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Development of mine underground transportation with use of suspended monorails

The development of suspended monorails is presented, indicating their advantages and limitations in use. Attention is paid to the development of monorails with battery drives in recent years. Example solutions including those developed in KOMAG – PCA-1 and GAD-1drive trains are given. The development of computer tools supporting designers and users of suspended monorails is described. Directions of further development of suspended transportation are discussed.

Key words: *mine suspended monorails, drives: cable, diesel, battery, virtual prototyping, direction of further development*

1. INTRODUCTION

Transportation of materials and run-of-mine as well as personnel movement are the most-important processes in mining operations. As long as floor transportation has been used from the beginning of the mining industry and first rail tracks appeared in the 17th century, the first use of suspended transportation took place in the mid-20th century. Designing state-of-the-art rope winches with the rope fixed to the roof (Fig. 1) on which transportation carriages were moved manually or by winches contributed to the development of suspended transportation.

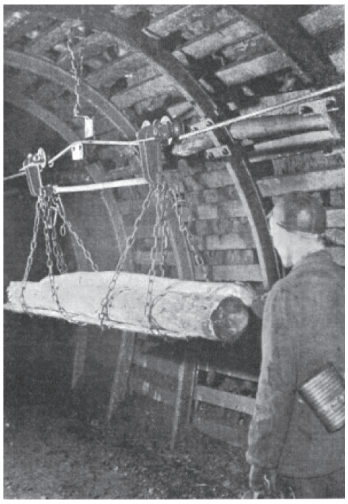

Fig. 1. Suspended rope transportation [1]

In the first half of the 1950s in Germany, a typical rail used in mine transportation was applied as the carrying component (Fig. 2) on which transportation carriages pulled by the rope were moved with loads of up to 1000 kg [2].

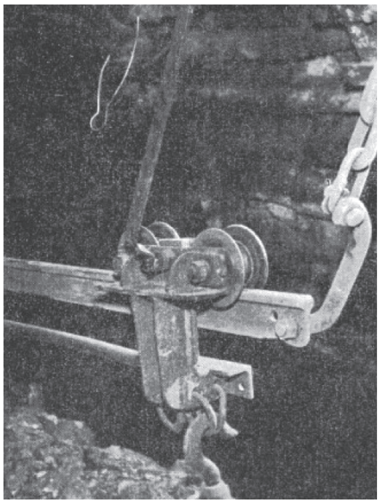

Fig. 2. Suspended monorail [4]

In 1956, the German company Scharf implemented the double-T bar as the carrying component in cable drive transportation (Fig. 3). The transportation set consisted of a pulling trolley, transportation cars with manual hoists and containers, and a braking trolley. Such a system became popular in German, English, and French mines [2].

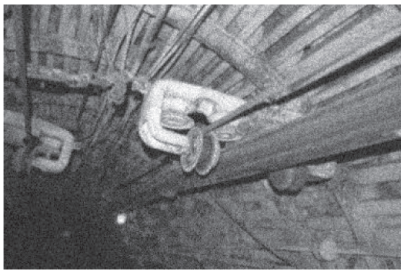

Fig. 3. Suspended monorail (double-T track) with rope drive [1]

The development of such transportation in Western Europe was a motivation to undertake the realization of such projects in KOMAG. At the beginning of the 1960s, KOMAG entered into collaboration with FMG PIOMA, the result of which was the development and commercialization (based on the license of the Becroit company) as well as implementation of the KSP-32 rope-driven monorail in mine undergrounds (also for the movement of people); they followed this with the KSP-63-type monorail. They became popular underground means of transportation – for example, FMG PIOMA S.A. implemented 1200 KSP-32 locomotives through 1992 [3]. Progress in the development of suspended monorails resulted in increases in the carrying capacity and strength of rail routes and transportation sets as well as an increase in the pulling force of the rope drive. Experience gained during the operation of rope-driven monorails indicated the following disadvantages:

- the possibility of transportation only along a previously determined route,
- a lack of visual contact of the operator with the transportation set,
- the possibility of an uncontrolled break of the pulling rope, which can cause a serious accident,
- the required costs for rope maintenance and guiding rollers on the transportation route.

At the end of the 1960s, the development of rope-driven monorails practically ended in Western Europe; however, according to authors' knowledge, 48 rope-driven monorails are in operation in Poland (as of December 31, 2016). Rope drives have been replaced by mobile traction devices – a suspended drive train (locomotive) with a diesel drive. The first prototype solutions of English companies were demonstrated in 1965. The German company Ruhrthaler started their commercial application, implementing a two-cabin HL 32H drive train in German and French mines in 1967. Drive trains (locomotives) made by Scharf from Germany and Stephanoise from France (1970) were the next commercialized solutions. In 1967, a research project on the development of such solutions started in Czechoslovakia in Prievidza (Bansky Vyskumny Ustav).

Together with the development of drive trains (locomotives), suspended monorail tracks were improved by increasing their carrying capacity as well as modernizing their connections and suspensions. According to the German DIN standard, profile I 140 (I 155 according to the Polish PN standard) became commonly used instead of I 120 profiles, and now profile I 250 is also used. Designs of carrying and braking trolleys as well as transportation sets (including hoists) were also modernized [2].

2. DEVELOPMENT OF SUSPENDED MONORAILS WITH DIESEL DRIVES USED IN POLISH HARD COAL MINES

In 1976, the first Polish Lps-80 diesel locomotive (drive train) for suspended monorails was developed in KOMAG, and it was later manufactured by Zakłady Urządzeń Naftowych i Gazowniczych in Krosno, Poland in 1979. During the years of 1979–1980, the first tests were conducted in the KWK Ziemowit Mine, allowing workers to gain operational experience. An SW-400 engine, requiring periodic adjustment due to the necessity of obtaining the required quality (purity) of the exhaust gases, was used in the drive. The engine drove the Rauch pump of changing efficiency (0–10 dm^3/min) and a pressure of 20 MPa and this pump drove the SW-160 hydraulic motors made by HYDROSTER. Exhaust after-treatment and the cooling system kept temperatures of the exhaust gases below the required 70°C [4].

On the basis of the Lps-80 locomotive's (drive train) operation test, documentation of the prototype Lps-90D suspended diesel locomotive (Fig. 4) was developed in 1980. The abovementioned diesel engine was also used as the drive of this locomotive along with the verified protection system, assuring the required purity level of the exhaust gases as well as their outlet temperature. A Rexroth PAG AZP250 pump with an installed set power controller as well as an efficiency and flow-direction remote (hydraulic) controller and a set of two gear pumps were used.

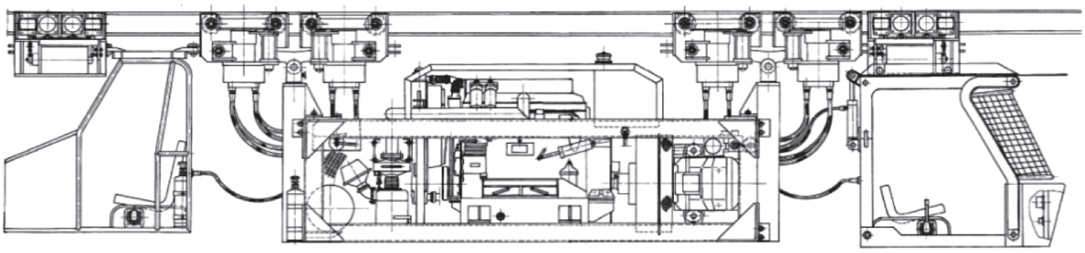

Fig. 4. Lps-90D suspended monorail locomotive [4]

The pump drove the SOK-160K hydraulic motor made by Hydroster. The prototype manufactured in 1982 by Zakład Naprawczy Taboru Samochodowego i Sprzętu in Brzesko (now Małopolska Wytwórnia Maszyn Brzesko Sp. z o.o.) underwent operational tests in the Murcki Mine and then in the Piast Mine. These tests confirmed the proper operation of most of the units. The low durability of the driving wheel's friction lining was the major problem [4].

During the years 1993–1996, the above experience was used during the realization of the "Underground transportation system for a suspended monorail with diesel drive" target project realized in collaboration with FMG PIOMA S.A. (now FAMUR S.A.). The LPS-90 locomotive (diesel drive train) (Fig. 5), designed to drive a suspended monorail for the transportation of materials, parts of machines, and equipment as well as personnel movement in mine workings with the potential hazard of methane and/or coal dust explosion, was developed, manufactured and tested in the laboratory and in situ.

Realization of the project contributed to the further development of suspended monorails with diesel drives at FMG PIOMA S.A. (now FAMUR S.A.) – Figure 6.

The implementation of a suspended monorail with a diesel drive took place in Polish coal mines in the first half of the 1990s. According to the authors, at the end of 1995, 35 such machines were being used in the following mines: the Ziemowit, Piast, Bogdanka (6 machines each), Mysłowice (4 machines), Wesoła, Staszic (3 machines each), Murcki, Czeczott (2 machines each), Brzeszcze, Janina, and Andaluzja Mines (1 machine each). These were machines manufactured by Ruhrthaler, Scharf, BVU Prievidza, and ORTAS Pribram. According to the authors, 566 suspended monorail locomotives (drive trains) with diesel drives are currently being used in Polish coal mines (as of December 31, 2016). The leading suppliers are BECKER-WARKOP Ltd., FAMUR S.A., SCHARF, BEVEX, and FERRIT. Figure 7 shows samples of the currently available locomotives (drive trains) with diesel drives; their basic parameters are presented in Table 1.

a)

b)

Fig. 5. LPS-90 locomotive (drive train): a) at KATOWICE'95 Fair;
b) in underground working [5]

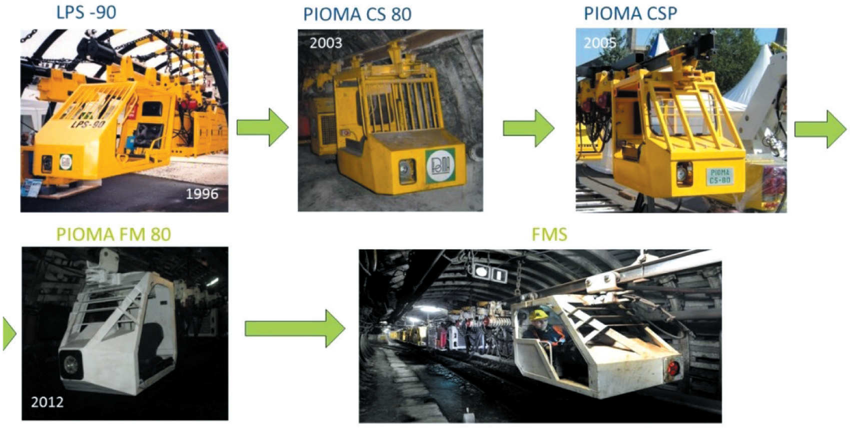

Fig. 6. Development of diesel monorails in FMG PIOMA S.A./FAMUR S.A [5]

Fig. 7. Currently offered diesel monorails [5]

Table 1

Basic parameters of selected diesel driven trains [5]

Type	Manufa cturer	Max. pulling force [kN]	Number of driving trolleys	Max. speed [m/s]	Max. inclination [°]	Diesel engine power [kW]	Diesel engine manufac-turer
KP-95	Becker-Warkop	40–240	2–12	2.5	30	80–95	Deutz
KP-96	Becker-Warkop	40–240	2–12	2.5	30	96	Perkins
KP-148	Becker-Warkop	40–240	2–12	2.5	30	148	Deutz
FMS	Famur	85/105/120/140	4/5/6/7	2.5	30	81 or 95	Deutz
CSZ	Famur	85/105/120/140	4/5/6/7	2.6	30	123	Deutz
DZ 80	Scharf	160	3–8	2	30	80	Liebherr
DZ 130	Scharf	160	3–8	2.5	30	130	Liebherr
DLZ 110F	Ferrit	60–140	4–7	2.0	30	81	Zetor
DLZ 210F	Ferrit	110–330	4–12	3.1	30	127–142	John Deere
LZH120D5.1	Ortas	80/100/120	4/5/6	2.0/1.7/1.4	30	81	Zetor
BEVEX 80	Bevex	60/80/100	3/4/5	2.0/1.8/1.5	25	81	–
BEVEX 90	Bevex	80/100/120	4/5/6	2.0/1.8/1.5	30	91	–

a) b)

Fig. 8. Examples of design solutions of transportation sets: a) for personnel movement; b) for transportation of complete powered roof supports [5]

The use of diesel monorails required the development and implementation of new tracks as well as their suspensions. The basic requirement was to achieve the ability to transmit longitudinal force, which resulted in the development of new solutions for track connections. Numerous solutions for underground transportation including the transport of personnel (Fig. 8a), materials, and devices as well as face equipment, etc. was implemented. Transportation sets for an entire power roof support (Fig. 8b), significantly speeding up the relocation of mining systems, were worthy of special attention. The main advantages of using the diesel driven trains are as follows [6]:

- transport capacity not limited by length and branching of the route,
- ability to observe the route by the train driver,
- fast and easy elongation or shortening of the route,
- easy loading and unloading,
- ease of suspending different carriers,
- improving the effectiveness of transportation (transportation of machines and mining equipment in one piece) due to great pulling force,
- locomotive infinite variable travel speed change,
- ability to transport (which includes personnel) directly to the face,
- improvement of work safety due to installing the electronic control and blockade systems as well as intrinsically safe electrical installation.

The operation of the trains showed the following essential disadvantages in using the diesel drives in underground coal mine workings [7]:

- emission of gases and heat to the coal mines' surrounding environments,
- noise emission,
- necessity to transport fuel to underground workings, which requires high safety requirements (especially during refueling).

3. INNOVATIVE SOLUTIONS OF SUSPENDED TRANSPORTATION DEVICES WITH BATTERY DRIVES

The disadvantages of the operation of monorails with diesel drives mentioned in Chapter 2 were the reason for undertaking the realization of projects regarding the development of battery drives.

The development and setting to the operation of state-of-the-art energo-electronic equipment meeting the requirements for safe use in a potentially explosive atmosphere as well as battery packs was the criterial factor stimulating the further development of battery drives. In 1997, the Scharf company designed the first suspended monorail (EMTS type) with a battery drive intended for the movement of people and transportation of materials in ore mine workings without the threat of explosion hazards.

Using the experience gained, the BZ 45-2-40 battery-drive train for suspended monorails operating in hard coal mines underground was developed (Fig. 9).

A similar monorail of the DLZA 90F type (Fig. 10) was offered by Ferrit and Becker; Warkop developed and implemented the suspended CMA-190 battery-drive train (Fig. 11). Acid-lead batteries were used in these devices, which limited their application due to their heavy weight and large size (low energy density) that limited the functionality of these solutions.

The KOMAG Institute, in collaboration with other research organizations and industrial partners, developed innovative solutions of battery-driven suspended transportation machines intended for operation in potentially explosive atmosphere in mine undergrounds. These solutions are as follows: the "GAD-1 battery-drive train" and "PCA-1 suspended battery-drive train."

Fig. 9. Battery-driven monorail BZ 45-2-40 of Scharf Company [5]

Fig. 10. DLZA 90F battery monorail made by Ferrit [5]

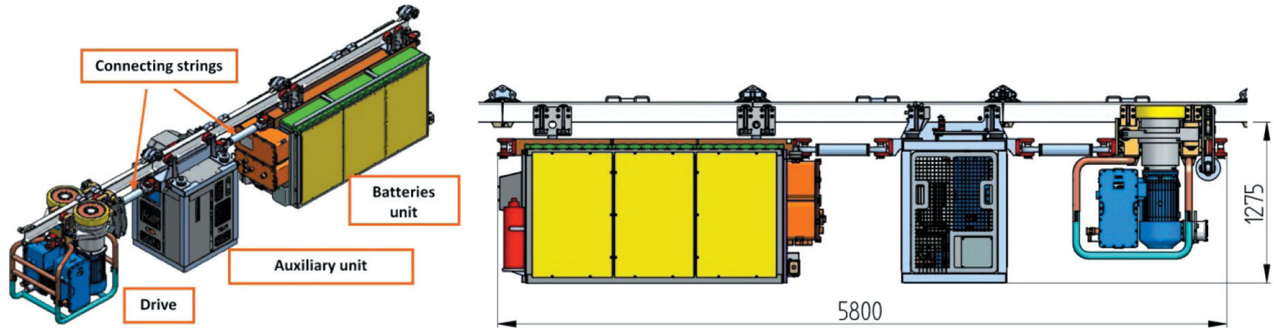

Fig. 11. Battery-driven CMA-1 drive train [5]

3.1. GAD-1 suspended battery-drive train

The GAD-1 battery-drive train (Fig. 12) adapted for suspended monorails is the result of the targeted project, the beneficiary of which was NAFRA Polska Sp. z o.o. (the manufacturer). This solution was realized in collaboration with the Institute of Electrical Drives and Machines KOMEL as well as the following companies: IMPACT S.C., VACAT Sp. z o.o., SOMAR S.A., and ENEL-PC Sp. z o.o.

Lithium-polymer cells with high density of energy not used so far in the mining industry were used to supply power to the drive train. Four units (each composed of 72 cells connected in series, making a battery with a total voltage of 265 V DC) were the source of power. A battery whose total energy equaled 160 kWh was placed in a flame-proof casing.

Brushless synchronous motors with permanent magnets were used in the driving trolleys. Torque from the motors is transmitted in a frictional way and (in the case of inclinations over 10°) through a toothed gear (on a rack-and-pinion route). Sequential changes of the driving mode from a frictional to rack-and-pinion one and reverse is realized

a)

b)

Fig. 12. GAD-1 suspended battery-drive train: a) at manufacturer stand; b) in underground working [8]

sequentially by each driving trolley automatically. The mentioned motors have high efficiency compared to inductive motors, and they can be precisely controlled by a torque vector.

A master system for controlling the GAD-1 drive train was designed on the basis on a fuzzy logic structure connecting all of the components of the control system using the CAN network (which is resistant to any disturbances).

The versatility of the used CanOpen protocol enables communication among the subassemblies made by different manufacturers as well as diagnosing the CAN network.

The possibility of energy recovery during motor braking is a great advantage of the GAD-1 suspended drive train. An intelligent battery management system (BMS), which monitors the parameters of the battery set as well as each cell, is responsible for the energy recovery process, even deciding about the distribution of power between cells. Additionally, the system plays a protective role regarding both the software and hardware against unwanted situations, such as overcharging or the excessive discharging of the batteries.

The proper selection of parameters of the components cooperating with the battery set as well as the developed safety algorithms enabled the design of a machine intended for operation under conditions of combined hazards (methane and/or coal dust explosion, fire, water hazards). Fulfillment of the European requirements was confirmed by the EU-type examination certificate issued by the certifying body. Separate certificates for the main modules of the drive train (i.e., the MB-1pack of batteries, MZS-1 supply and control module, as well as ML-1 charging module) enabled their use in other applications in devices intended to be operated in a potentially explosive atmosphere.

3.2. PCA-1 suspended battery-drive train

Demand for the mechanization of operations of moving loads or machine components for relatively short distances (up to 100 meters) (e.g., in driven roadway fronts) was the reason for the development of the PCA-1 battery-drive train (Fig. 13). It can be optionally equipped with a transportation set with electrically driven hoists (Fig. 13, Point 5). There is also a possibility of using manually operated hoists or hoists supplied by other mediums from external sources in the transportation set.

The driving trolley (Fig. 13, Point 1) equipped with two frictional drive units with electric motors moves the transportation set along the suspended track.

The installed electromagnetic disk brakes play the roles of emergency and parking brakes. The battery, with a voltage of 48V DC and capacity of 100 Ah, is the source of power supply, and it consists of 15 high-performance lithium-iron-phosphate (LiFePO4) cells connected in series. It operates under the supervision of the BMS system and battery charge controller UMA-1. The change of direct current into alternating current (with adjustable frequency) is realized by the frequency inverter made by ENEL Sp. z o.o. All of the components of the electric equipment together with the battery cells and frequency inverter are installed in the MZ-1 power supply module, which consists of three chambers: equipment chamber, battery chamber, and connecting chamber. Its compact design enable a limitation of the number of electric

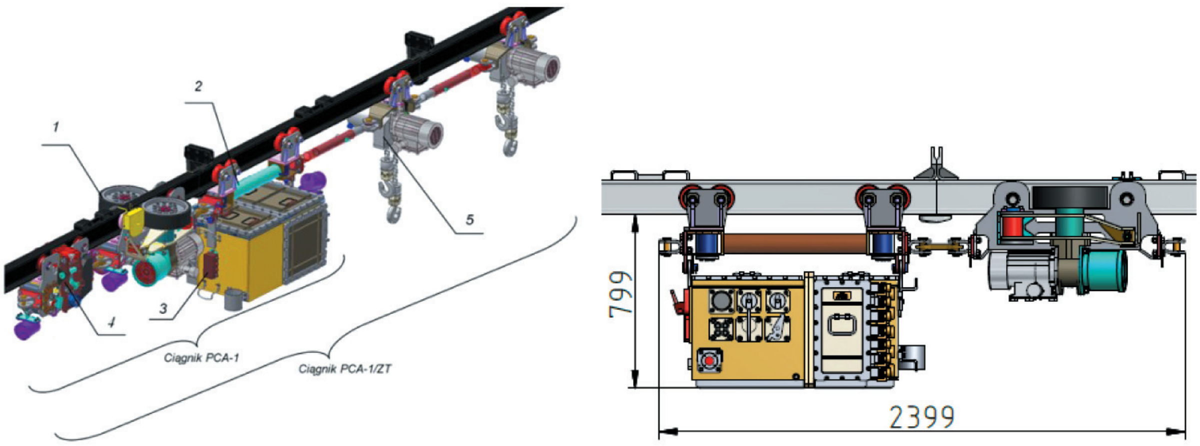

Fig. 13. PCA-1 suspended battery-drive train (PCA-1 – standard version, PCA-1/ZT – version with transportation set): 1 – driving trolley; 2 – battery trolley; 3 – supplying module; 4 – braking trolley; 5 – transportation set [8]

equipment components (especially protective ones), which means the size and weight of the module are reduced. A wired control from the box connected to the MZ-1 module or a wireless (radio) control are possible. Micro-processor torque vector control in four quarters of the torque-speed system enables the operation with a recuperation of energy during braking by the electric motors and during lowering the load by electric hoists. The possibility of charging the batteries at the place of operation from the available transformer units is another innovation, which eliminates the necessity of moving the drive train to the depot. HELLFEIER Ltd. is the manufacturer of the PCA-1 drive train.

4. COMPUTER TOOLS AIDING DESIGNERS AND USERS OF SUSPENDED TRANSPORTATION UNITS

For ten years or so, the designing of the technical means for auxiliary mine transportation including suspended monorails with their own drives has been fully realized in the computer environment. The design process starts from the preparation of spatial geometrical models of the entire transportation system using the CAD (*Computer-Aided Design*) program environment. The transportation system consists of a transportation unit and suspended track. Depending on the configuration, the transportation unit usually consists of a drive train, carrying set, and system of braking trolleys. At this stage of the designing process, the main design assumptions such as required dimensions, weight, and detection of possible collisions between the spatial model parts and subassemblies are verified. An example of the geometric model of the GAD-1 suspended drive train with own drive (electric) is shown in Figure 14.

The method for analyzing the kinematics and dynamics of the *Multi-Body System* (MBS) enabling the calculation of dynamic forces during acceleration and braking (including emergency braking, both in the transportation unit as in the route's suspensions and connections) is used for the verification of the required assumed technical parameters of the future technical means in different criterial states. This is the repeatedly, statically indeterminate system.

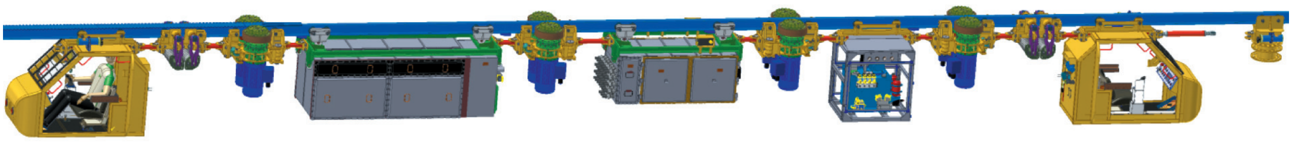

Fig. 14. Geometric model of mine suspended drive train prepared in CAD environment [8]

Initial geometrical models make the basis for the development of computational models, which consist of rigid and elastic bodies connected with different types of constraints (e.g., rotational, cylindrical, spherical, movable, and fixating ones). Apart from the constraints, the models of the contacts are applied. Advanced MBS class computer programs enable us to include the models of other subsystems of the drive transmission (e.g., chain gear) to the computational models. In Figure 15, an MBS computational model of the carrying unit for transporting of large-sized materials equipped with a complete system for lifting the longitudinal spreader beams is created in the MSC Adams computer program are shown. Computational models in the MBS program environment can be combined with other programs, making it possible to simulate the control systems. In such a way, the simulations of many stages of the transportation processes are conducted.

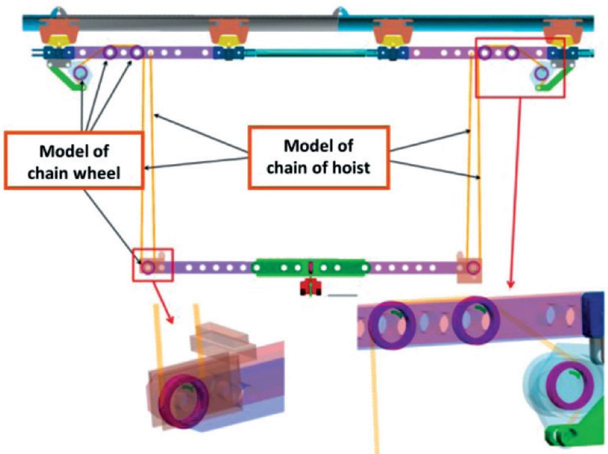

Fig. 15. Computational model of carrying unit created in environment of MBS computer program [9]

In the case of the carrying set, the stages are as follows: load lifting, its movement, and its descending. Examples of the force curves in the selected nodes of the carrying set during lifting the load, its stabilization, and then putting down on a floor is presented in Figure 16. The determination of force/time processing gives the possibility for identifying their maximum values in catches during the maneuvering of the transported load.

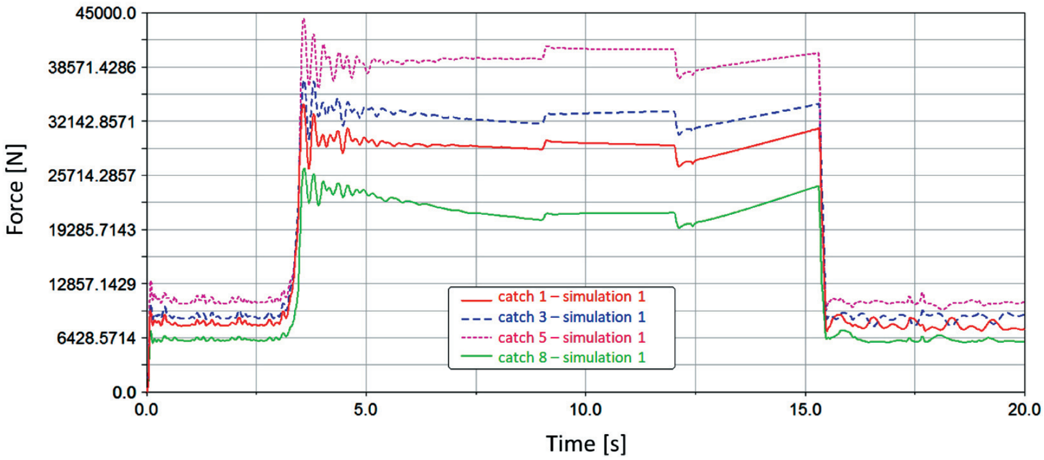

Fig. 16. Forces in carrying set during lifting large-size load and its descending [9]

The results of the MBS simulation are the input data for numerical analyses using the *Finite Element Method*. Besides the results presented above (force parameters), we can obtain information regarding the accelerations and decelerations acting on a technical mean (and at the same time on the operator) under so-called emergency conditions. Emergency conditions are usually associated with improperly used transportation means or its damage (e.g., traveling at speeds that are not allowed, using the brakes in the case of the transportation means' improper configuration, or hitting an obstacle). A sudden stop or change in travel direction can cause injuries to the operator and/or passengers. Identification of such a hazard requires special software for the simulation of rapid-changing phenomena. The computational models should include the models of anthropometric features, enabling the calculation of biomechanical parameters. These are the virtual equivalents of human dummies used in crash tests. In Figure 17, the effect of travel by suspended monorail with a speed of 5 m/s on a bend of a radius equal to 4 m is presented.

Computer aiding not only includes the designing stage but is also used by suspended monorail users. According to the regulations of the Ministry of Energy of November 23, 2016, on the special requirements for transport operations in underground mining plants, the users of suspended transportation systems are obligated to make traction calculations. At the KOMAG Institute, the Safe Trans Design (STD) system enables the proper selection of transportation unit components (e.g., drive train, braking trolleys, carrying sets) for the required transportation conditions.

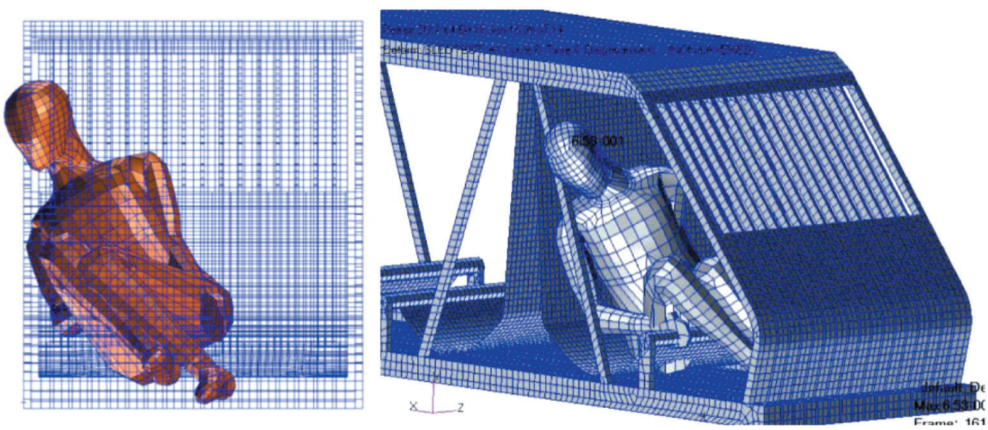

Fig. 17. Behaviour of virtual model of Hybrid III dummy during travel in cabin with speed of 5 m/s on bend [10]

In the case of a suspended monorail, these conditions are determined by the inclination of the roadway working in which materials are transported as well as the parameters of a suspended track (such as length, rail profile and type, as well as carrying capacity of the suspensions). The calculation results give us information about the maximum net weight of a transported load, braking distance, braking deceleration, distribution of longitudinal forces in the transportation set's strings, as well as enable us to perform a collision analysis in the case of transportation big-sized loads.

The STD system assists mining services in the preparation of documentation of the transporting system with suspended monorails to minimize errors during the configuration of suspended monorails as well as in traction calculations, which leads directly to improvements in work safety.

5. PERSPECTIVE OF DEVELOPMENT OF SUSPENDED TRANSPORT

Further development of the suspended rails in hard coal mines needs to be considered, taking the following aspects into account:

- mining-geologic conditions of current and future transport workings,
- parameters of transported loads (unit weight and size),
- safety level required for conducting transport operations,
- currently used means of transport, in the aspect of effectiveness,
- competitiveness of predicted new means of transport,
- minimization of effects to the environment,
- economic conditions – purpose and profitability of applying new means of transport.

Bearing in mind the borne investments, we can expect a radical replacement of diesel drives by battery drives. Thus, within a short period of time, we can expect:

- a reduction of emissions of harmful substances in exhaust gases,
- a reduction of emissions of noise and heat from diesel drive units.

In the near future, it is expected that ventilation conditions will force the implementation of electric drives. Thus, we will see further development of such drives; not only battery drives, but also those supplied from external source (e.g., from busbars).

The dynamic development of drives did not translate into an increase in track carrying capacity resulting from rail, rail connector strength parameters, and methods of suspending the transportation routes. Nominal loads of suspensions fixed to yielding support's arches due to the requirements of the current regulations is limited to 40 kN, which practically eliminates the transportation of bigger and heavier machines with the use of suspended monorails. An increase of load to the rail connectors is possible; e.g., in the result of using the spreader beams balancing load to the suspensions (Fig. 18).

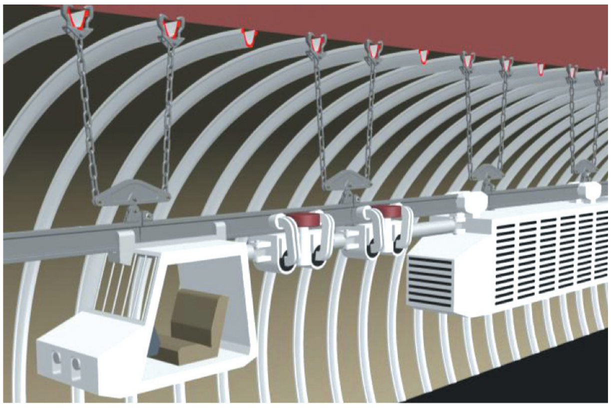

Fig. 18. Suspending transportation route on the support's arches with use spreader beam balancing load to suspensions (maximum load to rail connector towards suspension direction 80 kN) [11]

Methods for dynamic calculation (e.g., during railway braking – especially emergency braking) have not been developed so far. Development of the methods determining the dynamic forces in transportation route components is desired by both designers and users, especially in the aspect of possibilities for increasing the maximum speed of the railway (now 2 m/s). Thus, due to safety reasons, the specialists from the KOMAG Institute recorded the forces in the suspensions during braking in an underground roadway (including emergency braking) for a significantly reduced speed.

The fourth industry revolution (INDUSTRY 4.0) will incorporate automation, visualization, and monitoring systems to practical applications. In suspended monorails, we can expect the implementation of systems for travel control, enabling the current localization of the railway in a mine underground. Common use of RFID technology is also expected [12, 13].

The system will operate based on wireless data transmission, informing about the localization of transportation means as well as about their technical conditions. Software used for warning and alarming about emergency situations will be an important part of the system, contributing to the improvement of work safety on mine transportation routes.

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