CALCULATING ROLLING RESISTANCE OF FREIGHT WAGONS USING MULTIBODY SIMULATION

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INTRODUCTION

One of the factors that show sustainability of the freight railway is the energy consumed for hauling the train. The less is the rolling resistance of the train, the less power is consumed by the locomotive. The rolling resistance of the train depends on many factors, but some of them are strongly dependent on the suspension design of the vehicle. Thus the optimized suspension design should not only achieve acceptable running behavior and track forces, but also provide the reduction of power dissipated while the wagon is in motion.

The paper considers various sources of rolling resistance and proposes a method to calculate rolling resistance using numerical simulation of multi-body vehicle system. Finally comparison is done between energy consumption of the gondola wagon on bogies model 18-9855 (with 25 t per axle load) that are the Barber S-2-R design for Russian railways [1] and the same gondola on model 18-100 bogies (with 23.5 t per axle load).

1. REVIEW OF METHODS TO CALCULATE ENERGY CONSUMPTION

Power consumed by the locomotive when hauling the train is spent for energy transformation and mechanical work on moving the train over the rails [2-4]. Major energy loss appears while moving the wagons and overrunning the tractive resistance. Two types of tractive resistance are usually distinguished: major resistance – motion resistance that is always present due to friction forces in bearings, rolling and sliding resistance of wheels over the rails, dissipation in track structure, aerodynamic resistance; additional resistance – motion resistance due to special conditions, such as track inclination, track curvature, wind, low temperatures, etc.

Modern numerical simulation methods of rail vehicle dynamics allow calculating many members of the rolling resistance and determine their dependence on vehicle and suspension parameters:

- from creep forces by total power of creep forces in wheel-rail contacts;
- from wheels rolling over the rails and wheels sliding over the rails by total power of creep forces in wheel-rail contacts;
- from track irregularities by power of creep forces, power of dissipative forces in track and suspension;
- in track structure by power of dissipative forces in track model;
- from dissipation into the environment by calculating the power dissipated in suspension dampers and friction elements of various types;
- from track curvature by calculating the power dissipated in wheel-rail interface, suspension dampers and friction elements of various types while running the vehicle in curves.

Members of rolling resistance that are impossible to estimate numerically using multi-body approach and should be obtained from empirical data are resistance from friction in bearings, resistance from pure rolling, aerodynamic resistance, track slope resistance, resistance from wind and resistance due to low temperatures. Often in simulation the track structure is modeled in a rather primitive way, thus providing very rough estimation of resistance in track structure. In such case empirical information on track resistance can be used.

2. DYNAMIC MODEL OF WAGON MOTION SUPPLEMENTED WITH CALCULATION OF DISSIPATIVE FORCES’ POWER

Calculation of dissipative forces’ power was done using the gondola wagon model developed in MEDYNA software [5].

Dynamic model of gondola wagon consisted of 23 solid bodies that were car body, two bogie bolsters, four bogie side frames, four wheelsets, eight rail elements and four track elements (figure 1). Bodies were interconnected by elements representing center plate to center bowl interactions, side bearings, secondary suspension load springs, wedges to side-frames interactions, interaction between the wheelset axle box and the side frame, wheel-rail contact and track elastic-damping characteristics.

Inertia characteristics of bodies and interconnection elements parameters corresponded to the parameters of gondola wagon and two types of bogies: bogie model 18-100 being the typical for CIS countries three-piece
design with rigid side bearings with gaps (and the axle load of 23.5 t), and bogie model 18-9855 being the Barber S-2-R three-piece design with constant contact side bearings and split wedge (and the axle load of 25 t) [1].

Bogie model 18-100 secondary suspension with linear characteristic was simulated with a set of elements (further element numbers are given according to MEDYNA denotations [6]): stiffness in three directions of translation and rotation (No. 61) and dry friction in two dimensions (No. 296). Non-linear bogie model 18-9855 secondary suspension was simulated with the same elements plus element No.74 to implement piecewise linear force characteristic. Wedge to side-frame displacements in longitudinal direction were limited with element No.13.

Both bogies has only secondary suspension and wheelset axle box (in model 18-100) or adapter (in model 18-9855) to the side frame interactions were simulated by two elements, that implement limitation of horizontal displacements (No.80) within clearances in longitudinal and lateral directions, and two-dimensional dry friction (No. 296).

Side bearings’ interconnections of both bogies were simulated by element No. 296, which implements dry friction in two dimensions, with the differences in values of parameters, because of bogie model 18-100 rigid with gap side bearings and bogie model 18-9855 constant contact elastic side bearings.

Center plate to center bowl interconnections were simulated by set of elements: spherical joint that allows rotation in three directions (No. 13), elastic element (No. 61) that implements equivalent stiffness at bogies’ pitching and roll, and element No.298 which implements work of dry friction forces in horizontal plane and resistance to yaw.

Wheel-rail contacts were modeled by MEDYNA nonlinear elements No.21 that implement Kik-Piotrowski contact model with multiple non-elliptical contact patches and allow calculating creep forces.

Elastic and damping characteristics of track were implemented by elastic element (No. 61).

Calculation of dissipative forces’ power was made for bogies with maximum possible wear of friction wedges and average wear of wheels (figure 2). Wear of wedges was simulated by reduction of friction coefficient between wedge and side frame, reduction of bolster rotation stiffness value at warping of bogie side frames and lateral stiffness of wedge springs [7].

\[ w = N / \left( m_{\text{wagon}} \cdot V \right) \]

### 3. METHOD OF ESTIMATING THE ROLLING RESISTANCE IN DYNAMIC MODELS

When estimating the rolling resistance on dynamic models it is possible to account for damping forces in wheel-rail contacts and dissipation into the environment through suspension elements, that for three-piece bogies are: side bearings, center plate to center bowl interconnections, vertical surfaces of the friction wedges contacting the side frame friction plates, axle box units (side frames sliding over the axle boxes). The total specific rolling resistance in dynamical model is calculated using formula:
where $N$ is the total average (average taken over the time of motion) power of dissipative forces in the model, $V$ is speed of the wagon, $m_{\text{wagon}}$ is mass of the wagon.

The total average power is correspondingly a sum of power dissipated in wheel-rail contact and power dissipated in the suspension:

$$N = N_{\text{wr}} + N_{\text{susp}},$$

where the power dissipated in wheel-rail contact originating from instantaneous longitudinal and lateral creep forces ($F_{xi}$, $F_{yi}$) multiplied by corresponding creepages ($\xi_{xi}$, $\xi_{yi}$) and velocity (the upper line meaning taking the average value):

$$N_{\text{wr}} = \sum (F_{xi}\xi_{xi} + F_{yi}\xi_{yi})V.$$

The power dissipated in suspension elements (dry and viscous friction) originates from instantaneous values of dissipative forces $F_{\text{susp},j}$ multiplied by corresponding relative velocities $V_{\text{susp},j}$:

$$N_{\text{susp}} = \sum_j (F_{\text{susp},j} \cdot V_{\text{susp},j}).$$

If the distribution of curve radii is known for the certain portion of track, then the power can be further converted statistically:

$$\tilde{N} = \sum_{k=1}^{3} K_k \cdot N_k,$$

where $K_k$ is the proportion of the length of sections of track in in the total length of railway lines. In the work it is proposed to take 0.82 for straight track and large radius curves, 0.06 – for curves of small radius (350 m) and 0.12 – for curves of average radius (650 m).

To compare the suspension types the coefficient $k_\omega$ is introduced

$$k_\omega = (w_0 + w_1)/(w_0 + w_2),$$

where $w_1$ and $w_2$ are specific rolling resistance calculated for suspension 1 and suspension 2 that account for wheel-rail interface and suspension elements, $w_0$ is the specific rolling resistance from aerodynamic forces, dissipation in track and in axle box bearings (it is taken the same for all suspensions).

4. SIMULATION RESULTS AND COMPARISON OF SUSPENSIONS

4.1 Test simulation on straight track

Test simulation was done on straight track at 80 km/h speed. Table 1 shows the results for average power in suspension elements, Table 2 shows the total results for the wagon.

**Table 1: Average power dissipated in suspension elements**

<table>
<thead>
<tr>
<th>Bogie model</th>
<th>Power dissipated in wagon interconnections, kW</th>
<th>Total power, kW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Side frame - axle box</td>
<td>Wedge – side frame</td>
</tr>
<tr>
<td>18-100</td>
<td>0.19</td>
<td>1.78</td>
</tr>
<tr>
<td>18-9855</td>
<td>0.11</td>
<td>2.02</td>
</tr>
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</table>

**Table 2: Average total power dissipated in wagon**

<table>
<thead>
<tr>
<th>Bogie model</th>
<th>Average power in, kW</th>
<th>Total power, kW</th>
<th>Specific rolling resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suspension elements</td>
<td>Wheel-rail contacts</td>
<td>N/kN</td>
</tr>
<tr>
<td>18-100</td>
<td>2.34</td>
<td>5.96</td>
<td>8.30</td>
</tr>
<tr>
<td>18-9855</td>
<td>2.49</td>
<td>2.43</td>
<td>4.92</td>
</tr>
</tbody>
</table>

Analysis of the results of test simulation showed that the proposed methodology allowed seeing the difference between the suspensions of freight wagons from rolling resistance point of view. The power dissipated while wagon is in motion is oscillating and rolling resistance can be estimated using its average value over time.

In wagons with three-piece bogies the proportion of power dissipated in wheel-rail contacts and in suspension elements depends on whether the wagon is running stable or it is hunting. In test simulation the gondola on 18-9855 bogies showed stable running and the power dissipated in wheel-rail contacts was...
approximately equal to dissipation in suspension elements. Bogies model 18-100 having low warping stiffness and lower damping in secondary suspension showed a different distribution: 72% of power dissipated in wheel-rail contact and 28% in suspension elements due to unstable running.

Wheel and rail profiles, gauge, irregularities, friction coefficient between wheel and rail have significant influence on creep forces. As far as these parameters are not well determined, rolling resistance can only be estimated compared to the reference suspension when using numerical simulation.

4.2 Simulation for different sections of track

Figure 3 shows results of the comparison of relative contribution of bogies’ dissipative forces into average dissipated power on straight track and in curves when moving at the speed of 80 km/h.

Figure 3 – The relative contribution of bogies’ dissipative forces in average dissipated power: (a) on straight track; (b) in curve with 650 m radius; (c) in curve with 350 m radius

Analysis of the results of comparison showed that creep force power and dry friction power in suspension are most significant parts. At the speed of 80 km/h the bogie model 18-100 loses stability and is starting hunting and
dominance of creep force power confirms that fact. Bogie model 18-9855 remain stable at that speed, so power dissipation in the friction units dominates.

Figures 4 to 5 show results of simulation on straight and curve tracks for gondola wagon with variation of speed between 40 to 120 km/h with the step of 20 km/h. Table 3 shows the results for coefficient $k_w$.

![Figure 4 - Converted for sections of track power dissipated in the friction units](image1)

![Figure 5 - Converted for sections of track power dissipated in wheel-rail contacts](image2)

![Figure 6 - Converted for sections of track total dissipated power](image3)
Table 3 – The coefficient $k_w$

<table>
<thead>
<tr>
<th>Bogie model</th>
<th>Motion speed, km/h</th>
<th>Converted for the sections of tracks specific rolling resistance, N/kN</th>
<th>Resistance from friction in bearings, N/kN</th>
<th>Aerodynamic resistance, N/kN</th>
<th>Track slope resistance, N/kN</th>
<th>$k_w$</th>
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</thead>
<tbody>
<tr>
<td>18-100</td>
<td>120</td>
<td>1.39</td>
<td>1.80</td>
<td>0.08</td>
<td>1.00</td>
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<tr>
<td></td>
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<td></td>
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<td>40</td>
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<tr>
<td>18-9855</td>
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<td>1.80</td>
<td>0.09</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
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<td>1.15</td>
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<td>0.80</td>
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<tr>
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<td>0.35</td>
<td>0.50</td>
<td></td>
<td>0.95</td>
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<tr>
<td></td>
<td>40</td>
<td>0.34</td>
<td>0.25</td>
<td></td>
<td>1.04</td>
<td></td>
</tr>
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</table>

Analysis of the results comparison between gondola wagon on bogies model 18-9855 (with 25 t per axle load) and the same gondola on model 18-100 bogies (with 23.5 t per axle load) showed that:

- bogie model 18-9855 design features, such as: non-linear suspension with increased elasticity, friction in worn-out condition and resistance to warping, as well as constant contact side bearings provide reduction of creep forces and total rolling resistance, which reduce bogie and track wear and also energy consumption at speeds in the range of 40…120 km/h;
- bogie model 18-100 design in worn-out condition can’t provide sustainability after the speed of 85 km/h is exceeded, rapid increase of creep power forces confirms that.

References