The 21st International Congress on Sound and Vibration
13-17 July, 2014, Beijing/China

DYNAMIC CHARACTERISTICS STUDY AND VIBRATION CONTROL OF MODERN TRAM TRACK SYSTEM


Luoyang Ship Material Research Institute, Luoyang, China 471003

e-mail: zy_zhang10@126. com

This paper describes a removable structure for tramway track system of modern tram, which includes rubber casings, waterproof cushion, special fasteners and removable road bed. Tram vehicles and tracks are modeled and analyzed by using MSC Nastran and Simpack. The static and dynamic response of the structure to the tram operating and the road vehicle rolling loads are analyzed by finite element method. The results show that the rail head lateral deflection is less than 2mm, and stress is less than 214Mpa, which meet the rail safety criteria. The track-vehicle dynamic simulation software Simpack is used to predict the dynamic behavior of tram on the traditional tramway system with maximum speed of 70km/h. The analysis show that, without track excitation, the vertical force discrepancy on the tram rail can be reduced by 8.5kN comparing with on the traditional track, while derailment coefficient decreased by 0.1. When track is subjected to level 5 FTA excitation, the maximum reduction of the vertical force discrepancy with tram rail is 12kN than on the traditional rail, while derailment coefficient decreased by 0.7. So the removable rail system can ensure the safe operation of the vehicle while achieving easy maintenance and replacement, and reducing the dynamic response of the wheel-rail vehicle operation, with a significant effect on vibration reduction.

1. Introduction

The pressure on urban transportation with the rapid progress of urbanization in China continues to increase. The transportation dominated by road traffic brings many problems such as traffic congestion, noise, serious air pollution and so on. Although subway and light rail transit which can carry passenger in large masses, and are commonly used in the most of large cities, but for smaller cities, the high financial cost, long construction period of such systems are not always feasible. So modern trams as alternative with many advantages like environmental protection, energy saving\cite{1}, comfort, short construction period and low cost, emerge in recent years, becoming research priorities of rail transport all over the world.

Compared with the traditional ones, modern trams operate with high speed, comfort and precision operating time. And more importantly, unlike the tradition trams which need completely separate right of way, modern trams use tramway tracks, this enable them to share the road with other transportation vehicles. Also they can adapt to a smaller bend radius\cite{2}, therefore it needs less alterations to the existing road layout.

However there are other problems with tramway rail system. Because it is to be integrated into the current road system, the tramway tracks are close to the residential areas. The more attentions are needed to noise and vibration control, the safety of the rail and vehicles, while track drainage and turnout control also need careful considerations.
This paper describes a removable structure for tramway track system, which can ensure the safe operation of the vehicle, and reduce the dynamic response of the wheel-rail vehicle operation, with a significant effect on vibration reduction.

2. **Structure of the track system**

The tramway track system of modern tram includes rubber casing, waterproof cushion, special fastener and removable road bed as shown in Fig.1.

![Figure 1. Structure of modern tramway track system](image)

Both sides of rails are filled with rubber casings, which act as the protection of rails from water and hard contact with road bed, and also can reduce the vibration by increasing the line density of rails. Waterproof cushions are placed under tracks and laid continuously. For a better waterproof performance, the number of seams should be as little as possible, and the overlap width of cushions should be 30-50mm.

Tracks are fixed by special fasteners and removable road bed blocks, and this arrangement effectively reduces rail vibration. The removable blocks can also be filled and compacted on the same surface level with convenient construction. Because fasteners are buried under the road surface, a protective covers are adopted to prevent corrosion problems and damage during maintenance, and ensure normal operation.

The development of modern tram track system is still in the early stage in China. With many advantages, this track system will provide great opportunity for urban transportation in the near future.

3. **Safety evaluations**

Modern tram track systems are close to the residential areas, so the safety requirements are more stringent. Refer to the class I dynamic rail gauge maintenance standard of the "Railway Line Maintenance Rules"[3], when the vehicle speed \(v\) is less than 100km/h, track gauge offset shall be within the range between -6mm and +12mm.

Groove rail are used for the requirement of wheels operation space. Rail cross-section is shown in Fig.2; Table 1 shows some parameters of the track system.

<table>
<thead>
<tr>
<th>Structure parameters</th>
<th>value</th>
<th>Structure parameters</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail Young’s Modulus(GPa)</td>
<td>210</td>
<td>Rail sectional area(m²)</td>
<td>76.52E-4</td>
</tr>
<tr>
<td>Rail passion ratio</td>
<td>0.3</td>
<td>Rail pad stiffness(kN/mm)</td>
<td>20</td>
</tr>
<tr>
<td>Rail moment of inertia(m⁴)</td>
<td>3.302E-5</td>
<td>Sleeper spacing(m)</td>
<td>0.625</td>
</tr>
</tbody>
</table>
3.1 Security analysis of tram operating conditions

The numerical model is built by MSC Nastran. Different from using beam elements to simulate rails as usual\cite{4,5}, the solid elements are adopted\cite{6}, and fastener pads are simplified as uniform springs, so contact between rails and fastener pads can be considered. The track length in the model is 14500mm, the numerical model of the groove rail is shown in Fig 3. Tetrahedral elements are used at the groove part due to the irregular shape, and the hexahedral elements are used at rail waist because of the thin thickness and complex stress condition, besides the mesh size at rail waist is reduced for the accurate prediction of bending moment.

Refer to BS-EN13146-3-2002\cite{8} standard, at the middle of the model, which is also the middle of two fasteners, 25kN lateral load and 50kN vertical load were applied.

Calculated rail lateral displacement is 0.97mm, the stress is 214MPa, which is satisfied with the safety requirements.

3.2 Safety analysis under road vehicle rolling conditions

Due to installation and construction, there is some possibility of other road vehicles rolling on the small part of rubber casing between the rail and road bed. This produces the vertical load on the track system. It is difficult to estimate the value of these forces accurately, because the vertical force varies according to the type and weight of cars, and when car running over the tramway, not only on the casing provide support, but also the rail and the road bed, so the displacement is adopted instead of the force. Fig. 4 illustrates the relationship between vertical displacement and wheel diameter.

The vertical displacement can be calculated from the following formula:

$$
\Delta l = R - h = R - \sqrt{R^2 - \left(\frac{b}{2}\right)^2}
$$

\[(1)\]
Where \( R \) is the radius of the wheel, \( b \) is the width between the road bed and the rails. According to the formula, when smaller the wheel radius is, the greater the change amount of the vertical displacement of the wheel is, and vice versa.

Some types of common car tire size are listed as follows: 165/70R13; 185/60R14; 195/55R15; 195/60R15; 195/65R15; 205/55R16; 215/55R16; 225/50R17; 235/45R17, and common truck tire specification are: 9.00R20; 12.00R22.5-14. Among them, the minimum and maximum wheel widths are 228.6mm and 561.2mm.

For security check, the worst condition is chosen, namely the maximum vertical displacement effecting on the maximum contact area. For the outside rubber casing, \( b=38.3\text{mm} \), for the inside rubber casing, \( b=6.7\text{mm} \). To sum up, the least favourable conditions for the outside rubber casing is \( R=561.2\text{mm}, b=38.3\text{mm}, \) wheel width \( B=228.6\text{mm} \), the largest vertical displacement of the deformation \( \Delta l=0.33\text{mm} \), the largest contact area \( S=8744.0\text{mm}^2 \); whilst the least favourable conditions for the inside rubber casing is \( R=561.2\text{mm}, b=6.7\text{mm}, \) wheel width \( B=228.6\text{mm} \), the largest vertical displacement of the deformation \( \Delta l=0.01\text{mm} \), the largest contact area \( S=1529.3\text{mm}^2 \).

The stress due to the vertical force of two rubber casing under the road vehicle rolling condition was simulated through numerical method by MSC Nastran. The maximum stress is 0.063MPa, on the top of the outside rubber casing, ensuring safety of the track system in the worst conditions.

4. The dynamic performance of the track system

During the operation of loaded vehicles, natural frequencies of the track system are dropped; therefore the vibration control needs to cover a wider frequency range. The natural frequency should be reduced as much as possible without compromising the safety of tram operation. The natural frequency depends on the mass and stiffness of system, the stiffness and mass of the modern system are optimized. Its dynamic performance is compared with the traditional track system.

4.1 The numerical model of the track system

The numerical model of the modern tram track system is built based on the typical passenger train-track vertically simplified lumped equivalent model (shown in Fig.5) created by Zhai\textsuperscript{[9]}, and analysed by Simpack software. The key to the establishment of numerical model is to simplify continuous track system into the multi mass-stiffness system with limited degrees of freedom, which can avoid the process of solving the four order partial differential equations of rail dynamics. The subscript \( r, s, \) and \( b \) represents rails, sleepers and ballast bed, \( M \) represents the equivalent lumped mass, \( m \) represents mass per unit length of rail, \( K_p, K_b \) and \( K_f \) represents equivalent stiffness of rail pad, ballast and foundation, and \( C_p, C_b, C_f \) represents equivalent damping of rail pad, ballast and foundation.

![Figure 5. Typical passenger train-track vertical simplified lumped equivalent model](image-url)
As shown in Fig.5, continuous rails, sleepers and ballast bed are dispersed into equivalent lumped masses. The mass conversion requires the kinetic energy of original elastic beam distribution mass is equal to the kinetic energy of the vibrating system lumped mass.

Taking mass conversion of rails as an example, according to the relationship between flexural deformation and kinetic energy, and the principle that kinetic energy is constant, the rail equivalent lumped mass $M_r$ can be calculated by the following equation:

$$M_r = \left(3/2\beta\right)m_r$$

(2)

Where $\beta$ represents the coefficient of the stiffness of track system under rail and the stiffness of rail, and the unit is m$^{-1}$. The equation of $\beta$ is $\beta = \left(\frac{k_r}{4EI}\right)^{1/4}$. $k_r$ represents unit length elastic coefficient of track system under rail, for the stiffness of rail pad, ballast, and foundation are in series, so the equation is

$$\frac{1}{k_r} = \frac{1}{k_i} + \frac{1}{k_s} + \frac{1}{k_f}$$

(3)

The mass conversion above also applies to the track system under rails, and equivalent conversion coefficient of damping is the same with the conversion of mass.

The stiffness conversion requires the deflection of continuous track system and discrete system being equal under the same load. For continuous system, the deflection can be simplified as:

$$Z_i(t) = (\beta/2k_i)P_0e^{\omega t}$$

For lumped mass system, the deflection is $Z_i(t) = \left(1/k_i\right)P_0e^{\omega t}$, then

$$K_i = (2/\beta)k_i$$

(4)

As shown in the following equations, this relationship can also be used in vertical stiffness calculation of rail pad, ballast, and foundation. $K_r = (2/\beta)k_r$, $K_s = (2/\beta)k_s$, $K_f = (2/\beta)k_f$.

### 4.2 System parameters optimized

There are rubber casings in both sides of the groove rail in modern rail systems, the line density of the rail can be significantly increased to 80.00kg/m (the original linear density is 59.12kg/m), and thus the vibration mass of the rail can be increased. Common stiffness of single rail pad includes 20kN/mm, 60kN/mm and 100kN/mm. Refer to the track parameters of the schedule 5 in Reference [10], the model with two wheels is set up by the equivalent calculation. The sleeper spacing is taken as 0.625m, and the unsprung axle mass is 1600kg.

Through the calculation of wheel-rail forces under six cases consisting of two sets of parameters (stiffness of 20kN/mm, 60kN/mm and 100kN/mm, rail line density 60kg/m, 80kg/m), the rigidity and mass are optimized. Fig. 6 shows the wheel-rail forces when wheels running on the track systems corresponding to these six parameters at a speed of 70km/h.

![Figure 6. Wheel-rail forces on the track systems corresponding to six parameters](image-url)
Fig. 6 shows that, when the rail line density is constant, the natural frequency of the track system and the amplitude of wheel-rail force decrease with the rail pad stiffness decreases; when the rail pad stiffness is constant, the natural frequency of the track system and the amplitude of wheel-rail force decrease with the rail line density increases. From the extent of natural frequency reduction, it can be seen, the effect of rail pad stiffness on system natural frequency and amplitude of wheel rail force is more evident. According to the results, the rail pad vertical stiffness is taken as 20kN/mm, and the rail line density is 80kg/m, then comparing the dynamic characteristics of modern tram track system with these parameters with the traditional track system.

### 4.3 Analysis of the dynamic performance

There is no protection for fasteners in traditional track system during road construction. In this case, when the road is made, cement may penetrate in the fastener and fill around the rail pad, as shown in Fig. 7. This may cause the elastic failure of fasteners, so the stiffness of fasteners in traditional system is always greater.

![Figure 7. Construction of traditional track system](image)

Vehicle parameters refer to the Table 1 in reference [2] and the schedule 2 in reference [10], track parameters references the schedule 5 in reference [10]. As mentioned above, the vertical stiffness of fastener in traditional track is taken as 200kN/mm, referencing ballast stiffness. The vertical stiffness of fastener in modern system is 20kN/mm and the sleeper spacing is 0.625m. There are rubber casings in both sides of the groove rail in modern rail system, the line density of the rail is 80.00kg/m. The equivalent parameters of the two track systems under each wheel are shown in Table 2.

<table>
<thead>
<tr>
<th>Traditional track system</th>
<th>Modern track system</th>
</tr>
</thead>
<tbody>
<tr>
<td>item</td>
<td>value</td>
</tr>
<tr>
<td>Rail mass</td>
<td>67.98kg</td>
</tr>
<tr>
<td>Sleeper mass</td>
<td>144.31kg</td>
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<tr>
<td>Dispersed ballast block mass</td>
<td>758.94kg</td>
</tr>
<tr>
<td>Sleeper space</td>
<td>0.625m</td>
</tr>
<tr>
<td>Rail pad vertical stiffness</td>
<td>613.2 E6N/m</td>
</tr>
<tr>
<td>Rail pad vertical camping</td>
<td>5.65E4N • s/m</td>
</tr>
<tr>
<td>Ballast block vertical stiffness</td>
<td>588.7 E6N/m</td>
</tr>
<tr>
<td>Ballast block vertical camping</td>
<td>5.88E4N • s/m</td>
</tr>
<tr>
<td>Foundation vertical stiffness</td>
<td>10E10/N/m</td>
</tr>
<tr>
<td>Foundation vertical camping</td>
<td>5E4N • s/m</td>
</tr>
</tbody>
</table>
Assuming the tram operates on a curve track with a radius of 300m and the maximum speed of 70km/h, and the length of curve and transition curve is 50m. Fig. 8 shows the vertical wheel-rail forces on two track systems without track excitation. Fig. 9 shows the vertical wheel-rail forces on two track systems with level 5 FTA excitation. Fig. 10 shows the derailment coefficients on two track systems without track excitation, Fig. 11 shows the derailment coefficients on two track systems with level 5 FTA excitation.

When passing a curve, significant vertical force discrepancy between left and right wheels will likely causes the overturning of trams. Figures 8 and 9 shows that the maximal vertical force discrepancy appears when the tram just entering and leaving the transition curve. Figures 10 and 11 shows the maximal value of derailment coefficient also appears on the curve.

As shown in Fig.8 to Fig.11, the vertical force discrepancy and derailment coefficient on modern tram track are all clearly less than those on the traditional track on the curve. Without track excitation, the vertical force discrepancy on the tramway rail can be reduced by 8.5kN comparing with on the traditional track (decreasing amplitude of 9%), while derailment coefficient decreased by 0.1 (decreasing amplitude of 16%). When track is subjected to level 5 FTA excitation, the maximum reduction of the vertical force discrepancy with tramway rail is 12kN than on the traditional rail (decreasing amplitude of 13%), while derailment coefficient decreased by 0.7 (decreasing amplitude of 36%).

5. Installation and waterproof

During the installation, rails, rubber casings, protective cushion and isolation layer are fixed in turn firstly, and then the removable blocks can be done by prefab approach. A lifting device will
be set when installation of removable blocks, so during the track repair and maintenance, the parts can be easily removed by lifting machine.

Modern tram track system is located below the surface, thus requiring good waterproof performance. The gap between rails and foundation is filled with Waterproof caulking compounds, the contact surfaces between rails and rubber casing are brushed by adhesive glue, and the bottom of the rail system is equipped with specialized drainage system to drain water promptly.

6. Conclusions

Tramway and vehicle are modelled and analyzed using MSC Nastran and Simpack. The static and dynamic response of the structure to the tram operating and the road vehicle rolling loads are analyzed by finite element method. Through the study of different numerical calculations, the conclusions are as follows:

(1) The modern tram track system is safe in tram normal operation and road vehicle rolling conditions, with sufficient security (the lateral displacement of a rail head is less than 1.9mm, the stress 214MPa), and the rail system components are not destroyed (two rubber blocks maximum stress 0.063MPa).

(2) The natural frequency of the track system and the amplitude of wheel-rail force decrease with either the rail pad stiffness decreases, or the rail line density increases.

(3) Compared with the traditional track system, the modern tram track system can obviously reduce the vertical force discrepancy and derailment coefficient on the curve line.

REFERENCES