Research of the modern absorbing apparatus power characteristics influence on the freight train inter-car forces

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Abstract. A mathematical model of the inter-car connections used in the long and heavy train is presented. It takes into account the elastic-frictional properties of absorbing devices and gaps in automatic coupler devices connecting the train cars. There are demonstrated the calculation results of a homogeneous train motion along a straight horizontal track section at such non-steady modes as at starting, braking by the locomotive electrodynamic brakes and passing along a track profile section of a complex shape. A comparative assessment of the influence of the kind of the absorbing devices power characteristic on the maximal longitudinal forces arising in the train inter-car connections is carried out using the MSC ADAMS engineering software package. Transients with a smooth and sharp change in traction and braking forces are considered. Based on the obtained results, the main positive and negative properties of rigid, linear and soft power characteristics of the automatic couplers’ absorbing devices used on the railway rolling stock are determined. The results of performed computer simulation can be applied to the sphere of design and modernization of absorbing devices of automatic couplers and to the process of composition of various types of cars in trains of any length and weight.

1. Analysis of recent research
The general trend of the railway freight transportation is the maintenance of long and heavy trains, aimed at fuel and energy resources saving. In the inter-car connections of such trains, large longitudinal forces arise and have a significant effect on the cars motion stability and safety. These forces reach their maximal values at unsteady driving conditions: at starting, braking and passing along a track profile section of a complex shape. An increase in train weight standards requires a detailed study of trains longitudinal loading and a development of recommendations for their formation and operation with traffic safety improvement.

An analysis of modern absorbing devices [1] showed that the perspective elastomeric shock absorbers are the most effective from the point of view of longitudinal forces reducing in automatic couplings. The least effective are friction ones. A comparative evaluation of the operational qualities of absorbing apparatuses of various classes was carried out by the authors of [2, 3]. The presented statistics indicates that the introduction of elastomeric devices led to a decrease in the number of railcar injuries during shunting collisions by 3.8 times, incidents with dangerous goods due to damage to the boiler – by 2.1 times, and breakdowns of automatic couplings – by 2.7 times.

To evaluate the absorbing devices operation, a computer simulation is widely used, for example, in [4, 5], so it is required the accurate mathematical description of the objects to obtain reliable results. Articles [6, 7] present mathematical models and force characteristics of absorbing devices, a considered list of indicators and operating conditions of shock absorbers. In [8] it is investigated the possibility of creating a mathematical model based on the dependences of the change in stiffness, the
coefficients of dry and viscous friction on the elastomeric absorbing devices’ deformation. A comparison of the experimental data with the mathematical modeling results for the elastomer flow regime is given in [9]. It was shown that the laminar model has a smaller error in comparison with the turbulent one. Friction-polymer shock absorbers are considered in [10, 11]. In [10] an experimentally proved mathematical model of polymer elements is based on the concepts of hyperelasticity. The article [11] is devoted to the analysis of the influence of ambient temperature on the polymer shock absorbers’ force characteristics. It is shown that the temperature decrease from +15 °C to −60°C leads to a fivefold increase in the dynamic forces in the absorbing devices. The influence of gaps in the automatic couplers on longitudinal forces in homogeneous train inter-car connections is analyzed in the paper [12]. The attention of the article [13] is focused on the efficiency and relative simplicity of the machines’ and mechanisms’ dynamics modeling using the NX Motion Software, which allows to solve complex problems without possessing in-depth knowledge in the field of mechanics.

The final goal of the operation modeling of the automatic couplers’ absorbing devices is the ability of correct determination of the longitudinal dynamics of the train as a whole. The analysis of longitudinal forces using the Matlab/Simulink program was described in [14]. In [15] it is shown that an increase in deceleration from 0.65 to 1.39 m/s² leads to an increase in longitudinal forces maximum values by more than 2.3 times. At the same time, when the braking force growth time changes from 2 to 5 s, the maximal forces decrease by about 20%.

The paper [16] presents the simulation results of the homogeneous and heterogeneous train motion at starting and emergency braking. A comparative assessment of the arising longitudinal forces at unsteady movement modes is given for the train equipped with the spring-friction and with the friction-polymer absorbing devices. It is pointed that when using the last mentioned ones, the forces in the inter-car joints decreases by 10-20% on the average. In [17], the influence of the absorbing device initial tightening force on the train longitudinal accelerations at its transient motion is considered.

The purpose of the presented work is to investigate the influence of the absorbing device force characteristic shape on the value of the maximal longitudinal forces arising in the train inter-car joints.

2. Computer modelling

To solve the problem, there was created a scheme of a train motion model, shown in Figure 1. In the scheme the train is a chain of absolutely solid bodies – train cars moving rectilinearly without vertical vibrations and angular movements.

![Figure 1. A scheme of a train motion model.](image)

A system of differential equations of train motion is [18]:

\[
\begin{align*}
  m_1 \ddot{x}_1 - T_1 - m_1 g \sin \alpha_1 + R &= 0; \\
  m_k \ddot{x}_k + T_k - T_{k+1} - S_k - m_k g \sin \alpha_k &= 0; \\
  m_n \ddot{x}_n + T_n + S_n - m_n g \sin \alpha_n &= 0,
\end{align*}
\]

(1)

where \( m_1 \) – a locomotive mass; \( \ddot{x}_1 \) – longitudinal acceleration of the locomotive and the first car, respectively; \( k = 1, 2, ..., n \); \( T_k \) – forces, acting from the side of the inter-car couplings; \( g \) – acceleration of gravity; \( \alpha_1, \alpha_k \) – the slope of the way which the locomotive and the \( k \)-th car move along; \( R \) – an external force acting on the locomotive (at traction or electrodynamic braking),
including the resistant to movement forces; $S_k$ – force of resistance to movement of the $k$-th car (the calculated formulas of the resistant to the cars movement forces are given in [19]).

The longitudinal force between the cars simulates the operation of the couplers with absorbing devices. The force characteristic of the elastic-frictional absorbing device was adopted as a model of an automatic coupler device ad it can be determined in accordance with the expression [20]:

$$ |T| = \begin{cases} T_L(q), & \text{if } q\dot{q} \geq 0; \\ T_U(q), & \text{if } q\dot{q} < 0; \\ \in [T_L(q), T_U(q)], & \text{if } \dot{q} = 0, \end{cases}$$

(2)

where $q$, $\dot{q}$ – the device compression and compression rate correspondingly; $T_L(q)$, $T_U(q)$ – force characteristics during loading and unloading.

The last line in the expression (2) shows that for $\dot{q} = 0$ the force $T$ is controversially determined and it can have any value in the specified interval. The presented mathematical description simulates the operation of only one shock absorber. A model of an automatic coupler with gaps in the inter-car joints can be represented as a force defined by the expression:

$$ T = \begin{cases} C_L\left[q - \frac{\delta}{2}\right] + T_{0L} \cdot \text{sgn}(\dot{q}), & q \in \left[-h - \frac{\delta}{2}, \frac{\delta}{2}\right] \cup \left[\frac{\delta}{2}, h + \frac{\delta}{2}\right], \text{if } q\dot{q} \geq 0; \\ C_U\left[q - \frac{\delta}{2}\right] + T_{0U} \cdot \text{sgn}(\dot{q}), & q \in \left[-h - \frac{\delta}{2}, \frac{\delta}{2}\right] \cup \left[\frac{\delta}{2}, h + \frac{\delta}{2}\right], \text{if } q\dot{q} < 0, \end{cases}$$

(3)

where $C_L$ and $C_U$ – coefficient of the device rigidity at loading and unloading, respectively; $n_L$, $n_U$ – exponent at loading and unloading; $h$ – maximal stroke of the inter-car connection device; $\delta$ – total clearance in automatic couplings; $T_{0L}$ and $T_{0U}$ – initial protraction force of the absorbing device at loading and unloading.

A computer model corresponding to the presented mathematical description is implemented in the MSC.ADAMS software package. It allows to set the most important characteristics of the train’s movement for research: the number and weight of cars, the gap and the elastic-frictional characteristics of the inter-car joints, the track section profile. To estimate the influence of the absorbing device force characteristic’s type on the maximum longitudinal forces in the train three variants of characteristics were considered: rigid, linear and soft one.

Lines of loading and unloading are defined from the equation:

$$ T(q) = Cq^n + T_0, $$

(4)

where $C$ – stiffness coefficient of the device; $n$ – exponent depending on the design of the device; $T_0$ – force of the initial protraction.

The unloading line is assumed to be the same for the three variants of absorbing devices, and the load lines are selected in accordance with (3) so that the maximum energy intensity of the inter-car joint absorbing devices is the same and equal to 207 kJ. Line equations have the following form:

- for the soft characteristic $T(q) = 4260q^{0.6} + 200$,
- for the linear characteristic $T(q) = 10600q^2 + 200$,
- for the rigid characteristic $T(q) = 88000q^2 + 200$,
- for the unloading line $T(q) = 23000q^2 + 50$.

In the presented equations the stroke of the devices $q$ is assumed in meters.

The maximum values of the inter-car joint devices stroke and the coefficient of irreversible energy absorption are 180 mm and 0.74, respectively. Initial protraction forces are $T_{0L} = 200\,\text{kN}$, $T_{0U} = 50\,\text{kN}$. All parameters correspond to the absorbing device class T1. It should be noted that
ceteris paribus, the force reaches 3 MN, for linear – 2.1 MN, and for soft – 1.7 MN for the case of full compression of the device with a rigid characteristic.

In this work, it is considered the movement of a homogeneous freight train of weight equal to 8000 tons (100 train cars, 80 tons each) along a straight horizontal section of the rail track. The investigated transient modes are: starting, traction force disengaging, braking by the locomotive electrodynamic brakes, braking by the locomotive after disengaging the traction. In all cases, the gaps in the inter-car joints are taken equal to 65 mm, this corresponds to the values for cars after their long operation [21]. In the calculations, the values of external forces (traction or braking one), acting from the locomotive are taken equal to 500 kN, and they change from zero to maximum in 20 seconds.

3. Simulation results

The process of starting off is considered for the case of a pre-compressed train. Graphical dependencies of the maximum longitudinal forces in the train and their distribution along the train length are shown in Figure 2 (in Figure 2 and further, $k$ is the serial number of the train’s inter-car joint).

With a smooth increase in traction force, the tendency for the dynamic forces development and growth occurred in the inter-car joints with soft characteristics. This fact is probably caused by a high rate of force growth at the compression of the absorbing device, which leads to a decrease in the flexibility of the inter-car connection as a whole and an increase in the impact forces propagated along the train length under tension.

![Figure 2. Distribution of maximum forces along the train length at smooth starting off and rigid (1), linear (2) and soft (3) force characteristic of the inter-car joints.](image)

The greatest impact forces with soft characteristics arose in the region of the train free end and exceeded the friction force by 60%. In the train with rigid characteristics, the maximum forces are elastic and distributed in the first half of the train, while the dynamic forces do not reach large values. For the three cases, the elastic forces in the inter-car connections exceed the starting force by 15%.

The process of the locomotive electric braking is considered for two cases: the compressed and the stretched train. The initial braking velocity is 30 km/h. The results of the stretched train braking (Figure 3) are similar to the results obtained for case pre-compressed train starting off. Smooth braking leads to the impact forces appearance in the inter-car joints with soft characteristics, the largest of these forces exceed the braking force by 30%. It should be noted that the soft characteristic leads to the growth of not only shock compressive forces, but also tensile ones arising in the free end of the train at its pulling.

At smooth braking, the elastic damped oscillations occur in the train and the maximal compressive forces at it do not exceed the external influence value. The compressive forces of shock nature are not observed. All types of shock absorbers are characterized by the appearance of insignificant tensile forces in the inter-car joints of the first ten cars.
Figure 3. Maximal compressive forces along the stretched train length at its smooth braking for the cases of the rigid (1), linear (2) and soft (3) force characteristic of the inter-car joint.

There is investigated the process of a smooth transition to the locomotive braking mode after a sharp traction disabling. The train velocity at the beginning of the transition process is assumed equal to 30 km/h, the forces of traction and braking – 500 kN. The calculation results are presented in Figure 4.

As in previous cases, the greatest impact loads occurred in the train equipped with shock absorbers with soft force characteristics. At the same time, the maximal forces in automatic couplings of the train second half exceed the braking force by 30%. In trains with rigid and linear characteristics, the longitudinal forces exceed the braking force by less than 20%.

Figure 4. Distribution of the maximal compressive forces along the length of the train at its smooth braking after disabling the traction force for the cases of the rigid (1), linear (2) and soft (3) force characteristic of the inter-car joint.

The presented calculation results showed that a smooth change in the external force over 20 seconds at various transient motion regimes leads to an increase in dynamic impact forces, appearing due to the presence of the not eliminated gaps at the initial moment of force application. The maximal values arise in the trains equipped with absorbing devices with soft force characteristics. For the further analysis of the influence of the force characteristic type on the longitudinal forces in the train, there are considered the transient movement modes of the train at sharp changes in the external forces.

The transition from the traction to braking mode is investigated. The initial data is the same as for the case of a smooth force change. The only difference is that the locomotive braking power is applied sharply. The calculation results are shown in Figure 5. The highest values of forces, reaching 1.75 MN, arise in the train with rigid characteristics. The least compressive (about 1 MN) and the highest tensile (up to 0.5 MN) forces are observed in the case of soft characteristics of the inter-car connection.
Figure 5. Distribution of the maximal compressive (a) and tensile (b) forces along the train length at the sharp traction force disabling for the cases of the rigid (1), linear (2) and soft (3) characteristics of the inter-car joints.

The similar results are obtained for the cases of the sharp starting off of the compressed train and the stretched train emergency braking:

- at a sharp starting off there is a significant increase in impact forces, exceeding the traction force by two times or more for all types of the inter-car connections. The maximal values of these forces arise in the free train end. On average, the forces in the inter-car joints with a rigid characteristic are greater than the others by 100 kN;
- at an emergency (sharp) braking, the dynamic forces are 1.8-2 times higher than the braking force; the greatest ones arise in the trains with rigid force characteristics.

The longitudinal loading of the compressed train at its emergency braking is investigated. It should be noted that the dynamic forces occur in the first two thirds of the train length and the forces exceed the braking force by up to 42% for the case of shock absorbers with rigid power characteristics. With linear and soft characteristics, these forces almost do not exceed the applied external force.

The transient process is also caused by switching to the idle mode when the driver controller is turned off. After the traction force disabling, the stretched elastic elements begin to compress, this leads to the appearance of the elastic vibrations in the train. The traction force disabling is shifted by 30 seconds for each case. The smallest compressive forces are observed between cars with soft force characteristic, but in this case, tensile stresses arise in the last cars and reach 450 kN.

4. Conclusions

Based on the presented results, it can be concluded that there are both positive and negative features of all the considered force characteristics of the automatic couplers’ absorbing devices. The positive features of the shock absorber with a rigid force characteristic include the smoothness of the forces transfer between the cars with a slow change in the external force (traction or braking one) and a low tendency to the tensile forces appearing and increasing at the free train end pulling. With a sharp increase in the control action in the train equipped with such shock absorbers, the maximal longitudinal forces arise in comparison with other absorbing devices.

The soft characteristic of the absorbing device leads to a significant impact forces reduction with a sharp change in external influence, leading to the rapid longitudinal elastic vibrations damping in the train. At the same time, the main disadvantages of its operation are: the growth of dynamic forces in the train with a smooth change in the external influence, as well as the facilitation of the tensile forces appearing and increasing at the free train end pulling during transient movement modes.

According to the results of the performed investigation, the linear form of the force characteristic reflected the combination of the properties of hard and soft ones.

The presented results can be implemented in the design and modernization of absorbing devices of automatic couplers and in the composition of various types of cars in trains.
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