Analysis of Vehicle Dynamic Performance under MCAT Excitation

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Abstract. In order to validate the running safety on track of railway vehicle, a numerical analysis is performed with a multi-body vehicle dynamics model built. Follow the vehicle-track interaction (VTI) evaluation declared in north America standard declared by Federal Railway Association (FRA), a Minimally Compliant Analytical Track (MCAT) worthiness analysis is employed. In this investigation, the analytical track geometry irregularities which consist of surface, vertical and short warp are defined. Then the running performances concerning the derailment safety of the vehicle is discussed by evaluating the wheel unloading and derailment coefficients. Vibration acceleration of the carbody is also monitored to evaluate the ride comfort. By changing the track irregularities MCAT, the impact of track wavelength, gauge and cant deficiency on the dynamic performance of the vehicle can be assessed.

1. Introduction

As the running speed of high-speed trains increases, we make higher requirements for trains’ dynamic performance. Many countries have put forward their own vehicle dynamics standards which differ in ride comfort, running safety and stability of the vehicle. Trans for transnational intermodal must meet different dynamic standards. Shi[1] carried out a study of the American dynamics standard system. Hou[2][3]analyzed dynamic performance of High-speed train on MCAT. In addition, the existing research mainly focuses on the study of track irregularities limit[4][5], the research of vehicle dynamic performance evaluation under American standards VTI and MCAT excitation have not been investigated yet.

For a certain type of high-speed train whose bogie is widely used in the United States, a multi-body dynamic model is established by SIMPACK. The model is made up of several rigid bodies such as carbody, frames and wheelsets. Wheel-rail contact geometry, wheel-rail force and nonlinear suspension characteristics contribute to the nonlinear elements of the model. In this simulation, the excitation of the track is set as ideal geometric irregularities (MCAT). Calculating method and working conditions are introduced. Running safety and ride comfort of the vehicle under different track irregularities are evaluated according to the American dynamic standard VTI (Vehicle-Track Interaction).

2. Multi-body Vehicle Modeling

Railway vehicle is a complex multi-body system. It has not only the interaction force and relative motion between components, but also the interaction between wheel and rail. The following assumptions are made when establishing the mathematical model of vehicle system:
(1) The elastic vibration of wheelset, bogie and carbody is much smaller than that of suspension system. The elastic deformation of each component is neglected.

(2) Regardless of the interaction between adjacent vehicles, single vehicle is adopted in this model. The model of the vehicle is shown in Figure 1. The degree of freedom contained in each part of the model is shown in the Table 1. The specific modeling method of vehicle model refers to the literature[6][7].

| rigid name | longitudinal | lateral | vertical | roll | pitch | yaw |
|------------|--------------|---------|----------|------|-------|-----|
| carbody    | $X_c$        | $Y_c$   | $Z_c$    | $\Phi_c$ | $\Theta_c$ | $\Psi_c$ |
| frame      | $X_{b1-2}$   | $Y_{b1-2}$ | $Z_{b1-2}$ | $\Phi_{b1-2}$ | $\Theta_{b1-2}$ | $\Psi_{b1-2}$ |
| wheelset   | $X_{w1-4}$   | $Y_{w1-4}$ | $Z_{w1-4}$ | $\Phi_{w1-4}$ | $\Theta_{w1-4}$ | $\Psi_{w1-4}$ |
| axlebox    |              |          |          |      |      |     |
| traction beam |          |          |          |      |      | $\Psi_{1-2}$ |

2.1 Nonlinear wheel-rail interaction and force elements
Geometry of wheel-rail contact, can be expressed as a table of wheelset displacement. The median value is approached by linear interpolation, which can be derived by the wheel-rail contact program of SIMPACK. The creep force between wheel and rail is calculated by Kalker nonlinear simplified creep theory program in SIMPACK. Vertical dampers in primary and secondary suspension, lateral stop as well as yaw dampers in this model are considered as nonlinear force elements, and their damping characteristic curves are piecewise linearized[7].

2.2 Rubber spring elements
The static and dynamic characteristics of rubber spring are considered in the model by using N0.42 force element (Dynamic Bushing/Hydromount). The static stiffness of spring in longitudinal, lateral and yawing are simulated by spring force element. The parameters of the force element come from the static stiffness test of rubber spring. Dynamic characteristics are implemented by spring-damping series model. The spring stiffness in series model is 20% of the static stiffness. The damping coefficients are determined by limiting the transmission frequency to 2 Hz.

2.3 Parameters of wheel and rail
Wheel-rail contact plays an important role in vehicle dynamic performance. The parameters of wheel and rail in this model are shown in Table 2.

| parameter       | value   |
|-----------------|---------|
| wheel back distance | 53.39 inch |
3. Numerical Simulation

Minimally compliant analytical track (MCAT) is a common used excitation in American dynamic standard. As shown in Figure 2, irregularities are set as 9 different types such as hunting perturbation, gauge narrowing, gage widening, repeated surface, repeated alinement, single surface, short warp and combination perturbation in MCAT.

In Figure 2, $a$ stands for excitation amplitude and $d$ is the length of each section. The length of $d_3$ section is 1500ft, and that of other sections is 1000ft. $\lambda$ is wavelength of each excitation, among which wavelength of hunting perturbation and short warp are set to 10ft and 20ft respectively. According to FRA 49 CFR 213.333\[(8)\], the VTI limit is used to evaluate the results of simulation under MCAT excitation.

3.1 Evaluation indice

VTI indice for derailment coefficient and acceleration limit is shown in Table 3.

| parameter                              | limit          | filter/window |
|----------------------------------------|----------------|---------------|
| single wheel vertical load ratio $V/V_0$ | $\geq 0.15$    | 25Hz low-pass/5ft |
| single wheel $L/V$ ratio               | $\frac{\tan \delta - 0.5}{1 + 0.5 \tan \delta}$ | 25Hz low-pass/5ft |
| net axle lateral $L_\alpha/V_\alpha$ ratio | $\leq 0.4 + \frac{5}{V_\alpha}$ | 25Hz low-pass/5ft |
| bogie side $L_\beta/V_\beta$ ratio     | $\leq 0.6$     | 25Hz low-pass/5ft |
In Table 3, \( V \) and \( V_0 \) stand for actual and vertical normal vertical load of single wheel, respectively. 
\( L \) is the lateral force on the same wheel. \( L_2 \) is the net axle lateral force, which is exerted by the axle on the rail. Accordingly, \( V_0 \) is the static vertical load of the axle. \( L_3 \) and \( V_3 \) are the lateral and vertical forces that the wheels on one side of the bogie exert on the rail. When processing the acceleration of the carbody, any peak lasting less than 50ms should be excluded.

### 3.2 numerical cases

As shown in Table 4, the vehicle speed increases from 30mph to 105mph at intervals of 5mph, and the track class increase from 2 to 5 correspondingly\(^8\).

| Track Class | speed(mph) |
|-------------|------------|
| Class2      | 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 |
| Class3      | 1 2 3 4 5 6 7 8 9 |
| Class4      | 3 4 5 6 7 8 9 10 11 12 13 14 |
| Class5      | 15 16 17 18 19 |

When the working conditions contain curves, the speed and the cant deficiency need to be matched. Therefore, it is necessary to calculate the radius of the curve at different speeds. The calculation formula is as follows:

\[
R = \frac{C}{2\sin(D_c/2)} \tag{3.1}
\]

\[
D_c = \frac{h_0 + E_u}{0.0007V^2} \tag{3.2}
\]

In the Eq. (3.1) and Eq. (3.2), \( C \) is chord length, 100ft; \( D_c \) is curvature, deg; \( R \) is curve radius; \( E_u \) is cant deficiency, inch; \( V \) is speed, mph; \( h_0 \) is curve radius, inch.

### 4. Results and discussions

Given space limitations, this simulation is carried out under the condition of air spring inflation, new wheel and AW0 loading. When the wavelength of the track excitation turns to 31ft, the results of class 4 and class 5 are summarized in Table 5.

Table 5. VTI indice of class 4 and class 5

| parameter | limit | condition | Class 4 | Class 5 |
|-----------|-------|-----------|---------|---------|
|           | inch  | 65mph | 70mph | 75mph | 80mph | 85mph | 85mph | 90mph | 95mph | 100mph | 105mph |
| single wheel \( V/V_0 \) ratio | 15.0% | Tan. | 0.271 | 0.056 | 0.389 | 0.333 | 0.222 | 0.228 | 0.198 | 0.115 | 0.036 | 0.067 |
|           |       | 3" CD-56.5" | 0.255 | 0.261 | 0.272 | 0.282 | 0.345 | 0.278 | 0.257 | 0.269 | 0.278 | 0.288 |
|           |       | 3" CD-57.0" | 0.329 | 0.336 | 0.362 | 0.351 | 0.478 | 0.261 | 0.269 | 0.277 | 0.281 | 0.269 |
| single wheel \( L/V \) ratio | 1.128 | Tan. | 0.043 | 0.043 | 0.044 | 0.044 | 0.044 | 0.044 | 0.045 | 0.045 | 0.045 | 0.046 |
|           |       | 3" CD-56.5" | 0.351 | 0.363 | 0.377 | 0.397 | 0.424 | 0.425 | 0.446 | 0.456 | 0.484 | 0.501 |
|           |       | 3" CD-57.0" | 0.683 | 0.681 | 0.793 | 0.797 | 0.897 | 0.469 | 0.477 | 0.454 | 0.447 | 0.404 |
| net axle \( L_2/V \) ratio | 0.546 | Tan. | 0.033 | 0.033 | 0.033 | 0.034 | 0.034 | 0.034 | 0.034 | 0.034 | 0.034 | 0.036 |
|           |       | 3" CD-56.5" | 0.130 | 0.130 | 0.143 | 0.156 | 0.175 | 0.145 | 0.149 | 0.162 | 0.179 | 0.194 |
|           |       | 3" CD-57.0" | 0.230 | 0.233 | 0.299 | 0.300 | 0.372 | 0.153 | 0.166 | 0.164 | 0.168 | 0.155 |
Normalizing data in Table 5, that is to say, data in Figure 3 is the ratio of data in Table 5 to their respective limit. In this way, multiple indice can be drawn together to be comparable and we can analyze multiple dynamic indice in one picture, as show in Figure 3. It shows that when the speed increases from 65 to 85mph in class 4, the VTI indice is getting closer to the limit. When the speed exceeds 85mph in class 5, the VTI indice decreases rapidly. Dynamic performance of the vehicle tends to be stable at the speed of 90mph. In general, the vehicle has a good dynamic performance in this condition and the VTI indice is far below the limit in most cases. 3 inch cant deficiency and widening gauge will worsen the dynamic performance of the vehicle.

| bogie side | $L_3/V_3$ ratio | Tan. | 0.028 | 0.028 | 0.029 | 0.029 | 0.030 | 0.030 | 0.030 | 0.030 | 0.031 | 0.031 | 0.033 |
|------------|-----------------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|            | 0.600           |      |       |       |       |       |       |       |       |       |       |       |       |
|            | 3\(^{rd}\) CD-56.5\(^{\circ}\) | 0.227 | 0.243 | 0.255 | 0.267 | 0.291 | 0.277 | 0.288 | 0.292 | 0.300 | 0.308 |      |       |
|            | 3\(^{rd}\) CD-57.0\(^{\circ}\) | 0.408 | 0.407 | 0.457 | 0.459 | 0.515 | 0.300 | 0.297 | 0.284 | 0.278 | 0.252 |      |       |
| carbody P- P acc. Y | 0.650g | 0.043 | 0.044 | 0.046 | 0.049 | 0.050 | 0.050 | 0.052 | 0.054 | 0.056 | 0.058 |      |       |
|            | 3\(^{rd}\) CD-56.5\(^{\circ}\) | 0.074 | 0.076 | 0.070 | 0.076 | 0.084 | 0.080 | 0.067 | 0.067 | 0.078 | 0.090 |      |       |
|            | 3\(^{rd}\) CD-57.0\(^{\circ}\) | 0.122 | 0.124 | 0.127 | 0.120 | 0.137 | 0.073 | 0.075 | 0.079 | 0.077 | 0.075 |      |       |
| carbody P- P acc. Z | 1.000g | 0.011 | 0.012 | 0.013 | 0.013 | 0.013 | 0.013 | 0.013 | 0.014 | 0.014 | 0.014 |      |       |
|            | 3\(^{rd}\) CD-56.5\(^{\circ}\) | 0.018 | 0.018 | 0.016 | 0.017 | 0.020 | 0.018 | 0.016 | 0.016 | 0.018 | 0.021 |      |       |
|            | 3\(^{rd}\) CD-57.0\(^{\circ}\) | 0.030 | 0.031 | 0.032 | 0.032 | 0.035 | 0.019 | 0.021 | 0.021 | 0.020 | 0.020 |      |       |

5. Conclusions
In this paper, a multi-body dynamic model is established to evaluate the dynamic performance of the high-speed train whose bogie is widely used in the United States. The modeling of the multi-rigid vehicle model with various nonlinear elements is introduced. The VTI standard, which is applied to American trains, is the standard of vehicle dynamic performance evaluation in this paper. As the excitation of the simulation, MCAT provides us a variety of geometric irregularities of the track. We can make a complete assessment of the vehicle dynamic performance with the variation of curve, gauge and cant deficiency. In this simulation, the vehicle has a good dynamic performance and the VTI indice is far below the limit. Cant deficiency and widening gauge have an adverse influence on the dynamic performance of the vehicle.
vehicle in most cases.

Acknowledgement
This work was partially supported by National Key R&D Program of China (#2018YFB1201702).

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