Suspended monorail emergency braking trolley computational model verification based on bench tests

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Abstract. This article presents a test bench for the conducting of emergency braking tests. The test bench can be found at the laboratory of the Central Mining Institute. The second part of the article describes a computational model of a braking trolley and of the aforementioned test bench, developed at the KOMAG Institute of Mining Technology. It then proceeds to compare the bench test results with the numerical calculation results obtained at KOMAG. The braking trolley computational model was developed for the purposes of project INESI, in order to conduct analyses of the influence of a suspended monorail’s speed increase on the track load during emergency braking.

1. Introduction
In underground coal mine, the transportation system is very important. It can be divided to: main transport including run-of-mine transportation via the conveyors and auxiliary transportation system. The auxiliary transport is used to transport both materials and personnel. It could be realized via floor-mounted railway or via suspended monorail. The suspended monorail system is more and more popular since last two decades and is still intensively developed. In modern hard coal mining suspended monorails are one of the primary means of auxiliary transport. Nowadays, there is limit of velocity of suspended monorail. On the second hand the trends indicate that systematic elongation of people and materials transportation routes takes place. It means that increasing the velocity limits could be very profitable [1, 2, 3]. However the unforeseen circumstances may arise during a monorail system’s operation, which may necessitate the initiation of emergency braking procedures. Braking trolley activation results in a brake pads clamping on to the rail web and exerting maximum braking force. Depending on the track profile, transported cargo mass and travel speed, emergency braking may lead to dynamic overloads which can influence track suspension or excessive loads which can affect the monorail operator and the transported miners [4]. Work on the European project bearing the acronym INESI, financed by the Research Fund for Coal and Steel, is currently being coordinated at the KOMAG Institute of Mining Technology. One of the objectives of this project is to increase safety during suspended monorail emergency braking through the development of gradual braking force build-up depending on the conditions the monorail is subjected to while braking. A braking trolley computational model was developed and subsequently validated for this purpose. The validation was performed based on the results registered at the test bench located at the Central Mining Institute (GIG, CMI) [5, 6, 7]. This article describes the test bench and the computational model, as well as presents the test results registered at the test bench and obtained via numerical simulations. The verified braking trolley model will be utilised in a transportation system computational model that
will be developed in order to conduct analyses of the influence of emergency braking on monorail track dynamic overloads and of how excessive loads can affect the monorail operator and transported personnel. The analyses will be conducted based on various monorail travel speeds.

2. The Central Mining Institute test bench description

A facility for suspended monorail braking trolley tests can be found at the Central Mining Institute’s Department of Mechanical Device Testing. A diagram of this test stand is presented in figure 1 [5, 6, 7].

![Diagram of the test bench](image1)

**Figure 1.** Braking trolley test bench [7].

The 3 m-diameter flywheel has an 8 mm-thick ring gear. The wheel is driven by an electric motor via belt transmission. The tested braking trolley is mounted in the test stand frame between a clamp holder, to which it is fastened using a chain with a straining screw, and a braking force sensor. The accuracy of the braking force sensor is ±1%. A view of the test bench is presented in figure 2 [5, 6, 7].

![View of the test bench](image2)

**Figure 2.** View of the braking trolley at the test bench [0].
The idea of the test is to gradually bring the flywheel to a desired rotational speed and then brake using the braking trolley, which is released via a hand lever. A linear velocity measurement of a measuring point on the flywheel is carried out during the test. The measurement is performed by an optical sensor with an accuracy of ±0.2 mm/s which is placed in the wheel drive shaft axle. Another parameter measured during the test is the pressure drop in the trolley braking system. This measurement is performed using a strain gauge pressure sensor with an accuracy of 0.5%, while the location of the measurement is shown in figure 3 [5, 6, 7].

![Figure 3. The braking trolley during pressure measurements in the braking system [7].](image)

Data acquired from the measuring sensors during testing is registered on a computer hard disc drive via a measuring amplifier with a frequency of 100-150 Hz. Additionally, it is possible to perform a video recording of the course of the test, using a camera with a frame rate of 600-1200 fps. After the conclusion of the test and the appropriate processing of the acquired data, the following values are obtained: the course of the dynamic braking force, braking distance, pressure change in the braking trolley hydraulic system, flywheel rotational speed as well as the linear velocity of the measuring point on the flywheel. The mass of the rotating flywheel constitutes the equivalent of 521 kg of mass in the analysed linear motion, which was calculated by converting the formulas for kinetic energy in rotational motion. The GIG (CMI) test stand is constructed in such a way so as to make it possible to increase the flywheel rotational mass through certain modernisation efforts [5, 6, 7].

3. Test stand computational model description
A computational model of the GIG (CMI) braking trolley test bench was developed at the Laboratory for Modelling Methods and Ergonomics of the KOMAG Institute of Mining Technology. To develop the computational model, a Multibody System was used. In this method the kinematic and dynamic of the mechanism is calculated on the basis of the solutions of equations of motion, describing the mechanism. The main results of these simulations are: displacement, velocity, acceleration of each segment of the mechanism and the forces and torque acting on the joint and between the bodies [8, 9, 10].

The computational model presented in figure 4 was composed of:

- 10 moving rigid bodies;
- 2 cylindrical joints;
- 5 rotation joints,
- 5 spherical joints;
- 2 sliding joints;
- 2 contact models between selected bodies.
The model has 4 degrees of freedom (DOF).

![Diagram of a braking trolley model](image1)

**Figure 4.** Suspended monorail braking trolley test bench computational model [7].

The flywheel in the model is affected by a torque vector, which acts as the drive. The value of the torque vector was selected in such a way so that, as a result of its influence, the flywheel could reach a rotational speed corresponding to the assumed linear velocity on the measuring point located on the circumference of the wheel. A simplified braking trolley model was used for the computational model (figure 5). The trolley case was mounted in the same way as in the test bench. The brake arms were connected using an elastic-damping element, which ensured a brake release state until braking forces ($F_{brk}$) were engaged.

![Diagram of the braking trolley model](image2)

**Figure 5.** Braking trolley model in the test bench computational model [7].
In order to conduct braking simulations, contact parameters such as stiffness and damping coefficients, maximum penetration of both bodies and friction coefficient between bodies were defined between the brake pad bodies and the flywheel body [7, 8]. The data provided by the manufacturer of the monorail were used to determine the value of the coefficient of friction. According to the manufacturer the clamping force exerted by the brake pads equal to 70 kN resulted in static braking force equal to 83 kN. Based on these data the friction coefficient value of 1.18 was assumed for the numerical simulations [11]. The braking process in the computational model begins when the braking forces pressing the brake pad against the flywheel are initiated. However, the force clamping the brake pad does not increase in steps, but its build-up is spread over time, as presented in figure 6.

![Figure 6](image_url)

Figure 6. Build-up mode of the force clamping the brake pad [7].

The time necessary to reach the maximum brake pads clamping force is related to the inertia of the mechanical and hydraulic system in the actual trolley and constitutes one of the essential parameters during the validation of computational models related to emergency braking numerical analyses [7].

4. Braking trolley tests and numerical analyses
Three variants of braking trolley tests were conducted for both the bench testing and when utilising the computational model. The flywheel rotational speed differed in each variant, and thus: in variant 1, the flywheel rotational speed corresponded to the measuring point linear velocity, equal to 1 m/s; in variant 2, the flywheel rotational speed corresponded to a linear velocity equal to 2.8 m/s; while in variant 3 the flywheel rotational speed corresponded to a linear velocity equal to 5.7 m/s. The results registered during bench testing are presented in figure 7.
Figure 7. Results registered during braking trolley bench tests at linear velocity equal to a) 1 m/s; b) 2.8 m/s; c) 5.7 m/s (F – registered force, L – braking distance, V – measuring point linear velocity, p – pressure in the braking trolley hydraulic system) [6, 7].
In order to compare the results registered during bench testing and obtained from numerical simulations, the graphs in figure 8 present the linear velocity and the braking force. The value of force was recorded at the point of the braking trolley fixation.

**Figure 8.** Charts presenting the values of linear velocity and the force registered at the point of restraint for linear velocity equal to a) 1 m/s; b) 2.8 m/s; c) 5.7 m/s [7].
A quantitative comparison of the results registered during bench testing and calculated for the computational model is presented in table 1.

Table 1. Compilation of the results registered during bench testing and calculated by means of numerical simulations [7].

|                      | V1 – 1 m/s | V2 – 2.8 m/s | V3 – 5.7 m/s |
|----------------------|------------|--------------|--------------|
| Fmax – test bench    | 14 kN      | 40 kN        | 52.3 kN      |
| Fmax – numerical simulations | 15.1 kN    | 41.16 kN     | 53.6 kN      |
| Difference           | ~7.85%     | ~2.9%        | ~2.49%       |
| Braking distance – test bench | 22.5 mm   | 105.2 mm     | 335.5 mm     |
| Braking distance – numerical simulations | 24.9 mm    | 101.8 mm     | 352.3 mm     |
| Difference           | 10.6%      | 3.23%        | 5%           |

The above comparison encompasses the maximum values of the force exerted on the brake rod at the point of restraint as well as the braking distance. Differences in the obtained values were also calculated and presented in percentages. The worst discrepancy between the results obtained during the numerical simulations and the bench tests was 10.6%.

5. Summary
The authors conducted tests of braking trolley at the test stand. During these tests many parameters of the braking trolley were registered. During tests a several values of the angular velocity of the flywheel were taken into account. Next, a computational model of the test bench was built and validated. A computational model of braking trolley is part of bigger one, which contains a complete suspended monorail. Validation of braking trolley model was the first step of validation computational model of suspended monorail. During the validation process it was necessary to determine the following variables: time of braking force (pressing the braking pads to the rail) increasing from 0 to the maximum value and the contact parameters. After validation of all components and whole computational model of suspended monorail will be used to perform numerical simulations. It will be possible to assess the influence the emergency braking to the suspended rail and mining infrastructure. It is planned to carry out extended analyses related to the higher limits of velocity during personnel transportation.

A high consistency of results obtained from test bench and numerical simulation was observed. The lowest concurrence of results registered during the bench tests and calculated by means of numerical simulations was obtained at the lowest flywheel speed – in this case, the braking distance calculated based on numerical simulations was 10.6% longer than the one obtained during bench testing. The braking force difference in this case was just under 8%. The greatest concurrence for the braking force value was obtained at a flywheel rotational speed corresponding to a linear velocity of 5.7 m/s. As a result of numerical calculations, the force was 2.5% greater than the one registered during bench testing. As for braking distance, the greatest concurrence of results was obtained at a flywheel speed corresponding to a linear velocity of 2.8 m/s. In this case, the braking distance calculated based on the simulation was 3.23% shorter than the braking distance registered during bench testing. Based on the presented data, it can be concluded that the results obtained on the basis of numerical simulations reflect the behaviour of the braking trolley to a sufficient degree. The verified and validated computational model can be utilised in numerical simulations during the analyses of emergency states at various suspended monorail travel speeds.
The development and verification of the braking trolley computational model is one of the first stages of work planned as part of the project INESI. The developed braking trolley computational model will find application in the model, which is to be constructed, of a suspended monorail transportation system intended for personnel transport. Overloads affecting the personnel transported using the monorail will be determined based on further numerical simulations. Monorail track suspension loads will also be subjected to analysis. The conducted analyses will concern both the speed permitted by applicable laws as well as increased monorail travel speed. The obtained results will make it possible to develop a new type of braking trolley for which the emergency braking force will be released gradually, in such a way so that no excessive loads which can affect the transported personnel or monorail track may occur.

6. References

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