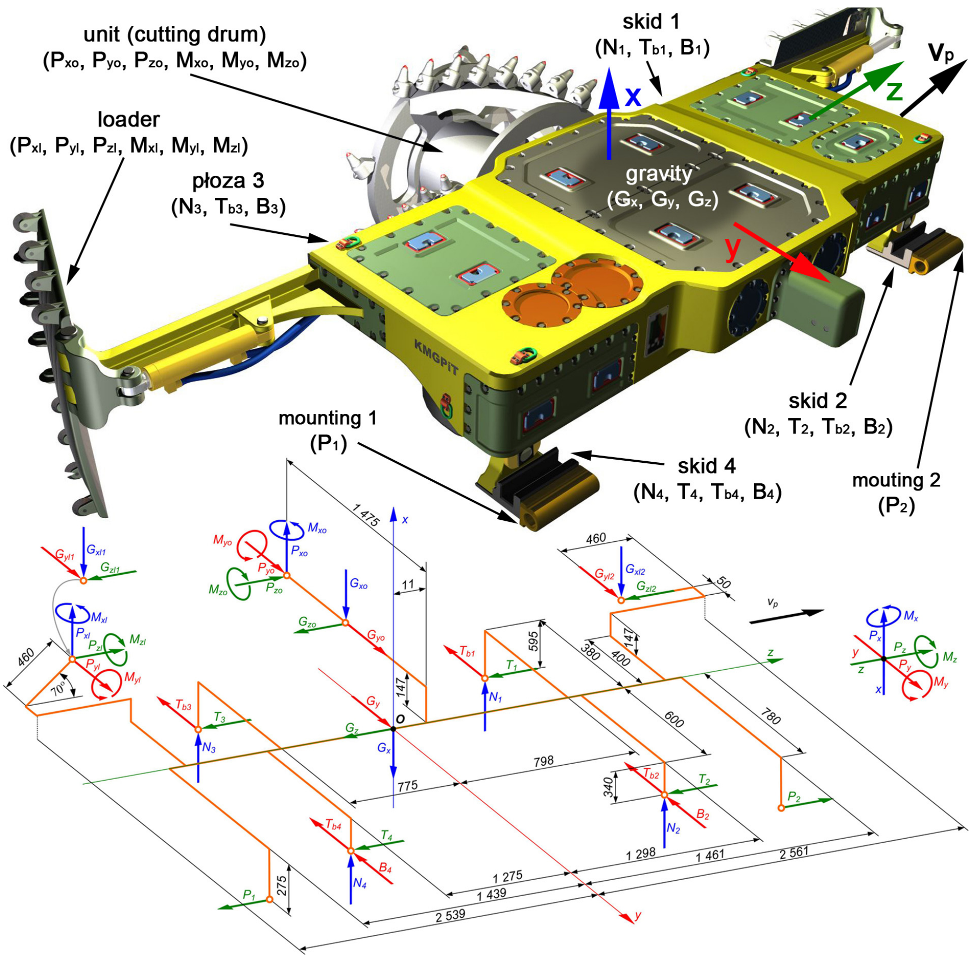

Fig. 2. Longwall shearer model and load diagram of the single-unit longwall shearer (dimensions in [mm])

differences, it is worth to emphasize that the model allows for six degrees of free of the longwall shearer, a continuous and evenly distributed weight of the chain, and the phenomenon of changing the weight of individual chain segments during the longwall shearer's operation, which makes it possible to simulate the longwall shearer's passage through the wall. A matrix equation of movements of the single-unit longwall shearer was derived as the final record of the model. The dynamic model of a longwall shearer with a feed thrust tendon system, recorded using equations, made it possible to determine a series of quantities describing its behaviour and load. Due to the complexity of the obtained equations, the study was conducted in the Matlab environment. The implemented dependencies were saved in the form of appropriate scripts. In order to solve differential equations, the Runge's-Kutta Level IV method was used. Due to the extent of the obtained equations, they are not included in the text of the article.

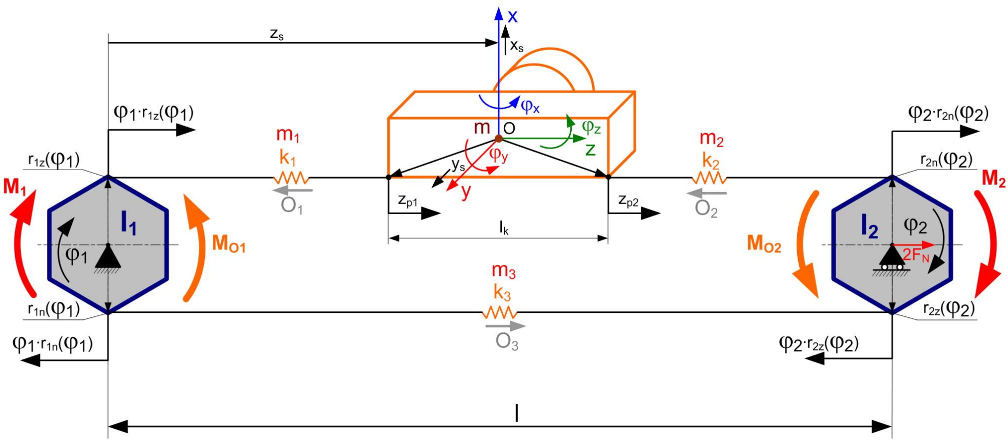

Fig. 3. Physical model of a single-unit longwall shearer with feed thrust system

3. Parameters of the system for thin seams

In order to perform model tests, the values of the input parameters had to be determined. The length of the wall excavation was assumed to be L = {180 m, 220 m, 260 m, 300 m} and the height of the wall H = {1.0 m, 1.2 m, 1.4 m, 1.6 m} and the height of the wall was assumed to be 0.8 m. Based on the initial design of the single-unit longwall shearer, Autodesk Inventor determines the weight of the longwall shearer (m = 10 760 kg), moments of inertia (I_x = 8 932 kgm^2, I_y = 10 827 kgm^2, I_z = 2 419 kgm^2) the location of centre of gravity and dimensions (Fig. 2).

The parameters of the link chain were adopted on the basis of the Thiele catalogue and PN-G-46701 standard: Mining link chains. Four sizes of the THD 18×64,22×86,26×92,38×137 type chain were assumed together with the corresponding nesting wheels. Based on preliminary tests, the required power of twin feed propulsion systems was determined. A 100 kW asynchronous motor was selected, based on the Damel catalogue. Static coefficient of friction of the skids of the longwall shearer and chain for guidance μ = 0.10, while kinetic coefficient of friction μ = 0.07. Friction coefficient of the spoil with a bottom of layer of μ_{ws} = 0.50÷0.80. Friction factor of the spoil with a surface of the loader μ_{wl} = 0.30÷0.50 (Bołoz, 2012).

4. Qualitative analysis of the load on the longwall shearer

By changing the values of individual parameters during researches we obtain different configurations. By altering the height and length of the wall, the size of the chain and the direction of rotation of the unit a total of 128 different configurations were obtained. Checking the influence of the longwall shearer position on the length of the wall in several places results in hundreds of parameters that should be simulated. In order to reduce the number of simulations, a qualitative analysis of load on the longwall shearer was carried out and irrelevant parameter configurations were excluded. The optimal calculation step h was also determined empirically. Analysing the duration of the simulation and the accuracy of the obtained results, the step value $h = 0.01$ s was determined.

Changing the height of the wall entails a change in the diameter of the unit, the height of the longwall shearer and the permitted feed rate of the longwall shearer. The change of the chain size is connected with the change of its stiffness and weight, moreover, the diameter of the drive wheels, gear ratios and reduced moments of inertia of the drives is changed. The length of the wall determines the length of the drive chain. The change of direction of rotation of the unit does not affect other model parameters. As part of the model tests, a full qualitative analysis was carried out. Selected results of influence of individual parameters are presented below.

Figure 4a presents the influence of wall height on the courses of longwall shearer feed rate. In accordance with assumptions, the speed of longwall shearer results from the right process of the miling process (cutting depth, motion angles). Starting time increases due to the modification in cutting resistance, resulted by the change in the unit diameter.

Figure 4b present the sample diagram of the wall height influence on the value of reaction force in the skid 2. Skids numbers are compatible with number of indexes assumed on the single-

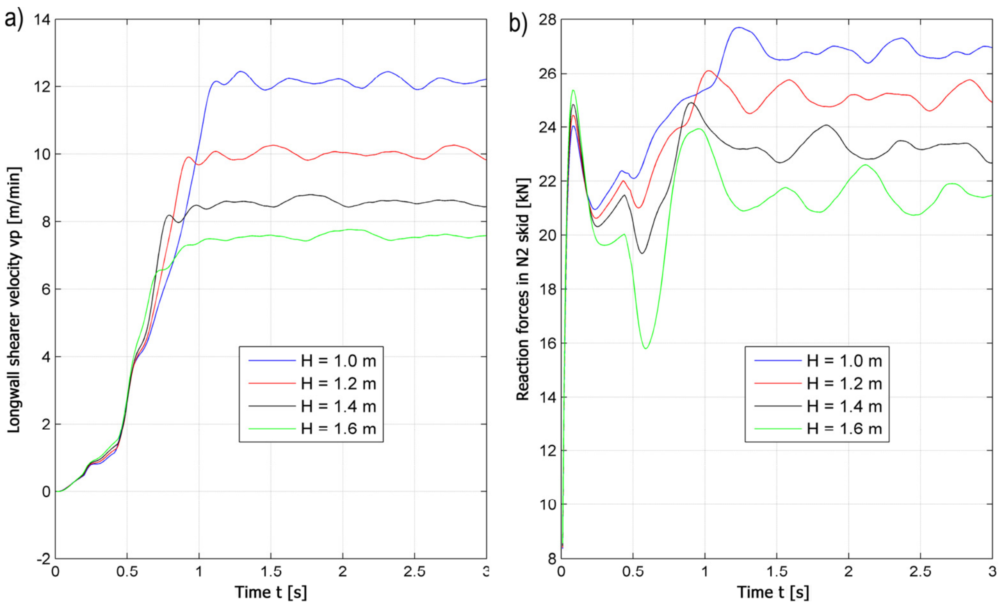

Fig. 4. Influence of the wall height on a) feed velocity of the longwall shearer, b) reaction force in the skid 2

unit longwall shearer load schemes (Fig. 2). Changing mining and loading resistance, depending on the height of the wall influences at the varying degrees the longwall shearer's behaviour, i.e. its speed and linear and angular displacements. The angular velocity of the longwall shearer ω_x increases during the start up phase as the load increases by up to 50%. During operation, the amplitude increases and the frequency decreases. The angular velocity ω_z also changes during startup and in fixed operation. The increase in speed ω_x and ω_z during startup affects the average values of the rotational angles of the longwall shearer's hull φ_x and φ_z during fixed operation. The average value of these angles increases by up to 30%. Increasing the diameter of the body affects the angular velocity ω_y, which in turn increases the mean value and amplitude of angular displacement during fixed operation of a longwall shearer. Increasing the height of the wall results in a decrease of the rotational speed of the body.

As the length of the wall increases, the relative elongation of the chains decreases, while the absolute elongation increases. No significant influence of the wall length on reaction forces in skids, friction force or side forces was observed. Due to the dependence of the coefficient of elasticity of the chain on its length, the change of the length of the wall influences the forces in the chain hooks on the longwall shearer. A longer wall generates less force in the hooks. Fig. 5 shows the effect of the wall length on the forces $P1$ and $P2$. Force values are given without taking into account the preload of the chain, hence the force $P1$ takes the negative value. To calculate the actual load value, a chain preload must be added to the specified force values. Intentionally, this procedure was applied because the preload force is based on, among other things, the value of the $P1$ force and must be such that there is no release of the chain. The value of the chain preload has been determined based on the results of all simulations taking into account also the extreme values of the parameters. The change in wall length does not affect noticeably the linear and angular velocities, linear and angular displacements of the longwall

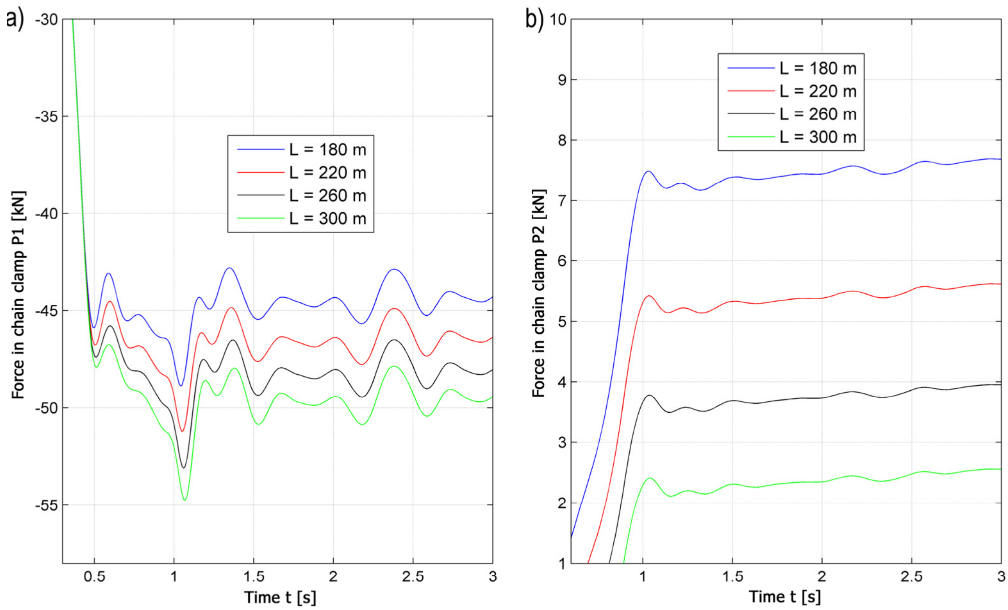

Fig. 5. Influence of the wall length on the clamping force a) force $P1$, b) force $P2$

shearer. With the length of the wall, the chain elongation increases slightly when the longwall shearer starts up.

Changing the chain size affects the longwall shearer's behaviour differently when it is at the beginning of the wall and differently halfway through. For a longwall shearer at the beginning of the wall, the change in chain size changes the v_{xs} and v_{ys} values at start-up. Changing the size and thus the stiffness of the chain has a significant influence on the amplitude of the feed speed of the longwall shearer. The greater the chain stiffness, the lower the amplitude of oscillations in the direction of the axis z. Increasing stiffness by about four times results in almost three times reduction of amplitude. The size of the chain slightly influences the starting time of the longwall shearer. Increasing chain size increases the amplitude of angular velocities ω_x and ω_z, which in turn increases the rotation angles of the hull of the φ_x and φ_z longwall shearer. The more rigid the chain, the greater the amplitude of angular vibration of the longwall shearer's hull. The speed of ω_z and thus the angle of φ_z do not change significantly.

For a longwall shearer located in the middle of the wall, the change in chain size affects the amplitude of linear vibrations in x and y directions and angular to all axes. The higher the rigidity, the greater the vibration amplitude of the longwall shearer. The starting time of the longwall shearer, located at a considerable distance from the ends of the wall, depends on the size of the chain. The higher the chain stiffness, the shorter the start-up time, which is associated with the smaller elongation. The size of the chain in a small range influences the values of the forces in the skids. However, increasing the chain stiffness causes the force in the chain's hooks to increase (Fig. 6), which is reflected in the increasing amplitude of the rotational velocity of the longwall shearer's feed rate. The increased feed force translates into a greater depth of cut, i.e. increased mining resistance, which in turn influences the vibration of the longwall shearer. A chain with low stiffness and natural frequency does not introduce such dynamics into the system.

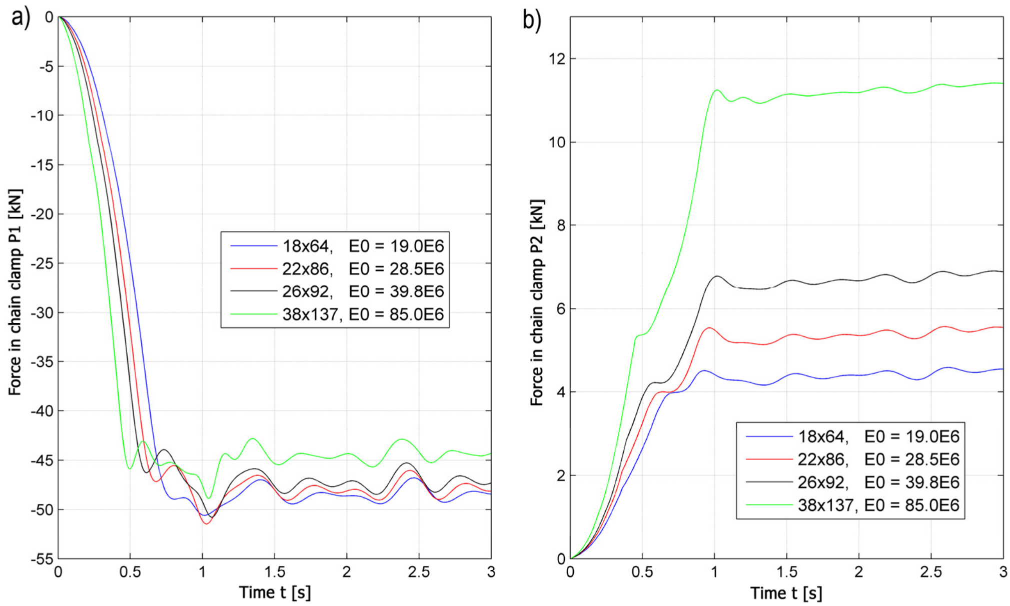

Fig. 6. Chain size influence on forces (a) in hook of P_1, (b) in hook P_2

The forces in the hooks change not only as a function of chain size but also as a longwall shearer position in the wall. The position of the longwall shearer also influences the amplitude and frequency of vibrations. For a longwall shearer close to the beginning or end of a wall, one of the chain branches is shorter, which results in higher vibrations. The closest to the middle of the wall the smaller vibration.

The change of force in the hooks during the longwall shearer's passage through the entire wall is shown in figure 7. The difference between the forces in the hooks, at each point of the wall length, is the load on the longwall shearer in the direction of its movement. The waveform extensions shown in the figure indicate an increase in the amplitude and frequency of vibrations when commuting to one of the wall ends. The passes were made for a wall of 180 m long, during the pass from 10 m to 170 m. Fig. 8 shows the l_2 chain length elongation and l_1 shortening during

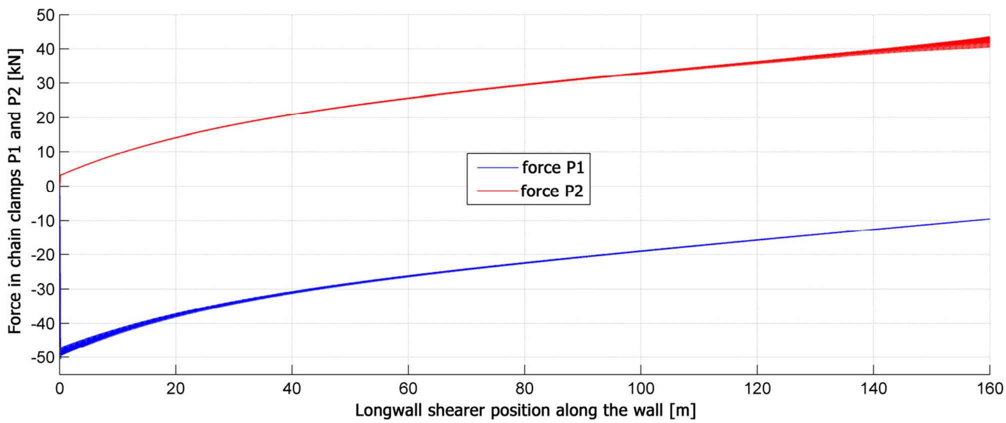

Fig. 7. Change in the value of P_1 and P_2 forces when the longwall shearer pass through the wall

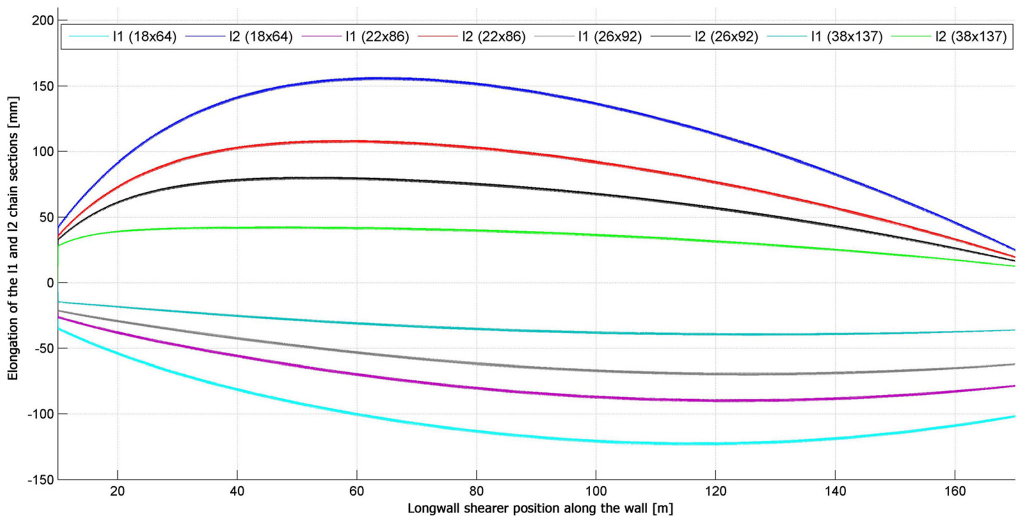

Fig. 8. Influence of the longwall shearer position in the wall on the absolute elongation of chains

the longwall shearer's transfer as in the previous case. The transfers is plotted as a function of the chain size. During startup, the chain becomes elongated, the value of which depends on the load, preload and its size. The elongation then increases to the maximum value and decreases when the longwall shearer approaches the end of the wall. The location of the maximum elongation is offset from the centre of the wall length due to the speed of the drive wheels.

The milling unit can squeeze the face in backwards or overshot operation. Changing the direction of rotation causes a change in the return of the cutting forces acting in the x-axis and y-axis, which affects the behaviour and load of the longwall shearer during machining. Changing the direction of rotation from backward to overshot reduces the speed of v_{ys} and v_{xs} during start-up. It also changes the signs of these speeds during fixed speed operation (Fig. 9a). This affects the displacement of the longwall shearer (Fig. 9b). The direction of rotation of the unit is similarly influenced by angular velocities of ω_y and ω_z and angular displacements of φ_y and φ_z. Angular velocity of ω_x changes slightly, while angular displacement of φ_x increases by about 20%. No influence of the direction of rotation of the unit on the amplitude of the speed and displacement during fixed operation was noticed, except for the influence on the amplitude of the feed speed of the longwall shearer. The feed rate after the change of direction into overshot is characterized by a smaller amplitude of changes, however, the differences are insignificant. The direction of the machine's backward rotation generates a lifting force on the longwall shearer. The reaction in the position, from the unit side, is much greater after the direction of rotation has been changed to positive. This translates directly into increased frictional forces, between skids and guide rails.

Figure 10 shows the reaction values in the skids for both directions of rotation, shown in one diagram. The above mentioned increase of forces can be observed on the wall guides as well as decrease of forces on the buckling guides.

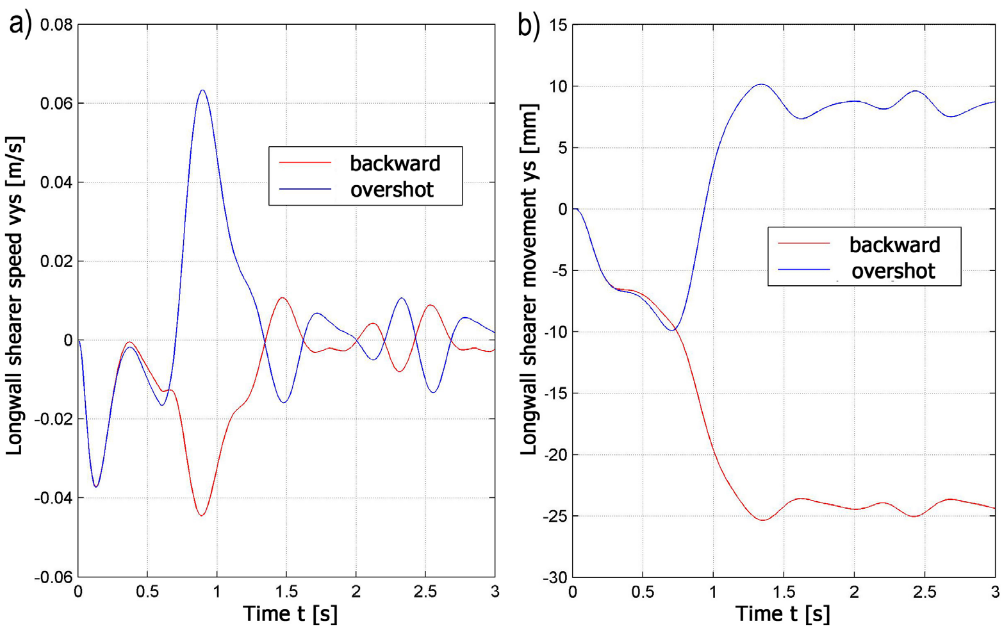

Fig. 9. Effects of unit direction of rotation on speed v_{ys} and displacement y_s

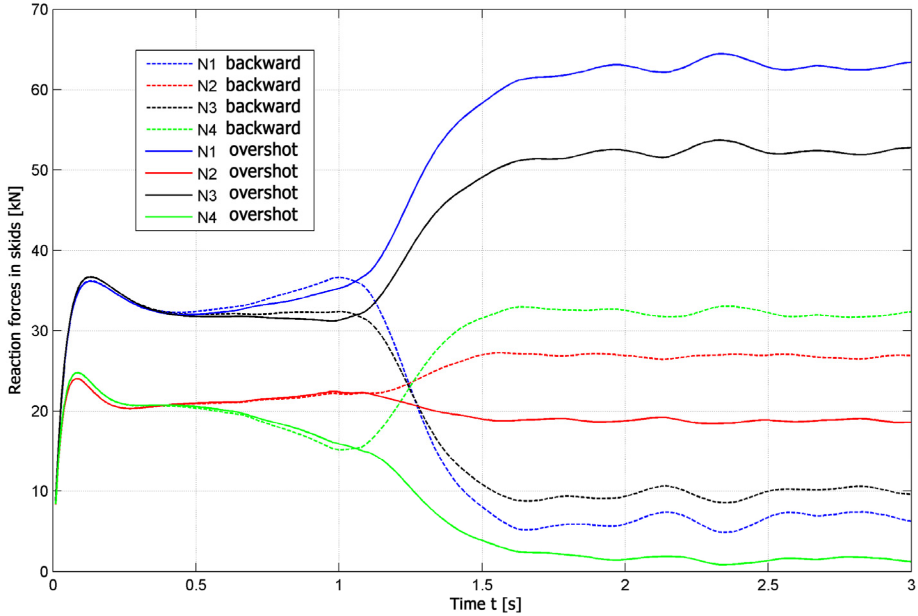

Fig. 10. Influence of unit rotation direction on reaction forces in skids

Changing the direction of the unit's rotation to backward causes an increase in chain hooks forces of about 10%. The chain elongation is also increased by about 10% for backward revolutions. This is due to increased frictional forces between skids and guide rails. The direction of rotation influences to a large extent the values of the reaction forces and friction in the skids, which must be taken into account in the load analysis.

The qualitative analysis of the load and behaviour of the longwall shearer allowed us to reduce the number of simulations necessary to determine the maximum values of forces and moments that load particular nodes of the longwall shearer.

5. Quantitative analysis of the load on the longwall shearer

The main load on the longwall shearer during the operation of the coal wall is mining and loading resistance. The loading resistance depends on the height of the wall, while the mining resistance depends on the height of the wall and the direction of rotation of the organ.

On the basis of the simulation, the values of forces in the longwall shearer's skids were also determined. The results are presented in tabular form. Examples of the results are shown in Table 5.1. The entered in italic force values are the instantaneous values that occur during startup. In addition, the frequency values of transfers are also given.

The presented vibration frequencies of the longwall shearer from the mining process depend on the rotational speed of the unit, which is related to the height of the wall. In addition to the analysis of vibrations generated by the mining unit, the analysis of the longwall shearer own vibration frequency as a function of wall length, chain size and the longwall shearer position in the wall was also carried out. These frequencies are important for analysing the possibility of resonance. For the analyzed range of wall length and all sizes of units, frequency changes are small and fall within the range of 0.60 Hz÷2.86 Hz.

TABLE 5.1

Summary of the maximum load values of the longwall shearer’s skids as a function of the height of the wall and the direction of rotation of the unit

Wall height *H* [m]	**Rotations direction**	**Frequency *f* [Hz]**	N_1 **[N]**	N_2 **[N]**	N_3 **[N]**	N_4 **[N]**	T_1 **[N]**	T_2 **[N]**
1.6	backward	1.78 1.18 0.60	2 904 7 020 10 830 *41 140*	20 385 21 480 22 803 *25 380*	11 058 14 015 16 622 *35 770*	30 358 32 921 35 489	203 491 758 *3 464*	1 939 1 969 1 990
	overshot		65 697 68 714 71 893	18 089 18 553 18 967 25 340	51 983 53 961 56 153	–3 661 –5 578 –-7 487	4 599 4 810 5 036	2 207 2 239 2 267

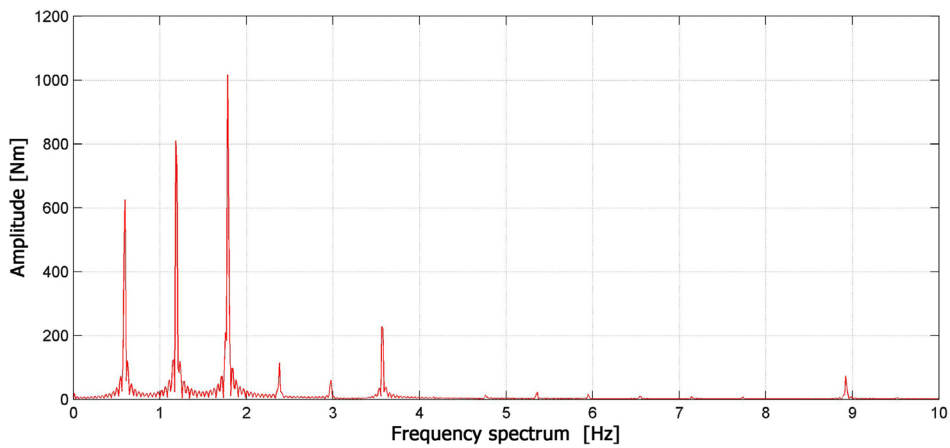

Fig. 11. Frequency spectrum of moments My of unit f1600

The frequency of the longwall shearer’s own vibrations is also influenced by the rigidity of the chain and its position on the length of the wall. The vibration frequency increases with increased chain stiffness.

When designing a single-unit longwall shearer, in addition to the specified loads and frequencies, the relative chain elongation will also be important. Applying the preload force causes the chain to be tensioned within the range of 0.451%÷0.544%. The drive chain is directly loaded on the longwall shearer’s hooks, so it was necessary to determine the maximum value of this load. The highest force in the hooks was observed for 300 m long walls and 38×137 chain size. The required chain preload force of 60 kN was determined for a wall height of 1.0 to 75 kN for a wall of 1.6 m. Taking into account the value of the preload force, the actual values of the forces in the hooks should not exceed 115 kN were determined.

The research carried out allowed us to determine the maximum expected forces and moments in significant nodes of the longwall shearer. In addition, the values of the combine's vibration frequency, generated by the mining process and the natural vibration frequency are given. The maximum chain elongation during the longwall shearer's operation in the wall was also combined with the required preload force of the tendon.

6. Completion and conclusions

The significant participation of thin coal seams and the high costs of their extraction necessitate the need to search for new possibilities of their profitable exploitation while maintaining the required safety and comfort of the crew. The longwall shearers and coal plows, currently available on the market, are designed for thin hard coal seams because of their construction and working methods, which do not allow the planned daily extraction to be achieved. The proposed system solves a number of problems related to the exploitation of these seams. The presented solution is a new construction, significantly different from the currently produced longwall shearers, which necessitates many changes in the construction of machines cooperating with it to create a number of compatible devices forming a specialized longwall shearer complex for thin seams.

The created mathematical model was used to conduct comprehensive model tests, which resulted in determining the values of forces that can be expected in particular nodes of the longwall shearer. Particularly important is the load acting on the longwall shearer's skids, the loader arm, chain hooks and the milling unit shaft. Correct operation of the pulling system requires, among other things, an adequate chain tension force, which has been determined for various cases. The results of tests in the form of waveforms and tables comparing forces and moments values are necessary for the design of a longwall shearer with a feed string system.

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