Research of the Rate of Changing the Mine Suspended Monorail Brakeforce When Braking

E L Ignatkina¹, A V Kostenko², S N Tsarenko²
¹Donetsk National Technical University
²Kamchatka State Technical University

E-mail: fareastcon.2020@gmail.com

Abstract. A technique to determine the rate of increase in brakeforce developed by the braking device of a mine suspended monorail is proposed. Based on the experimental study, the results of the analysis of the rate of change in the brakeforces developed by the brake shoes are given.

1. Introduction
One of the ways to improve the production and technical base of coal mining enterprises is the use of suspended monorails, which has several advantages, among which the below ones should be outlined [1, 2]: the ability to move along curved, alternating routes with small curvature radii; the possibility of combining processes since the lower space used to perform the coal mining work is not cluttered; susceptibility to the rock pressure and mining-induced deformations.

When operating monorails, great attention should be given to safety issues. Braking of rolling stocks (RS) of a mine suspended monorail (MSM) has a significant impact on safety. In the RS braking mode, processes occur that adversely affect the MSM elements. Therefore, the RS braking and its impact on the MSM operation safety in the conditions of underground coal mining require detailed study. Thus, improving the safety of the mine suspended monorails operation is a relevant problem.

The study objective is the development of a technique for obtaining the braking rate values to use in simulating the MSM braking.

To achieve the goal, the below problems should be solved:
– classifying the braking devices used in railway transport in general and identifying those used in the MSM,
– justifying the use of a coefficient determining the braking rate in the mathematical model of the MSM RS motion,
– performing experimental studies to obtain the braking rate values and processing the results,
– introducing a technique for obtaining the braking rate values.

2. Theoretical
The braking mechanisms creating and applying the braking force have a decisive impact on the braking dynamics parameters. In railway transport, braking devices of various designs and operating principles are used. In Fig. 1, a general classification of braking devices is given [4-6].
For the MSM, the scheme of which is shown in Fig. 2, shoe braking devices are most often used [1, 5]. They are usually installed in the front in the direction of travel of the control cabin located in the rolling stock head and behind the last one located at the rolling stock end. Also, braking devices are installed on traction equipment.

Fig. 3 shows the braking mechanism scheme and the brakeforce $T$ created as a result of the applying downforce $P$ to the shoes.
\[ \begin{align*}
\dot{m}_1 \ddot{x}_1 + T_{q1}(t) + c_{12}(x_1 - x_2 + \delta) + b_{12}(\dot{x}_1 - \dot{x}_2) &= 0; \\
\dot{m}_2 \ddot{x}_2 - c_{12}(x_1 - x_2 + \delta) - b_{12}(\dot{x}_1 - \dot{x}_2) + c_{23}(x_2 - x_3 + \delta) + b_{23}(\dot{x}_2 - \dot{x}_3) + \\
+ F_q(t) &= 0; \\
\dot{m}_3 \ddot{x}_3 - c_{23}(x_2 - x_3 + \delta) - b_{23}(\dot{x}_2 - \dot{x}_3) + c_{35}(x_3 - x_5 + \delta) + b_{35}(\dot{x}_3 - \dot{x}_5) + \\
+ m_4 g / h_c(x_3 - x_4 + \delta) &= 0; \\
\dot{x}_4 - g / h_c(x_3 - x_4 + \delta) &= 0; \\
\dot{m}_5 \ddot{x}_5 - c_{35}(x_3 - x_5 + \delta) - b_{35}(\dot{x}_3 - \dot{x}_5) + c_{57}(x_5 - x_7 + \delta) + b_{57}(\dot{x}_5 - \dot{x}_7) + \\
+ m_6 g / h_c(x_5 - x_6 + \delta) &= 0; \\
\dot{x}_6 - g / h_c(x_5 - x_6 + \delta) &= 0; \\
\dot{m}_7 \ddot{x}_7 - c_{57}(x_5 - x_7 + \delta) - b_{57}(\dot{x}_5 - \dot{x}_7) + c_{79}(x_7 - x_9 + \delta) + b_{79}(\dot{x}_7 - \dot{x}_9) + \\
+ m_8 g / h_c(x_7 - x_8 + \delta) &= 0; \\
\dot{x}_8 - g / h_c(x_7 - x_8 + \delta) &= 0; \\
\dot{m}_9 \ddot{x}_9 - c_{79}(x_7 - x_9 + \delta) - b_{79}(\dot{x}_7 - \dot{x}_9) + c_{910}(x_9 - x_{10} + \delta) + b_{910}(\dot{x}_9 - \dot{x}_{10}) + \\
+ F_q(t) &= 0; \\
\dot{m}_{10} \ddot{x}_{10} - c_{910}(x_9 - x_{10} + \delta) - b_{910}(\dot{x}_9 - \dot{x}_{10}) + T_{q10}(t) &= 0,
\end{align*} \]

where \( m_i, m_{10} \) are the brake car masses; \( m_3, m_5, m_7 \) are the carriage masses; \( m_4, m_6, m_8 \) are the masses of the RS suspended elements considering the mass of the cargo; \( m_2, m_9 \) are the masses of traction trolleys; \( h_i \) is the distance between the mass centers of cars and transported goods; \( c_{12}, c_{23}, c_{35}, c_{57}, c_{79}, c_{910} \) are the coupling stiffness coefficients; \( b_{12}, b_{23}, b_{35}, b_{79}, b_{910} \) are coupling damping factors; \( x_1, x_2, \ldots, x_{10} \) are the longitudinal displacements of the RS masses; \( F_q(t), T_{q1}(t), T_{q10}(t) \) are braking forces created by traction trolleys and brake cars.

In theoretical study of the braking dynamics, the below MSM RS motion differential equation system is used [7]:

Figure 3. The MSM Braking Mechanism Scheme:
1 - monorail; 2 - brake shoe; 3 - rod; 4 - lever;
5 - hydraulic cylinder; 6 - spring.
The above mathematical model of RS braking considers parameters significantly affecting the forces in couplings that occur during braking, which affects the oscillation of the MSM elements: elastic-damping links, stiffness, and mass parameters of RS components, and the transported cargo oscillations. Also, the model considers the gaps in the rolling stock couplings since the gap size significantly affects the magnitude and nature of the longitudinal dynamic loads acting on the train carriage structure in the transition modes [7].

Included in the motion equation values of the brakeforces, which are developed during braking, are not constant ones but changing in time \( t \). Also, after acting on the brake mechanism and pressing the shoes to the monorail, the maximum possible brakeforce determined by the traction conditions develops not instantaneously but with a certain delay depending on the material and condition of the interacting surfaces, which affects the braking dynamics and the MSM oscillation processes. Therefore, this should be considered in theoretical studies. The nature of the braking rate can be described by the exponential dependence shown in Fig. 4.

![Figure 4. Curves of Brakeforce versus Braking Time:](image)

\[ T \]

\[ T_{\text{max}} \]

\[ 1 \]

\[ 2 \]

\[ 3 \]

\[ T_1 = T_{\text{max}} (1-e^{-\varepsilon t}), \]

\[ T_2 = f(t), \]

\[ T_3 = f(t). \]

The curves in Fig. 4 differ in the braking rate and can be described by the below equation [8]:

\[ T_j = T_{\text{max}} (1-e^{-\varepsilon t}), \]

where \( \varepsilon \) is the coefficient determining the braking rate; \( t \) is the time; \( T_{\text{max}} \) is the maximum brakeforce determined by the traction conditions.

The coefficient \( \varepsilon \) depends on the material and the condition of the surfaces interacting during braking. The principle of determining its value for monorails in underground coal mining is currently not well understood. In this case, both the frictional properties of contacting materials and the surface conditions should be considered.

In [9], a unit simulating the MSM rolling stock braking device is shown. When performing experimental studies, at the first stage, the braking shoe friction coefficient values under various conditions have been obtained. The results of this experimental stage are given in the above paper.

At the second stage of experimental studies, transient processes occurring in the braking mechanism during braking have been investigated. As a result of the experiment, on the measuring section monitor of the unit, the dependence of brakeforce on the braking time (Fig. 5) has been plotted, which is the result of converting a strain gauge signal using the special ZETLab software.
In the plot represented in Fig. 5, four sections should be distinguished: I - the mechanism response time; II - braking rate; III - steady brakeforce; IV - reduction of brakeforce after a stop.

The coefficient used in the dependence (1) affects the braking rate, i.e. the steepness of the second section of the plot shown in Fig. 5. Therefore, the second section of the plot should be considered in more detail. The table shows the numerical brakeforce values for the second section.

**Table 1. The Brakeforce T Experimental Determination Results.**

| Parameter      | Results      |
|----------------|--------------|
| Time, s        | 0.5 1 1.5 2 2.5 3 3.5 4 |
| Brakeforce, kN | 0.573 1.410 3.381 3.973 3.929 3.941 3.903 4.332 |

Let us represent formula (2) as follows:

\[ T = \Delta T \left( 1 - e^{-\varepsilon(t-t_0)} \right) \]  \hspace{1cm} (3)

where \( \Delta T = T_{\text{max}} - T_{\text{min}} \) is the output value (brakeforce) variation range; \( t_0 \) is the scale origin.

The coefficient \( \varepsilon \) is determined by the least square method:

\[ \sum_{i=1}^{n} (\bar{T}_i - \hat{T}_i)^2 \rightarrow \text{min} , \]  \hspace{1cm} (4)

where \( \bar{T}_i \) is the experimental table force value; \( \hat{T}_i \) are the values obtained from the regression dependence (4) for the corresponding time instant \( t_i \), \( n = 8 \) is the number of points. From condition (4), the below equation has been obtained:

\[ \sum_{i=1}^{n} t_i \ln \frac{T_{\text{max}} - \bar{T}_i}{T_{\text{max}}} - \varepsilon t_i = 0 . \]  \hspace{1cm} (5)

From equation (5), we obtain the equation for determining the coefficient \( \varepsilon \)
\[
\varepsilon = \sum_{i=1}^{n} t_i \ln \frac{T_{\text{max}} - T_i}{T_{\text{max}}} - \frac{\sum_{i=1}^{n} t_i^2}{n}.
\]  

(6)

For the case under consideration, we obtain \(\varepsilon = 0.426\).

In Fig. 6, curve 2 and polygonal line 1 built based on the dependence (3) and the tabular data, respectively, are shown.

![Figure 6](image)

Figure 6. Dependencies of Brakeforce on Braking Time for Section II: 1 - experimental; 2 – theoretical.

To check the adequacy of the dependence obtained, let us determine the adequacy variance [10]:

\[
S_{ad}^2 = \frac{m}{n-1} \sum_{i=1}^{n} (T_i - \bar{T}_i)^2,
\]

(7)

where \(m = 1\) is the number of parallel experiments; \(l = 1\) is the number of significant coefficients of the regression equation; \(T_i\) is the tabular output value for \(m\) parallel experiments, \(\bar{T}_i\) is the output value obtained from the regression equation (2).

For this case, \(S_{ad}^2 = 1.459 \cdot 10^5\)

Since the number of parallel experiments \(m = 1\), the adequacy can be assessed by the relative error value:

\[
\lambda = \frac{S_{ad}}{\Delta T} \leq [\lambda],
\]

(8)

where \(\Delta T = T_{\text{max}} - T_{\text{min}} = 4.500 - 573 = 3.927\) N is the output value (braking force) variation range; \([\lambda] = 0.1\) is permissible relative error.

In our case,

\[
\lambda = \frac{1.459 \cdot 10^5}{3927} = 0.097 < 0.1.
\]

Thus, the dependence adopted can be considered adequate.

3. Conclusions

The technique proposed herein to obtain the braking rate allows determining the values of this coefficient for the materials and conditions of surfaces interacting during the MSM RS braking. The numerical braking rate values obtained allow performing theoretical studies of the MSM braking
dynamics aimed at reducing the impact of negative oscillatory processes occurring during braking on the MSM elements and increasing the MSM operational safety level.

4. References

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