Supporting development of suspended underground monorails using virtual prototyping techniques

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Abstract. Self-propelled suspended railways are one of the main means of auxiliary transport in underground coal mines. Their dynamic development and increase of their widespread use in Poland took place at the turn of the 20th and 21st centuries. Due to their advantages which include among others no need to maintain tracks on the floor and transport safety. The suspended railway is used instead of other means of transport. Individual subassemblies of the suspended monorails are still under development. Improvement of safety and increase of the work comfort of the operator and conveyed persons are among the objectives of manufacturers of these machines. A possibility of increasing the speed of suspended monorails, especially when convoys are transported, associated with a continuous extension of the access roads to coal mining faces, is also an important aspect. Increasing the speed will enable a more efficient use of personnel’s working time. This article presents an example of using one of virtual prototyping methods to support the modernization process of existing solutions or to support designing of new machines. Use of this method for a modification of the operator’s suspended cabin in a suspended monorail is described.

1. Introduction
The transport system in underground hard coal mines includes the main haulage means, connected with the transport the run of mine to the surface as well as auxiliary means of transport to convey people and to transport materials and equipment to the workplace. The floor-mounted railway, rope-driven suspended monorails and the suspended monorails with their own drive are used in the auxiliary transportation systems. A widespread use of self-propelled suspended monorails increased significantly at the end of the twentieth century. This is confirmed by a rapid increase in the length of suspended monorails routes in the Polish hard coal mines. The suspended monorails gradually replace other auxiliary means of transport. An intensive development and numerous implementations of the suspended self-propelled monorails result from their advantages. Their basic advantages are as follows: no need to keep the track on the floor or a much better mobility as well as increased safety compared to rope-driven suspended monorail [[1], [2], [3]]. However, self-propelled suspended monorails are still under development and there is a lot of intensive research work to be done in this area. Among the objectives that the manufacturers of these machines strive for is an improvement of safety or increase of the operator and conveyed personnel’s comfort. A possibility of increasing the maximum speed of suspended monorail, especially while conveying of personnel is also an important aspect. It is connected with a continuous extension of the routes length to work places. An increase of
the speed limit will enable a more efficient use of employees' work time [1], [4], [5], [6], [7], [8], [9], [10].

Conceptual work on new solutions used in suspended monorails designs or research work aiming at an improvement of already existing designs can be supported by use of virtual prototyping techniques [11], [12]. An analysis of kinematics and dynamics of multibody systems (MBS) is one of these methods. Its use enables, among others, to speed up the designing process of new solutions or a selection of correct parameters of sub-assemblies of suspended monorails. An analysis of stiffness impact of elastic-damping components, used in the suspension of the operator's cabin on the monorail operator’s overload, is one of the examples of using the MBS method. By changing the properties of these components, the operator's overload, especially the one acting in the vertical axis, can be significantly reduced or even eliminated. Correctly selected parameters of elastic-damper components improve the operator's work comfort, which is especially important in terms of a possibility of increasing speed limits of suspended monorails. The results, presented in the article, are developed within the INESI project (Increase Efficiency and Safety Improvement in Underground Mining Transportation Routes), conducted by the international consortium, coordinated by the KOMAG Institute of Mining Technology [1], [4], [8]).

2. Analysis of the operator's cabin suspension

2.1. Verification of the computational model

A preparation and a verification of the computational model are required to conduct numerical simulations and analysis of the stiffness impact of elastic-damping components to overloads acting on the operators of suspended monorails. Figure 1 shows a simplified computational model used to simulate an impact of the stiffness coefficient change of elastic components of the operator's cabin suspension to overloads, acting on the operator during his work. This model consists of the operator's cabin (1) of 450 kg weight, the trolley of the operator's cabin (2) of 208 kg weight, a toothed gear drive (3) of 640 kg weight and the suspended monorails which include the rails of 2 m length (4) and its slings (5). The operator's cabin is connected to the trolley by four elastic-damping components (E1 – E4).

Figure 1. Computational model of the operator's cabin [4].
The stiffness coefficient of the elastic components E1 - E4 has been selected in such a way that it corresponds to the components currently used in the construction of the operator's cabin. Figure 2 shows the method for the computational model adjustment and verification.

The first step (Figure 2 A) consisted in the compression test of the elastic suspension component made of the currently used material. These tests were carried out on a strength testing machine. The compressive force and the deflection of the tested component were recorded during five tests. The test stand, on which the compression tests were carried out, is shown in Figure 3.

On the basis of the results of the carried out tests, the stiffness coefficient of the tested component was calculated in relation to each compression test of the elastic suspension component. Then the average stiffness coefficient was calculated (Figure 2 B). The values calculated on the basis of the tests are shown in Table 1.
Table 1. The results of elastic component compression tests of the operator's cabin suspension [4].

| No. | Stiffness coefficient [N/m] |
|-----|----------------------------|
| Test 1 | 1.379·10^6 |
| Test 2 | 1.589·10^6 |
| Test 3 | 1.575·10^6 |
| Test 4 | 1.649·10^6 |
| Test 5 | 1.66·10^6 |
| Average value | 1.57·10^6 |

Next, a simplified computational model of the test stand was prepared. It consisted of two jaws, the lower one was fixed and the upper one exerted force on the elastic-damping component which replaced the tested elastic component (Figure 2 C). The average stiffness coefficient of the elastic-damping component, calculated on the basis of the previous step of the stand test, was introduced. A value of the compressive force increase was defined in the same way as for the test stand. A deflection of the elastic-damping component of the set stiffness coefficient was recorded during simulations. This step was conducted to verify the correct operation of the elastic-damping component. The deflection values of the elastic damping component, obtained in the model as a result of the set compressive force, were compared with the deflections of the tested suspension component obtained on the test stand. Figure 4 shows a simplified computational model of a test stand and two sample charts showing the comparison of the results calculated by numerical simulation and recorded on the test stand.

Figure 4. The calculation model for verification of the elastic - damping component and test results [4].
After verifying the correct operation of the elastic-damping component as a flexible component of the operator's cabin suspension, the determined stiffness coefficient was introduced to the computational model of the operator's cabin (Fig. 2 D). This value was used in all elastic components of the suspension E1 – E4. Then, a travel of the operator's cabin on a straight section of the suspended monorail, consisting of 2-meter long rails (Fig. 5) was simulated. The cabin speed during simulations was equal to 2 m/s. The acceleration acting on the operator in the cabin was recorded during the cabin movement simulation.

The next step in a verification of the operator's cabin computational model was to compare the overloads acting on the operator calculated by numerical simulations with the values recorded during the vibration tests in the real cabin (Figure 2 E). The tests were carried out on the test track by the machine manufacturer. The overloads were recorded both in the operator’s front and end cabins of the real object. The analyzed components of the operator's cabin suspension were designed to minimize the overload impact acting on the operator mainly in the vertical axis. This is the reason why in the process of the computational model verification an attention was paid to this type of overloads.

Table 2 presents the comparison of vertical axis overloads acting on the operator, recorded on the real object and calculated on the cabin computational model after the correction of the stiffness coefficient of E1 – E4 components.

| No.                      | Stiffness coefficient [m/s²] |
|--------------------------|------------------------------|
| Real measurement         |                              |
| Cabin 1: 0.66 – 0.69     |                              |
| Cabin 2: 0.62 – 0.65     |                              |
| Numerical simulation     | 0.6326                       |

On the basis of the presented comparison of overload values acting on the operator, it is assumed that the computational model of the operator's cabin is verified and can be used in numerical simulations and analyses of the stiffness impact of the cabin suspension components on the operator’s overload.
2.2. Impact analysis of change in the stiffness coefficient of the suspension components on the operator’s overloads

Monorail connections in the suspended monorail track should allow for the rails deflection against each other in the vertical axis by less than $3^\circ$ in both directions. A change in the position of rails against each other can affect the operator’s overloads, when passing through these connections. Due to this fact, the computational model of the operator's cabin was modified by introducing a possibility of changing a deflection of two rail sections on the track on which the cabin moves. The computational model with the modified track is shown in Figure 6.

![Figure 6](image)

**Figure 6.** The computational model of the operator's cabin with the modified track [4].

The computational model prepared in this way was used in numerical simulations. And then, basing on the obtained results, an impact of the stiffness coefficient of the suspension components on values of the overloads acting on the operator in the vertical axis, was analyzed. For this purpose, within the INESI project research work, three materials of different stiffness coefficients were selected.

The components of the operator's cabin suspension were made of these materials. Similarly as for the suspension components made of currently used material, the stiffness coefficient was determined for each of the selected materials. Table 3 presents the determined stiffness coefficients of the analyzed materials.

| Material        | Stiffness coefficient [N/m] |
|-----------------|----------------------------|
| Current material| $1.64 \cdot 10^{16}$       |
| Material A      | $2.122 \cdot 10^{16}$      |
| Material B      | $9 \cdot 10^{5}$           |
| Material C      | $4.72 \cdot 10^{5}$        |

Then, five numerical simulations of the operator's cabin movement on the modified track were conducted. The simulations were performed assuming the stiffness coefficient of the currently used suspension, i.e. the stiffness coefficient determined for the materials A, B and C and for the operator's cabin fixed to the trolley. The overload which affected the operator during the motion was recorded in each simulation. Figure 7 shows the recorded overloads experienced in the vertical axis in the case of the analyzed materials.
Figure 7. The overloads acting on the operator in the vertical axis [4].

A deflection of the components of operator's cabin suspension was another parameter recorded during the simulation. A deflection of the suspension (E1) elastic component of in relation to the analyzed materials is shown in Figure 8.

Figure 8. Deformation of the elastic component E1 of the operator's cabin suspension [4].

Figure 9 shows a comparison of the numerical calculations results of in relation to the material with the highest (material A) and the smallest (material C) stiffness coefficients of the cabin suspension elastic component.

The overloads affecting the operator in the cabin, in the vertical axis, are presented in Table 4. The table shows the maximum, minimum and RMS value of overloads determined by numerical simulations in relation to four selected materials used for a manufacture of the cabin suspension elastic components as well as in relation to the fixed joint between the operator's cabin and the trolley.
Figure 9. Comparison of simulation results for the material with the lowest and the highest stiffness coefficients a) deformation of the elastic suspension component, b) overload acting on the operator, c) displacement of the operator's cabin in the vertical axis [4].

Table 4. Maximum, minimum and RMS values of overloads affecting the operator in relation to different materials used for elastic components of the cabin suspension [4].

| Material                        | Maximum overload [m/s²] | Minimum overload [m/s²] | RMS value of overload [m/s²] |
|---------------------------------|-------------------------|-------------------------|-----------------------------|
| Fixed joint between the cabin and the trolley | 10.0523 | -7.5171 | 1.3431                   |
| Current material                | 5.0549 | -7.0158 | 0.9692                   |
| Material A                      | 5.1997 | -7.6237 | 1.0958                   |
| Material B                      | 3.7267 | -4.3735 | 0.869                    |
| Material C                      | 2.9748 | -4.3695 | 0.7288                   |

Basing on an analysis of the results obtained in numerical simulations, it can be concluded that the stiffness of elastic components used in the operator's cabin suspension has a big impact on the overloads affecting the operator during his work. The fixed joint between the operator's cabin and
the trolley resulted in the biggest overloads affecting the operator's body. It was observed that the material currently used for a manufacture of elastic components, despite the fact that it reduces overloads, is not an optimal solution. Material A from the analyzed materials turned out to be too stiff and thus its use causes an increase in the operator’s overload in relation to the currently used material. The most favourable overloads acting on the operator were observed when using the material with the smallest stiffness coefficient, i.e. Material C. Its use resulted in the biggest deflection of the elastic components in the suspension of the operator's cabin during the motion on the track test segment. It also resulted in the biggest displacement of the operator's cabin and the smallest overloads acting on the operator.

3. Conclusions
The article presents an example of using the MBS numerical simulations in analyzes aimed at a development of suspended monorails solutions. Basing on simulations, the impact of changing the elastic component stiffness coefficient of the operator's cabin suspension was analyzed, concluding that from the materials selected by the manufacturer, the use of type C material is best to minimize the overloads to the operator. In this way, a change of the material used for the elastic components will improve the operator's work comfort.

The computational model was limited only to the operator's cabin of the suspended monorail. However, it is possible to expand the computational model in such a way that it can represent any component of the suspended monorail. The current computational model, developed by the author, also includes a cabin for personnel transportation. Similarly to the method of the analysis described in the article, it is possible to assess the overloads affecting the conveyed personnel. In addition, the use of computer simulations enables an analysis of overloads that affect both the operator and the miners carried in the passenger cabin, not only during normal operation of the suspended monorail but also in emergency situations such as emergency braking. Such simulations enable to estimate hazards in different situations, such as emergency braking while going upward and downward or emergency braking at different speeds. Such a comprehensive analysis enables to develop innovative systems aimed at increasing the safety of personnel conveyed by suspended monorail systems.

In addition, the use of MBS numerical simulations enables an analysis of forces and torques acting at any place of the model. This feature can be used, for example, to analyze the overloads to suspended track suspensions or forces acting in the rail joints. Such knowledge contributes to a development of suspended monorail transportation systems, by modifying the existing designs in order to increase the transportation capacity of the suspended monorail or to analyze a possibility of increasing the maximum speed limit of the suspended monorails. The results of the MBS simulations can also form be boundary conditions for strength calculations of each subassembly of the suspended monorails.

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