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Use of the MBS method in mining industry R&D projects

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Kamil SZEWERDA [1*], **Tibor KRENICKY** [2]

Author's affiliations and addresses:

[1] KOMAG Institute of Mining Technology, Pszczyńska 37, 44-101 Gliwice, Poland

[2] Faculty of Manufacturing Technologies of the Technical University of Kosice with a seat in Prešov, Bayerova 1, 080 01 Prešov, Slovak Republic

*** Correspondence:**

e-mail: kszewerda@komag.eu

Abstract:

Virtual prototyping methods are an important aspect both in the designing process and in research processes aimed at the modification and optimization of machines and devices. It allows one to analyse the way of operation, the flow of forces, the cooperation between components, as well as finding the weakest points of the structure. This article presents the possibilities of using the MBS method, which is one of the tools used in virtual prototyping, on the basis of the results of R&D projects realized at the KOMAG Institute of Mining Technology. The main objective of the MBS method is to simulate the kinematics and dynamics of multi-body systems, the results of which will enable a series of analyses related to the operation of machines and devices.

Keywords: numerical simulations, kinematics and dynamics, MBS (MultiBody System), mining industry

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1. Introduction

Development in the field of computers, state-of-the-art software as well as staff, enabled implementation, application and continuous improvement of virtual prototyping techniques, which are used in R&D projects at the KOMAG Institute of Mining Technology. Virtual prototyping allows learning and analyse many aspects related to the design, manufacture and operation of machines and devices. Ability to check and then modify innovative solutions and new ideas without the need to build a physical prototype is the most important advantage of the research work in developing the virtual prototyping. Use of virtual prototyping techniques, apart from economic benefits (no need to build a prototype), is in line with the current trends in taking care for the natural environment and reducing greenhouse gas emissions during the manufacture of physical prototypes. In addition, attention should be paid to the unquestionable advantage of virtual prototyping methods over traditional bench tests, consisting in the possibility of analysing the flow of forces, distribution of stresses and deformations in any structure node, which is often unattainable for technical reasons at traditional test stands. Virtual prototyping is therefore a perfect complement to traditional testing even before the production of each components of machines or devices.

Virtual prototyping is used in the following tasks in the research projects of KOMAG Institute: creation of geometric models of the selected machines and devices for strength calculations using the FEM (Finite Element Method) method for the selected machine components, simulating kinematics and dynamics (simulations such as MBS - MultiBody System) of the selected kinematic systems and entire machines and devices, for CFD (Computational Fluid Dynamics) simulations related to fluid mechanics and heat flow simulations. The above-mentioned virtual prototyping tools are complemented by the work related to visualization of both the obtained results and ready-made solutions developed at the Institute. Photogrammetry, the use of which allows one to easily and simply visualize the space in which a given device is to work is one of the methods used for this purpose. Using this method, you can also make inventories of large post-industrial areas. This article presents the possibilities of using MBS simulations. This method is used in research projects and in scientific work related to the development of innovative machines and devices.

2. MBS method

MBS method consists in numerical simulations aimed at kinematic or dynamic analysis of a mechanical system. For this purpose, the real object is represented by a geometric model consisting of many bodies (solids). In the process of building a computational model, geometric constraints are superimposed on the geometric model of a mechanical system, thus creating the kinematic pairs with a certain number of degrees of freedom. Moreover, the computational model can define excitations in the form of various vectors of forces and moments acting in selected nodes of the mechanical system.
Kinematic or dynamic analyses of the selected mechanical system are the purpose of the MBS simulation. In the case of kinematic analysis, the movements of each body of the mechanical system is searched for, assuming that at least movement of one member, being for example a driving body, is known. In this type of simulation, the number of degrees of freedom is the same as the number of factors determining motion defined in the so-called directional constraints. The solution of the kinematics problem consists in solving the system of N algebraic equations with N variables collected in a vector **q (1),** as well as constraints in relation to speed (2) and generalized accelerations (3) [1]:

$$\boldsymbol{\Phi}(\mathbf{q},\mathrm{t}) = \begin{bmatrix} \boldsymbol{\Phi}^K(\boldsymbol{q}) \\ \boldsymbol{\Phi}^D(\boldsymbol{q},t) \end{bmatrix} = 0_{Nx1} \quad (1)$$

where:
- q - vector of generalized coordinates,
- K - number of kinematic pairs in the system,
- D - number of driving constraints,
- Φ^K - vector of constraints of kinematic pairs,
- Φ^D - vector of driving constraints,
- Φ - system of N nonlinear algebraic equations.

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$$\mathbf{\Phi}_q \dot{q} = -\mathbf{\Phi}_t \quad (2)$$

$$\mathbf{\Phi}_q \ddot{q} = -(\mathbf{\Phi}_q \dot{q})_q \dot{q} - 2\mathbf{\Phi}_{qt} \dot{q} - \mathbf{\Phi}_{tt} = \Gamma \quad (3)$$

where:

- Φ_q - Jacobian matrix,
- t – time,
- Γ - constraint equations for accelerations.

Using the above equations, the components $\mathbf{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}$ of the position, velocity and general acceleration vectors are determined in given time t_0, t_1, ..,t_M.

In the case of dynamic analyses, the defined geometric constraints do not receive all the degrees of freedom of the analysed mechanical system. In dynamic analyses, initial conditions are defined in the form of position and velocity of all bodies of the mechanical system, as well as time curves of all forces acting on each bod of this system. During dynamic analyses, it is important to correctly define the masses and moments of inertia of each member of the system. During the dynamics task, the movement of the mechanical system is determined as a result of forces acting on it. In order to solve the dynamics problem, it is necessary to integrate the system of differential algebraic equations. The Euler-Lagrange equation can be written in the form of (4) [1, 2, 3, 4]:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\boldsymbol{q}}}\right) - \frac{\partial L}{\partial \boldsymbol{q}} + \mathbf{\Phi}_q^T \boldsymbol{\lambda} = \boldsymbol{Q} \quad (4)$$

where:

- *L* – Lagrange function (5) i.e. difference of kinetic energy *T* and potential energy *V* of the system:

$$L = T - V \quad (5)$$

- **λ** – vector of Lagrange multipliers,
- Q – vector of generalized forces acting on a multi-body system (6):

$$\boldsymbol{Q} = \boldsymbol{Q}(\boldsymbol{q}, \dot{\boldsymbol{q}}, t) \quad (6)$$

Generally the Newton-Raphson iteration method, most often is used to solve the nonlinear Differential-Algebraic Equations of motion. Apart from the geometrical constraints between the selected bodies of the mechanical system, it is possible to define the method of mutual interaction in the case, when the bodies colliding with each other. The nature of the collision behaviour is defined by the contact parameters between these solids. The characteristic parameters of the contacts include contact stiffness, damping coefficient, penetration depth of one body into another, coefficient of friction, etc.

3. Application examples - results

Analysis of correct operation of a new type of planetary gear is an example of applying the MBS method for kinematic analyzes. At the first stage of the analysis, a simulation has to verify geometrical form of the gear wheels to avoid a situation of wedging each gear stage (Fig. 1).

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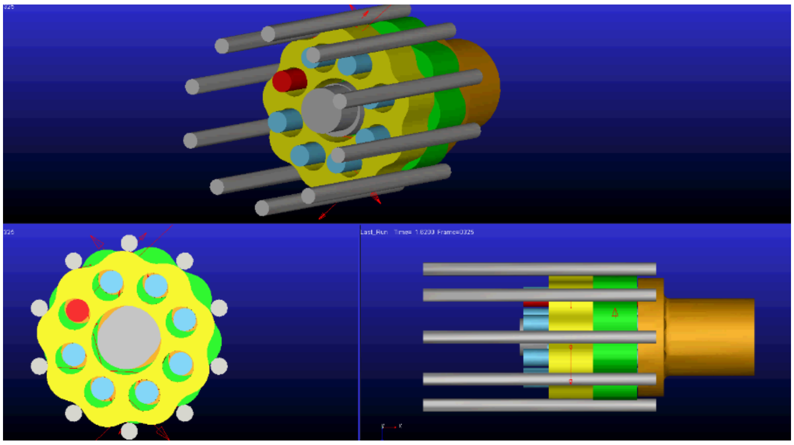

Fig. 1. Simulation of planetary gear operation [5]

After the stage of geometry verification which excluded the possibility of wedging the gears, dynamic analyzes were made to analyze the flow of forces in the gear and to optimize the new solution.

Dynamic analyzes are the majority of analyzes as a part of R&D work. Distribution of forces in the powered roof support was an example of dynamic analysis in various variants of testing the roof support on test stand (Fig. 2).

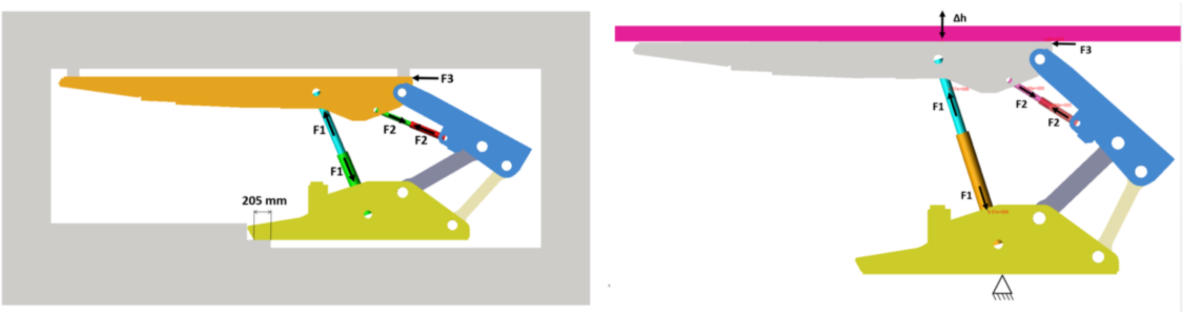

Fig. 2. Analysis of the flow of forces in powered roof support

Based on the simulations, it was possible to accurately determine the forces in each node of the roof support in each type of stand tests, allowing the specialists to select the proper test variant. Moreover, the forces determined during such simulations may constitute the boundary conditions, such as the forces acting on particular places of the structure, for the FEM strength analyzes.

Simulation of emergency situations, e.g. braking of the suspension during the transport of powered roof support using the suspended monorail was another example of dynamic analyzes with the use of the MBS method (Fig. 3).

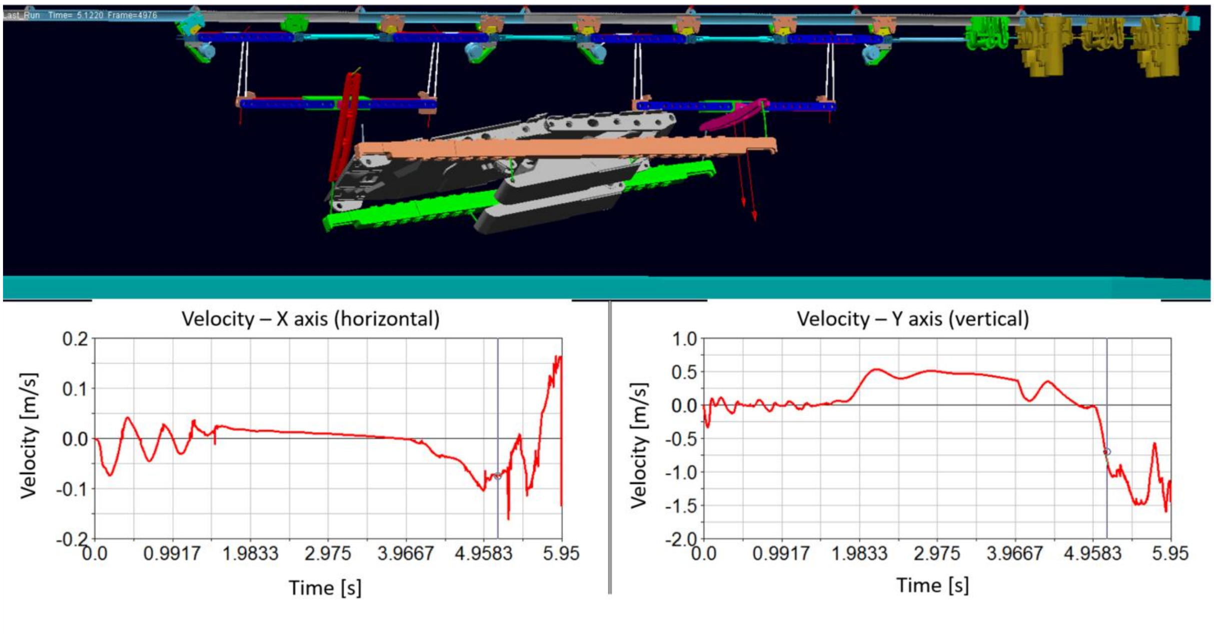

Fig. 3. Simulation of emergency situations, breaking the suspension during transportation of a powered roof support [6]

Analysis of forces in the chains that did not break, as well as in the joints and suspensions of the rails of the suspended monorail route was possible in simulation. The results of the simulations also include the speed and acceleration of the roof support, as well as the predicted trajectory of its motion during the fall. Extensive analyzes of such simulations may result in development of guidelines aimed at increasing the safety of both the personnel and the mine infrastructure.

Ensuring the proper load-bearing capacity of the rail joint during the development of a new type of 4 m long rails was one of the tasks related to the safety of the suspended monorail route (Fig. 4).

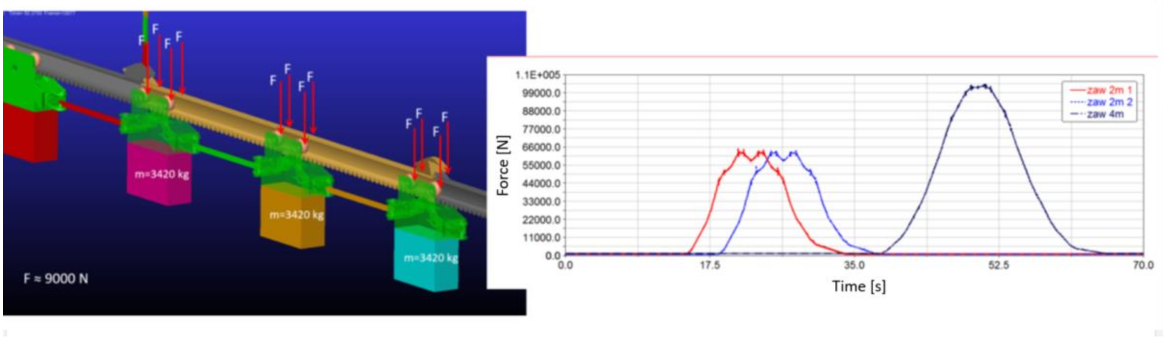

Fig. 4. Simulation of the load on the rail joints of a suspended monorail regarding the length modification [7]

For this purpose, a series of simulations were made. Forces in each direction acting on the rail joints during the monorail travel were the simulations result. These data were boundary data for FEM strength analyzes.

Simulations of emergency braking of a suspended monorail at various speeds, including driving at a speed of 5 m/s (driving at this speed is impossible in real conditions due to legal restrictions) were another example of analyzes affecting safety. The forces in the route suspensions, the forces in the rail joints, the forces acting on the transported load, as well as the forces acting on the arches of the roadway support were simulated (Fig. 5) [7, 8, 9, 10].

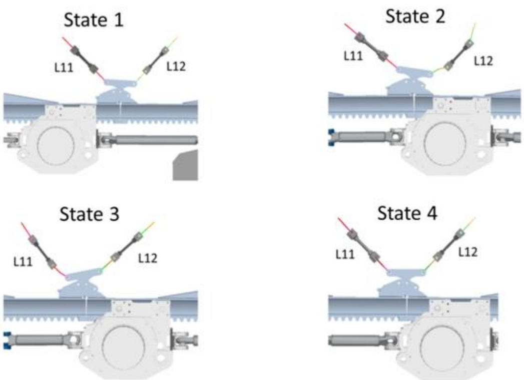

Fig. 5. Different states of the suspension tension depending on the emergency braking phase of the set [8]

Acceleration and vibrations acting on the monorail operator in the operator's cabin and on the moved personnel in the passenger cabin were also recorded, during the simulation of emergency braking and monorail travel at higher speed (5 m/s) Fig. 6 [8, 11, 12].

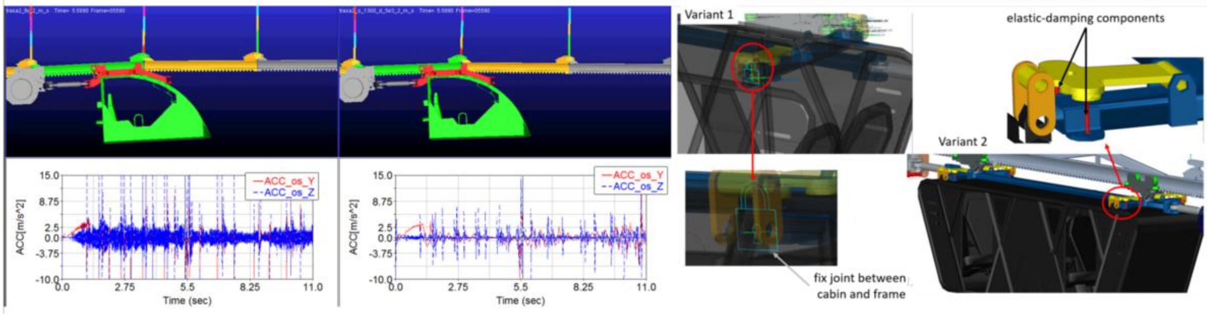

Fig. 6. Simulations of vibrations affecting operator and personnel in suspended monorail [7]

The simulation series for acceleration and vibration analysis was aimed at optimizing the design of the operator's cabin by selecting the optimal stiffness of the vibration damping inserts, installed as a component of the operator's cabin suspension (Fig. 7) [7, 12].

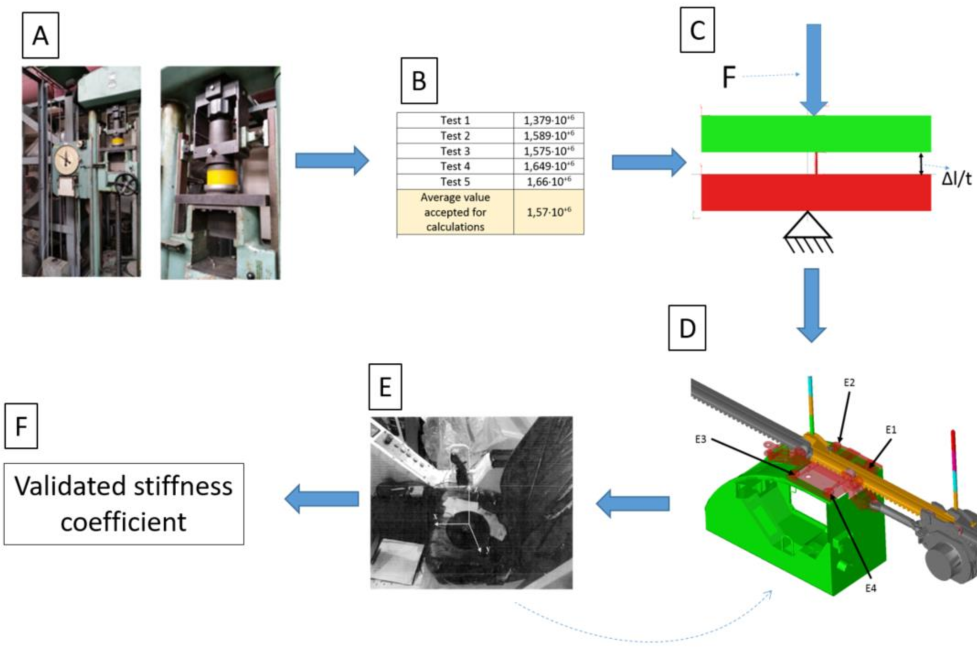

Fig. 7. Process of selecting the rigidity of flexible components in the operator's cab suspension and their verification [12]

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In simulation of a multi-bucket excavator operation in open pit mines, vibrations were also analyzed. Capability to build a computational model with flexible solids (flex type) was used in this simulation. This allowed for the analysis of vibrations resulting from the excavator's operation and in emergency situations, such as hitting the bucket on a boulder in the excavated deposit. The vibrations recorded at selected points on the excavator structure were presented both in the time domain and in the frequency domain (Fig. 8). Selecting the optimal place for installing the additional measuring equipment and assessment of the vibration impact on of these devices operation of and on the accuracy of measurements was the tests objective [13, 14].

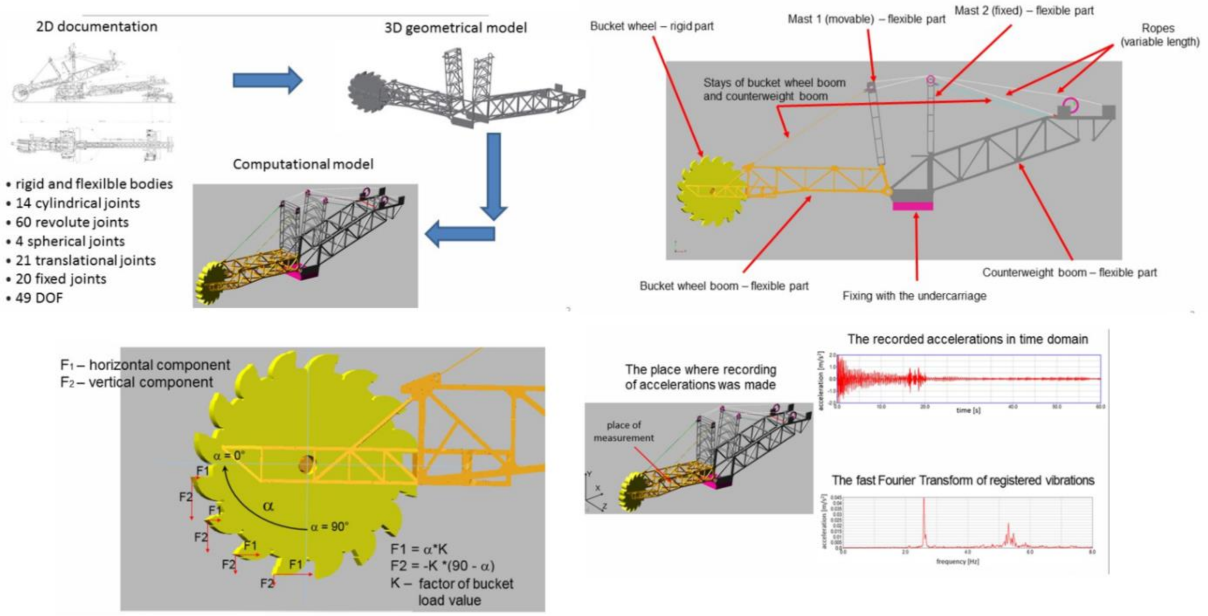

Fig. 8. simulation of a bucket excavator operation [14]

Moreover, due to the use of flexible solids, deformation of the structure resulting from the load on the excavator was taken into account in the model. The natural vibrations of selected components of the excavator, e.g. rope masts, were also analyzed (Fig. 9).

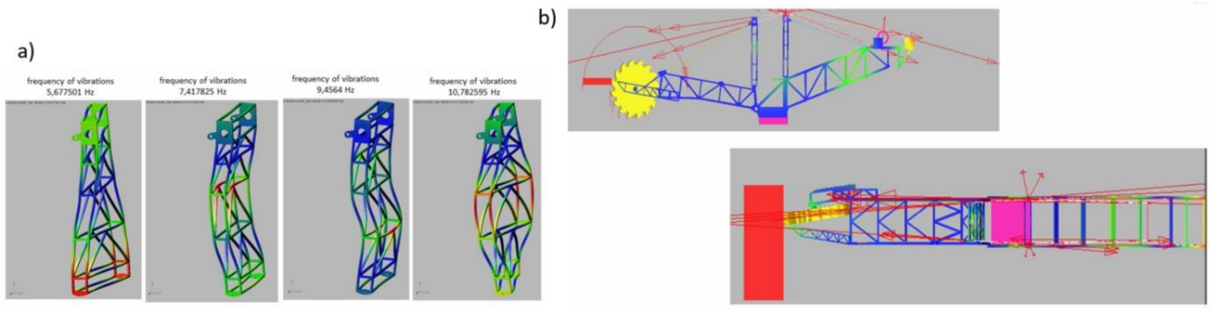

Fig. 9. Simulation with the use of flexible solids:
a) modal analysis of the rope mast, b) deformation of the excavator structure [13]

The ability to perform co-simulations in conjunction with e.g. MATLAB/Simulink software is a very useful and valuable functionality of MBS analyzes. Building a virtual controller that controls the model in the environment for the analysis of kinematics and dynamics is possible due to such integration. Another module that can be integrated with the calculation model in a similar way is the model of additional electrical equipment, including own models of electric motors, models of sensors, controllers, etc. (Fig. 10).

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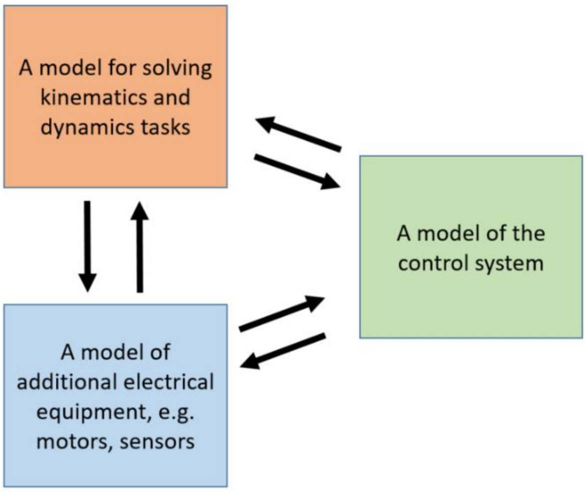

Fig. 10. Co-simulation principle**.**

This approach can be used when simulating a monorail run at a given speed or in other simulation cases where there is a need to use a PID controller, or other methods of controlling or maintaining the set values of selected parameters depending on external factors, e.g. machine load (Fig. 11).

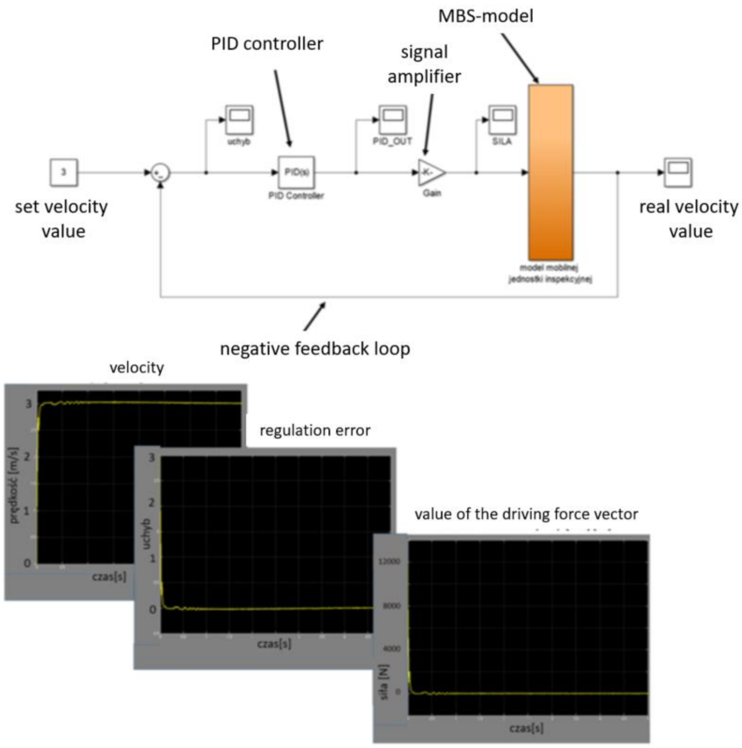

Fig. 11. Possibility of using the PID controller in MBS simulations

Another example of the application of the MBS simulation coupled with the model of the control system and additional electrical equipment were simulations of the operation of the scraper conveyor (Fig. 12) [15, 16].

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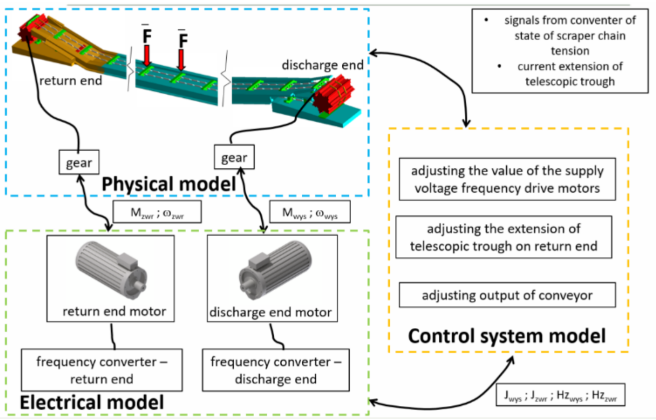

Fig. 12. An example of applying the simulation to analyze the scraper conveyor operation [16]

The simulations enabled identifying the conveyor's operating condition by detecting the condition of excessive tension on the scraper chain or its excessive loosening at the discharge or end station. Then, on the basis of the relationships implemented in the model of the control system, the power frequency of the drive motors was corrected or the extension of the telescopic chute on the return drive was corrected (Fig. 13).

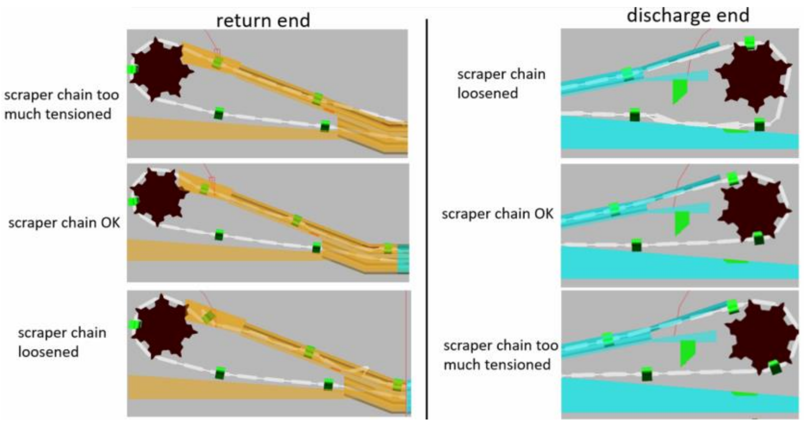

Fig. 13. Selected conditions of the scraper chain tension on the return and discharge drive [15]

Application of the presented co-simulation approach allowed for the development, testing and improvement of the control algorithm aimed at optimizing the operation of the conveyor by maintaining the optimal tension of the scraper chain, regardless of the load condition of the conveyor.

4. Conclusions

Use of the MBS method in virtual prototyping allows for many analyses to support the optimization and development of new innovative machines and devices. As presented, such simulations are used in simple analyses aimed at checking the possibility of a collision, but also in simulations aimed at analysing the flow of forces and determining the boundary conditions for FEM strength analyses. The MBS method is an important tool in analyses aimed at improving the safety and minimizing the impact of vibrations on the operator and the simulations taking into account the machine control depending on their load. Use of virtual prototyping techniques accelerates development of the product and contributes to the care of the environment by not having to build a physical prototype until its correct operation is proved. In addition, numerical simulations enable the analysis of forces, dynamic overloads, even in cases, where bench tests are impossible. Such a situation took place, for example, during the tests of impact of changes in the speed of a suspended monorail. Tests on movement at higher speed required

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constructing the special dedicated test track. It is not possible to test the behaviour of the railway in emergency situation outside this track.

Creating the computational model and its validation on the basis of the above-mentioned test stand enables simulations at any driving speed with emergency braking at different braking forces. In this way, it is possible to analyse the sequential braking method with any distribution of the braking force among a defined number of braking stages. Due to technical limitations consisting in the lack of the possibility of smooth and cheap control of the braking force, such bench tests were not possible. Incorrectly selected parameters in the computational model may result in large errors in the obtained simulation results that is why it is very important to properly validate the computational model. The computational model should be verified and validated whenever it is possible. Such verification may consist in comparing the time process of the forces recorded on the real object with the values calculated in numerical calculations. Fig. 14 shows an example of verification of the validated model of the suspended monorail during in-situ measurements.

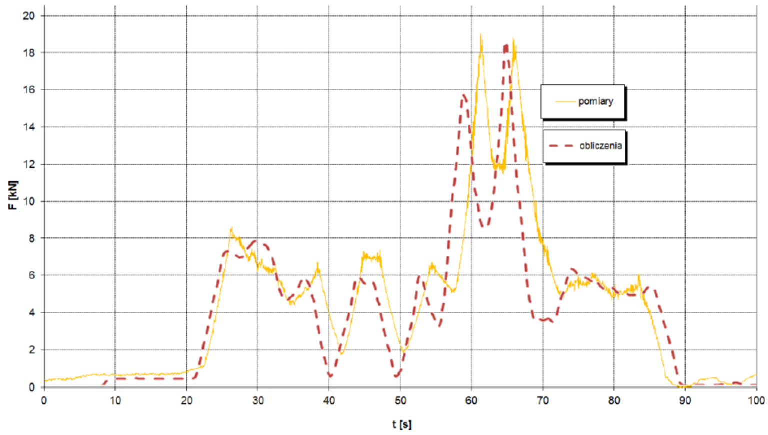

Fig. 14. Comparison of the forces in the suspension recorded in real conditions and obtained in numerical calculations [17]

Sometimes, however, it is not possible to compare the results of numerical analyses with real values, because the analysed device or machine is at the design stage and it is not possible to test it. In such cases, experience simulation is very important, as well as a thorough analysis of the obtained simulation results. Use of MBS methods supports conceptual and modernization work in designing new and innovative machines and devices, the use of which increases their capabilities and at the same time improves the comfort and safety of employees.

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